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WET GAS METERING WITH V-CONE METERS

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1 INTRODUCTION

With the industrial requirement to meter wet gas flows increasing worldwide McCrometer has tested the performance of the single phase V-Cone meter (a Differential Pressure (DP) type meter) in wet gas flows in both the NEL and CEESI wet gas loops. These tests have shown how the V-Cone meter responds to different amounts of liquid entrained in a gas flow and have enabled correction factors to be developed.

This paper first reviews the 6”, 0.55 beta ratio V-Cone meter data collected at NEL in 2001 and the correction factor developed [1]. (These tests were funded by the UK’s Department of Trade and Industry (DTI)). The new repeat data from NEL in 2003 is introduced allowing the two data sets to be compared along with a review on the applicability of the 2001 correction factor to the 2003 data. Data is then presented that shows the 6”, 0.55 beta ratio V-Cone meters performance at higher liquid loadings than has previously been discussed. Finally, the Differential Pressure meter beta ratio wet gas effect is discussed by comparing NEL 6” 0.55 to 0.75 beta ratio data and CEESI’s 4”, 0.60 beta ratio data to the NEL 6”, 0.55 beta ratio data, and conclusions are drawn.

2 THE SINGLE PHASE V-CONE METER

In order to discuss the V-Cone meter performance with wet gas flows, a brief discussion of the meter in dry gas is first given.

The V-Cone meter is a Differential Pressure (DP) type flow meter with a centrally mounted cone pointing upstream, supported 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. Figure 1 show sketches of the V-Cone meter.

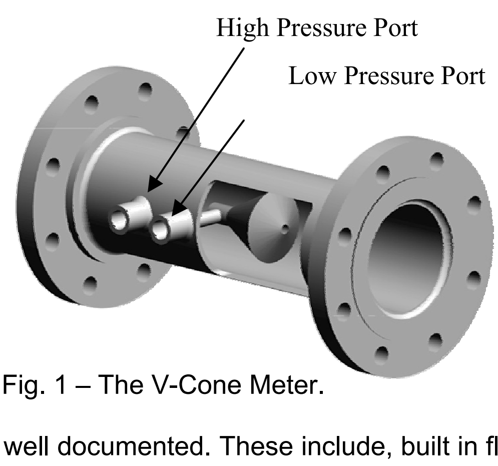

Fig. 1 – The V-Cone Meter.

The shape and position of the primary element is the only difference between the V-Cone meter and other DP meters. The V-Cone meter is in every way a DP meter (with 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 similar to any other 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 [2, 3], low total head loss [4] and high turndown achieved for a single DP transmitter [5]. The V-Cone meter has been tested in accordance with “API 5.7-Testing Protocol for Differential Pressure Flow Measurement Devices” [6]. For single phase flows with calibration the V-Cone meter will give an uncertainty of 0.5%.

3 THE ORIGINAL NEL 6" 0.55 BETA RATIO V-CONE METER WET GAS TESTS

3.1 The Original 2001 Tests and Results

In 2001 NEL tested a 6" 0.55 beta ratio V-Cone meter and a 0.75 beta ratio V-Cone meter. The results of the 0.55 beta ratio V-Cone meter (discussed in detail in Ref. [1]) are reviewed here.

The NEL wet gas test loop has a test section of 6" schedule 80 pipe. The test fluids are nitrogen and a kerosene substitute. The meter was tested at 60, 30 and 15 Bar. The gas flowrate range was 400 – 1000 m^3/hr and the "Lockhart-Martinelli" parameter (i.e. the liquid quantity) range was 0 - 0.3 (see below for an explanation).

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 (denoted by "X" and is a non-dimensionalised description of the relative amount of liquid entrained in the gas flow), the pressure (or gas to liquid density ratio) and the gas densiometric Froude number (denoted by "Fr_g" and which can be thought of as a non-dimensionalised description of the gas flowrate for a set meter geometry and test pressure). 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 this 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 (usually called the "over-reading") 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} (where "tp" is from "two-phase")) 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 $\sqrt{\Delta P_{tp} / \Delta P_g}$. For example an over-reading of $\sqrt{\Delta P_{tp} / \Delta P_g}$ = 1.2 indicates a DP meter with wet gas flow over-reading the actual gas mass flowrate by 20%. Alternatively, the absolute percentage liquid induced error for any DP meter can be approximated to $\left(\sqrt{\Delta P_{tp} / \Delta P_g} - 1\right) * 100\%$.

It was reported [1] that, as the Lockhart-Martinelli parameter (X) increased, for a set gas to liquid density ratio and Froude number (Fr_g), the over-reading increased. If the gas to liquid density ratio increased, for a set Lockhart-Martinelli parameter and Froude number, the over-reading reduced. If the Froude number increased for a set Lockhart-Martinelli parameter and gas to liquid density ratio the over-reading increased. (This last phenomenon is only seen clearly at higher X values.)

Figures 2 to 4 are sample graphs showing these results. Figure 2 shows all the wet gas data taken by NEL in 2001 for the 6”, 0.55 beta ratio V-Cone meter. The strong influence of the Lockhart-Martinelli parameter is clearly seen. Figure 3 shows the same data with the three pressures tested separated out. A pressure (or gas to liquid density effect) is evident. As the pressure increases the over-reading reduces. Figure 4 shows a sample of one pressure data set with the Froude number separated out. The small Froude number effect is evident and can be seen more clearly at higher Lockhart-Martinelli parameter values. As the Froude number increases so does the over-reading.

