V-Cone Wet Gas Metering

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1. INTRODUCTION

Single phase differential pressure (DP) meters can be used to meter wet gas flows if the liquid flow rate can be obtained from an independent source and a suitable wet gas correction factor is available. As it is not a trivial task to measure the liquid flow rate of a wet gas flow, sophisticated wet gas flow meters have been developed that meter the gas and liquid phases simultaneously. The complexity of most wet gas meters means that they tend to be expensive (relative to standard gas meters). Therefore, due to economic necessity, many wet gas flow applications still have single phase gas meters being fitted to meter wet gas flows. This situation is not ideal, as it means poorer metering performance than what is really desired.

An industry goal is to reduce the cost of wet gas metering by producing simpler wet gas metering systems so as all wet gas flow metering applications can have a wet gas meter installed. One simple design concept is the use of a downstream pressure tapping on a Venturi meter to give a second primary reading. This is used in conjunction with the classical DP to derive the gas and liquid phase flow rates simultaneously. This paper describes a decade long DP meter research project that started with Venturi meters and led to the creation of a simple wet gas DP meter design that utilises the V-Cone DP meter and a downstream pressure tapping with a novel, yet simple, methodology for deriving the gas and liquid phase flow rates. The details of the fluid mechanics principles applied, the errors made at various stages of the development and the subsequent lessons learned that led to the successful system are described along with descriptions of the wet gas meters performance. Data from a NEL Venturi meter test and different V-Cone meters at NEL, CEESI and K-Lab's wet gas test facilities are shown.

2. DEFINITION OF WET GAS FLOW PARAMETERS

In this paper wet gas flow is defined as any two phase flow (i.e. gas and liquid flow) that has a Lockhart Martinelli parameter [1] value (X_{LM}) less or equal to 0.3. The Lockhart Martinelli parameter is:

$$X_{LM} = \sqrt{\frac{Superficial\ Liquid\ Inertia}{Superficial\ Gas\ Inertia}} = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}} \quad \text{---- (1)}$$

where $\dot{m}_g$ & $\dot{m}_l$ are the gas and liquid mass flow rates and ρ_g & ρ_l are the gas and liquid densities respectively. Many gas meters have wet gas flow responses that are dependent on pressure. It is possible to non-dimensionalise this effect when analyzing meter wet gas responses by using the gas to liquid density ratio. Often, the gas to liquid density ratio is indicated by the letters "DR". That is $DR \equiv \rho_g / \rho_l$.

The gas and liquid densiometric Froude numbers are expressed as Equations 2 and 3:

$$Fr_g = \sqrt{\frac{Superficia\ l\ Gas\ Inertia}{Liquid\ Gravity\ Force}} = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \quad \text{---- (2)}$$

$$Fr_l = \sqrt{\frac{Superficia\ l\ Liquid\ Inertia}{Liquid\ Gravity\ Force}} = \frac{U_{sl}}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l - \rho_g}} = \frac{\dot{m}_l}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_l(\rho_l - \rho_g)}} \quad \text{---- (3)}$$

Note, "g" is the gravitational constant, A is the pipe cross sectional area, D is the pipe inside bore diameter and U_{sg} and U_{sl} are the superficial gas and liquid velocities respectfully. Note that:

$$U_{s_g} = \frac{\dot{m}_g}{\rho_g A} \text{ ---- (4)} \quad \text{and} \quad U_{s_l} = \frac{\dot{m}_l}{\rho_l A} \text{ ---- (5)}$$

Finally, it is a recurring theme for DP meters that the liquid present in a gas flow tends to induce a positive bias or "over-reading" in the gas flow rate prediction. When a gas DP meter is used with wet gas flow the uncorrected gas mass flow rate prediction is often called the "apparent" gas mass flow ($\dot{m}_{g,Apparent}$). The over-reading is the ratio of the apparent gas flow rate to actual gas flow rate. Often the over-reading (denoted by "*OR*") is expressed as approximately the square root of the ratio of the actual wet gas (or "two-phase") differential pressure (ΔP_{tp}) read and the differential pressure (ΔP_g) that would be read if the gas flow flowed alone (Equation 6) or as a percentage (Equation 6a).

$$OR = \frac{\left(\dot{m}_{g,Apparent}\right)_{TM}}{\dot{m}_g} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \text{ -- (6)}, \quad OR\,(\%) = \left(\frac{\left(\dot{m}_{g_{Apparent}}\right)_{TM}}{\dot{m}_g} - 1\right) * 100\% \cong \left(\sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} - 1\right) * 100\% \text{ -- (6a)}$$

Note subscript "TM" indicates "traditional meter" as it will later be necessary to identify the traditional meter from an unorthodox meter design to be discussed in this paper.

3. PRE - 1997 TWO-PHASE / WET GAS FLOW METER DESIGNS

Prior to the modern oil and gas industries wet gas metering research drive there were several different two-phase designs discussed in the literature. In 1972 Medvejev [2] discussed positioning a positive displacement (PD) meter upstream of an orifice plate meter. Figure 1 reproduces Lin's [3] representation of the Medvejev system. From suitable manipulation of the data from the two independent meters Medvejev showed the gas and liquid phase flow rates could be predicted. In 1982 Chen et al. [4] did similar work and it was claimed that "within the experimental range the root mean square of this method for volumetric flow rate of each phase is less than 7%".

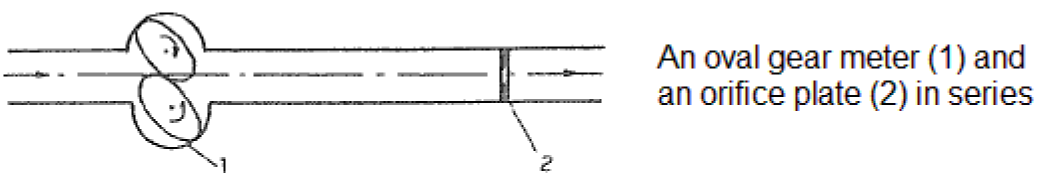


Figure 1. Medvejev Two-Phase Flow Metering System

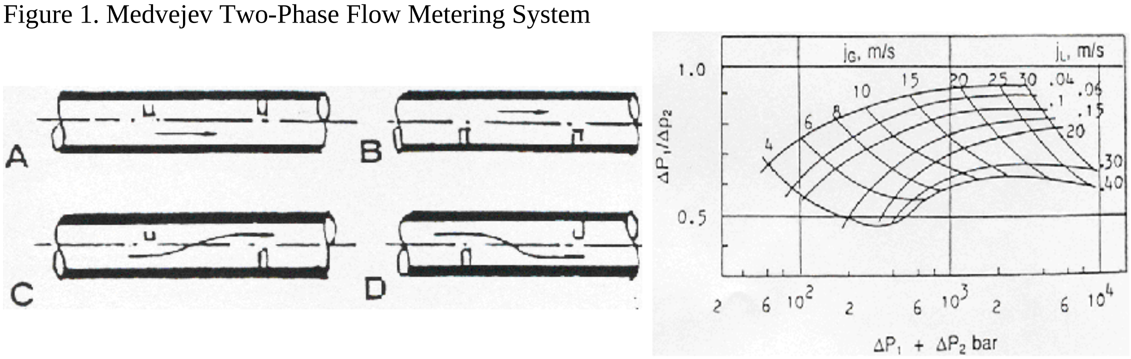


Figure 2. The Sekoguchi Segmental Orifice Plates in Series with a Sample Sekoguchi Data Plot.

In 1978 Sekoguchi [5] placed variously orientated segmental orifice plate meters in series as shown by Lin [3] in Figure 2. The analysis of the data was however, unsophisticated. Sekoguchi plotted constant superficial gas and liquid velocity lines on graphs with the abscissa as the sum of the two differential pressures and the ordinate as the ratio of the two differential pressures. Note Sekoguchi used j_G and j_L to denote superficial gas and liquid velocities. The methods reported accuracy was poor with flow rate errors of $\pm 30\%$. However, this appears to be the first attempt to meter two-phase flow with DP meters in series.

In the 1980's Nguyen [6], patented measuring two-phase flow by placing an orifice plate meter in series with a Venturi meter (see Nguyen's Figure 3 - it is not known if Nguyen took a classical DP or the DP across the Venturi meter as shown in his patent sketch.) Nguyen [7] then patented two orifice meters in series. By the early 1990's British Gas was investigating pairs of DP meters as a wet gas flow metering system. This led to the SolartronISA Dualstream II [8] product. Other derivatives of this generic idea exist. A common theme of these two-phase flow meters is that they rely on two gas meters in series having different wet gas flow responses so as a measurement by difference technique can be utilised.

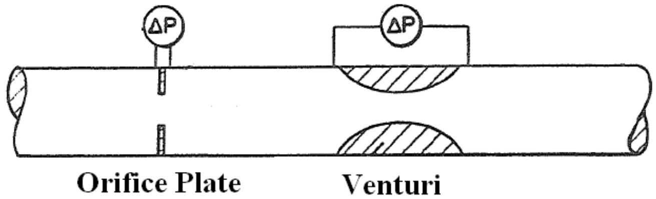


Figure 3. Nguyen's Patented Orifice Plate and Venturi Meter Two-Phase Flow Metering System.

4. DE LEEUW 1997: A SINGLE VENTURI WET GAS FLOW METER CONCEPT

The modern era of wet gas flow meter research started in erhnest with a paper by de Leeuw [9] in 1997. This paper described the response of a Venturi meter to wet gas flow. It was found that a Venturi gas meter has a gas flow over-reading due to liquid present with the gas that is dependent on the Lockhart Martinelli parameter, the gas to liquid density ratio and the gas densiometric Froude number, i.e:

$$OR = \frac{\left(\dot{m}_{g,Apparent}\right)_{TM}}{\dot{m}_g} = f\left(X_{LM}, \frac{\rho_g}{\rho_l}, Fr_g\right) = f\left(\frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}}, \frac{\rho_g}{\rho_l}, \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g\left(\rho_l-\rho_g\right)}}\right) \quad \text{---- (7)}$$

De Leeuw gave the form for the function "f" and this equation is now the most common correction factor for Venturi meters with wet gas flow. The Achilles heel of this metering method is the same as that which exists for all DP meters[1] with wet gas correction factors. That is, the system requires that the liquid flow rate is found from an independent source. The common liquid prediction methods are not continuous and have relatively large uncertainties. This then has a knock affect on the gas prediction method uncertainty.

De Leeuw [9] discussed research that aimed to alieviate this limitation. It was suggested that the permanent pressure loss across the Venturi meter was affected by the liquid presence in the gas flow. Therefore, reading the upstream to throat DP and also the upstream to downstream DP could potentially give enough information to predict both phase flowrates without any requirement for an independent liquid flowrate estimation. Figure 4 shows such a Venturi meter installation [9]. Note a tracer dilution method is also shown but this is outwith the scope of this discussion. The crux of the de Leeuw argument is that it was found that the "pressure loss ratio", which de Leeuw defined as the ratio of the permanent pressure loss (ΔP_{PPL}) to the classic DP read by the Venturi meter (ΔP), is different between dry and wet gas flows. Furthermore, de Leeuw suggested that the change in the pressure loss ratio is directly related to the Lockhart Martinelli parameter, gas to liquid density and gas densiometric Froude number. Figure 5 shows a de Leeuw graph [9] indicating for a set pressure / gas to liquid density ratio, how the Lockhart Martinelli parameter and the gas densiometric Froude number affect the pressure loss ratio. Hence, it was suggested that a function of the form shown as equation 8 (found by data fitting) could be substituted into equation 7 to give some function "h" (as shown in equation 7a), and where, for known fluid properties, a known meter

[1] In this paper the term "DP meter" excludes the cases of pitot static devices and laminar element devices.

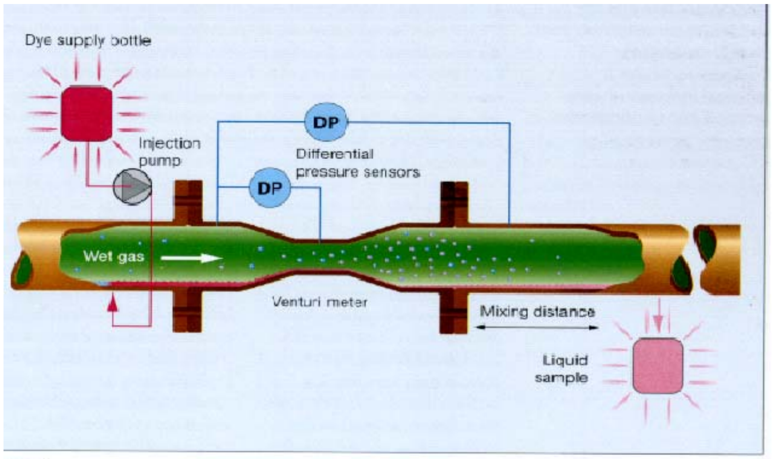


Figure 4. De Leeuw's Double DP Venturi Meter Set Up (with a Tracer Dilution System Indicated).

