

Research Developments In Wet Gas Metering with McCrometer V-Cone® Meters

Richard Steven, McCrometer Inc.

1 INTRODUCTION

At the 2002 North Sea Flow Measurement Workshop (NSFMW) NEL and McCrometer jointly presented the results and analysis of the UK's Department of Trade and Industry (DTI) funded V-Cone® meter wet gas flow tests on the NEL Wet Gas Loop. Two 6" beta ratios (0.55 and 0.75) were tested and for each meter the parameters influencing the differential pressure reading with wet gas flows were identified and found to be similar to other Differential Pressure (DP) meters. Correlations were then offered that would correct for the V-Cone meters' liquid induced error in the gas flowrate prediction for a known liquid flowrate or liquid to gas flowrate ratio.

This paper briefly summarises the V-Cone meter technology and then discusses the results of repeat wet gas flow tests at NEL in May 2003 (at nominally 15 and 60 Bar) for the 0.75 beta ratio V-Cone meter, to show the repeatability of the meter with wet gas flows and the reliability of the previously published wet gas flow correlation within the NEL parameter range. This paper then discusses wet gas flow testing done on a 4", 0.75 beta ratio V-Cone meter at CEESI in October 2002 across a different parameter range to that of NEL and compares the 0.75 beta ratio data sets at the two test facilities. The V-Cone meters 0.75 beta ratio correlation is then applied to the independent CEESI wet gas flow data set to investigate the applicability of the NEL data based correlation out with the NEL test range. With the correlations applicability shown, a discussion on the industrial advantages of a proposed Tracerflow and V-Cone meter combination is given. This is followed with new data showing the 0.75 beta ratio V-Cone meters performance at greater Lockhart-Martinelli parameters than previously tested (up to 0.5). A new correlation is discussed for this expanded range and the results of applying this new correlation to the NEL data set are presented. Finally, a rare field test showing the performance of a Wafer-Cone® meter with wet gas flow is discussed.

2 THE V-CONE METER

The V-Cone meter is a patented DP Meter. There are two forms of the meter, one called the precision tube "V-Cone" meter and the other the "Wafer-Cone" meter. The precision tube "V-Cone" meter has a centrally mounted cone pointing upstream supported at its nose by a strut. The upstream pressure is read from a wall tapping and the downstream pressure is read from the centre of the back face of the cone. The "Wafer-Cone" meter has a centrally mounted cone pointing upstream supported by a downstream strut. The upstream and downstream pressures are read from a wall tapping. Figures 1a and 1b show sketches of the precision tube "V-Cone" and "Wafer-Cone" meters respectively.

The shape and position of the primary element is the only difference between these meters and other DP meters. The precision tube "V-Cone" and the "Wafer-Cone" meters are in every way DP meters (with some advantages gained from the choice of a cone as the primary element). Therefore with single phase flow the generic DP meter equation form is used (with unique V-Cone meter constants) and all secondary instrumentation is the same as for any DP meter.

The advantages of using a cone as a DP producing element with single phase flows are well documented. These include built in flow conditioning reducing the required upstream lengths to very short lengths –typically no more than three pipe diameters [1, 2], low total head loss [3] and high turndown achieved for a single DP transmitter [4]. For single phase flows with calibration the precision tube V-Cone meter will give $\pm 0.5\%$ and the Wafer-Cone meter will give $\pm 1\%$.

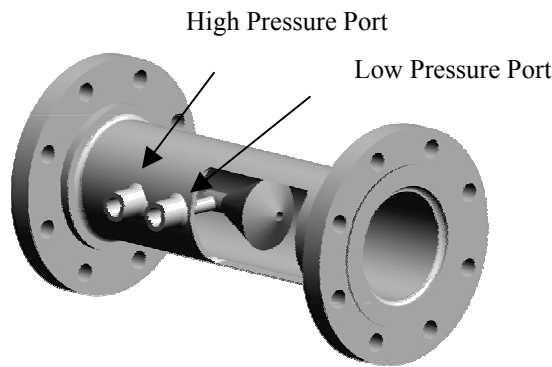


Figure 1a. The Precision "V-Cone" Meter

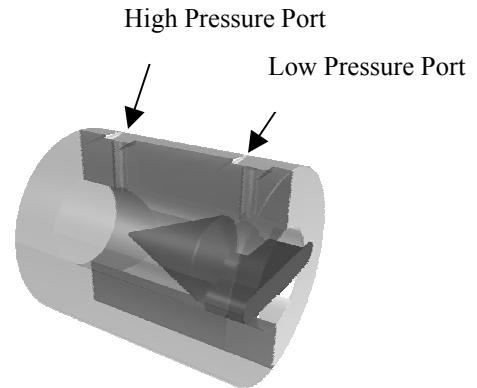


Figure 1b. The 'Wafer-Cone' Meter.

Research on the precision tube V-Cone meters performance with wet gas flows has been on going for the last few years and this paper will now discuss previously unpublished tests, analysis and conclusions from research carried out after the NSF MW 2002 meeting. In this paper unless otherwise stated the "V-Cone" meter refers to the precision "V-Cone" meter (Figure 1a).

3 THE REPEATIBILITY OF THE V-CONE METER WITH WET GAS FLOWS

In 2002 NEL tested 6" 0.55 and 0.75 beta ratio V-Cone meters and the results and analysis were reported at the 2002 NSF MW [5]. It was found that like other DP meters the V-Cone meter over-read the gas flowrate with a wet gas flow. The scale of this positive error induced by a liquids presence in a gas flow was reported to be dependent on the Lockhart-Martinelli parameter (X), the pressure (or gas to liquid density ratio) and the gas densiometric Froude number (Fr_g). The definition of the Lockhart-Martinelli parameter is the square root of the ratio of the superficial liquid flow inertia force to the superficial gas flow inertia force. It is calculated by equation 1. The definition of the gas densiometric Froude number is the square root of the ratio of gas inertia force to the liquid gravitational force. It is calculated by equation 2. Note that in equation 2 the term U_{sg} is the superficial gas velocity which is calculated by equation 3.

$$X = \frac{\dot{m}_l}{\dot{m}_g} \sqrt{\frac{\rho_g}{\rho_l}} \quad \text{---(1)}$$

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad \text{---(2)}$$

$$U_{sg} = \frac{\dot{m}_g}{\rho_g A} \quad \text{---(3)}$$

The positive error induced on any DP meter by a liquids presence in a gas flow is commonly presented in the form of the square root of the ratio of the actual read DP from the wet gas flow (ΔP_{tp}) and the DP that would be expected to be read from that DP meter if the gas phase flowed alone through the meter (ΔP_g). Therefore the over-reading is usually expressed by the term $\sqrt{\Delta P_{tp} / \Delta P_g}$. Alternatively the absolute percentage liquid induced error for any DP meter can be approximated to be $(\sqrt{\Delta P_{tp} / \Delta P_g} - 1) * 100\%$.

It was reported [5] that as the Lockhart-Martinelli parameter (X) increased for a set gas to liquid density ratio and gas densiometric Froude number (Fr_g) the over-reading increased. If the gas to liquid density ratio increased for a set Lockhart-Martinelli parameter and gas Densiometric Froude number the over-reading reduced. If the gas densiometric Froude number increased for a set Lockhart-Martinelli parameter and gas to liquid density ratio the over-reading increased.

In May 2003 McCrometer re-tested the 6" 0.75 beta ratio meter at NEL. The original test matrix covered 15, 30 and 60 Bar, Lockhart-Martinelli parameters up to 0.3 and gas flowrates from 400 to 1000 m³/hr. The new tests were at 15 and 60 Bar, Lockhart-Martinelli parameters up to 0.5 and gas flowrates between 400 and 1000 m³/hr. A significant obstruction (not described for confidentiality reasons) was positioned ten diameters upstream of the V-Cone meters. The old and new results were compared. Figure 2 shows the comparison of all the 2001 and 2003 0.75 beta ratio data sets (with the exception of $X > 0.3$ data which is discussed later).

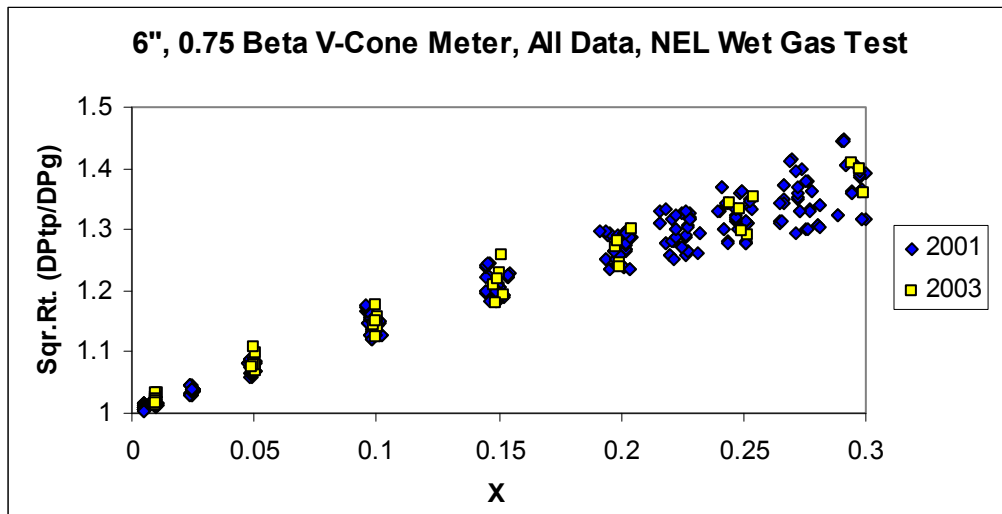


Figure 2. The NEL 2001 and 2003 data sets.