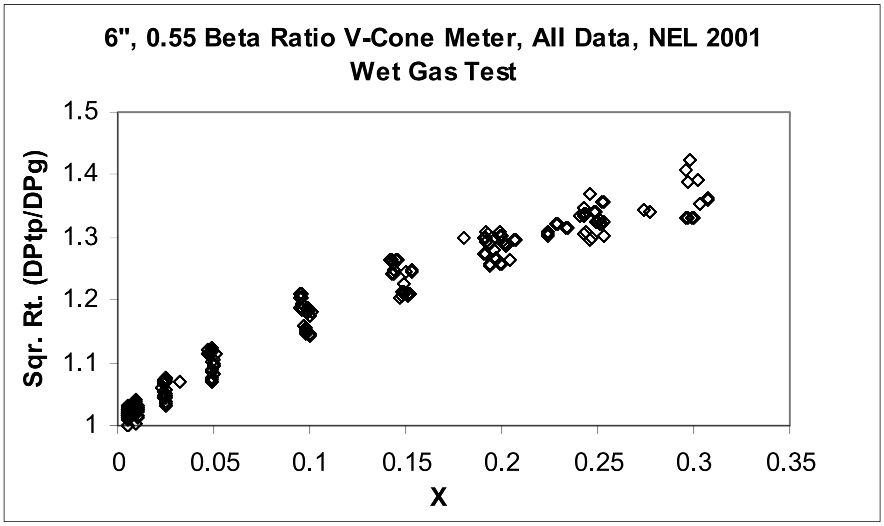

Fig 2 – All Pressure and Froude Number Data Points.

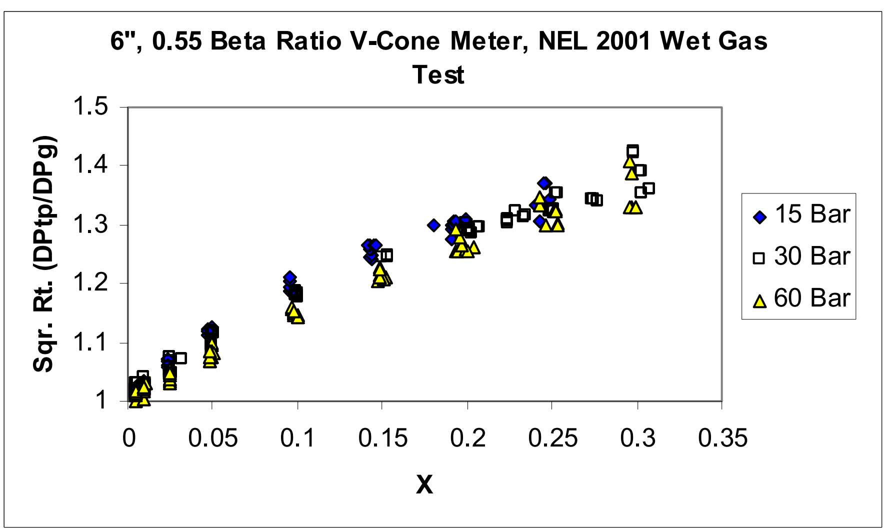

Fig 3 – Separate Pressure Data Points.

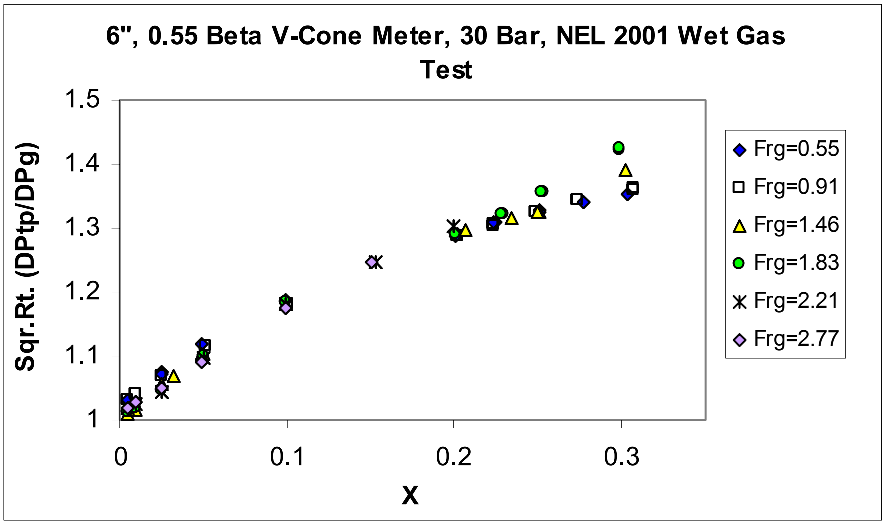

Fig 4. - Single Pressure with Six Sets of Froude Number Data Points.

3.2 The 6” 0.55 Beta Ratio V-Cone Meter Correlation

These results led to the development of the 0.55 beta ratio V-Cone wet gas correlation:

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{\left(\dfrac{1 + AX + BFr_g}{1 + CX + BFr_g}\right)} \quad \text{--(4)}$$

$$A = 1.224 + \frac{0.141}{\left(\dfrac{\rho_g}{\rho_l}\right)} \quad \text{--(4a)}$$

$$B = -0.0334 - \frac{0.00139}{\left(\dfrac{\rho_g}{\rho_l}\right)} \quad \text{--(4b)}$$

$$C = \sqrt{0.0805 + \frac{0.0109}{\left(\dfrac{\rho_g}{\rho_l}\right)^2}} \quad \text{--(4c)}$$

The gas/liquid density ratio applicability limit of equations 4a to 4c is 0.022 to 1.0. Figures 5 and 6 show the correlations performance. The correction is to within 2% (with a few outliers).