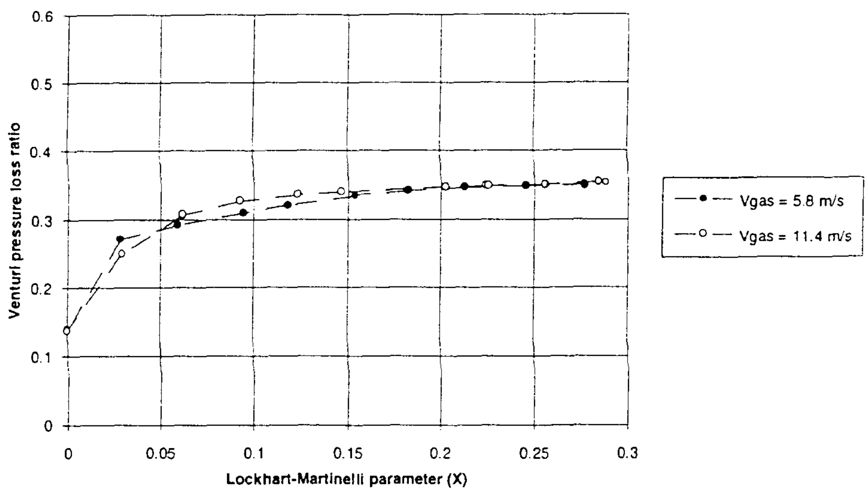


Figure 5. 4", 0.4 Beta Ratio Venturi Meter Pressure Loss Ratio vs. X_{LM} at 45 Bar.

geometry and read DP's, the only unknown in equation 7a is the gas mass flow rate. Once this value is found equation 1 could be utilised to calculate the liquid mass flowrate hence making the stand alone Venturi meter a wet gas meter. A limitation of this method was found independently by de Leeuw [9], Steven [10] and NEL [11] to be that while the relationship is extremely sensitive at low Lockhart-Martinelli parameters it becomes less sensitive at higher Lockhart-Martinelli parameters (e.g. see Figure 5). This idea is therefore seen as useful as a wet gas metering tool, especially at low liquid loadings, but also limited, due to the reduced sensitivity of the permanent pressure loss ratio to the Lockhart-Martinelli parameter at higher wet gas liquid loadings. (Note that in equations 8 and 7a subscript "tp" indicates "two-phase" or "wet gas" conditions.)

$$X_{LM} = g\left(\frac{\Delta P_{PPL_{tp}}}{\Delta P_{tp}}, \frac{\rho_g}{\rho_l}, Fr_g\right) \text{--(8) \&} \quad \frac{\left(\dot{m}_{g,Apparent}\right)_{TM}}{\dot{m}_g} = h\left(\frac{\Delta P_{PPL_{tp}}}{\Delta P_{tp}}, \frac{\rho_g}{\rho_l}, \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g\left(\rho_l - \rho_g\right)}}\right) \text{--(7a)}$$

5. A WET GAS FLOW VENTURI METER PhD PROJECT (1997-2001)

In October 1997, when de Leeuw [9] presented Shell's wet gas Venturi meter paper at the North Sea Flow Measurement Workshop (NSFMW), this author started a wet gas Venturi meter PhD project at NEL / Strathclyde University. This de Leeuw paper was to greatly influence this PhD as de Leeuw had remarked:

"The potential for the pressure loss measurement is to use it as a means to determine the liquid content of the flow, from which the over-reading factor can be determined accordingly. In essence this would form a simple two-phase flow meter. To date, however, no acceptable correlation formula has yet been found that would relate the pressure loss ratio to the actual liquid content and the over-reading. Additional requirements might be required."

The challenge was to sucessfully create a wet gas metering system that was simple and practical for industry. The challenge, on the face of it, this author was to dismally fail. By April 2001 the PhD viva discussion was focused on why the techniques developed had not worked. However, as will be explained in the following chapter the fix was somewhat closer than was then realised, although it was to take nearly four more years for this to become clear. To begin with though, to understand the later V-Cone meter work the PhD generic DP meter theories and test results must first be explained.

The initial PhD work was to review the fundamental single phase flow theories of the DP meter. It immediately became apparent that the same physical principles that apply to the traditional metering section of a DP meter (i.e. the geometric constriction section) could be applied to the downstream geometric expansion section. That is, for single phase gas flow, a flow rate prediction could be made by the classic reading of the difference in pressure between the upstream to throat (i.e. the minimum cross sectional area) or by reading the difference in pressures between a downstream section and the throat. Figure 6 shows a sketch of a generic Venturi meter. Figure 7 shows a sketch of the pressure fluctuation typical through generic DP meters such as Venturi and V-Cone meters. Note that the differential pressure between the upstream to throat (ΔP_t), the downstream to throat (ΔP_r) and the upstream to downstream (ΔP_{PPL}) is related by equation 9:

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \text{--- (9)}$$

Equation 9 is true for all DP meters whether the flow is a gas, liquid or any mix of gas and liquid flow.

The single phase flow equation for the classical DP meter (i.e. using ΔP_t) is given by equation 10 and the unconventional single phase flow equation for the "expansion" DP meter (i.e. using ΔP_r) is given by equation 11. A full derivation of these equations from first principles is given in the Appendix.

$$\dot{m}_g = EA_t \varepsilon C_d \sqrt{2\rho \Delta P_t} = EA_t K_g \sqrt{2\rho \Delta P_t} \quad \text{--- (10)} \quad \text{and} \quad \dot{m}_g = EA_t K_g^* \sqrt{2\rho \Delta P_r} \quad \text{--- (11)}$$

Note "E" is the velocity of approach, A_t is the minimum cross sectional area (or "throat"), K_g and K_g^* are experimentally found coefficients and ρ is the gas density. It can be shown that all DP meters should have the conditions C_d<1, $\varepsilon < 1$ and therefore K_g <1, and, K_g^* >1.

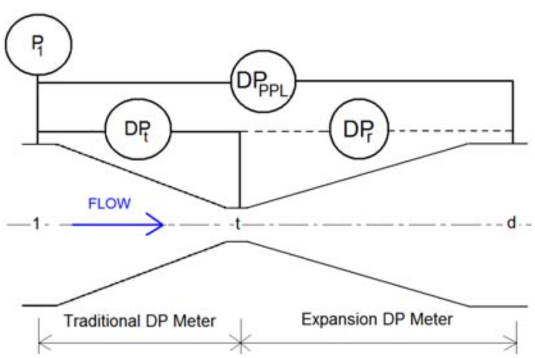


Figure 6. Venturi with DP's Marked Out

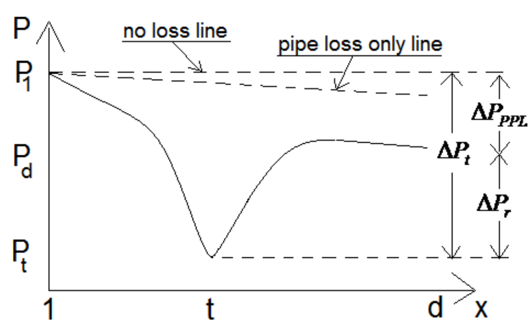


Figure 7. Pressure Fluctuations Through DP Meter.

Figure 8 shows a sketch of the ISA Controls (now known as Solartron ISA) supplied 6", sch 80, 0.55 beta ratio, ISO 5167 Part 4 compliant Venturi meter Steven [10] tested at NEL during commissioning of the

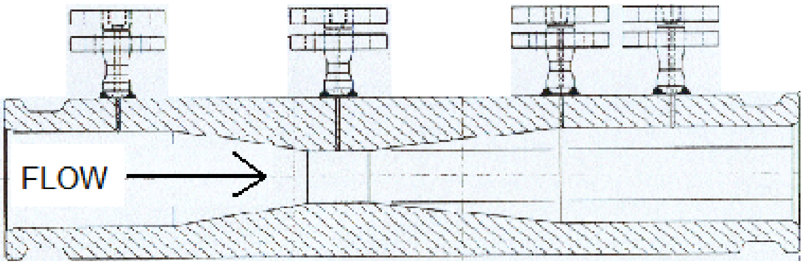


Figure 8. ISA Controls, 6”, 0.55 Beta Venturi Meter Wet Gas Tested at NEL.

NEL wet gas flow facility in September 1999. Note the two downstream tappings. One is at the junction of the diffuser exit and the other is one diameter further downstream. At the time of production early in the PhD project this author requested downstream tappings on the Venturi meter to test de Leeuw’s theories. On request from ISA Controls on where they should be placed this author did not then know. In this very early period of the research (1997) where this author was still learning basic DP meter theory it was guessed that as a Venturi meters diffuser section exists to recover the pressure, the exit of the diffuser must be the position of pressure recovery completion. As an after thought it was countered that this may not be true in reality so as a safe guard a second pressure tapping was included at a further one pipe diameter downstream. Of course, it was realised later in the project that this was a mistake. ISO 5167 part 4 suggests that full pressure recovery is not guaranteed to up to six diameters downstream of the diffuser exit. (However, the meter was built and the tests went ahead with the available equipment. Two differential pressures were read along with the upstream pressure. These were the traditional differential pressure (i.e. the upstream to throat, ΔP_t) and the permanent pressure loss, ΔP_{PPL} (or in this particular case the upstream to furthest downstream pressure tapping available).

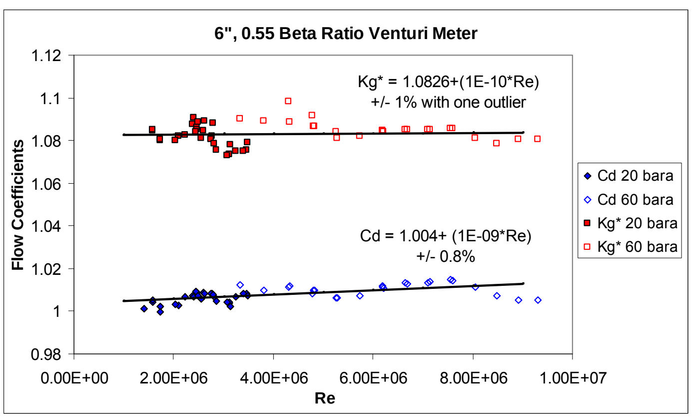


Figure 9. PhD Venturi Meter Traditional and Expansion Meter NEL Calibration Results.

Figure 9 shows the PhD Venturi meter dry gas flow calibration for equations 10[2] and 11[3]. The classic discharge coefficient was found to be slightly greater than unity which is a violation of the basic DP meter theory but a common result for Venturi meters due to the actual value being so close to unity and with real meters having non-ideal effects. The result is therefore a discharge coefficient linear fit slightly greater than unity and a traditional gas meter design with a ±0.8% performance across a ten to one turndown. The unconventional expansion flow coefficient was found to be greater than unity (as expected) and except for

[2] After 8 years the author could not find the zeroing data in the archived PhD raw data sets for the DP transmitters and hence when reproducing the discharge coefficient and expansion flow coefficient values the results are approximate and for explanation purposes only.

[3] In the PhD thesis [10] the Velocity of Departure term was combined with the expansion flow coefficient to simplify the flow equation. In hindsight this has not been done here as it is not convention in industry to combine the Velocity of Approach with the discharge coefficient and it is deemed best for explanatory reasons to keep the new equation as analogous to the conventional DP meter methods as possible.

one outlier (with a repeat point within the range) this downstream meter design had a ±1% performance across a ten to one turndown. (Note that Figure 8 shows pressure has no influence on the coefficient values.) Hence, the data shows that there are two metering opportunities in any one DP meter design and that the second downstream meter is of practical industrial use.

The NEL 6” 0.55 beta Venturi meter nitrogen & kerosene wet gas tests were for 21 Bara, 41 Bara and 61 bara between 400 and 1000 m^3/hr and $X_{LM} \leq 0.3$. The results showed the same Venturi meter wet gas flow trends as reported by de Leeuw [9]. Figures 10 and 11 show this for the three set pressures / gas to liquid density values tested (Figure 10) and for a sample of one pressure with varying gas densiometric Froude numbers (Figure 11). As the Lockhart Martinelli parameter increases for all other parameters constant a DP meters gas over-reading increases. As the gas to liquid density ratio increases for all other parameters held constant the over-reading reduces. As the gas densiometric Froude number increases for all other parameters constant the gas over-reading increases. Figure 11 shows that the apparent scatter for each set pressure (see Figure 10) is in fact not scatter but rather a gas densiometric Froude number effect.

The wet gas Venturi data was fitted using TableCurve 2D and 3D software to produce the correlation shown here as equation 12.

$$\dot{m}_g = \frac{\left(\dot{m}_{g,Apparent}\right)_{TM}}{\left(\dfrac{1 + AX + BFr_g}{1 + CX + DFr_g}\right)} \text{ --- (12)}$$

where A, B, C and D where functions of pressure. It was suggested by the PhD examiners in April 2001 that the function would have been more fitting with $B = D$ and the resulting A, B, C parameters functions of the gas to liquid density ratio to non-dimensionalise the terms.

The expansion meter wet gas data showed some scatter and a complicated relationship between the liquid induced gas flow rate error and the Lockhart Martinelli parameter, gas to liquid density ratio and the gas densiometric Froude number. Figure 12 shows the 61 bara wet gas data as an example. The plot shows the expansion meter “over-reading” (OR*) vs. X_{LM} for the set gas to liquid density of 0.088 and various gas densiometric Froude numbers. In fact, in this case the gas flow rate error is not always positive so the term “over-reading” is used here loosely only to prompt the reader to see the expansion meter liquid induced gas flow rate error as analogous with the traditional DP meter gas error over-reading. Note:

$$OR^* = \frac{\left(\dot{m}_{g,Apparent}\right)_{EM}}{\dot{m}_g} \cong \sqrt{\frac{\Delta P_{r,tp}}{\Delta P_{r,g}}} \text{ --- (13)}$$

where subscript “EM” denotes “expansion meter” and $\Delta P_{r,tp}$ and $\Delta P_{r,g}$ are the recovery (i.e. downstream to throat) differential pressures with two-phase (or “wet gas”) and dry gas flows respectively. Even the simplest useable data fit (say function “j” – as shown in equation 14) was a complex equation.

$$\dot{m}_g = \frac{\left(\dot{m}_{g,Apparent}\right)_{EM}}{j\left(X_{LM}, \dfrac{\rho_g}{\rho_l}, Fr_g\right)} \text{ --- (14)}$$

It was considered unlikely that this complicated equation would fit subsequent data sets precisely as over fitting of data was a significant concern. Furthermore, this complex equation 14 could not have the Lockhart Martinelli parameter separated out to allow substitution into equation 12 (i.e. it was not possible to set up a solution procedure directly analogous to that described for de Leeuw’s method). The only practical method of finding a solution to the two wet gas correlations (i.e. equations 12 and 14) was to separate out the Lockhart Martinelli parameter from equation 12 and substitute that into equation 14.

The results were mixed. There were three types of result across the 243 point data set. The first type of result was the correct prediction of the gas and liquid mass flow rates with relatively small uncertainties. The second was an entirely incorrect prediction. The third was no prediction of any kind. With approximately a third of the results giving good gas and liquid flow rate predictions it was clearly not a coincidence and there was some useful data in the downstream to throat differential pressure reading[4]. It was therefore necessary to investigate why some data sets gave such poor results and others no results. This was done by selecting three individual data points, one for each type of result, and plotting a graph of gas mass flow rate vs. Lockhart Martinelli parameter. These graphs immediately showed the problems. Figures 13 to 15 replicate the graphs shown by Steven [10]. In the legend of these Figures note that "Meter 1" is the traditional Venturi meter and "Meter 2" is the downstream "expansion" meter.

Figure 13 shows one PhD result where the method worked well. Equations 12 and 13 intersected at a gas mass flow rate prediction of 10.45 kg/s and a Lockhart Martinelli parameter of 0.0186. The actual gas flow rate (i.e. reference gas meter reading) was 10.47 kg/s, i.e. a difference of -0.2%. The actual Lockhart Martinelli parameter (derived from the NEL gas and liquid reference meters and density calculations) was

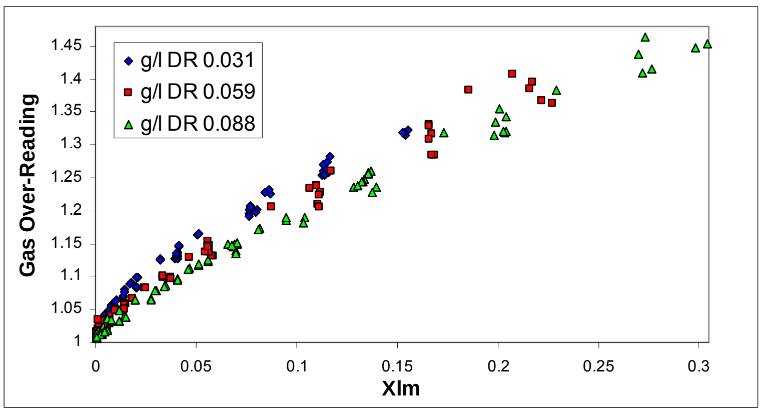


Figure 10. NEL PhD 6" 0.55 Beta Ratio Venturi Meter Wet Gas Data.