Figure 2 shows that the meter is giving repeatable results for the relationship between the over-reading and the Lockhart-Martinelli parameter across the same pressure (i.e. gas and liquid density ratio) and gas densiometric Froude number ranges.

Figure 3 shows the 2003 data ($X < 0.3$) for separate pressures. Here no obvious pressure effect is visible. However Figures 4 and 5 show the individual gas densiometric Froude numbers at 15 and 60 bar respectively. Here it is seen that the gas densiometric Froude number effect is clearly reproduced with the gradient on the graph increasing with increasing gas densiometric Froude number. (This effect is seen to be slightly more pronounced at the lower pressure which is a repeat of the performance found in the original 2001 data set.) It can be seen from Figures 4 and 5 that the ranges of the gas densiometric Froude number in the 15 Bar and 60 Bar tests are not similar. For 15 Bar the tests matrix had $0.83 \leq Fr_g \leq 1.99$ and for the 60 Bar tests the test matrix had $1.7 \leq Fr_g \leq 4.30$. Therefore the reason no pressure (or gas to liquid density ratio) effect is visible in Figure 3 is solely due to the differences in gas Densiometric Froude number masking the effect. In fact the effect is still there as is shown with the good results obtained when applying the new data set to the previously published V-Cone 0.75 beta ratio wet gas correlation [5].

To numerically show similarity between the old and new data sets the correlation formed from the old 2001 data [5] (reproduced here as equation 4 with gas to liquid density ratio parameters 4a to 4c) was applied to the new 2003 data with the liquid reference meter reading used as an input. The results are shown in Figures 6 and 7.

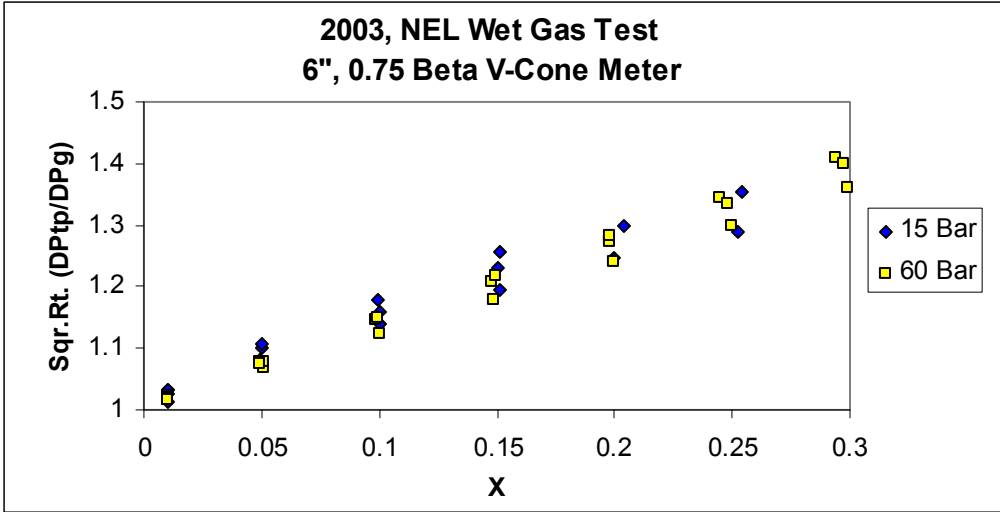


Figure 3. The 2003 0.75 beta ratio data with separated pressures.

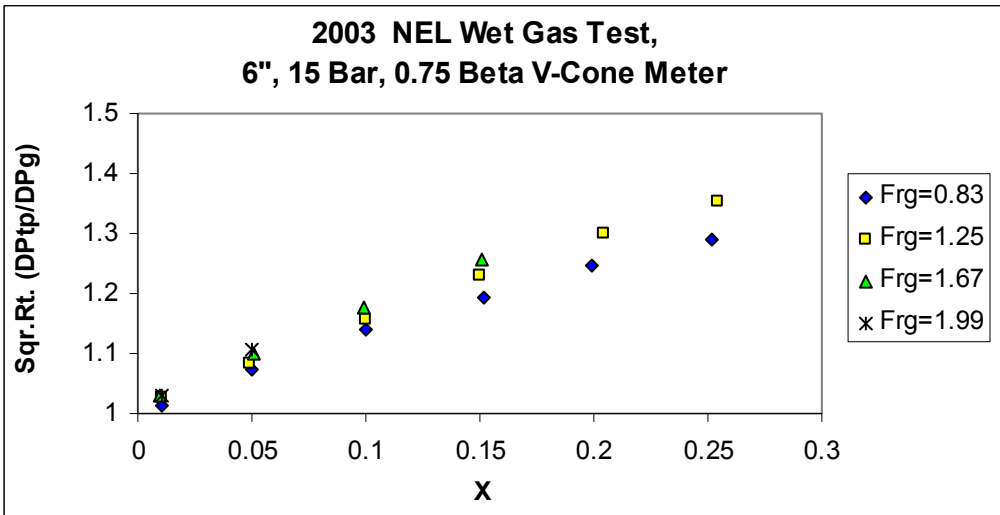


Figure 4. The 2003 0.75 beta ratio 15 Bar data with separated gas densiometric Froude numbers.

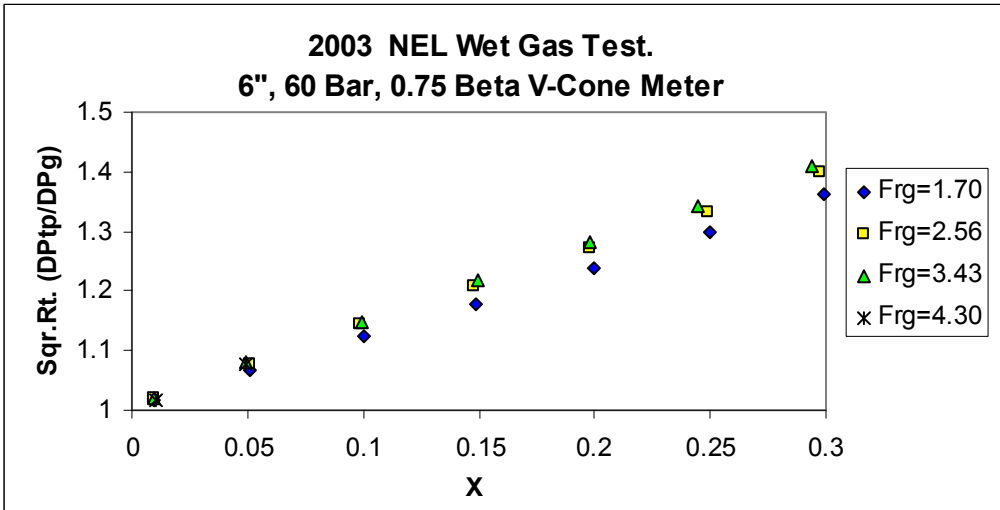


Figure 5. The 2003 0.75 beta ratio 60 Bar data with separated gas densiometric Froude numbers.

V-Cone Meter Wet Gas Correlation:

$$m_g = \frac{\dot{m}_g (tp)}{\left(\frac{1 + AX + BFr_g}{1 + CX + BFr_g} \right)} \quad (4)$$

0.75 Beta V-Cone Meter:

$$A = -0.0013 + \frac{0.3997}{\sqrt{\frac{\rho_g}{\rho_1}}} \quad (4a), \quad B = 0.0420 - \frac{0.0317}{\sqrt{\frac{\rho_g}{\rho_1}}} \quad (4b), \quad C = -0.7157 + \frac{0.2819}{\sqrt{\frac{\rho_g}{\rho_1}}} \quad (4c)$$

The gas to liquid density ratio limit of the applicability of equations 4a to 4c is from 0.022 to 1.0.

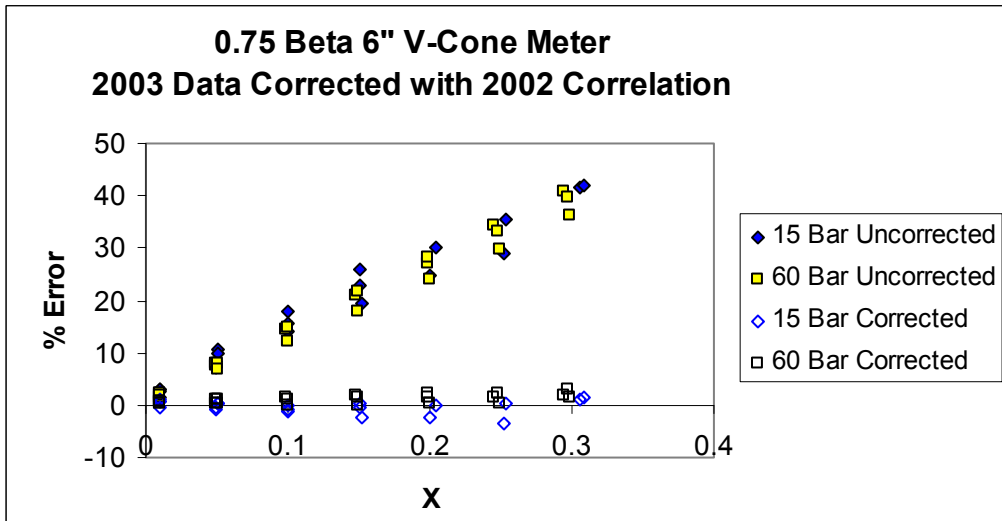


Figure 6. The uncorrected and corrected gas mass flowrate percentage error.