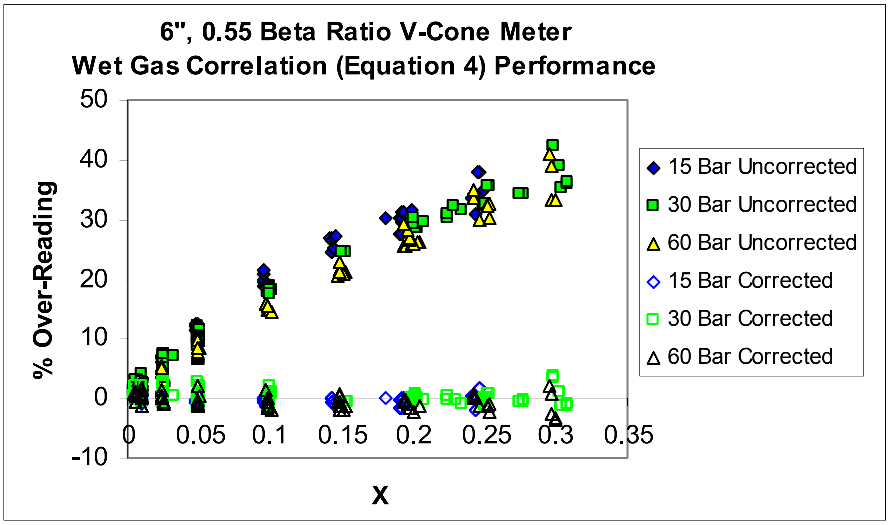

Fig 5 – The Un-Corrected & Corrected Data using the above Correlation.

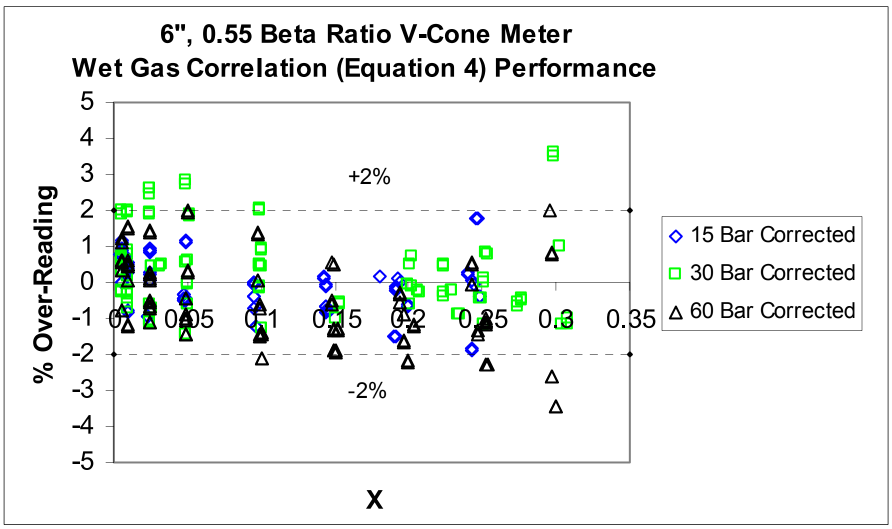

Fig 6 – The Corrected Data Magnified.

4 THE NEW NEL 6" 0.55 BETA RATIO V-CONE METER WET GAS TESTS

In May 2003 McCrometer carried out a series of wet gas flow tests at NEL. One of the meters tested was the same 6", 0.55 beta ratio V-Cone meter previously tested in 2001. The test matrix was with the same tests fluids and gas flowrate range of 400 – 1000 m^3/hr. Two pressures were tested, 15 and 60 bar. Most test points were within the "Lockhart-Martinelli" parameter range of 0 - 0.3 but some points were tested up to 0.5. (Note that many operators call $X \leq 0.3$ wet gas and $X > 0.3$ general two-phase / multi-phase flow.) The other difference between the two tests is that in 2003 a significant obstruction (not described for confidentiality reasons) was positioned 10D upstream of the V-Cone meter. The old and new results are now compared.

4.1 The New Results and Comparisons with the Original Data

Figure 7 shows all the 2003 data (with the exception of $X > 0.3$ data which is discussed later). Clearly the Lockhart-Martinelli parameter has a similar effect as was previously found. Likewise, again a pressure (or gas to liquid density ratio) effect is seen where for all other parameters held constant an increasing pressure gives a reducing over-reading. Figures 8 and 9 show the Froude number effect at the two constant pressures. Again as found in 2001, it can be seen, that for all

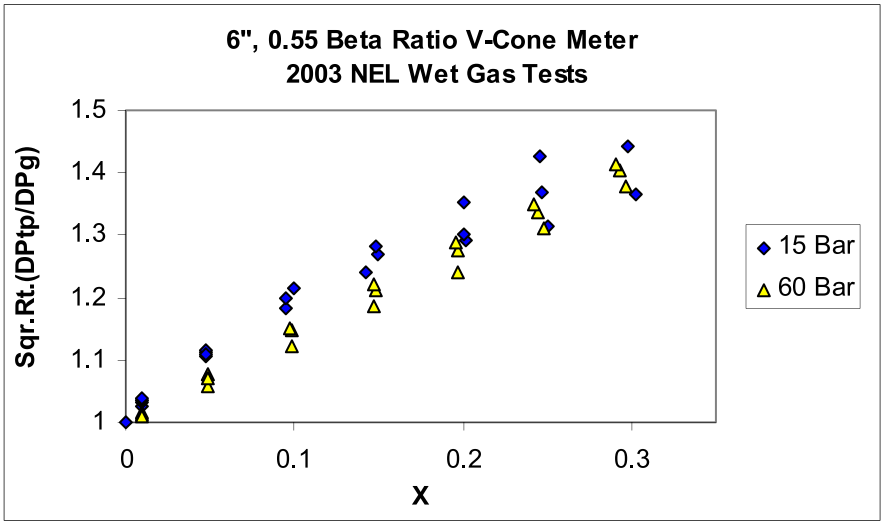

Fig 7 – All 2003 0.55 Beta Ratio Data for 2 Pressures.