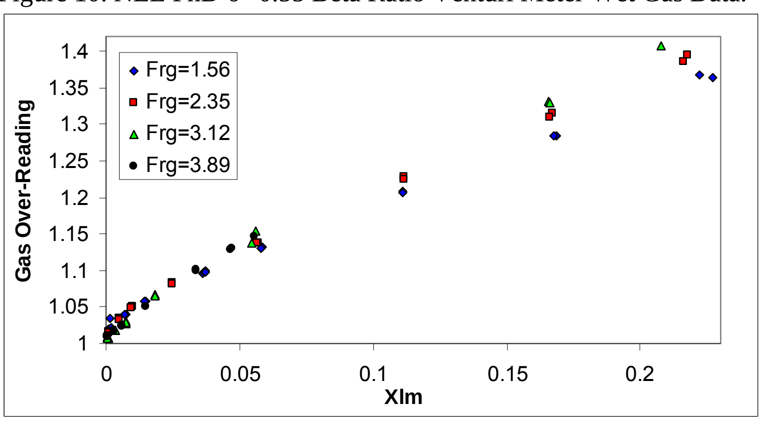


Figure 11. NEL PhD 6" 0.55 Beta Ratio Venturi Meter Wet Gas Data for 41 Bara / DR 0.059.

[4] The Venturi meter tested [10] had the traditional upstream to throat DP and the upstream to downstream DP recorded and the "recovery" DP, i.e. downstream to throat DP was derived from equation 9. There is therefore additional uncertainty in this data compared to if the recovery DP was measured directly. It should also be remembered that the "downstream" pressure tapping was at one diameter downstream of the diffuser exit and hence full recovery had not occurred at the measurement point. A pressure tap position further downstream could possibly reduce the level of scatter. Furthermore, the DP transmitter used was the only available instrument and had a higher Upper Range Limit than was ideal.

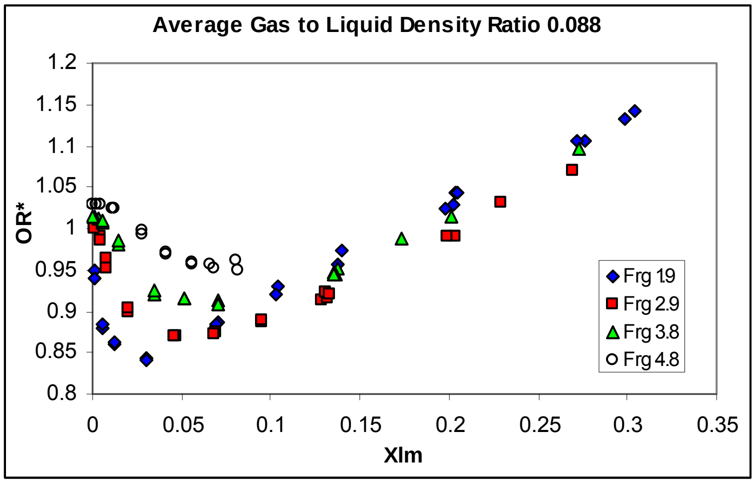


Figure 12. Venturi Downstream / Expansion Meter Equation 11 Wet Gas Response at 60 Barg.

0.0194. This is therefore an error of –3.955% and this error is then passed on to the liquid flow rate prediction. The predicted value of the liquid flow rate of was 0.78 kg/s compared with the NEL liquid reference meter value of 0.80 kg/s, a percentage difference of -3.4%.

Figure 13 shows a problem. It can be seen that for Figures 13 to 15, equation 12 is rather constant in that it always the same general shape when plotted on a gas mass flow rate vs. Lockhart Martinelli parameter graph. However, the complex equation 14 curve has more variation in shape and varies in position relative to equation 12's curve. In Figure 14 this has caused two intersections of the equations. That is, there is a correct result and a false (or "phantom") result. Whether the correct or phantom result is obtained is wholly dependent on what starting gas mass flow rate value is used in the iteration. As this is nothing more than an educated guess this is a problem. In Figure 14 the actual values were gas mass flow rate of 4.1 kg/s, Lockhart Martinelli parameter of 0.162 and a liquid mass flow rate of 3.63 kg/s. The "correct" convergence gives gas mass flow rate of 4.18 kg/s (+2%), the Lockhart Martinelli parameter of 0.144 (-11%) and the liquid mass flow rate as 3.30 kg/s (-9%). The "incorrect" convergence gives gas mass flow rate of 4.82 kg/s (+18%), the Lockhart Martinelli parameter of 0.039 (-76%) and the liquid mass flow rate as 1.03 kg/s (-72%). However, it is noteworthy that the differences in results are relatively large and an operator may be able to tell which result is the real result. However, this is far from ideal.

Figure 15 shows another adverse affect of the equations 14 complex nature. Naturally both equations 12 and 14 have uncertainty limits. That is, the actual data point values they predict do not necessarily lie on the equations but in the uncertainty band associated with each equation. In Figure 15 we see that there is no solution because the two equations do not intersect. As is required by mathematics both equations have the actual point within their respective uncertainty bands (shown in Figure 15 by broken lines). These intersect but the actual equations do not. The result is no solution by attempting to solve by simulatneous equations but when plotting the equations on a graph (Figure 15) it is obvious what the approximate result is. In Figure 15 this "visual estimate" and actual reference data point are marked. A visual estimate is a gas mass flow rate of 5.5 kg/s (compared to the actual 5.44 kg/s, i.e +1%) and a Lockhart Martinelli parameter of 0.1 (compared to the actual 0.122, i.e. -18%). The corresponding liquid mass flow rate estimation is 3.1 kg/s (compared to the actual 3.65 kg/s, i.e. -15%).

This then was the results of the PhD [10] research project. It was concluded it was technically possible to make a simple wet gas meter out of a stand alone standard DP meter using this method but much work was required to produce a workable system for industry. The PhD thesis fell short of offering this. One unanswered question was just what affect the downstream tapping position had had on the results. It was unknown if placing the downstream tapping at or beyond the full recovery point would reduce the complexity of the expansion meters wet gas response. It was also unknown what results other DP meter designs would give under similar test conditions. There was the possibility that another DP meter design would have a better performance than a Venturi meter.

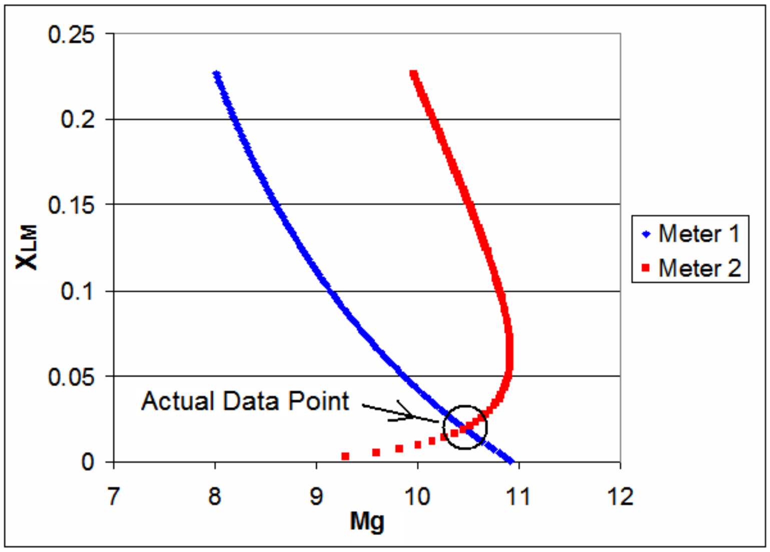


Figure 13. A Succesful Result of Combining Equation 12 and Equation 13.

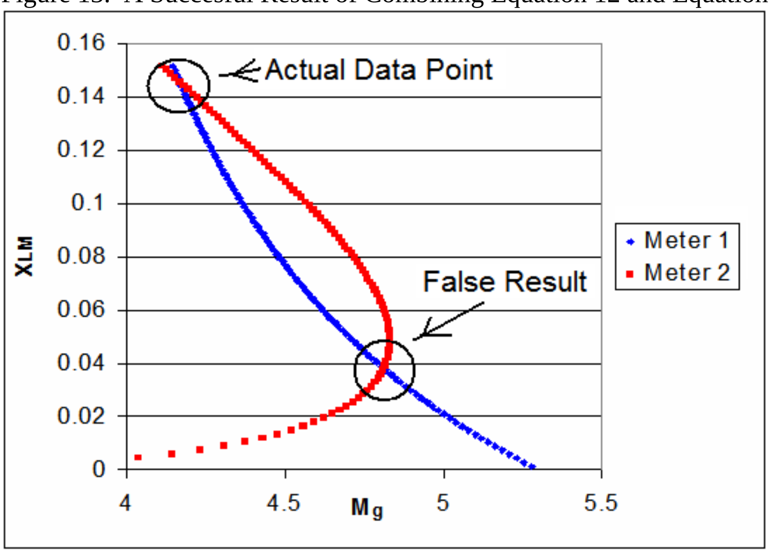


Figure 14. Correct and False Results of Combining Equation 12 and Equation 13.

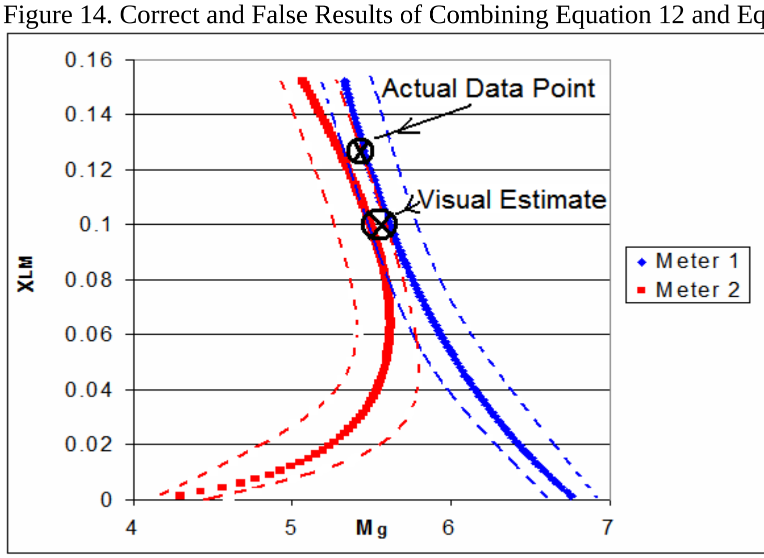


Figure 15. Non-Convergence Result of Combining Equation 12 and Equation 13.

5. McCROMETER 2001-2004, V-CONE METERS AND THE PhD THEORIES

During the final stages of the PhD research this author was interviewed by McCrometer who expressed a desire to develop a V-Cone based wet gas meter. The PhD generic DP meter wet gas flow theories were explained to McCrometer. In the UK, the NEL (where the author was still resident as a Post Graduate Training Partnership research associate) was preparing to carry out Flow Programme funded research into the reaction single phase gas meters had to wet gas flows. The NEL wet gas flow loop, commissioned with the PhD Venturi meter tests in late 1999, was the facility to be used. Two 6”, schedule 80, V-Cone meters (i.e. beta ratios of 0.55 and 0.75) were scheduled for Flow Programme testing in September 2001. On agreement of future employment McCrometer and this authour therefore requested that NEL also recorded the permanent pressure loss during these wet gas tests. The immediate hope was that the PhD generic DP meter theories and lessons could be directly transferred to V-Cone meters.

It was initially decided to place a downstream tapping in each meter body one diameter downstream of the back face of the cone as there was no room in the meter body to place it further downstream. Figure 16 shows a drawing of the 0.75 beta ratio V-Cone meter. However, it was one of the main lessons from the PhD research that it may be better to place the downstream tapping on a DP meter at or downstream of the full pressure recovery location. A problem was there had been no previous V-Cone meter research aimed at finding precisely where even the single phase pressure recovery position was. It was judged probable that the available pressure tapping downstream of the cone was not far enough downstream. A downstream spool was therefore built to give pressure tappings at the estimated / guessed recovery location four pipe diameters downstream of the back face of the cone.

It subsequently became clear that a 0.75 beta ratio V-Cone meter had the most stable wet gas flow response and therefore the rest of this paper concentrates on the 0.75 beta test results only.

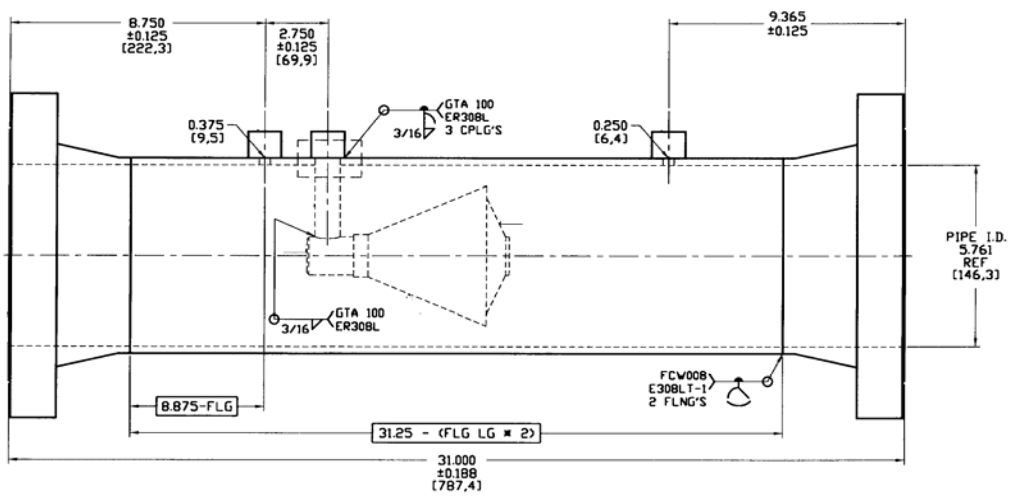


Figure 16. The 6”, 0.75 Beta Ratio V-Cone Meter Wet Gas Tested by the UK DTI’s Flow Programme.