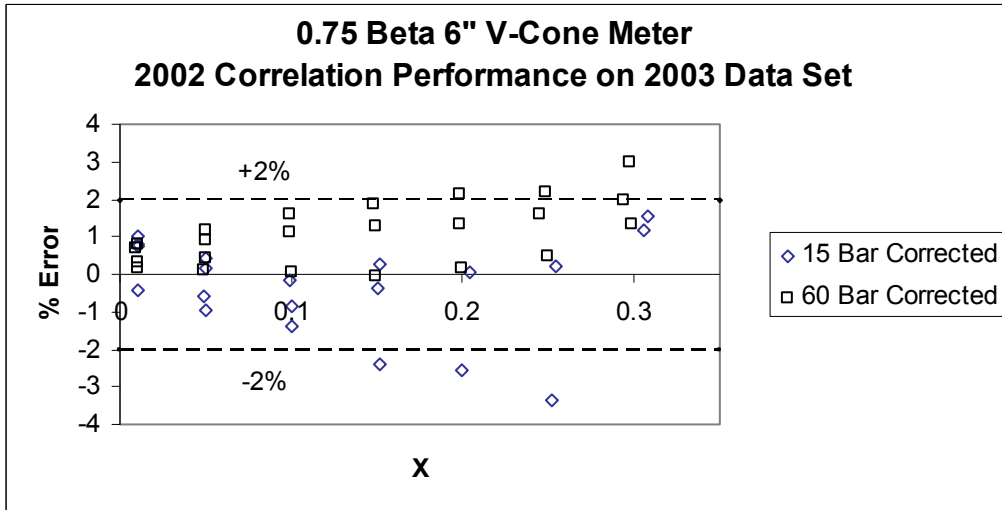


Figure 7. The corrected gas mass flowrate percentage error.

Therefore, the repeat tests at NEL have shown that the V-Cone meter is repeatable in wet gas flow and the 0.75 beta ratio V-Cone meter correlation can be relied upon to give a correction for a known liquid flowrate at the NEL conditions at least. It was seen that the obstruction ten diameters upstream had no significant effect on the wet gas meters performance.

The question was now whether the 0.75 beta ratio V-Cone meter correlation could be relied upon to give reliable corrections for a known liquid flowrate for other conditions such as different pipe size, gas flowrates, fluid types etc. Data independent of the NEL tests exists from an October 2002 wet gas flow test at the CEESI wet gas loop. This therefore allowed a test on the validity of the NEL based 0.75 beta ratio V-Cone meter wet gas correlation on conditions out with the NEL test conditions. The NEL test conditions were nitrogen and kerosene at 15, 30 and 60 bar, 400 to 1000 m³/hr up to a Lockhart-Martinelli parameter value of 0.5 in a 6" schedule 80 pipe. The CEESI test conditions were natural gas with decane at 50 bar, 150 to 400 m³/hr up to a Lockhart-Martinelli parameter value of 0.25 in a 4" schedule 80 pipe. Figure 8 shows the CEESI 0.75 beta ratio V-Cone meter results on an over-reading to Lockhart-Martinelli parameter graph.

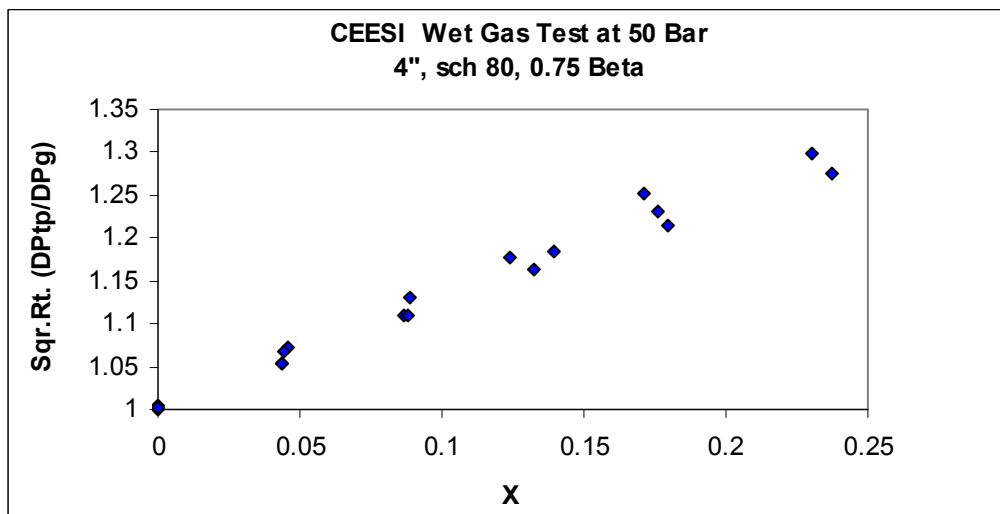


Figure 8. All the CEESI 0.75 beta V-Cone meter data

As only one pressure was tested it is not possible to see any gas to liquid density ratio effect but three gas flowrates were tested so the three corresponding gas densimetric Froude numbers can be separated out. Figure 9 shows this. So as at NEL, the CEESI data is showing that as the gas densimetric Froude number increases for a set Lockhart-Martinelli parameter and pressure (or gas to liquid density ratio) the over-reading increases.

It is interesting to plot the NEL and the CEESI wet gas test loops 0.75 beta ratio V-Cone meter data on the same over-reading to Lockhart-Martinelli parameter graph. This is done in Figure 10. As the pipe size, fluids types and gas flowrates are different for the two test rigs this shows the combined effect these different parameters have on the magnitude of the 0.75 beta ratio meters over-reading. There appears to be no significant effect. If the correlation prediction of pressure effect is correct then as the NEL data based correlation was formed from three pressures (15, 30 and 60 bar) and the CEESI data is set at 50 bar it would be expected that the CEESI 50 bar data would fall between the NEL 30 and 60 Bar data. It is seen in Figure 10 that this does happen. The final check on the applicability of the NEL data based correlation is to apply the correlation to the CEESI data set (with the CEESI liquid reference meters values used as an input). The results of this analysis are shown in Figures 11 and 12. Here it is seen that the previously published NEL data based wet gas correlation corrects the liquid induced error found at CEESI for a known liquid flowrate to $\pm 2\%$ with a few outliers slightly out with this. It is therefore concluded that the correlation can be used with some confidence for different pipe sizes, gas flowrates and fluid types.

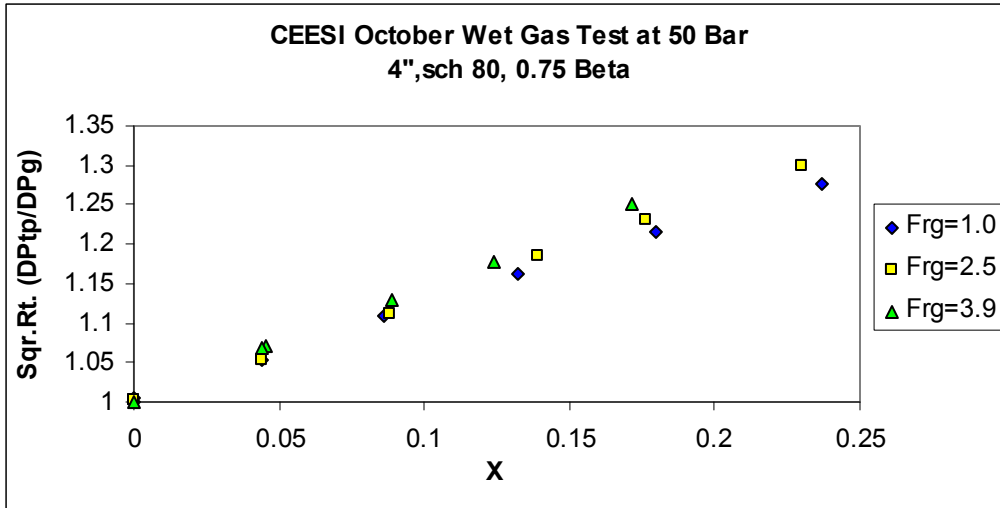


Figure 9. The CEESI tests with separated out gas densimetric Froude numbers.

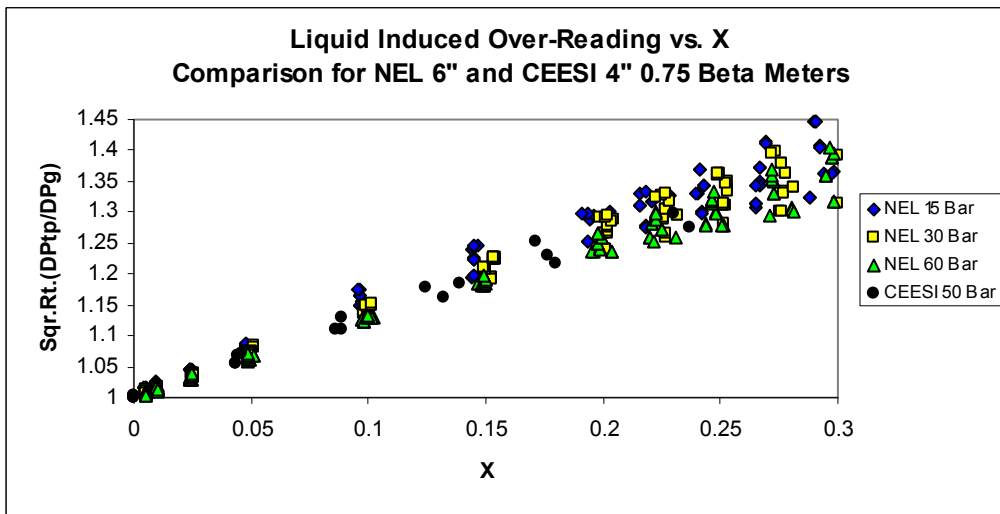


Figure 10. The combined data from NEL and CEESI.