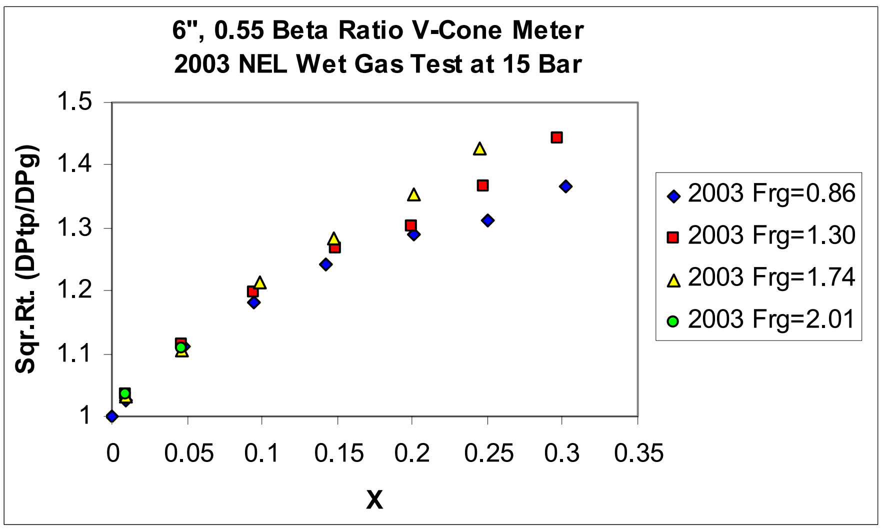

Fig 8 – 2003 0.55 Beta Ratio 15 Bar Data for 4 Froude Numbers.

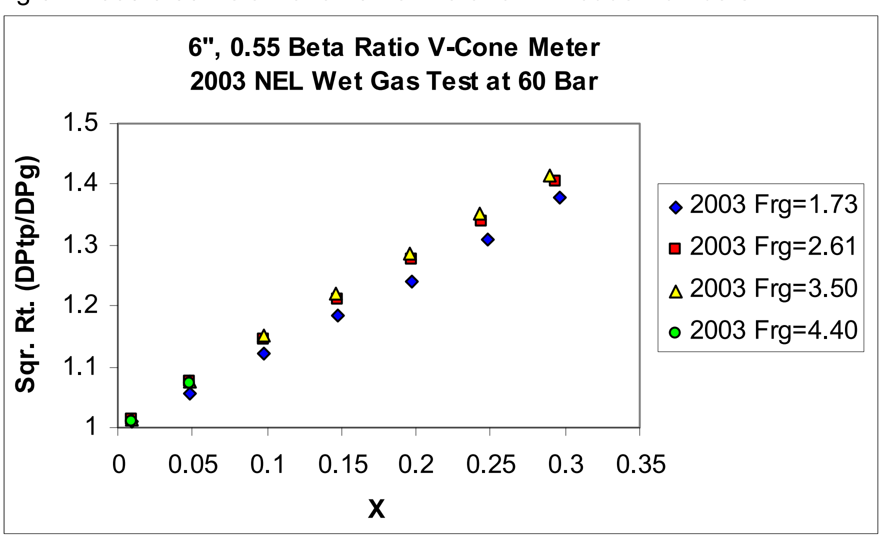

Fig 9 - 2003 0.55 Beta Ratio 60 Bar Data for 4 Froude Numbers.

other parameters held constant as the Froude number rises so does the over-reading. This effect is more clearly seen at higher Lockhart-Martinelli parameters, especially at lower pressures (as previously reported). Therefore the 2003 data set shows the same characteristics as was found in the 2001 data set.

The next step in the analysis is to directly compare the two data sets. Figure 10 shows the 15 Bar results for both data sets. Clearly as expected the data sets are very similar. The only visible difference is at the higher Lockhart-Martinelli parameter values the 2003 data does have two points that appear to be indicating a higher over-reading than the 2001 data but the rest of the data (i.e. 93% of the 2003 data points) is fully repeatable. Figure 11 shows the 60 Bar results for both data sets. In this case all the data is seen to be repeatable.

Figures 12 and 13 show the 2003 data sets corrected using the previously published 0.55 beta ratio V-Cone meter correlation (see equation 4, 4a to 4c). As expected Figure 12 shows the corrected values cluster around to the abscissa (i.e. the zero error line). Figure 13 show a magnified view of the corrected values only. These results numerically confirm what is visually