The 6”, 0.75 beta ratio V-Cone meter was set up by NEL as sketched in Figure 17. That is, with traditional inlet pressure and DP transmitters and on request, although it was outwith the scope of the Flow Programme requirements, a second DP transmitter between the upstream pressure port and pressure port four diameters downstream of the back face of the cone. The recovery DP was found by equation 9. This added DP transmitter was the only available device and it had a higher upper range limit (1 bar / 400 ”WC) than would have been ideal. The result was that to reduce scatter on the recovery DP data only differential pressures read by this device greater than 1”WC were used. (This is why some points are missing from the expansion meter low Reynolds number calibration plots in Figure 18.)

Figure 18 shows the gas calibration results of the 6”, 0.75 beta ratio V-Cone meter across a 10:1 turndown. The traditional and expansion DP meter equations 10 and 11 were both calibrated by linear fits to less than

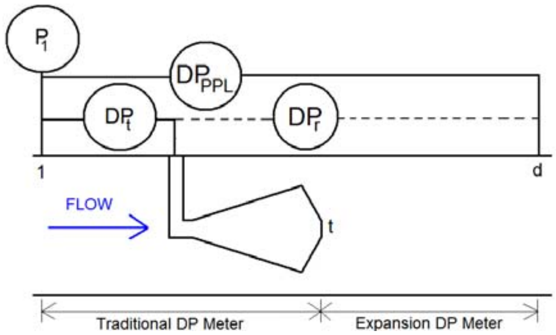


Figure 17. NEL V-Cone Meter Test Configuration.

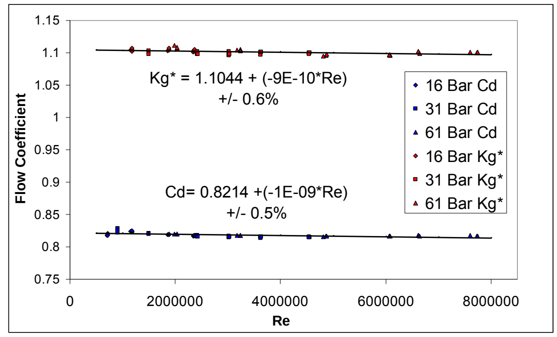


Figure 18. 6", 0.75 Beta V-Cone Gas Calibration.

±1%. Note that as expected, $C_d<1$ and $K_g^*>1$. Also note that the pressure has no effect on either calibration. This result re-enforces the idea that the expansion meter equation of any DP meter is a practical gas metering method and not just an academic curiosity.

The wet gas over-reading results of the traditional V-Cone meter have been well documented. The test matrix (Table 1) and results of the Flow Programme tests at NEL were presented at the NSFMW in 2002 by Stewart et al [12]. The same wet gas flow trends were reported for a V-Cone meter as were reported by de Leeuw [9] for a Venturi meter. That is, a V-Cone meter with wet gas flow responds to changes in the Lockhart Martinelli parameter, gas to liquid density ratio and densiometric Froude number in the same general way as a Venturi meter.

Nominal Pressure (Barg)	Average Density Ratio	Fr_g range	X_{LM} range
15	0.0239	0.57 – 1.91	$0 \le X_{LM} \le 0.3$
30	0.0456	0.54 – 2.75	$0 \le X_{LM} \le 0.3$
60	0.0889	0.92 – 3.53	$0 \le X_{LM} \le 0.3$

Table 1 - Envelope for NEL 2001 Wet Gas Flow 6", 0.75 Beta Ratio V-Cone Meter Test

Further 0.75 beta ratio V-Cone meter repeat data from NEL and CEESI was shown by Steven et al in 2003 and 2004 [13,14] before a final summarising paper was given by Steven [15] in June 2005. This paper superimposed all the available NEL and CEESI data on to one graph. Figure 19 shows a further update with the inclusion of a data set from a CEESI Joint Industry Project. Steven et al [15] gave the latest 4" and 6" 0.75 beta ratio V-Cone meter wet gas correction factor (which is a slight modification to that originally shown by Stewart et al [12]) and this is reproduced here as equation set 12a and equations 15a to 15c. It is the performance of this V-Cone meter wet gas correlation that is used in Figure 19 for the case of a known liquid mass flow rate. It should be noted that equation 12a is in fact simply the PhD Venturi equation 12 form with the PhD examiners suggestions that B=D applied, and, that the resulting parameters A, B and C are functions of the gas to liquid density ratio. For a known liquid mass flow rate this correlation predicts the gas mass flow rate to ±2% (with a few outliers).

Although most V-Cone meter wet gas flow tests between 2001 and 2005 at NEL, CEESI and K-Lab have included the recording of downstream pressure tapping data, up until now no downstream wet gas flow data has been released by McCrometer. Figure 20 shows all the wet gas over-reading data taken from the Flow Programme tested 6", 0.75 beta ratio V-Cone expansion meter as produced internally by McCrometer in 2001. Figure 21 shows one gas to liquid density ratio set with the gas densiometric Froude numbers separated out. The finding was that, when using a V-Cone meter with a downstream tapping that is positioned to allow good pressure recovery, a wet gas flow trend was clearly visible and could be described by a relatively simple function. (This was a considerable improvement on the PhD Venturi meter with little distance for pressure recovery.) Figures 20 and 21 show a clear over-reading with an almost linear relationship with the Lockhart Martinelli parameter. A gas to liquid density ratio effect is also evident. In Figure 21 a gas densiometric Froude number effect is evident. The mid range gas to liquid density ratio data set was chosen as a sample graph. It should be remembered that this data was taken as an add on to the main test program and the permanent pressure loss transmitter was not ideal (i.e. over sized) so there is knock on affect of a high uncertainty in some of the lower value recovery DP measurements / low gas densiometric Froude numbers. It is postulated that this is the reason that the lowest two gas densiometric Froude numbers do not show the same trend as the higher values.

$$\dot{m}_g = \frac{\left(\dot{m}_{g,Apparent}\right)_{TM}}{\left(\frac{1+AX_{LM}+BFr_g}{1+CX_{LM}+BFr_g}\right)}$$ --- (12a) where for $\rho_g/\rho_l < 0.027$, then A=2.431 , B=-0.151 , C=+1

and for $\rho_g/\rho_l \geq 0.027$, then[5]:

$$A = -0.0013 + \frac{0.3997}{\sqrt{\rho_g/\rho_l}} \text{ ---(15a)}, \quad B = 0.0420 - \frac{0.0317}{\sqrt{\rho_g/\rho_l}} \text{ ---(15b)}, \quad C = -0.7157 + \frac{0.2819}{\sqrt{\rho_g/\rho_l}} \text{ ---(15c)}$$

A 6”, 0.75 beta ratio V-Cone expansion meter wet gas correlation was formed (which is not designed for extrapolation). Unlike for the Venturi meter a relatively simple correlation form could be successfully applied. In fact, the PhD DP meter wet gas correlation form (equation 12a) was applicable. This is shown as equation 12b with equation 16a to 16c:

$$\dot{m}_g = \frac{\left(\dot{m}_{g,Apparent}\right)_{EM}}{\left(\frac{1+A'X_{LM}+B'Fr_g}{1+C'X_{LM}+B'Fr_g}\right)} \text{ --- (12b)}$$

where:

$$A' = -0.116 + \left(\frac{0.0094}{\left(\rho_g/\rho_l\right)^{1.5}}\right) \text{--(16a)}, \quad B' = -0.166 + \left(\frac{0.0009}{\left(\rho_g/\rho_l\right)^{1.5}}\right) \text{--(16b)}, \quad C' = -0.616 + \left(\frac{0.007}{\left(\rho_g/\rho_l\right)^{1.5}}\right) \text{--(16c)}$$

Figure 22 shows the uncorrected data for the 6”, 0.75 beta ratio V-Cone expansion meter and the performance of the correction (equation 12b with equations 16a to 16c) for the case of known liquid mass flow rates. The expansion meter wet gas correlation therefore predicts the gas flow rate to ±5% with a few outliers. This is therefore a poorer performance to the traditional meters wet gas correlation at ±2% (see Figure 19). Nevertheless it is a second working wet gas correlation for the same V-Cone meter body. The V-Cone meter is therefore, in affect, two DP meters in series with two wet gas correlations.

Figure 23 shows the mid pressure (DR 0.046) wet gas response of both the traditional and expansion meter equations. It appeared that there was a significant difference in the two metering methods and hence a measurement by difference technique was possible. Furthermore, unlike equation 14, equation 12b can have the Lockhart Martinelli parameter separated out (see equation 12c).

$$X_{LM} = \frac{\left(1+B'Fr_g\right)\left(1-OR^*\right)}{\left(OR^*C' - A'\right)} \text{ --- (12c)}$$

Therefore, a wet gas meter design attempt was made for a known gas and liquid density by substituting into equation 12a, equation 12c, equation 2, equations 6 and 13, equation set 15a to c and equation set 16a to c and solving for the only unknown, i.e. gas mass flow rate. The iteration was started with the expansion meter uncorrected gas mass flow rate (which we see from Figure 23 has a lower over-reading than the traditional V-Cone meter flow rate calculation method and therefore is the closest value to the gas mass flow rate).

[5] Note that Steven et al [15] gave the value of the parameter C at a gas to liquid density ratio less or equal to 0.027 as C = -0.669. This is an error. The correct value is in fact C = +1. 000.

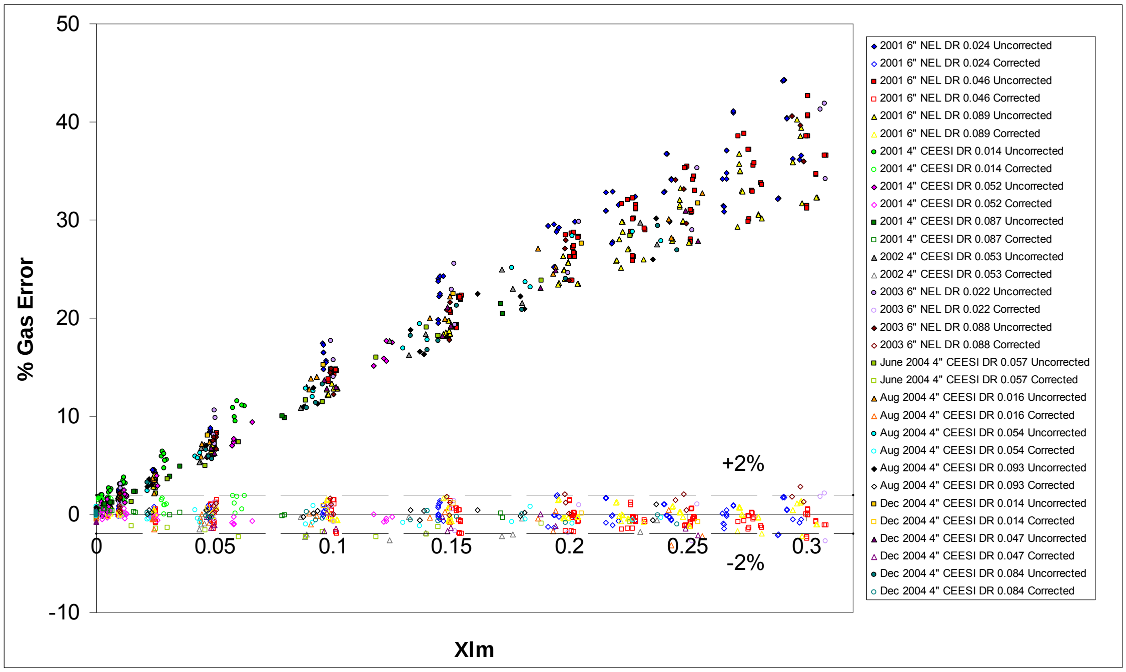


Figure 19. Flomeko 2005 [15] Graph with Additional CEESI JIP Data Showing Uncorrected and Corrected 4” and 6”, 0.75 Beta V-Cone Meter Wet Gas Flow Response.

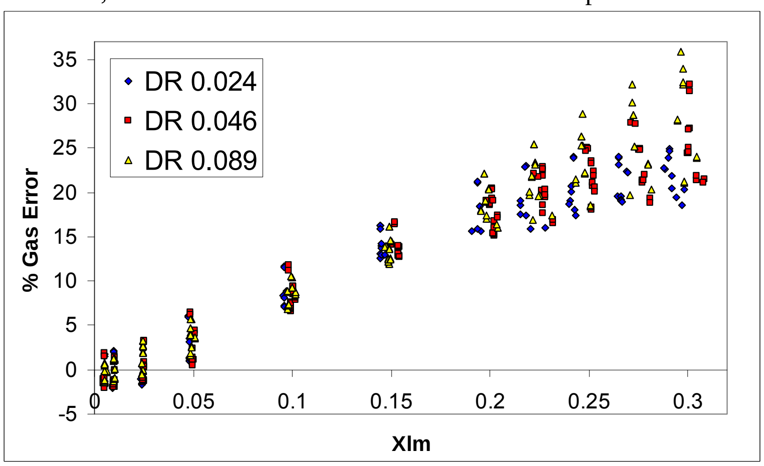


Figure 20. All NEL 6”, 0.75 Beta V-Cone Meter Expansion Meter Wet Gas Response Data.

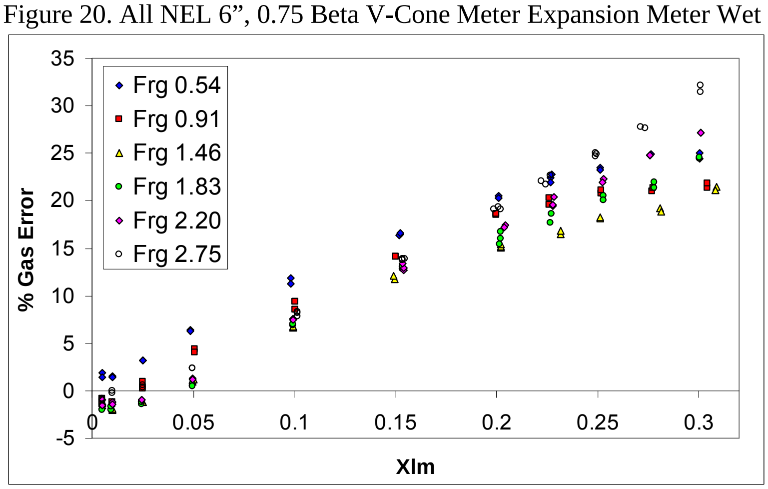


Figure 21. NEL 6”, 0.75 Beta V-Cone Meter Expansion Meter Mid-DR 0.046 Wet Gas Response Data.