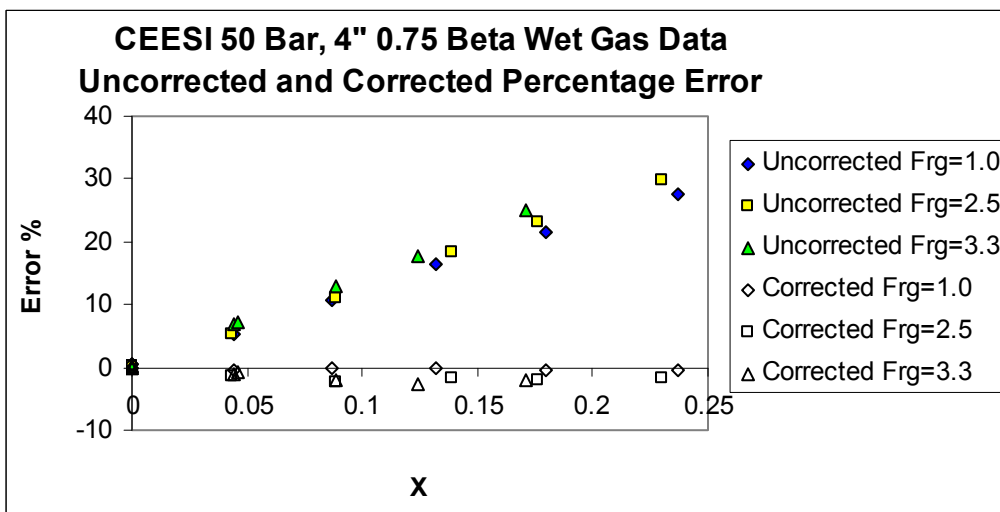


Figure 11. The NEL data based correlation corrected and uncorrected CEESI data.

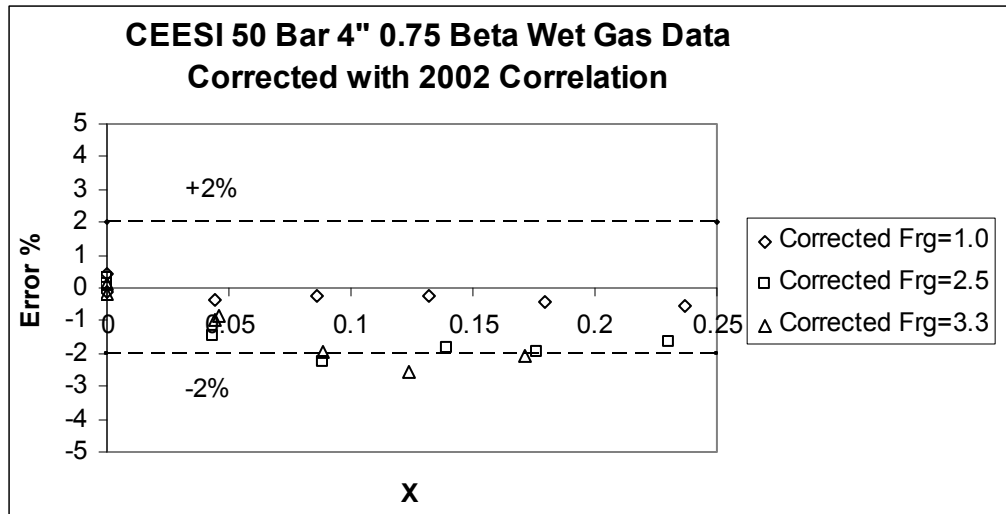


Figure 12. The NEL data based correlation corrected CEESI data.

3 THE APPLICATION OF TRACER INJECTION TECHNIQUES WITH V-CONE METERS

The published 0.75 beta ratio V-Cone meter wet gas correlation has been shown to give reliable results for repeat tests at NEL and independent tests at CEESI under different flow conditions. The repeat tests at NEL also indicated that a disturbance ten diameters upstream of the V-Cone has no significant effect on the wet gas performance. This builds confidence in the V-Cone meters performance with real wet natural gas production flows. The V-Cone meter has been used for some years as a meter for wet natural gas production flows although often the operators have ignored the liquid induced error (as they have done with many other flow meters). With confidence in the V-Cone meter wet gas correlations performance the correlation can be applied on new or existing wet natural gas flows with V-Cone meters for known liquid flowrates.

A popular method for finding the liquid flowrate in a wet natural gas flow is to use a tracer injection method. The Shell developed technique is well documented [6, 7] and it offers water and liquid hydrocarbon flowrate estimations to $\pm 10\%$. For the last few years the tracer injection technique has been applied with the Venturi meter and a Venturi meters wet gas flow correlation to predict the gas and liquid flowrates. With the development of the V-Cone meter wet gas correlation this same metering technique can be applied using a V-Cone meter as the primary meter. In fact comparing wet gas meter results from the NEL test loop it appears that the V-Cone meter has advantages over the Venturi meter. These are now discussed.

The main advantage is that the V-Cone meter is less sensitive to the liquid loading of a gas flow than the Venturi meter. That is for identical wet gas flow conditions a V-Cone meter has a smaller error than a Venturi meter and for a set wet gas differential pressure for each meter type a fluctuating liquid flowrate corresponds to a smaller fluctuation in the gas flowrate for a V-Cone meter compared to a Venturi meter. When the responses of Venturi and V-Cone meters at the same wet gas flow conditions are plotted on an over-reading to Lockhart-Martinelli parameter graph the gradient of the V-Cone meter is slightly less than that of the Venturi meter. Figure 13 shows a plot of NEL 6", 0.55 beta ratio V-Cone and Venturi meter 60 Bar data sets from the DTI funded Flow Programme. For a simple example of how this relates to a V-Cone meter advantage when applying tracer injection technology the basic "Murdock" type wet gas correction [8] has been fitted to the data. The Murdock correction method for predicting the gas mass flowrate is equation 5. Note "M" is the "Murdock" gradient of the plots in Figure 13.

$$m_g = \frac{EA_t YC_d \sqrt{2\rho_g \Delta P_{tp}}}{1 + MX} \quad (5)$$

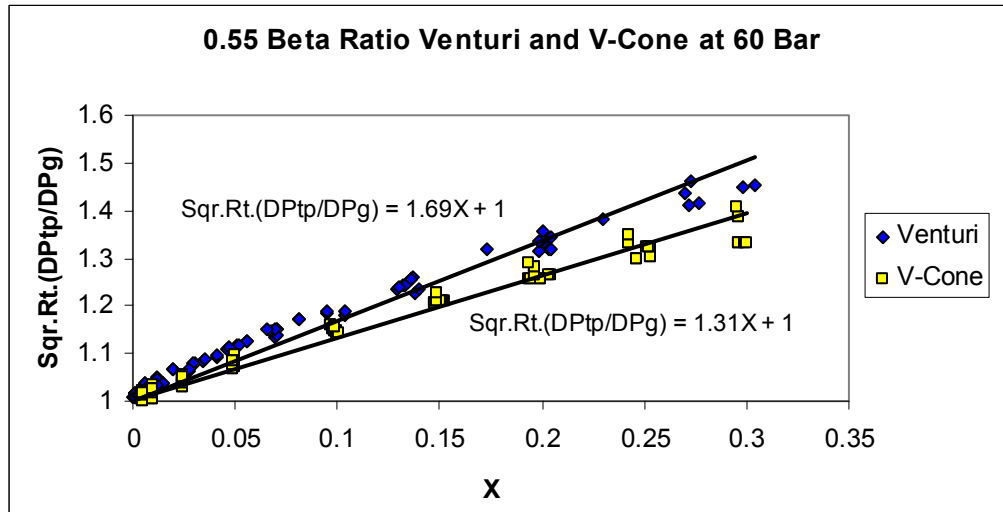


Figure 13. V-Cone and Venturi data for the same wet gas flow conditions.

Substituting equation 1 into equation 5 gives equation 6.

$$m_g = \frac{EA_t YC_d \sqrt{2\rho_g \Delta P_{tp}}}{1 + M \left(\frac{m_l}{m_g} \sqrt{\frac{\rho_g}{\rho_l}} \right)} \quad (6)$$

Now note that for any given DP meter type the numerator (the single phase equation) for a given steady wet gas flow condition will be a constant as will be the gas to liquid density ratio. Also M is constant for a chosen meter (for this simple correction method). Therefore we can group some of the terms in equation 6 to give constant values for that particular wet gas flow condition in question as shown in equation 7 and equation 8.

$$K_1 = EA_t YC_d \sqrt{2\rho_g \Delta P_{tp}} \quad (7)$$

$$K_2 = M \sqrt{\frac{\rho_g}{\rho_l}} \quad (8)$$

Equation 6 can now be written as equation 9 and rearranged to equation 10.

$$m_g = \frac{K_1}{1 + K_2 \frac{m_l}{m_g}} \quad (9)$$

$$m_l = \frac{K_1}{K_2} - \frac{m_g}{K_2} \quad (10)$$

Taking the derivative of equation 10 gives equation 11:

$$\left(\frac{d m_l}{d m_g} \right) = -\frac{1}{K_2} = -\frac{1}{M \sqrt{\frac{\rho_g}{\rho_l}}} \quad (11)$$

For a set wet gas flow the densities are constant. The Venturi and V-Cone “Murdock” gradients are set and the Venturi meter gradient is found from experiment to be greater than the V-Cone meter gradient (e.g. see Figure 13). Therefore we have equations 11a and 11b:

$$\left(\frac{d m_l}{d m_g} \right)_{\text{Venturi}} = -\frac{1}{M_{\text{Venturi}} \sqrt{\frac{\rho_g}{\rho_l}}} \quad (11a) \quad \text{and} \quad \left(\frac{d m_l}{d m_g} \right)_{\text{V-Cone}} = -\frac{1}{M_{\text{V-Cone}} \sqrt{\frac{\rho_g}{\rho_l}}} \quad (11b)$$

As it is found that $M_{\text{V-Cone}} < M_{\text{Venturi}}$ then we now know that the magnitude (or modulus) of the V-Cone meters liquid to gas mass flowrate gradient is greater than the Venturi meters liquid to gas mass flowrate gradient (see equation 12).