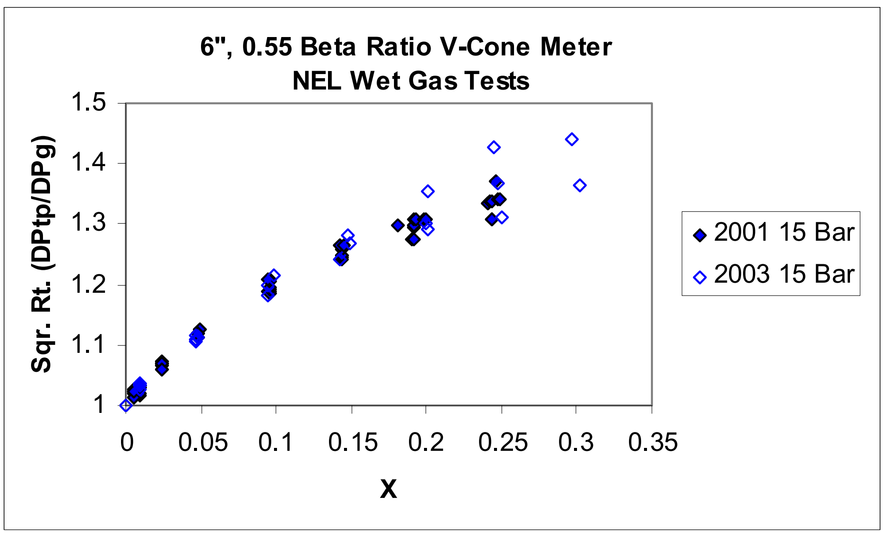

Fig 10 - All 0.55 Beta Ratio 15 Bar Data with Lockhart-Martinelli parameters less than 0.3.

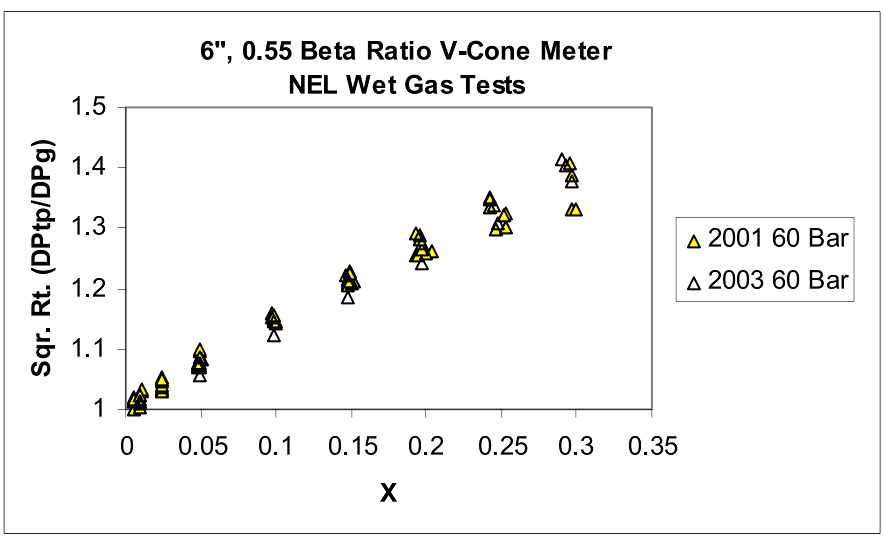

Fig 11- All 0.55 Beta Ratio 60 Bar Data with Lockhart-Martinelli parameters less than 0.3.

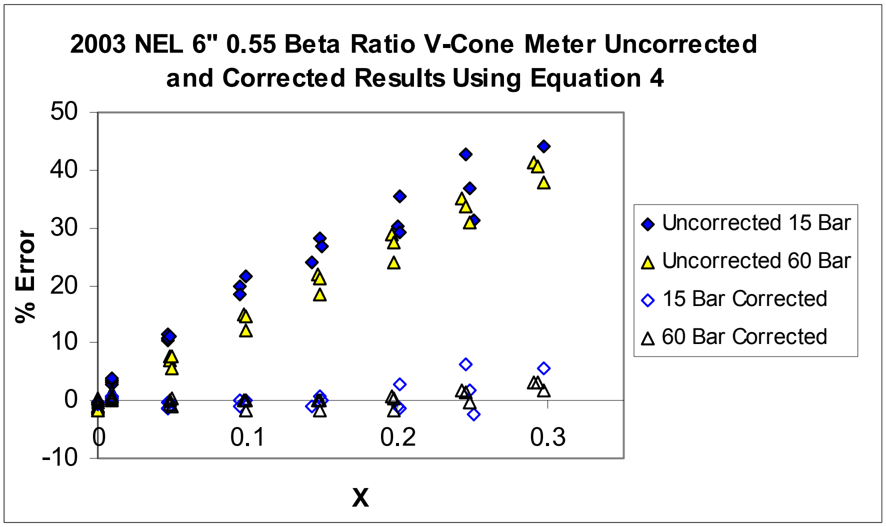

Fig 12 – All 2003 0.55 Beta Ratio Data Uncorrected and Corrected by Equation 4.

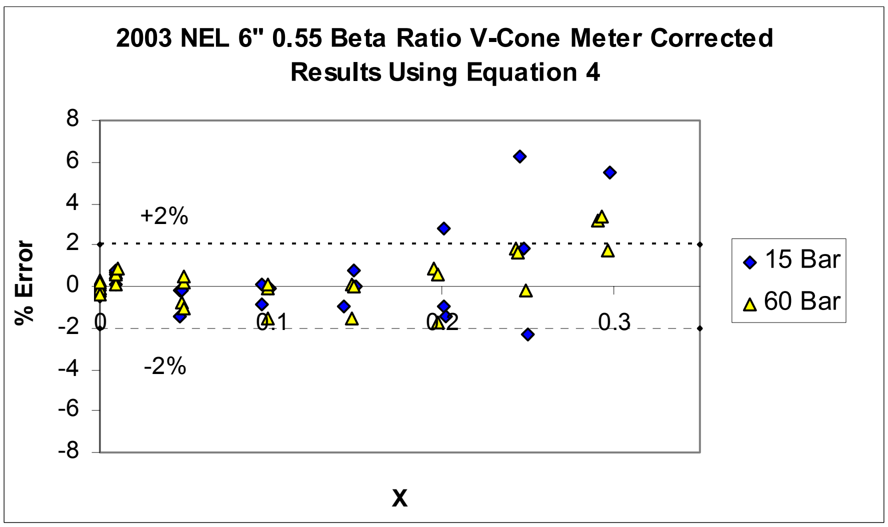

Fig 13 - 2003 0.55 Beta Ratio Data Corrected by Equation 4.

seen in Figures 10 and 11. That is, the 2003 15 and 60 Bar data is similar to the 2001 data and the existing 0.55 beta ratio V-Cone wet gas correlation will predict the gas flowrate to an uncertainty of 2% with a few outliers. (The only difference in the data sets is that at 15 Bar there are two outliers that are of greater error than is found in the 2001 data set. McCrometer has an on going research program in wet gas flow metering and the question of why these two outliers exist will be investigated.)