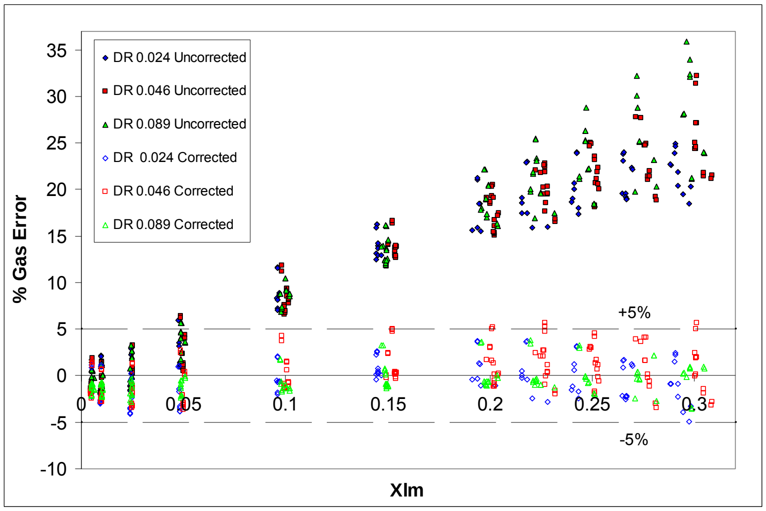


Figure 22. NEL 6", 0.75 Beta V-Cone Meter Expansion Meter Uncorrected and Corrected Results.

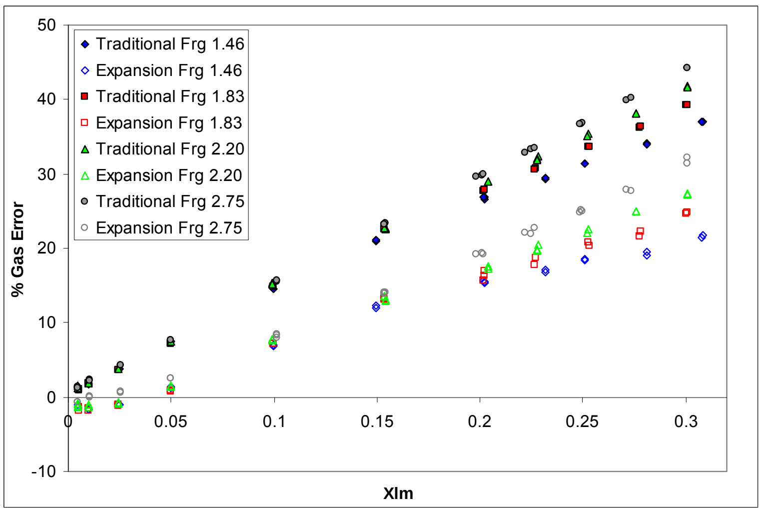


Figure 23. NEL 6", 0.75 Beta Ratio Traditional and Expansion Meter Wet Gas Responses.

The results were poor. Even though the traditional V-Cone meter had as good a wet gas correction factor as the PhD Venturi meter, and the V-Cone expansion meter wet gas response was relatively well predicted by a vastly simpler equation than found for the PhD Venturi meter, the method showed the same problems as the PhD research. Some data points had the phase flow rates predicted well, some poorly and again some data points had iterations that failed to converge. Again, plots of X_{LM} vs. gas mass flow rate were produced and they showed the same story.

Figures 24 shows a sketch representing a typical result. The traditional V-Cone meter over-reading equation gave a predictable shape on the X_{LM} vs. gas mass flow rate curves in all cases, similar to the PhD Venturi meter. However, the V-Cone expansion meter had a more predictable (less variable) wet gas curve than that found for the Venturi meter. This however was still not enough to alleviate the problem explained with the PhD data. The uncertainty bands of the V-Cone expansion meter wet gas correlation were still too large compared to the relative gradients of the two correlations. The actual data points always fell within the uncertainty bands of both equations. However, whereas for some data the equations intersection gave good predictions, for much of the data, due to the similarity in the traditional and expansion meter X_{LM} vs. gas mass flow rate gradients, there were very significant errors (see Figure 24). That is, the V-Cone expansion meter wet gas correlation was a considerable improvement on the PhD Venturi expansion meter wet gas correlation, but the uncertainty bands of the traditional and expansion V-Cone meters were still too large to allow the creation of a V-Cone meter wet gas system by solving these simultaneous equations.

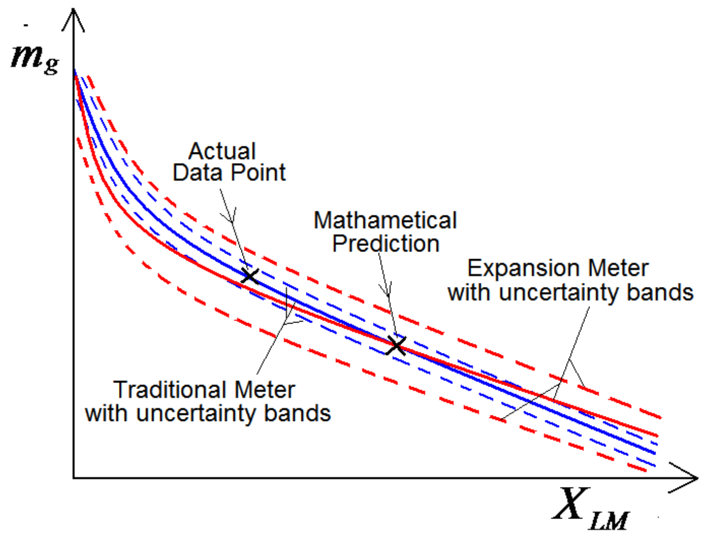


Figure 24. An Unsuccessful V-Cone Traditional and Expansion Meter Wet Gas Correlation Pairing.

6. McCROMETER 2004-5, V-CONE METERS, THEORIES & ALTERNATIVE DATA ANALYSIS

By early 2002 this author had reported to McCrometer that the research program had failed to produce a V-Cone wet gas meter. The decision was made to continue with other avenues of research. From October 2002 until August 2004 McCrometer carried out multiple theoretical wet gas meter design reviews and wet gas testing runs at NEL and CEESI. Theoretical design concepts investigated included (but were not restricted to) placing Venturi and V-Cone meters in series and orifice plate and V-Cone meters in series. Actual wet gas test projects at NEL and CEESI included (but were not restricted to) placing wedge and V-Cone meter in series, placing a vortex and V-Cone meter in series, changing the cone design for wet gas flow applications, placing a capacitance sensor and V-Cone meter in series and partnering with Petroleum Software Ltd. to investigate if the ESMER concept could be utilised with the V-Cone meter design (as described by Toral [16]). Much of this work is still held in confidence by McCrometer.

By the early summer of 2004 despite considerable effort and expense the research had not led to McCrometer getting any closer to a wet gas metering system. Radical steps were required. This author therefore decided that as there were wet gas flow meter systems on the market that were essentially two DP meters in series, operating by utilising measurement by difference techniques, it must be technically possible to produce this. What was evidently required in order to use the V-Cone meter in conjunction with a second meter design, was a second meter design with a wet gas over-reading value far in excess of that produced by the V-Cone meter. That is, when measuring by difference, the bigger the difference the better the measurement and the reduction of uncertainty levels.

In August 2004 CEESI wet gas tested an extreme design of DP meter (the details of which are held in confidence by McCrometer) in series with a V-Cone meter. The over-reading of this new design was significantly higher than that publicly released before for any DP meter design. The measurement by difference technique as applied above for the Venturi and V-Cone traditional and expansion meter pairs was attempted using the two DP meter traditional wet gas correlations. Again, the results were as before. At this stage, however, it was becoming very unlikely that any of the marketed wet gas meter products based on measurement by difference of gas meter over-readings could have a greater difference in over-reading values than this extreme test. Therefore, rather belatedly, this author began to wonder why these rival products worked and the McCrometer prototypes did not.

The answer was found in the literature. In 2003 Wood [17] had presented at the NSFMW a paper describing the operation of the Dualstream II wet gas meter. Graphs were presented to show the relationship between the two DP meter wet gas over-readings. These are reproduced as Figure 25. The term "DOR" appears to mean the "Difference in Over-Reading" between the two DP meters in series. In the autumn of 2004 this author re-read the paper, concentrating on all direct and indirect comments regarding

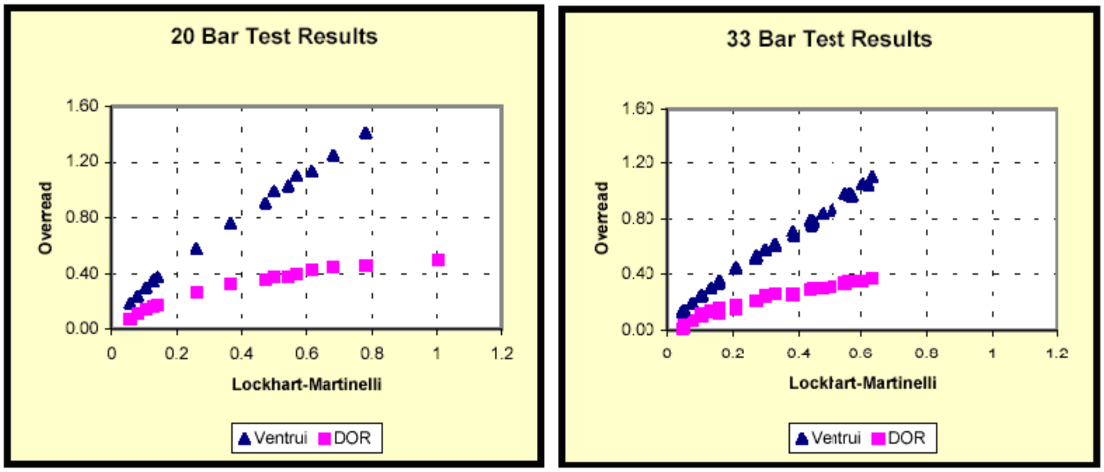


Figure 25. The 2003 Solartron ISA / Shell Wet Gas Flow Data Plots of A DualstreamII Wet Gas Meter.

the mathematical manipulation of the data. It became clear that SolartronISA were not using the same technique as described above. The Lockhart Martinelli parameter was directly shown as a function of the difference of the over-readings of the two DP meters. An immediate comparison was made between Woods DOR values and those found for the V-Cone traditional and expansion meter wet gas over-readings. They were of the same magnitude. It was also noticed that Wood [17] showed an equation pairing the two DP meter over-readings ratio to the Lockhart Martinelli parameter. All post 2002 research was immediately put on hold and this author returned to the original Flow Programme 6”, 0.75 beta ratio V-Cone meter data sets to re-evaluate the data analysis techniques.

The ratio of the 6”, 0.75 Beta Ratio V-Cone traditional and expansion meter wet gas over-readings (denoted here as "theta", ϕ) vs. Lockhart Martinelli parameter were plotted for set averaged values of gas to liquid density ratio and gas densiometric Froude number. Figure 26 shows this result. Note that theta, ϕ, is a measurable parameter as:

$$Theta, \phi = \frac{OR}{OR^*} = \frac{\left(\dot{m}_{g,Apparent} \big/ \dot{m}_g \right)_{TM}}{\left(\dot{m}_{g,Apparent} \big/ \dot{m}_g \right)_{EM}} = \frac{\left(\dot{m}_{g,Apparent} \right)_{TM}}{\left(\dot{m}_{g,Apparent} \right)_{EM}} \quad \text{--- (17)}$$

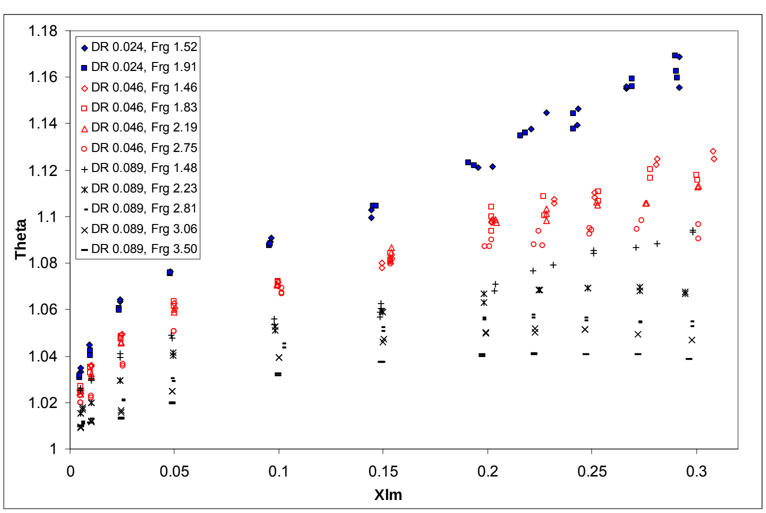


Figure 26. Plot of Theta (Equation 17) to X_{LM} for 2001 NEL 6”, 0.75 Beta Ratio V-Cone Wet Gas Data.

The resulting curves were all fittable to a parabolic equation. That is:

$$(\phi-1)^2 = 4aX_{LM} \text{ --(18),} \quad \text{i.e. } X_{LM} = \frac{(\phi-1)^2}{4a} = \left\{(\phi-1)^2\right\} \Big/ \left\{4\left[f_1\left(\frac{\rho_g}{\rho_l}, Fr_g\right)\right]\right\} \text{--(18a)}$$

$$\text{as } a = f_1\left(\frac{\rho_g}{\rho_l}, Fr_g\right) \text{--(19)}$$

The term "a" is the focus of the parabola which has been found to be solely a function of the gas to liquid density ratio and gas densiometric Froude number. From TableCurve3D a blind fit showed that in the case of the NEL / Flow Programme 6", 0.75 beta ratio V-Cone meter tests:

$$a = 0.0024 + \frac{0.00051}{(\rho_g/\rho_l)} - 0.00056Fr_g^2 \text{ --- (19a)}$$

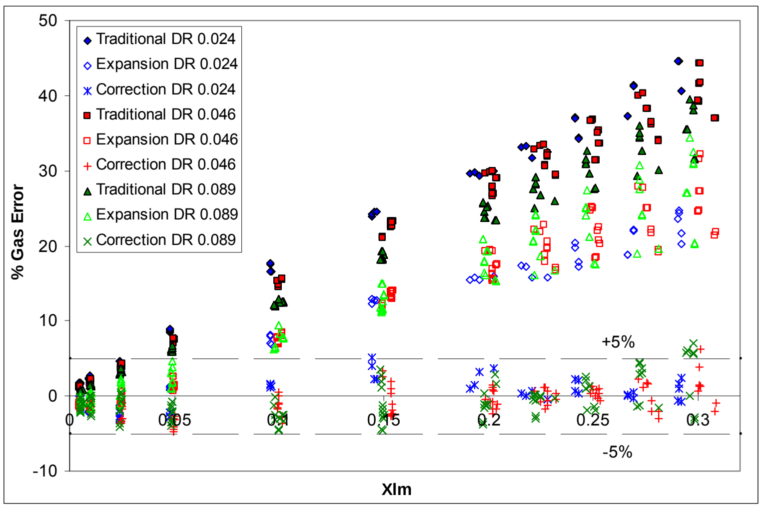


Figure 27. Results of Applying Iteration Sequence to 2001 NEL 6", 0.75 Beta Ratio V-Cone Wet Gas Data.