$$\left| \left(\frac{d m_l}{d m_g} \right)_{\text{V-Cone}} \right| > \left| \left(\frac{d m_l}{d m_g} \right)_{\text{Venturi}} \right| \quad (12)$$

Both terms are negative so the V-Cone meter has a steeper negative gradient than the Venturi meter in a gas mass flow to liquid mass flow plot for the set differential pressures being read by each meter for that particular wet gas flow condition. A steeper gradient is an advantage when applying the tracer injection technique to obtain the estimated liquid mass flowrate to $\pm 10\%$ in order to use this liquid flowrate value as an input to the chosen meters gas mass flowrate correction factor. The reason for this is as following. If a Venturi meter and a V-Cone meter were used in identical wet gas flow conditions both have published correlations stating that for a known liquid flowrate the gas flowrate can be found to $\pm 2\%$. Therefore, if this $\pm 2\%$ (or what ever the small simplified correlation uncertainty of this particular Murdock correlation example is) is ignored it can be assumed that for a given wet gas flow condition with a precise liquid mass flowrate entered into the correlations both meters give the same correct gas mass flowrate. That is equation 5 leads to equation 12.

$$m_g = \frac{(EA_t YC_d \sqrt{2\rho_g \Delta P_{tp}})_{\text{venturi}}}{1 + M_{\text{Venturi}} X} = \frac{(EA_t YC_d \sqrt{2\rho_g \Delta P_{tp}})_{\text{V-Cone}}}{1 + M_{\text{V-Cone}} X} \quad (12)$$

However, in reality there will not be a precise liquid mass flowrate value available. The available estimation will be the tracer injections $\pm 10\%$ value. That is, the liquid mass flowrate input may be out by $\pm 10\%$ and this error will have a knock on effect on the gas mass flowrate prediction error for both meter types. However, the steeper the negative gradient value of equation 11 the less this knock on effect will be. In other words the V-Cone meter wet gas flow correlation is less sensitive to errors in the liquid flowrate estimation than the Venturi meter wet gas flow correlation. Graphically this is seen in Figure 14.

Figure 14 is a sketch of a situation where for a set wet gas flow condition the V-Cone and Venturi meters individual differential pressures are read and for those set differential pressures the family of possible gas to liquid mass flowrates for each meter are calculated with equation 12. The liquid mass flowrate is found by a tracer injection method with a $\pm 10\%$ uncertainty. The black horizontal line indicates the actual liquid flowrate and the dashed lines are the $\pm 10\%$ limits. That is the estimated liquid mass flowrate will be anywhere within these dashed lines. Where as for the correct liquid mass flowrate input either meters correlation gives the correct gas mass flowrate (ignoring both meter correlations same small uncertainty) an incorrect liquid mass flowrate gives an associated gas mass flowrate error. For a set differential pressure read an over estimation of the liquid flowrate leads to an under prediction of the gas flowrate and an under estimation of the liquid flowrate leads to an over prediction of the gas flowrate. Figure 14 shows that for the V-Cone

meter with the steeper gradient this associated gas mass flowrate error ($\Delta m_{g,V-Cone}$) is smaller than for the Venturi meter with shallower gradient ($\Delta m_{g,Venturi}$). Hence, using a V-Cone meter instead of a Venturi meter with tracer injection technology gives a lower uncertainty in the gas mass flowrate prediction.

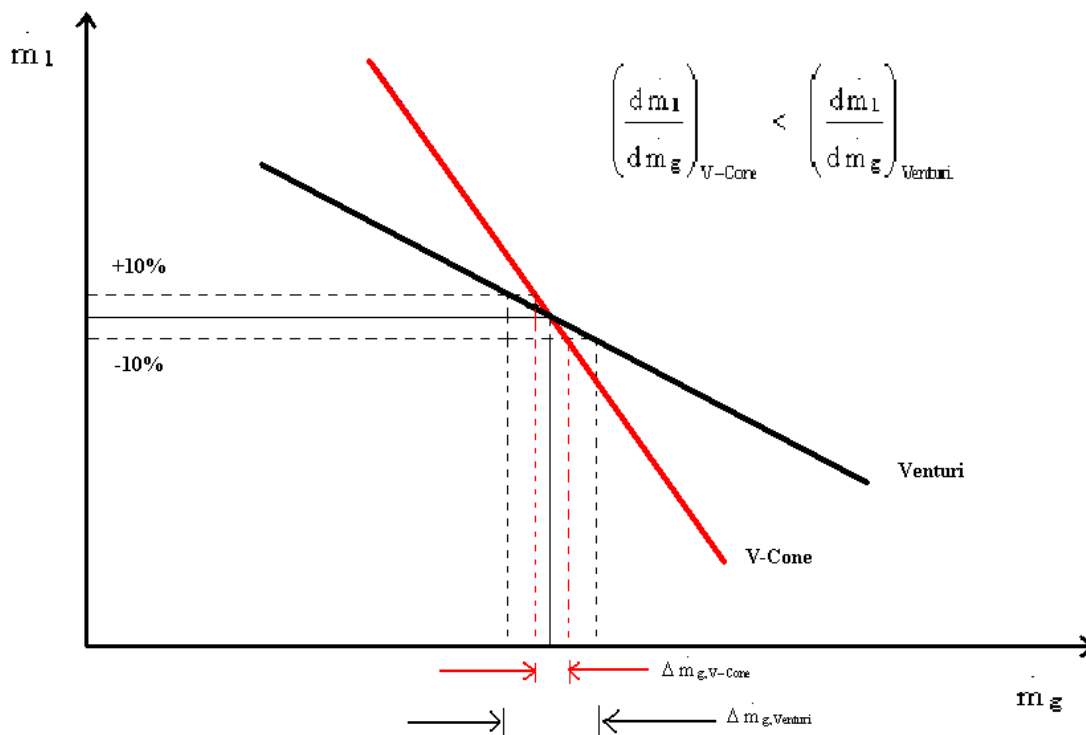


Figure 14. Constant differential pressure graph showing the V-Cone and Venturi meter relative gas mass flowrate errors due to the $\pm 10\%$ tracer injection liquid mass flowrate estimation.

Note: Theoretically if the two DP meters were installed in series the intersection of the two meters lines in Figure 14 gives the correct gas and liquid flowrate values. Unfortunately in practice with most DP meters the gradients are not different enough for the area encompassed by the uncertainty bands (not shown in Figure 14) to give an acceptable gas and liquid mass flowrate prediction uncertainty. Hence V-Cone and Venturi meters are not put in series as a wet gas

metering device and in Figure 14 the two meter results are shown together for tracer injection /DP meter comparison purposes only.

With this simple correlation discussion showing a better V-Cone meter performance compared to the Venturi meter when using a tracer injection technique with wet gas correlations an obvious question is what difference in the gas mass flowrate uncertainty will be obtained using the more complex and accurate DP wet gas correlations and is the difference large enough to be of practical significance to the natural gas production industry? With the popular Venturi meter wet gas correlation [7] and the V-Cone correlation (equations 4, 4a to 4c) more complex here for simplicity a numerical example is now worked through.

A random mid-range NEL wet gas loop flow point was selected for this example (from the DTI Flow Programme flow test data). The flow in the 6", schedule 80 pipe at a nominal 60 Bar was 13.91 kg/s of gas (682 m³/hr) and 8.1 kg/s of liquid. The gas density was 73.4 kg/m³ and the liquid density was 806.8 kg/m³. Therefore from equations 1 to 3 the Lockhart-Martinelli parameter was 0.176 and the gas densiometric Froude number was 2.94. The gas to liquid density ratio was 0.091. Assuming for simplicity that both the V-Cone and Venturi meter have an expansion factor of approximately unity and approximately constant discharge coefficients (0.85 and 0.995 were used respectively) with the known geometry of the meters (for this example 0.75 beta ratios were used) the dry gas differential pressures were predicted. From these known wet gas parameters the respective correlations were used to predict the actual wet gas differential pressures. For each meter that set wet gas differential pressure was then held constant (as it would appear in a real situation) for the calculations and the liquid flowrate input was varied and the associated gas flowrate predictions were calculated by the meter wet gas correlations. The results are plotted in Figure 15 along with the $\pm 10\%$ Tracerflow liquid mass flowrate estimation. The possible gas flowrate error induced by the liquid flowrates 10% uncertainty is shown for both meters. The shallower gradient of the Venturi meter is producing a wider spread of gas mass flowrate results around the actual point associated with the liquid uncertainty than the steeper V-Cone gradient.