It is concluded that with 51 points of the total 53 points recorded in 2003 repeating the 2001 results, the 0.55 beta ratio meter can be considered repeatable in wet gas flows. The significant obstruction 10D upstream of the meter inlet has had no significant effect and therefore this suggests that disturbances in the wet gas flow pattern directly upstream of the V-Cone meter will not seriously effect the meters performance.

4.3 An Extended 6" 0.55 Beta Ratio V-Cone Meter Correlation

The 2003 tests tested the V-Cone meter in heavier liquid loadings ($X \leq 0.5$). Figure 14 shows all the 2003 data. Clearly the meter continues to give predictable results at these higher liquid loadings. Figures 15 and 16 show the gas densiometric Froude number effect for each pressure.

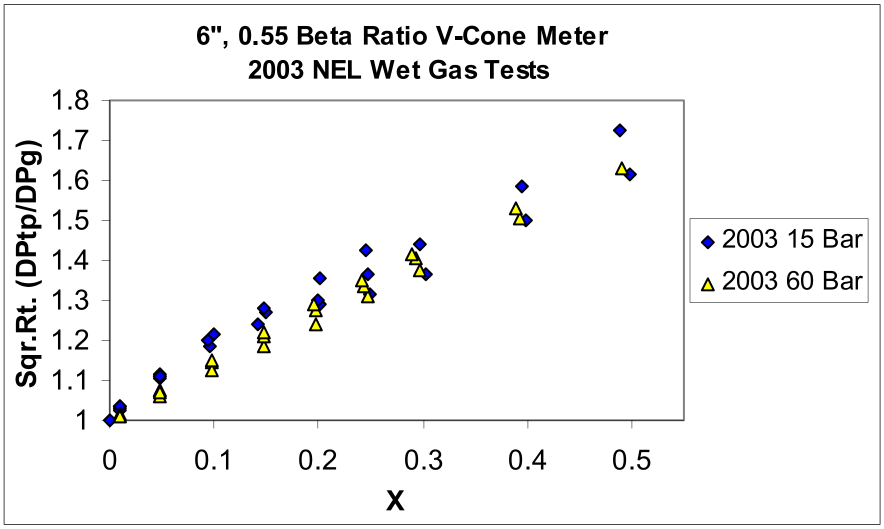

Fig 14 - All 0.55 Beta Ratio 60 Bar Data.

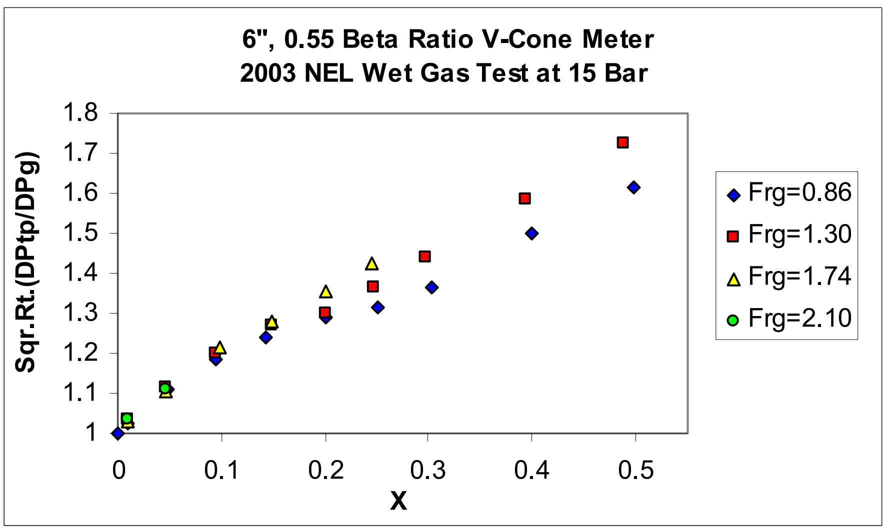

Fig 15– All 2003 0.55 Beta Ratio 15 Bar for 4 Froude numbers.

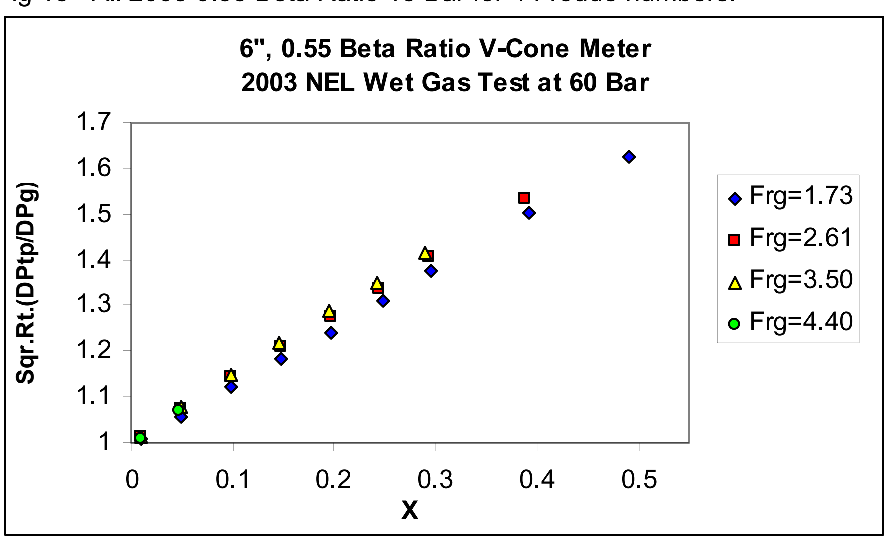

Fig 16- All 2003 0.55 Beta Ratio 60 Bar Data for 4 Froude numbers.