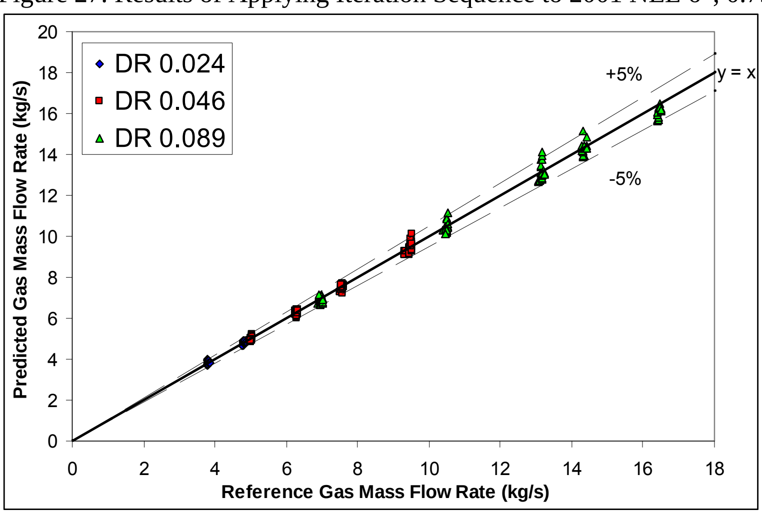


Figure 28. Alternative Plot of Results of Applying Iteration Sequence to NEL V-Cone Wet Gas Data.

Therefore, if we substitute equation 17 and equation 19a into equation 18a we have an expression for the Lockhart Martinelli parameter that is independent of the as yet unknown liquid flow rate. In fact it is solely a function of the known theta value, the known gas to liquid density ratio and the as yet unknown gas densiometric Froude number. Substituting this resulting Lockhart Martinelli parameter expression with

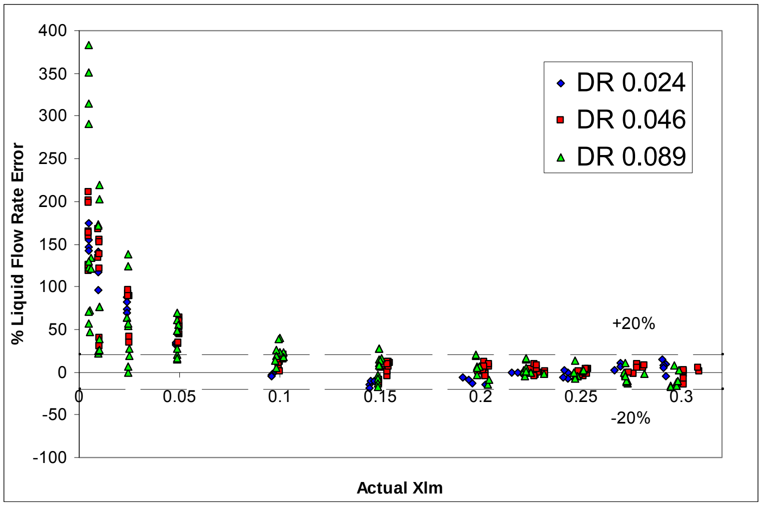


Figure 29. Results of Applying Liquid Flow Rate Calculation to 2001 NEL V-Cone Wet Gas Data.

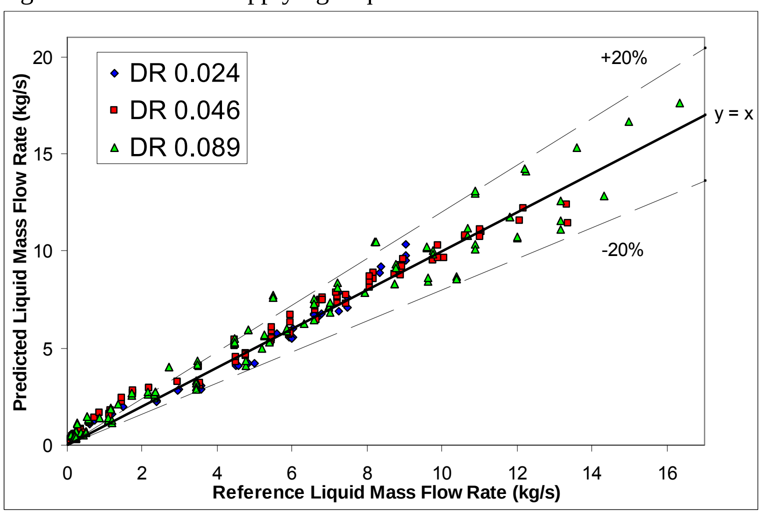


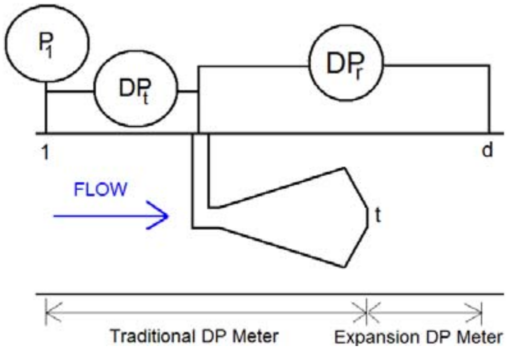
Figure 30. Alternative Plot of Results of Applying Liquid Flow Rate Calculation to NEL V-Cone Data.

equations 2 and equation set 15a to 15c into equation 12a results in an equation with only one unknown, i.e. the gas mass flow rate. Iterating, by starting say, with the uncorrected gas mass flow rate prediction of the V-Cone expansion meter equation, equation 12a will predict the gas mass flow rate.

The result of applying this technique to the NEL data is shown in Figures 27 and 28. The gas mass flow rate has been predicted to within ±5% with a few outliers at the very highest liquid loading. Of the 255 useable points (i.e. the permanent pressure loss was > 1"WC) there were 7 gas flow rate predictions > ±5%. The prediction method therefore has a 95% confidence level. The predicted Lockhart Martinelli parameter values can be substituted into equation 1 with the gas mass flow rate prediction and for a known gas to liquid density ratio a liquid mass flow rate prediction is obtained. Figures 29 and 30 show the results. The target of predicting gas mass flow rate to ±5% was achieved. The secondary target of predicting liquid mass flow rate to ±20% (until the liquid mass flow rate reduces to small quantities, i.e. X_{LM}<0.05) for a set meter geometry and known fixed fluid properties was approached but not fully achieved.

7. McCROMETER 2005 - A CONFIRMATION TEST AT CEESI

In March 2005 McCrometer tested a 4", 0.75 beta ratio V-Cone meter at the CEESI wet gas flow facility. The recovery differential pressure (ΔP_r) was now read directly. The test set up is sketched in Figure 31. Note that the downstream pressure tapping is shorter than sketched in the NEL set up (i.e. Figure 17). This



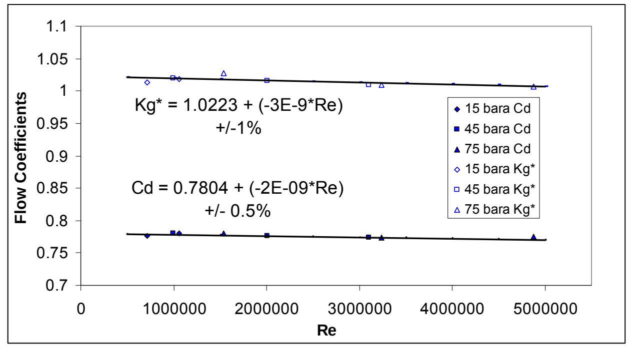


Figure 31. CEESI V-Cone Meter Configuration. Figure 32. 4”, 0.75 Beta V-Cone Gas Calibration.

indicates an effort to shorten the prototype meter design, i.e produce a more compact and lighter design. The downstream tapping was now approximately pipe 2.5 diameters downstream of the cones back face.

The V-Cone traditional and expansion meter calibration result is shown in Figure 32. The traditional meter operated to ±0.5% and the expansion meter to ±1% across a 10:1 turndown. Again we see that C_d <1, and K_g^* >1. However, whereas the discharge coefficient is a very familiar range for standard V-Cone meters the expansion flow coefficient is just above unity where as it was approximately 1.1 at the NEL test. This is evidence that the downstream pressure tapping position can significantly affect an expansion meters calibration. It is not certain if pressure recovery is complete by the downstream tap location in this meter installation. Nevertheless, the unconventional expansion meter still calibrates to ±1% across a 10:1 turndown which is acceptable for many conventional DP meter designs on the market.

Nominal Pressure (Bara)	Average Density Ratio	Fr_g range	X_{LM} range
15	0.015	0.90-1.50	$0 \le X_{LM} \le 0.27$
45	0.046	0.85-2.55	$0 \le X_{LM} \le 0.27$
75	0.083	1.15-3.50	$0 \le X_{LM} \le 0.27$

Table 2 - Envelope for CEESI 2005 Wet Gas Flow 4”, 0.75 Beta Ratio V-Cone Meter Test.

Table 2 shows the CEESI natural gas / Stoddard solvent (mainly of C9-C12) test matrix. The standard reaction of the traditional V-Cone meter was as expected. That is, Figure 33 shows the over-reading to Lockhart Martinelli parameter graph with the results for a standard correction (equation 12a with equations 15a to 15c) for a known liquid flow rate being ±2%. Figure 34 shows this data sets plot of theta, ϕ vs.Lockhat Martinelli parameter. Again, as with the NEL data set, for set gas to liquid density and gas densiometric Froude numbers the data can be described well by a parabolic equation. Fitting the focus to the gas to liquid density and gas densiometric Froude number variables found the equation 19b.

$$a = \exp\left\{ -2.74 + (-22.3\frac{\rho_g}{\rho_l}) + (-\frac{1.27}{Fr_g}) \right\} \quad \text{--- (19b)}$$

Figure 35 shows the traditional ("TM") and expansion ("EM") V-Cone meter over-readings and the result of applying the correction method with equation 19b. Figure 36 shows the gas flow rate prediction result in an alternative format. Figure 37 and 38 show representations of the liquid flow rate predictions. The results are similar to the NEL results, that is, the gas flow rate is predicted to ±5% with a few outliers. The liquid flow rate is generally predictable to ±20% at X_{LM} > 0.1, but at lower values (X_{LM} < 0.1) this system – like most wet gas systems – has a considerable increase in liquid flow rate uncertainty.

Note that both NEL’s Figure 26 and CEESI’s Figure 34 show that for set gas to liquid density ratio and gas densiometric Froude numbers, theta vs. Lockhart Martinelli parameter can be fitted well using a parabolic equation. For both data sets, as the gas to liquid density increases the trend is for theta to tend to unity. However, the gas densiometric Froude number trends are different. The NEL data shows increasing gas

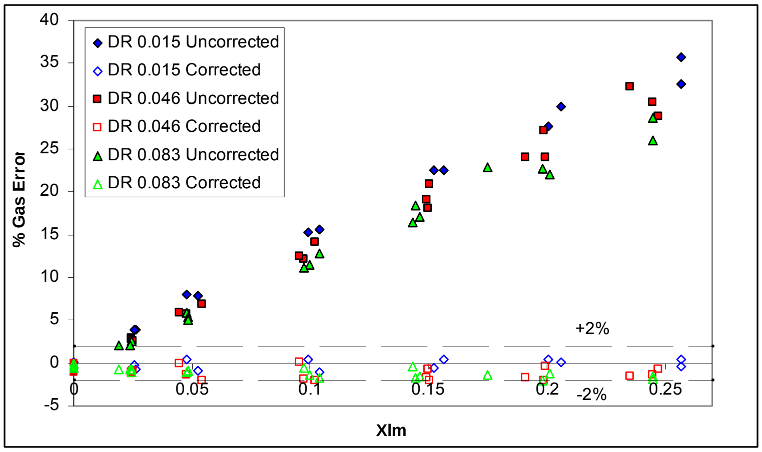


Figure 33. CEESI 2005 4", 0.75 Beta Ratio V-Cone Meter Uncorrected and Corrected Data.

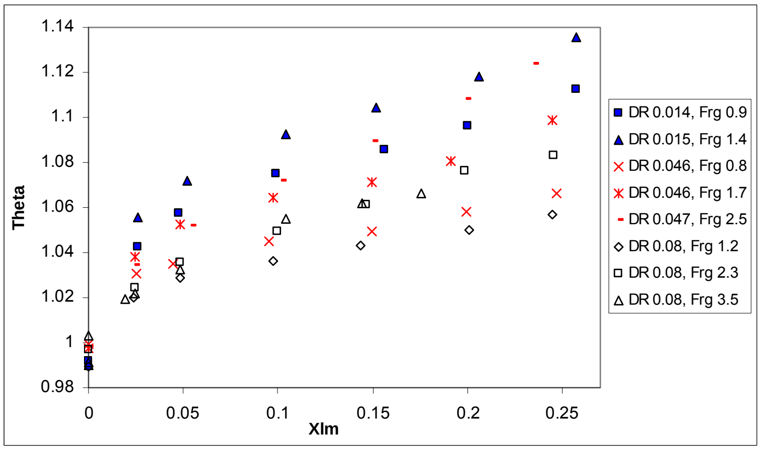


Figure 34. CEESI 2005 4", 0.75 Beta Ratio V-Cone Meter Theta vs. Lockhart Martinelli Parameter Data.