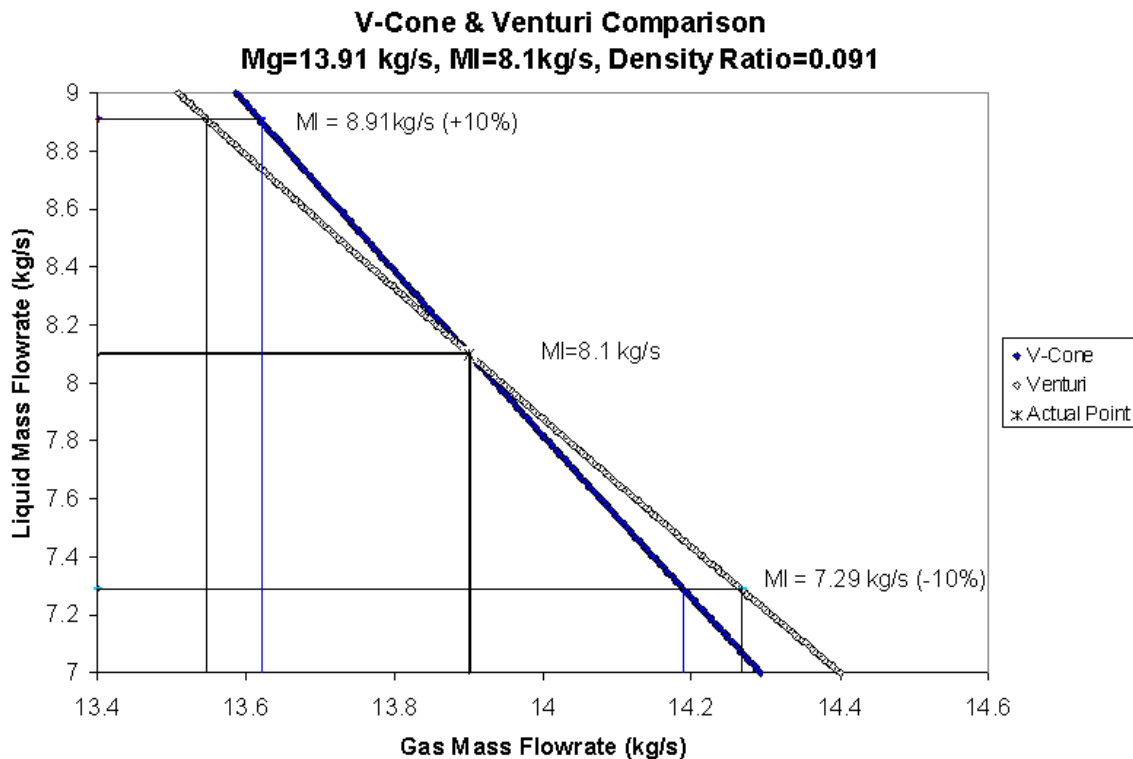


Figure 15. A comparison of the liquid mass flow uncertainty induced gas mass flow uncertainty.

The V-Cone meter result was $13.91 \text{ kg/s} \pm 0.29 \text{ kg/s}$ ($\pm 2.1\%$). The Venturi meter result was $13.91 \text{ kg/s} \pm 0.36 \text{ kg/s}$ ($\pm 2.6\%$). The difference of spread of $\pm 0.5\%$ was $\pm 0.07 \text{ kg/s}$ or ± 6 metric tonnes of gas / day for this modest flowrate example of $682 \text{ m}^3/\text{hr}$. Therefore this result shows this issue is of practical significance to the natural gas production industry.

Another advantage the V-Cone meter has over other DP meters with wet gas flows is there is some evidence from the 2003 NEL results that the V-Cone meter can cope with some wet gas flow upstream disturbance the inlet conditions. Many DP wet gas correlations are formed with wet gas flows with straight unobstructed upstream flows and no mention of less than perfect conditions are mentioned in the various publications. In practice of course often ideal upstream conditions do not exist. In the event there are no upstream obstructions close to the meter the tracer fluids injected will have no mixing aids to help shorten the distance required to achieve the complete mixing of produced liquid and tracer fluid. A V-Cone meter is known to be an excellent mixer and would aid the mixing of these liquids.

A final advantage the V-Cone meter has over other DP meters when using the tracer injection method is that in reality it is difficult for users to predict the precise Lockhart-Martinelli parameter. If the prediction is for a relatively high number, say 0.28, and in reality it is actually, say 0.35, most published DP meter wet gas correlations only operate up to 0.3 and so it is found that the correlations are not useable after the system is bought and installed. During the latest NEL tests the 0.75 beta ratio V-Cone meter was tested beyond the old limit of Lockhart-Martinelli parameter of 0.3 and up to 0.5. The relatively few points taken (compared to the large data set at $X < 0.3$) showed that the V-Cone meter still functions in flows up to Lockhart-Martinelli parameters of 0.5. That is, it continues to give predictable readings beyond 0.3. Figure 16 shows all the 2003 NEL 0.75 beta ratio V-Cone meter results.

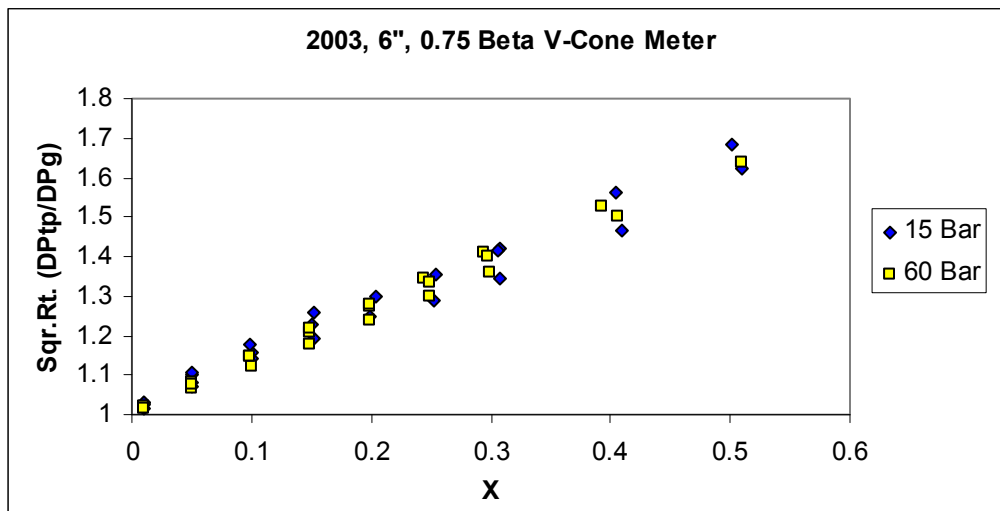


Figure 16. All the 2003 NEL 0.75 beta ratio V-Cone wet gas data set.

Industry often assigns the Lockhart-Martinelli parameter value of 0.3 as the border between wet gas and multi-phase flow. Figure 16 shows that the V-Cone meter gives useable results after the "wet gas" limit and continues to work into the multi-phase regime until the highest tested value at 0.5 (which corresponded to a Gas Volume Fraction of 87%). An expanded wet gas correlation was formed in the same form as equation 4, 4a to 4c. The functions of parameters A, B and C for this expanded correlation are withheld in commercial confidence. There was some change in the gradient at these higher Lockhart-Martinelli parameters especially at the lower pressure. Figures 17 and 18 show this. Due to this the expanded wet gas correlation to be used (at $X > 0.3$ only) corrects the liquid induced gas mass flowrate error to $\pm 4\%$. Figure 19 shows this correction on all the existing NEL 0.75 beta ratio wet gas data (although its application will be for $X > 0.3$ only).

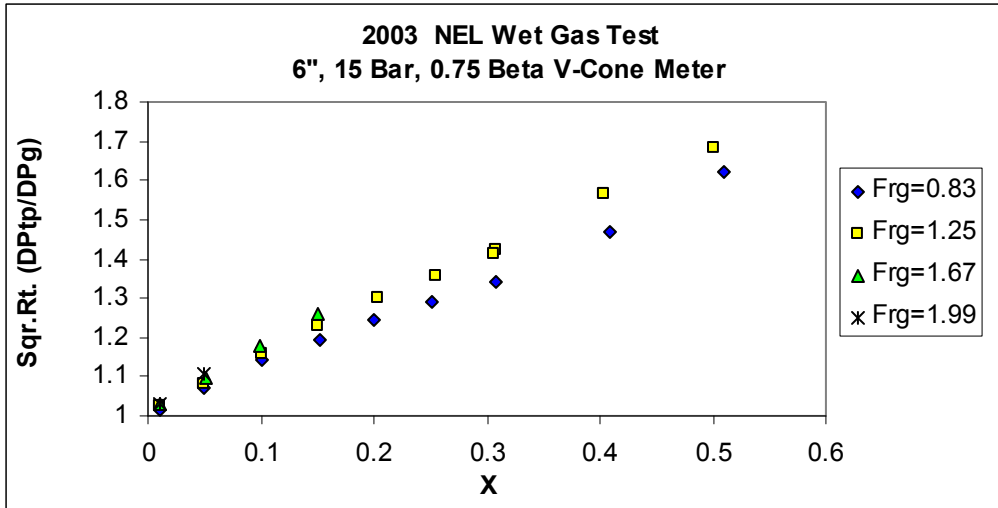


Figure 17. The full 15 bar NEL 2003 0.75 beta ratio V-Cone wet gas flow results.

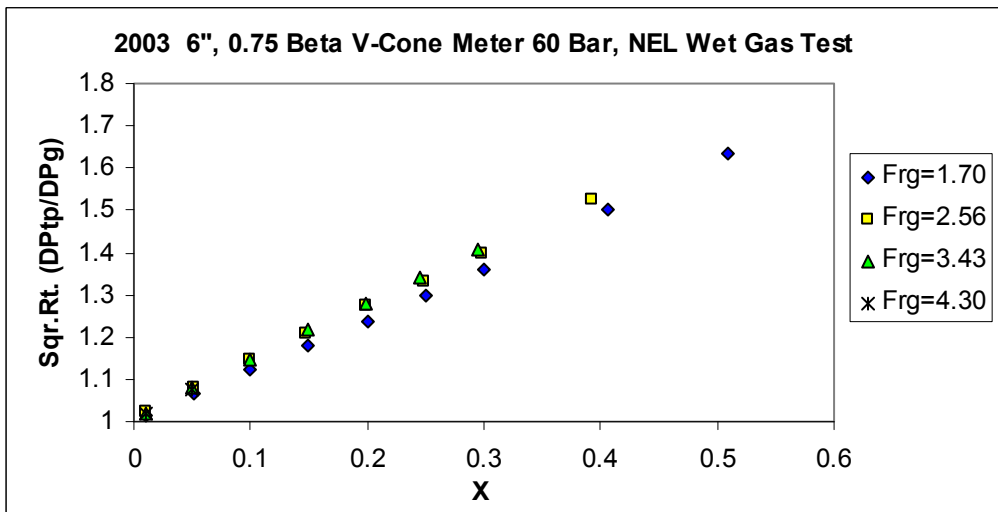


Figure 19. The full 60 bar NEL 2003 0.75 beta ratio V-Cone wet gas flow results.