Figure 15 shows that at the relatively low pressure of 15 Bar there is a Froude number based spread of the data starting at Lockhart-Martinelli parameter values of approximately 0.2. Figure 16 shows that at the higher pressure of 60 Bar the over-reading at higher Lockhart-Martinelli parameters continues to increase linearly with no such spread effect.

Clearly from these graphs an extended correlation could be created that would allow the meter to be used at these higher liquid loadings. Figure 17 shows all the 0.55 beta ratio V-Cone meter data from both data sets, corrected by an extended 0.55 beta ratio V-Cone meter wet gas correlation. (The form of the equation is currently held in commercial confidence.) Figure 18 shows the magnification of the corrected data. It can be seen that for the more extreme case of liquid loadings up to Lockhart-Martinelli parameter values of 0.5 the meter can be corrected to an uncertainty of 5% (with a few outliers). Note that if the Lockhart-Martinelli parameter was less than 0.3 then equation 4 would be used and an uncertainty of 2% would be expected. In these applications users should be aware that slugging may occur in the pipeline and action to protect a DP transmitter from damage may be required.

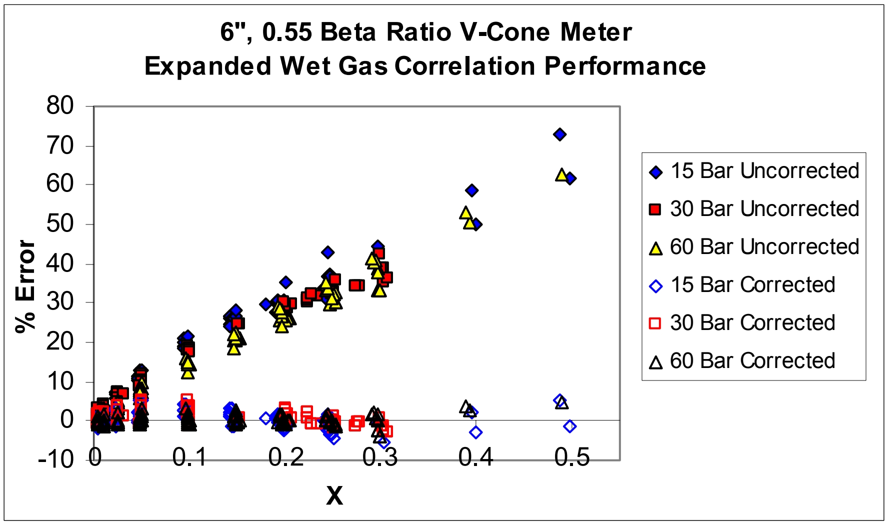

Fig 17 – All the NEL 0.55 Beta Ratio Data Uncorrected and Corrected by a New Expanded Correlation for use at Lockhart-Martinelli parameters greater than 0.3.

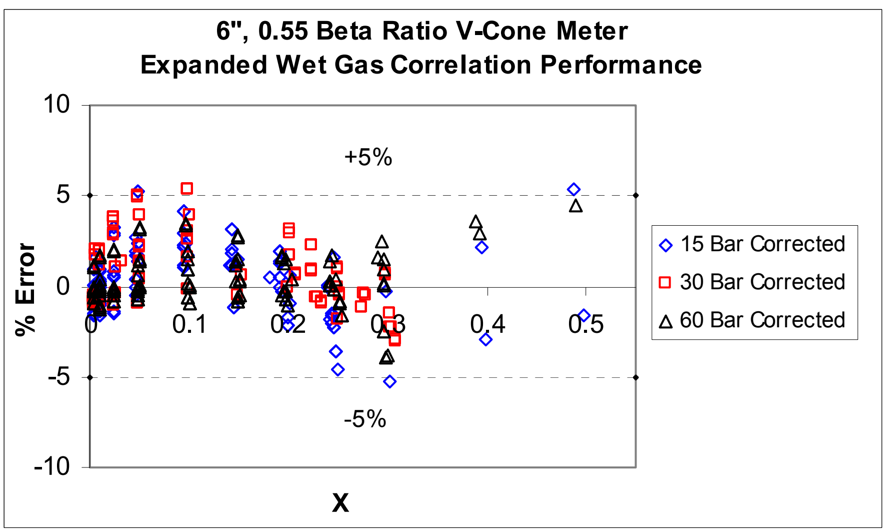

Fig 18 - All the NEL 0.55 Beta Ratio Data Corrected by a New Expanded Correlation for use at Lockhart-Martinelli parameters greater than 0.3.

5 CEESI 4” 0.60 BETA RATIO V-CONE METER WET GAS TESTS

In 2002 CEESI tested a 4” 0.60 beta ratio V-Cone meter in a wet gas loop. The results of this test will now be reviewed.