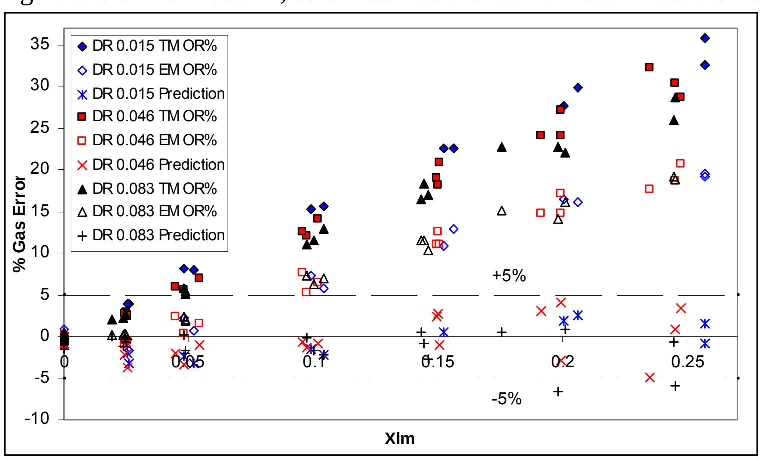


Figure 35. CEESI 2005 4", 0.75 Beta Ratio V-Cone Meter Traditional, Expansion and Corrected Results.

densiometric Froude numbers reducing theta's value but CEESI's data shows the opposite. Theoretically, as the gas dynamic pressure increases the wet gas flow should tend towards homogenous (i.e. pseudo single phase) flow and theta should therefore tend towards unity. It is possible that the CEESI result may be due to the short downstream tapping distance meaning recovery has not yet been completed. Whatever the reason the data fit on the relationship between the parabolas focus and the gas to liquid density ratio and gas densiometric Froude number is different for the two data tests. Both work well for the data set that created them but they are not similar. This suggests that until further research is conducted at least, such a

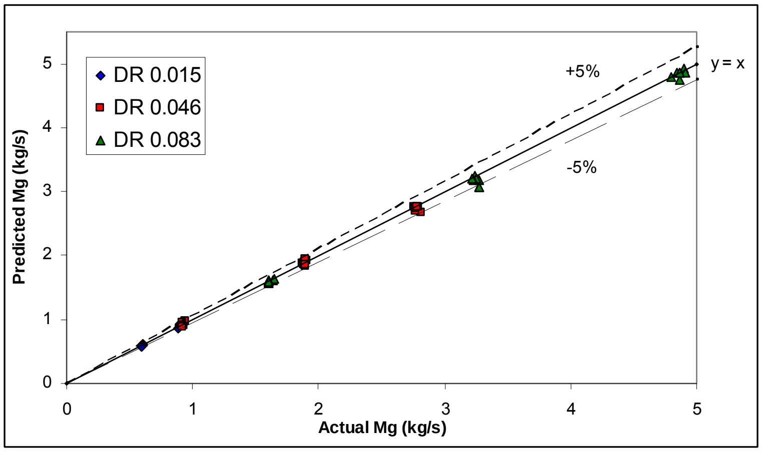


Figure 36. CEESI 2005 4”, 0.75 Beta Ratio V-Cone Meter Gas Flow Rate Prediction Results.

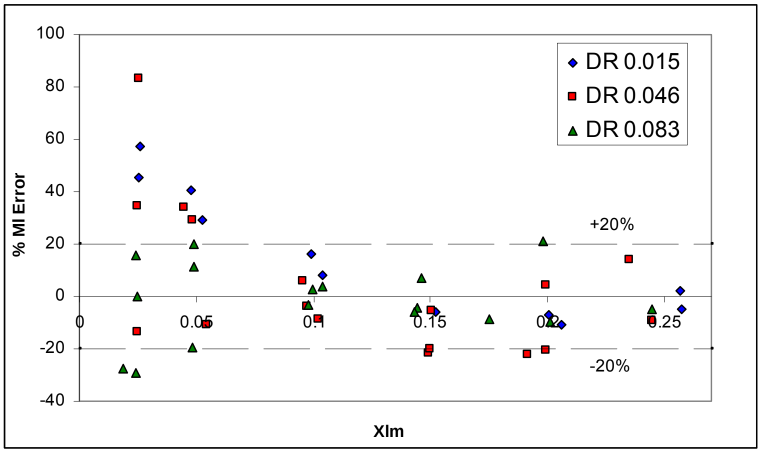


Figure 37. CEESI 2005 4”, 0.75 Beta Ratio V-Cone Meter Liquid Flow Rate Prediction Results.

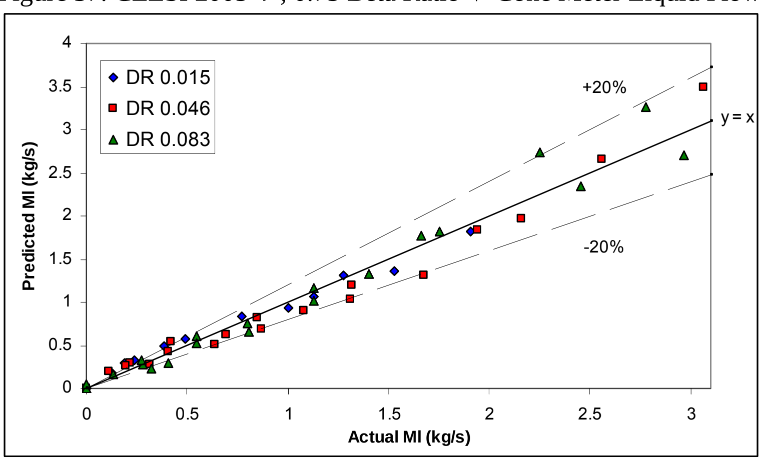


Figure 38. CEESI 2005 4”, 0.75 Beta Ratio V-Cone Meter Liquid Flow rate Prediction Results.

wet gas V-Cone meter would have to be calibrated in the range of conditions it was to be used.

8. A SPECIAL BG GROUP V-CONE METER WET GAS TEST AT K-LAB

In Feburary 2005 McCrometer tested a BG Group 6”, sch 160, 0.75 beta ratio V-Cone meter with wet gas flow at K-Lab. The test matrix was unusual as along with moderate (i.e. typical) flow conditions the meter was to be tested under extreme gas flow rate conditions. Table 3 shows the test matrix.

Nominal Pressure (Bara)	Average Density Ratio	Fr_g range	X_{LM} range
34	0.045	4.3 – 8.8	$0 \leq X_{LM} \leq 0.28$
49	0.060	6.7	$0 \leq X_{LM} \leq 0.26$

Table 3 - Envelope for K-Lab 2005 Wet Gas Flow 6", 0.75 Beta Ratio V-Cone Meter Test.

McCrometer requested K-Lab record the permanent pressure loss as well as the traditional DP. As no such tap existed on the meter body the tap was on the downstream spool and was approximately six pipe diameters downstream of the back face of the cone. Figure 17 indicates both the K-Lab and NEL V-Cone meter set ups (although this 6" meter had the pressure tapping two pipe diameters further downstream than the 4" NEL set up – 6 diameters downstream).

Figure 39 shows the K-Lab dry gas calibration result. The traditional discharge coefficient is in the typical region for a V-Cone meter at approximately 0.8. The linear fit gives a ±0.5% performance. The expansion flow coefficient is in the region of 1.14. The linear fit gives a ±0.6% performance. Here again, the expansion meter concept stated in this authors PhD as applicable to all DP meters is shown to work well for a V-Cone meter. It is notable that the CEESI test with a downstream tapping distance of 2.5D gave an expansion flow coefficient of approximately 1.02, the NEL test with a downstream tapping distance of 4D gave an expansion flow coefficient of approximately 1.1 and the K-Lab test with a downstream tapping distance of 6D gave an expansion flow coefficient of approximately 1.15. The downstream pressure tap location appears to affect the expansion flow coefficient. However, as long as the meter is calibrated to specific pressure tap locations this single phase flow metering system works well.

Figure 40 shows the three V-Cone meter wet gas test matrices on the Shell Flow Pattern Map. This map was based on 4" observations and so the 6" NEL and K-Lab flow pattern predictions have more uncertainty than the 4" CEESI predictions. However, these are all reasonable approximations. The meters tested at NEL and CEESI therefore saw very similar wet gas flow patterns whereas the meter tested at K-Lab had a significantly different flow pattern. Whereas CEESI and NEL had wet gas flow ranges where the flow conditions created stratified flow, a transitioning flow pattern between stratified and annular-mist flow or annular mist flow, at K-Lab the extremely high gas velocities and even lighter condensate hydrocarbon liquid[6] than used by other test facilities meant the flow was likely to be further into the annular-mist flow region. In fact, at these conditions it is expected the liquid could be close to fully atomised meaning the flow tends to homogenous flow. That is, the higher velocity K-Lab wet gas flows could act like pseudo-single phase flow. These flow conditions are at the extreme end of real industrial flow applications.

Figure 41 shows the K-Lab 6", sch 160, 0.75 beta ratio V-Cone traditional meter wet gas data with the released V-Cone meter wet gas correction factor (i.e. equation 12a with equations 15a to 15c) applied for the case of a known liquid mass flow rate. It is of interest to note that the gas to liquid density ratio range is well within the range tested by NEL and CEESI. The lowest gas densiometric Froude number (a relatively high value of 4.37) is just above the values tested at NEL and CEESI. That data set, with minimal extrapolation, is corrected well by the existing correlation. However, the higher gas densiometric Froude number values are poorly predicted by the current V-Cone meter wet gas correction factor. The correction factor considerably "over corrects" the gas flow rate prediction. This is an example of the dangers of extrapolating any correlation. It should be noted that this is not a problem specific to V-Cone meters. All DP meter designs have this problem. Similar trends were shown by Steven et al [20] for the orifice meter

[6] In 2006 [18] this author stated that wet gas flows with kerosene would, for otherwise set flow conditions, have a flow pattern further into the annular mist region than wet gas flows with water, as water is more viscous and has a higher surface tension than kerosene. There is an error in this statement. Kerosene is more viscous than water (but does have a lower surface tension than water). There is limited information on the combined effects of liquid viscosity and surface tension parameters on flow patterns. It is still assumed from limited indirect evidence (e.g. the Baker map or an argument can be based on the findings of Reader Harris et al [19]) that light oil wet gas flows become annular mist flows at lower gas dynamic pressures than water wet gas flows. This suggests that surface tension is more important in determining flow patterns than viscosity. It is assumed that K-Labs condensate has a lower surface tension than NEL or CEESI liquids and therefore K-Lab wet gas flows becomes annular mist at lower gas dynamic pressures.

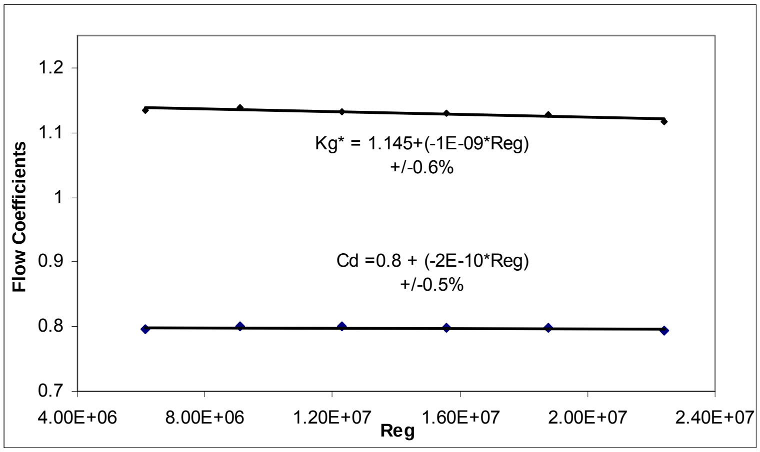


Figure 39. K-Lab 6", 0.75 Beta V-Cone Gas Calibration.

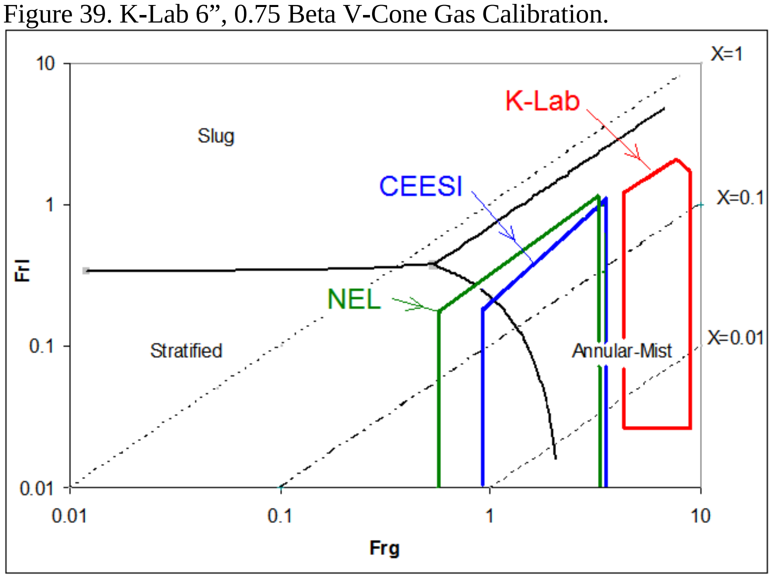


Figure 40. Shell 4" Natural Gas / Light Hydrocarbon Liquid Based Flow Pattern Map.

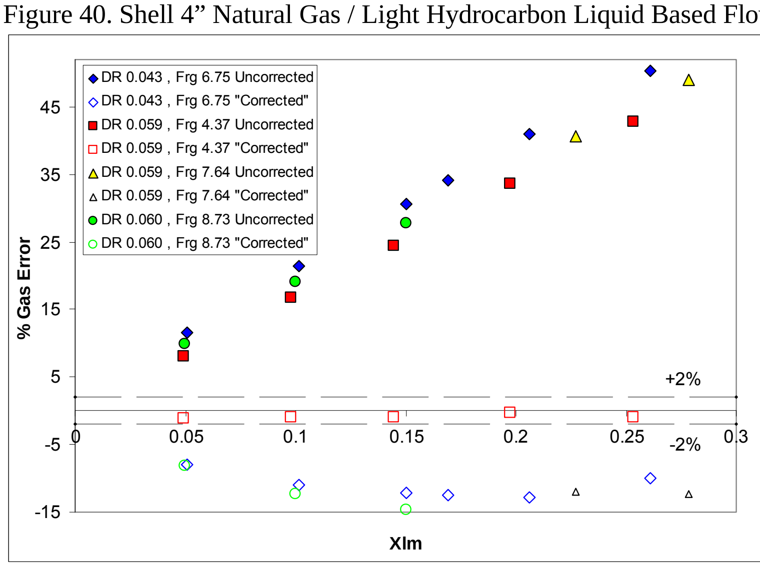


Figure 41. K-Lab 6", 0.75 Beta Ratio V-Cone Meter Uncorrected and Corrected Data.

and the Chisholm equation but the test conditions were not as extreme. Furthermore, this is not a limit of DP meter designs, but rather a limit on the available data sets in which to create the wet gas correlations. In this case McCrometer set a new (unpublished) correlation for the BG Group that correctly (±3.5%) predicted the gas flow rate across the NEL/ CEESI / K-Lab ranges for known liquid flow rates.