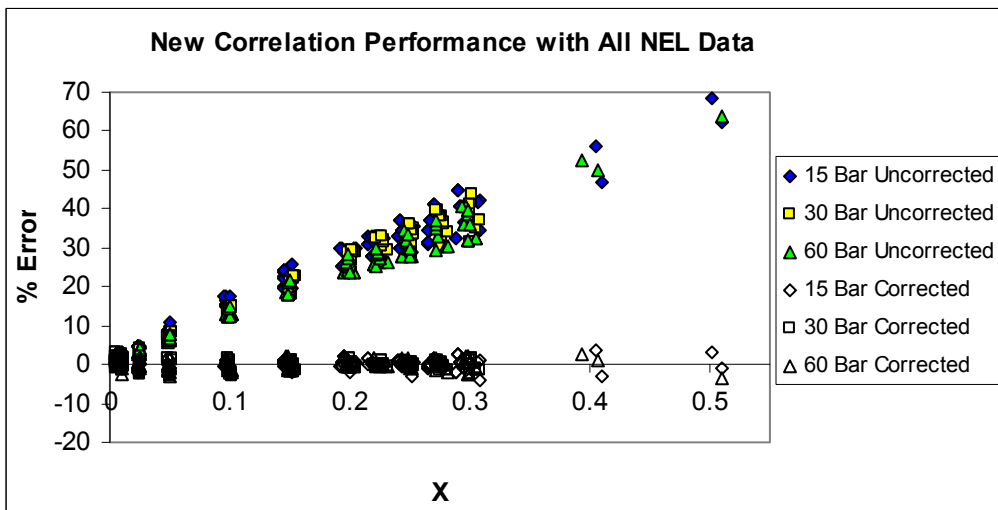


Figure 20. The complete NEL 0.75 beta ratio V-Cone wet gas results and the expanded Lockhart-Martinelli range correction results.

Figure 21 shows the expanded Lockhart- Martinelli range correction results alone.

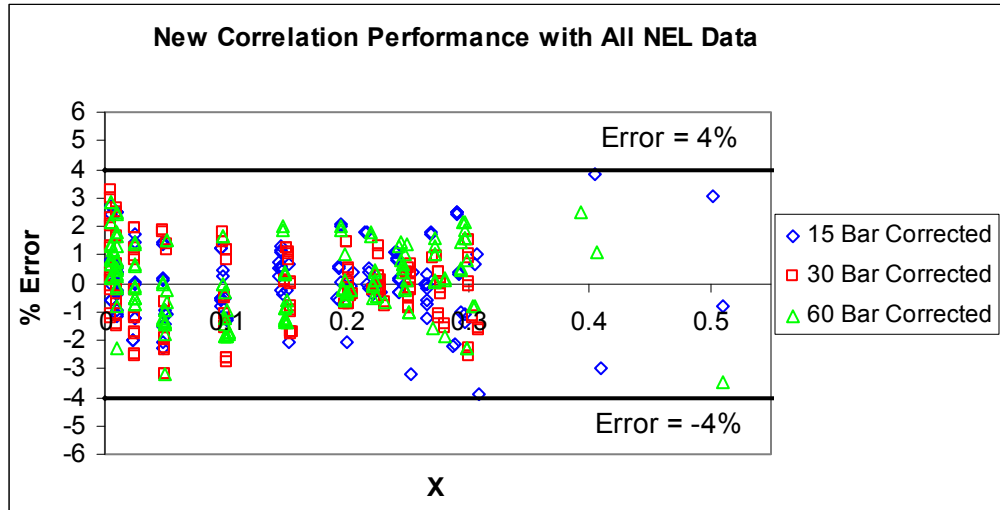


Figure 21. The expanded Lockhart- Martinelli range correction results for all NEL 0.75 beta ratio V-Cone data.

Hence, the V-Cone meter is a good choice to use with tracer flow injection techniques as the correlation is proven, the meter is relatively insensitivity to the liquid mass flowrate uncertainty, it has good liquid mixing abilities, it has the ability to work with at least some upstream obstruction and it will operate beyond the wet gas range into the upper GVF end of the general multiphase flow range.

4 A WET GAS FIELD TEST FOR THE WAFER-CONE METER

In March 2001 BP tested a 4" 0.55 beta ratio Wafer-Cone in real wet flow upstream conditions at Whitney Canyon, Wyoming, USA. K. Bright of BP has kindly released the test results. Figure 22 shows a sketch of the test set up. A 4" 0.55 beta ratio Orifice Plate meter was positioned upstream of the Wafer-Cone meter 30 diameters downstream from a bend. The Wafer-Cone meter was positioned 36" downstream of this wet gas Orifice Plate meter. Both these meters were subjected to a wet gas flow as the natural gas flow had condensate and water entrained in it. The separator was a further 12" downstream of the Wafer-Cone meter. After the separator an identical dry gas flow Orifice Plate meter to that installed upstream of the separator was installed according to API 14.3. (This reference meter was proved with a mobile gas prover.)

The average gas flowrate metered by the dry gas Orifice Plate meter was approximately 489,000 SCFH. The gas molecular weight was quoted by BP as being 22.17 mW and the pressure was approximately 370 psia so the actual gas flowrate was approximately 523 m³/hr. The liquid loading was quoted by BP as being 3.93 barrels of condensate / million SCFH and 3.76 barrels of water / million SCFH. That is a total liquid flow of 7.69 barrels / million SCFH. At a gas flowrate of 489,000 SCFH the total liquid flowrate is 3.76 barrels (or 0.598 m³/hr). The mix of condensate and water was therefore approximately 51% and 49% respectively. Taking water density to be approximately 1000 kg/m³ and the condensate density as 635 kg/m³ (quoted by BP) this leads to the approximate homogenous liquid density of 773 kg/m³. The gas density is approximately 21.9 kg/m³. Therefore converting volume flow to gas mass flow and applying equation 1 gives a Lockhart-Martinelli parameter in the upstream flow in the order of 0.007. BP declared the gas outlet to be effectively dry.

The results read by BP over a 24 hour period are shown graphically in Figure 23.

BP, Whitney Canyon, Wyoming, USA.

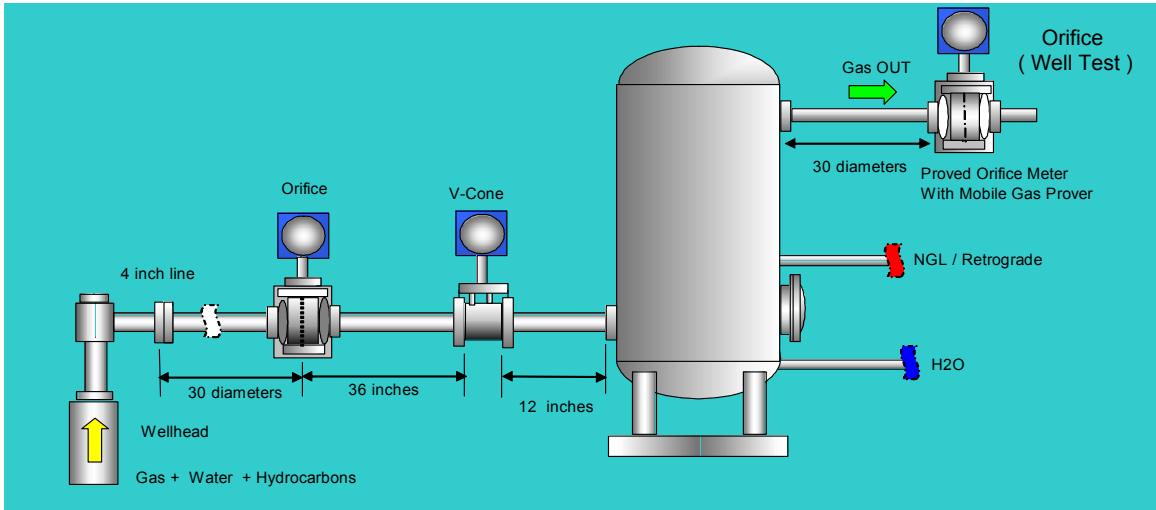


Figure 22. The BP wet gas Wafer-Cone meter test set up.

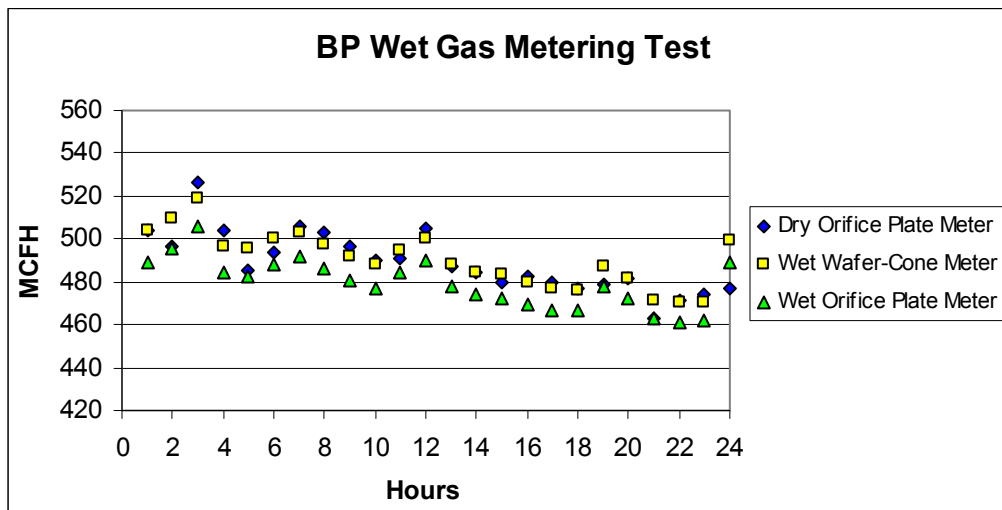


Figure 23. The BP wet gas flow field test results.