In 2006 this author [18] suggested that when fitting wet gas data from any gas meter to create a wet gas correction factor it is advisable to set an upper boundary condition for extraploation of both gas to liquid density ratio and gas densiometric Foude number to the homogenous model. This data is a good example of why this is appropriate. A DP meters homogenous wet gas correction factor has been shown to be:

$$\dot{m}_g = \frac{\dot{m}_{g\,Apparent}}{\sqrt{1+CX_{LM}+X_{LM}^2}} \quad \text{---- (20)} \qquad \text{where:} \qquad C = \left(\frac{\rho_g}{\rho_l}\right)^{\frac{1}{2}} + \left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{2}} \quad \text{---- (21)}$$

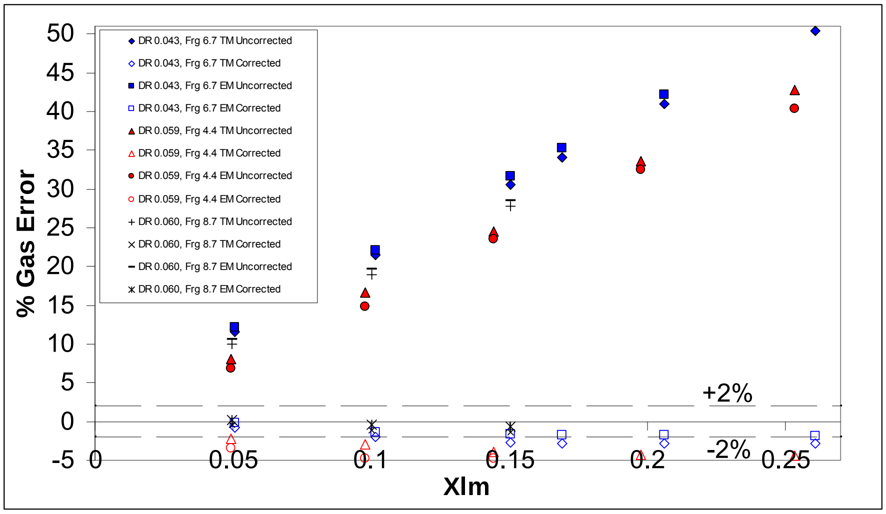


Figure 42. K-Lab 6", 0.75 Beta Ratio V-Cone TM & EM Meters Data Corrected by Homogenous Model.

Figure 42 shows the K-Lab 6", 0.75 beta ratio V-Cone traditional ("TM") and expansion ("EM") meter data superimposed on one graph with the homogenous model correction applied to both DP meter types for the case of a known liquid flow rate. One important observation is that there is no significant difference between the two metering methods. This is evidence that the wet gas flow is tending towards the homogenous flow pattern. Here the meters act like single phase flow meters as they are effectively metering a flow of a homogenous mixture. When a wet gas flow is perfectly homogenised any DP meters gas flow rate error would solely be caused by the gas density being applied to the flow rate calculation when the DP read is actually being caused by the flow with the homogenous mixes density. Hence, by theory, all DP meters in this special extreme condition give the same wet gas over-reading. Note that for the 0.059 / 0.06 gas to liquid density cases as the gas densiometric Froude number (i.e. gas flow rate) increases the performance of the homogenous correction model improves as would be expected.

Wet gas flows tending to homogenous flow is a theoretical limit to all DP meter in series wet gas meter techniques. With no difference between different DP meter wet gas over-readings no measurement by difference technique can be utilised. Fortunately, DP meters appear to influence the local flow pattern in such a way that, for any given gas to liquid density ratio, it takes the exceeding of different gas densiometric Froude number values for different DP meter designs to reach the homogenous flow model over-reading prediction. This fact extends the usefulness of the general technique considerably. In extreme pressure and flow rate condition wet gas flow cases where two DP meters in series give the same gas flow rate prediction the flow could be single phase gas or homogenised wet gas flow. With measurement by differrence not possible in this case it is postulated here that in such cases, phase fraction devices may predict the approximate density of the flow and therefore predicting the gas and liquid phase flow rates with a combination of a DP meter and phase fraction device would be at least theoretically possible. However, as yet no such reseach of this kind is known to have been published.

9. CONCLUSIONS

The PhD thesis's claim that the expansion section of any DP meter is a DP meter in its own right, first shown with one Venturi meter data set has now been backed by three V-Cone meter tests. The performance of these expansion meter designs is only slightly inferior to the traditional DP metering method.

When combining the V-Cone traditional and expansion meter wet gas flow data information it is possible, by use of appropriate mathematical analysis, to predict the gas and liquid flow rates. This creates a simple inexpensive wet gas metering system that could operate well across a significant range of industry wet gas flow applications. Currently, like most simple wet gas metering systems, it is necessary to data fit test results across the range of its use as extrapolation of the correlations (e.g. use with different liquid properties, meter diameters, higher gas flow rates, pressures etc.) is not adviseable.

The limitation of this method is the same as for all other DP meters in series wet gas flow meter designs. As the wet gas flow tends to a homogenous mix flow the measurement by difference technique is increasingly difficult as the difference diminishes. There are currently conceptual ideas as yet to be proven on how this limitation can be overcome.

10. ACKNOWLEDGMENTS

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APPENDIX

It is convention for DP flow meters to use a geometric constriction to create the required momentum change. By applying the mass and energy conservation equations an expression for the flow rate is obtained that is a function of the geometry, fluid density and differential pressure across two points on the constriction. However, a geometric expansion can also be used. This was discussed by Steven [10].

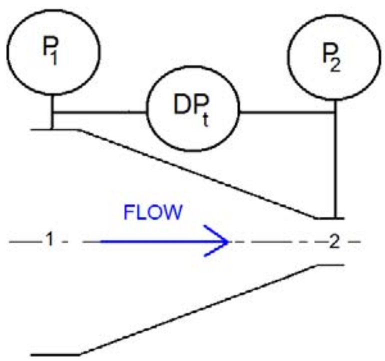

Figure A.1a. Generalised Constriction DP Meter

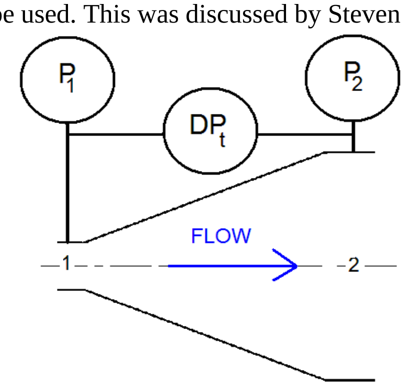

Figure A.1b. Generalised Expansion DP Meter

Derivation of Single Phase Generalized Constriction DP Meter Generic Flow Equation

Consider incompressible, horizontal, reversible flow through a meter of the geometry shown in Figure A.1a. Mass continuity (equation A.1) and energy conservation (equation A.2) gives:

$$\dot{m} = \rho \dot{Q} = \rho A_1 U_1 = \rho A_2 U_2 \text{ --- (A.1)} \quad \text{and} \quad \frac{P_1}{\rho} + \frac{U_1^2}{2} = \frac{P_2}{\rho} + \frac{U_2^2}{2} \text{ --- (A.2)}$$

where $\dot{m}$ is the mass flow rate, $\dot{Q}$ is the volume flow rate A_1 and A_2 are the inlet and outlet areas respectively, P_1 and P_2 are the inlet and outlet pressures respectively, U_1 and U_2 are the inlet and outlet velocities respectively and ρ is the density. Let β be defined by equation A.3 and re-arrange:

$$\beta = \sqrt{\frac{A_2}{A_1}} \text{ -(A.3)}, \frac{P_1 - P_2}{\rho} = \frac{U_2^2 - U_1^2}{2} = \frac{U_2^2}{2}\left(1 - \left(\frac{U_1^2}{U_2^2}\right)\right) = \frac{U_2^2}{2}\left(1 - \left(\frac{A_2}{A_1}\right)^2\right) = \frac{U_2^2}{2}\left(1 - \beta^4\right) \text{-(A.2a)}$$

Let E (the velocity of approach) be defined by equation A.4 and substitute equation A.4 into equation A.2a and re-arrange:

$$E = \frac{1}{\sqrt{1 - \beta^4}} \text{ --- (A.4)} \quad , \quad U_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho(1 - \beta^4)}} = E\sqrt{\frac{2(P_1 - P_2)}{\rho}} \text{ ---- (A.2b)}$$

Substituting equation A.2.b into equation A.1 gives:

$$\dot{m} = \rho A_2 U_2 = E A_2 \sqrt{2\rho(P_1 - P_2)} \text{ ---- (A.5)}$$

Derivation of Single Phase Generalized Expansion DP Meter Generic Flow Equation

Consider incompressible, horizontal, reversible flow through a meter of the geometry shown in Figure A.1b. Mass continuity (equation A.1) and energy conservation (equation A.2) still hold true. Let $\beta^{'}$ be defined by equation A.3a and re-arrange such that we get:

$$\beta^{'} = \sqrt{\frac{A_1}{A_2}} \text{ -(A.3a) , } \frac{P_2 - P_1}{\rho} = \frac{U_1^2 - U_2^2}{2} = \frac{U_1^2}{2}\left(1 - \left(\frac{U_2^2}{U_1^2}\right)\right) = \frac{U_1^2}{2}\left(1 - \left(\frac{A_1}{A_2}\right)^2\right) = \frac{U_1^2}{2}\left(1 - \beta^{'4}\right) \text{-(A.2c)}$$

Let $E^{'}$ (the velocity of departure) be defined by equation A.4a and substitute this into equation A.2c and re-arrange:

$$E^{'} = \frac{1}{\sqrt{1-\beta^{'4}}} \text{ ----(A.4a) , } U_1 = \sqrt{\frac{2(P_2 - P_1)}{\rho\left(1-\beta^{'4}\right)}} = E^{'}\sqrt{\frac{2(P_2 - P_1)}{\rho}} \text{ --- (A.2d)}$$

Substituting equation A.2.d into equation A.1 gives:

$$\dot{m} = \rho A_1 U_1 = E^{'} A_1 \sqrt{2\rho(P_2 - P_1)} \text{ ---- (A.6)}$$

Comparison of the Classic and Expansion Type DP Meter Results

Note equations A.5 and A.6 are mirror images of each other. As this analysis assumed incompressible and reversible flow through Figure A.1a, then the incompressible and reversible flow analysis for the flow through Figure A.1b is precisely the flow through Figure A.1a in reverse. In reality gas flows are compressible and irreversible. As a result the traditional DP meter style has corrections factors. The discharge coefficient is defined by equation A.7. This correction factor takes account of all real world factors that are not accounted for by the theory. With traditional gas DP meters the gas density drops with the pressure and hence the assumption of incompressible flow is not valid. The correction factor is called the expansion factor (denoted by ε in Europe). This is some function f_1 as shown by equation A.8:

$$C_d = \frac{\dot{m}_g}{\dot{m}_{g,theoretical}} = \frac{\dot{m}_g}{EA_2\sqrt{2\rho(P_1 - P_2)}} \text{ --- (A.7) and } \varepsilon = f_1(P_1, \Delta P, \kappa, \beta) \text{ --- (A.8)}$$

where $\dot{m}_g$ is the actual gas mass flow rate, $\dot{m}_{g,theoretical}$ is the value predicted by equation A.5 and κ is the gases isentropic exponent and note $\Delta P = P_1 - P_2$. From theory, for a traditional DP meter C_d <1 and $\varepsilon < 1$. Sometimes these two factors are accounted for by one "flow coefficient" ("K_g"), i.e. the flow coefficient is the product of the discharge coefficient and the expansion factor (and therefore $K_g < 1$). We now have:

$$\dot{m}_g = EA_2\varepsilon C_d\sqrt{2\rho(P_1 - P_2)} = EA_2K_g\sqrt{2\rho(P_1 - P_2)} \text{ --- (A.5a)}$$

An expansion meter would have the equivalent discharge coefficient to that of the constriction meter (see equation A.9.). The flow expansion slows the flow causing an increase in gas density as the pressure increases. A compression factor ($\varepsilon^{'}$) would account for this phenomenon (see equation A.10).

$$C_d^{'} = \frac{\dot{m}_g}{\dot{m}_{g,theoretical}} = \frac{\dot{m}_g}{E^{'}A_1\sqrt{2\rho(P_2 - P_1)}} \text{ --- (A.9) and } \varepsilon^{'} = f_1\left(P_2, \Delta P^*, \kappa, \beta^{'}\right) \text{ --- (A.10)}$$

Note that here $\dot{m}_{g,theoretical}$ is the value predicted by equation A.6, and $\Delta P^* = P_2 - P_1$. For an expansion DP meter $C_d^{'} > 1$ and $\varepsilon^{'} > 1$. These two factors can be accounted for by one "expansion flow coefficient" (K_g^*).This is the product of the expansion discharge coefficient and the compression factor. Therefore, as

$K_g^* = C_d^{'}\varepsilon^{'}$ and as $C_d^{'} > 1$ and $\varepsilon^{'} > 1$ we get $K_g^* > 1$. When we include the expansion flow coefficient in the derived expansion DP meter gas equation we get:

$$\dot{m}_g = E^{'} A_1 C_d^{'} \varepsilon^{'} \sqrt{2\rho(P_2 - P_1)} = E^{'} A_1 K_g^* \sqrt{2\rho(P_2 - P_1)} \text{ ---- (A.11)}$$

<u>Traditional DP Meters and the Downstream Expanding Flow</u>

It was pointed out by Steven [10] that traditional DP meters expand the flow back to the pipe area. That is once the minimum area has passed (i.e. the vicinity where the low pressure is read) the flow expands back to the cross sectional area of the pipe as it flows downstream. Hence, from the minimum area point to the recovered pressure point there is in effect, a second DP meter imbedded within the body of the any traditional DP meter. That is, <u>any</u> DP meter is a constriction and expansion DP meter in series. For example Figure 6 shows a sketch of a Venturi meter. For traditional and expansion DP meters in series made from one meter body such as a Venturi meter we have $\beta = \beta^{'}$ and $E = E^{'}$ and the two flow equations are:

$$\dot{m} = EA_t K_g \sqrt{2\rho\Delta P_t} = EA_t K_g^* \sqrt{2\rho\Delta P_r} \text{ --- (A.12)}$$

where is $\Delta P_t = P_1 - P_t \equiv \Delta P = P_1 - P_2$ and $\Delta P_r = P_d - P_t \equiv \Delta P^* = P_2 - P_1$

Also note that the density of the downstream meter will be slightly different than the upstream meter due to pressure differences. However, with the exception of extremely high velocity gas flow this is a small difference.

In 2001, Steven [10] (in Chapter 7, section 2 of the PhD Thesis) stated that "…the same principles apply for metering with a DP Meter whether the pressure differential is produced by a constriction or expansion in the flow area." In other words, this statement is saying the above derivation is applicable to <u>all</u> DP meters. It therefore, is applicable to V-Cone meters.