Figure 23 shows each meters average reading over each hour. It shows that the wet gas Wafer-Cone meter was seen to track the dry gas Orifice Plate reference meter better than the wet gas Orifice Plate meter even though the wet and dry Orifice Plate meters are identical. The wet gas Orifice Plate meter is seen to under-read the actual gas flowrate. There is evidence of the Orifice Plate meter under-reading with wet gas flows in the literature [9].

It is generally accepted in industry that for very low Lockhart-Martinelli parameter values (typically $X < 0.02$) dry gas DP meters can be used with no correction required as the liquid induced error will be negligible. With an approximate Lockhart-Martinelli parameter of 0.007 this condition therefore conforms to this situation. The relative error of the wet gas Orifice Plate and Wafer-Cone meters are shown compared to the dry gas Orifice Plate meter (i.e. the reference meter) base line in Figure 24. It is seen that the dry gas Orifice Plate meter and the wet gas Wafer-Cone meter data points are mostly within $\pm 2\%$ and the majority are actually within $\pm 1.5\%$. It should

be noted that the API 14.3 quoted uncertainty for Orifice Plate meters with dry gas is 0.5% and the Wafer-Cone meter uncertainty with dry gas is said to be 1%. Hence the points are mostly

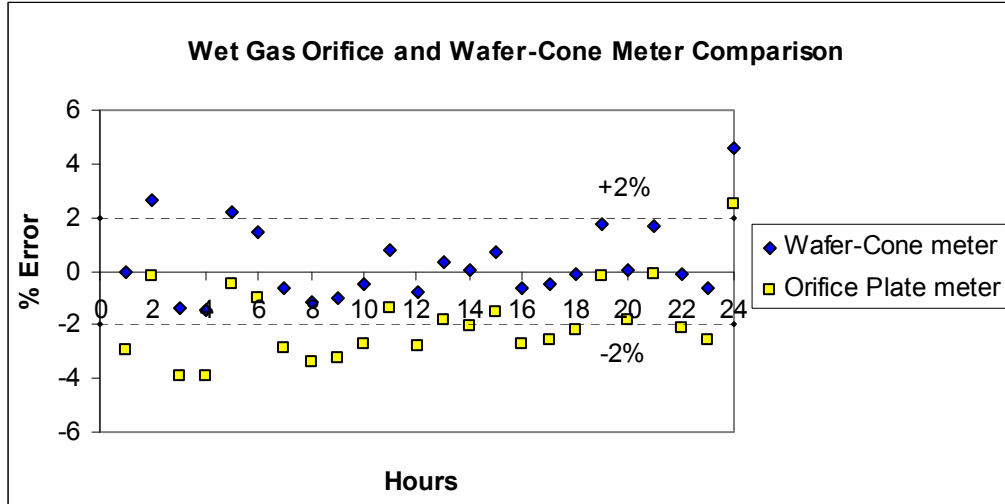


Figure 24. The relative error of the wet gas Orifice Plate and Wafer-Cone meters compared to the dry gas reference meter.

within dry gas metering acceptability. In Figure 24 the points out with the $\pm 2\%$ lines show the Wafer-Cone meter over-reading as would be expected with liquid presence. As the data is from a field test and the conditions are not therefore held precisely these points represent averaged values and it is assumed that over each hour the higher over-readings of the Wafer-Cone meter are due to periodic small increases in the Lockhart-Martinelli parameter. The Orifice Plate meter appears to have a more significant negative error with many points below -2% . Therefore, in this test it is shown that for no correction applied the wet gas Wafer-Cone meter successfully tracked the Orifice Plate dry gas reference meter whereas the wet gas Orifice Plate meter did not. Over the course of the 24 hour test the Orifice Plate dry gas reference meter read a total 11.737 million SCF, the wet gas Orifice Plate meter read a total of 11.509 million SCF and the wet gas Wafer-Cone meter read 11.771 million SCF. Therefore the wet gas Orifice Plate meter read 228,100 SCF low an over all difference of -1.9% . The wet gas Wafer-Cone meter read 33,900 SCF high an over all difference of $+0.3\%$. Hence, if the Wafer-Cone meter was installed in this application alone rather than an Orifice Plate meter the meter operator would avoid registering 228,100 SCF/day of gas low and register 33,900 SCF/day high thus vastly reducing the exposure to error for buyer and seller. In particular the producer would not be giving away a free 228,100 SCF/day. Therefore, the Wafer-Cone meter is a good choice for use in unprocessed wet natural gas flows with low Lockhart-Martinelli parameter values. The results are summarised in Table 1.

	Dry Gas Orifice Plate Meter	Wet Gas Orifice Plate Meter	Wet Gas Wafer-Cone Meter
Total Volume Flowrate (Million SCF)	11,737,000	11,509,000	11,771,000
Absolute Difference Between Dry and Wet Meters (Million SCF)	N/A	-228,100	+33,900
% Error Between Dry and Wet Meters	N/A	-1.9	+0.3

Table 1. The wet gas Orifice Plate and Wafer-Cone meters performance over 24 hours compared to the dry gas reference meter.

The raw data collected by BP is shown in Table 2.

		Dry Gas Orifice Plate Meter	Wet Gas Wafer- Cone Meter	Wet Gas Orifice Plate Meter	Upstream Pressure	Upstream Temperature
--DATE--	--TIME--	MCFH	MCFH	MCFH	-PSIA-	-DEGF-
1/22/2001	17:00:00	504.41	504.053	489.526	373.5	119.9
1/22/2001	18:00:00	496.5	509.756	495.586	375.6	119.9
1/22/2001	19:00:00	526.25	519.024	505.496	374.9	119.6
1/22/2001	20:00:00	504.04	496.692	484.337	371.7	119.5
1/22/2001	21:00:00	484.87	495.705	482.686	371.9	119.4
1/22/2001	22:00:00	493.45	500.691	488.556	373.2	119.4
1/22/2001	23:00:00	506.04	502.829	491.551	373.8	119.4
1/23/2001	0:00:00	503.08	497.401	485.979	369.8	119.3
1/23/2001	1:00:00	496.79	491.94	480.75	369.4	119.3
1/23/2001	2:00:00	490.04	487.84	476.625	371.2	119.3
1/23/2001	3:00:00	491.04	495.004	484.341	371.5	119.2
1/23/2001	4:00:00	504.5	500.487	490.445	372.3	119.2
1/23/2001	5:00:00	486.87	488.422	477.947	370.7	119
1/23/2001	6:00:00	484.45	484.779	474.372	369	119
1/23/2001	7:00:00	479.67	483.022	472.455	368.4	119
1/23/2001	8:00:00	483	479.931	469.689	366.5	118.9
1/23/2001	9:00:00	479.58	477.279	467.129	367.8	118.9
1/23/2001	10:00:00	476.83	476.231	466.232	370.9	118.8
1/23/2001	11:00:00	478.54	486.98	477.817	361.3	118.6
1/23/2001	12:00:00	481.29	481.302	472.392	362.8	118.6
1/23/2001	13:00:00	463.2	470.997	462.513	376.7	118.7
1/23/2001	14:00:00	471.2	470.623	461.351	373.2	118.7
1/23/2001	15:00:00	474	470.861	461.711	373	118.7
1/23/2001	16:00:00	477.33	499.061	489.357	355.3	118.6
Total Flow		11736.97	11770.91	11508.84		

Table 2. Raw data from BP wet gas field test (reproduced with permission).

5 CONCLUSIONS

It is concluded from repeat tests at NEL of a 6", 0.75 beta ratio V-Cone meter that the previously published wet gas performance [5] is repeatable and that a disturbance 10 diameters upstream of the V-Cone meter inlet has no noticeable effect on the performance of the V-Cone meter with wet gas flows. From analysis of the CEESI wet gas 0.75 beta ratio V-Cone results it is concluded that the previously published wet gas correlation [5] can be applied to neighbouring pipe sizes, fluid types and gas flowrates than were not in the correlations data set. It is further concluded that NEL and CEESI wet gas loops produce similar DP meter behaviour even though the pipe size, gas flowrate range and fluid types are different.

From consideration of the known wet gas flow performances of different DP meters it is concluded that the V-Cone meter shows advantages over other DP meter designs when employing the tracer injection technique to form a system that meters both the liquid phases flowrates and the gas phase flowrate.

Finally, it is concluded that for unprocessed natural gas flows with low Lockhart-Martinelli parameter values the Wafer-Cone meter is a good choice of meter.

Notation

X	The Lockhart-Martinelli parameter
m_g	The actual gas mass flowrate
m_l	The actual liquid mass flowrate
$m_{g(tp)}$	The over estimated gas mass flowrate using the read wet gas differential pressure
ρ_g	The gas density
ρ_l	The liquid density
ΔP_{tp}	The read wet gas (or “two-phase”) differential pressure
ΔP_g	The gas superficial differential pressure
C_d	The discharge coefficient
Fr_g	The gas densimetric Froude number
U_{sg}	The superficial gas velocity
g	The gravitational constant
D	The meter inlet diameter
A	The meter inlet cross sectional area
E	The DP meter Velocity of Approach
Y	The DP meter expansibility factor
M	The Murdock gradient
MSCF	Thousand standard cubic feet
SCFH	Standard cubic feet per hour

Acknowledgment

McCrometer would like to thank BP for kindly giving permission for the Wafer-Cone meter wet gas field test data to be presented. In particular thanks are due to K. Bright for release of the data and to the late M. Haefele for allowing the test to be carried out.

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