The CEESI wet gas test loop has a test section of 4” schedule 80 pipe. The test fluids are natural gas and a hydrocarbon liquid (decane). The meter was tested at 50 Bar. The gas flowrate range was 80 – 350 m^3/hr (and in fact three Froude number values were used, 1.0, 2.5 & 3.4) and the Lockhart-Martinelli parameter range was 0 - 0.23.

Figure 19 shows the results. Again a clear Lockhart-Martinelli parameter effect is seen. (No pressure effect could be investigated as only one pressure was tested.) The Froude number effect is not clear in the CEESI tests as it was in the NEL tests. However for the higher two values the same phenomenon can be seen as at NEL (that is, with all other parameters held

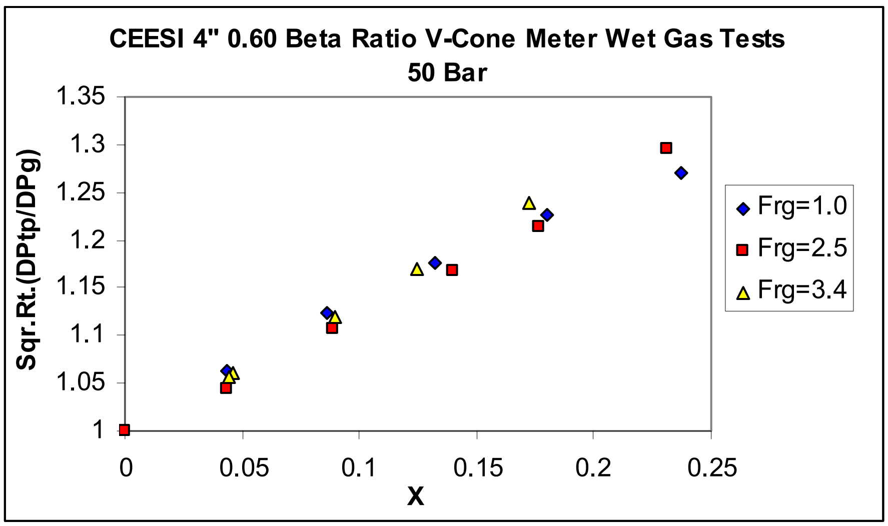

Fig 19 – All CEESI 4” 0.6 Beta Ratio V-Cone Meter Data.

constant an increasing Froude number gives a higher over-reading). Only at the lowest Froude number is this not seen. However it can be noted that by the highest value of Lockhart-Martinelli parameter (about 0.23) this low Froude number data set is dropping into the expected position below the higher values. In the examination of the NEL data it was found that the Froude number effect wasn’t clearly evident until Lockhart-Martinelli parameter values greater than 0.2.

6 Comparisons with NEL 0.55 Beta Ratio V-Cone Wet Gas Results

Researchers have found that DP meters with different beta ratios give slightly different magnitudes of over-readings for identical wet gas flow inlet conditions [1, 7 & 8]. It is known that as the throat area reduces the larger the over-reading for any set condition. As an example of this Figure 20 shows two 6” V-Cone meters (a 0.55 beta ratio and a 0.75 beta ratio) tested across the same conditions at NEL. As the beta ratio reduces in a V-Cone meter the cone size gets larger meaning the minimum cross sectional area (or “throat” area) reduces. In Figure 20 it can be seen for the same conditions, the bigger cone (i.e. the smaller beta ratio) gives the bigger over-reading.

At the time of writing, no research has yet been published which conclusively proves whether DP meter over-readings, with wet gas flows, are dependent on meter size and fluid properties. The current consensus tends towards thinking that there may be a meter diameter effect but it should only be evident between significantly different diameter sizes. That is, between a 6” and 4” meter

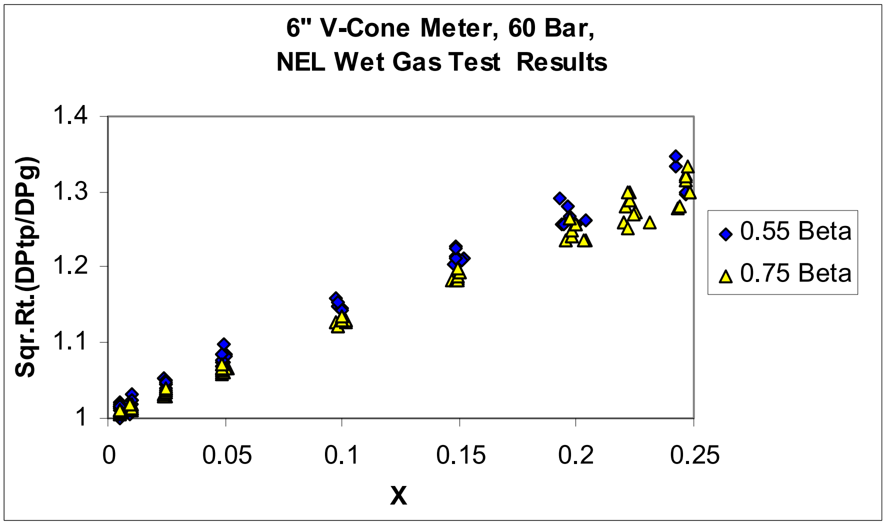

Fig 20 – NEL 6” 0.55 and 0.75 Beta Ratio Comparison.

it is assumed there is little diameter effect (whereas between a 4” and say a 24” meter this assumption is more questionable). The current consensus on fluid properties is that the viscosity and interfacial tension values of liquids could have an effect on DP meter over-readings. However, for the particular fluids used at NEL and CEESI, previous work [9] has shown that little effect was noticeable. (That does not mean that across different fluid combinations the same can always be considered true.) It is therefore assumed here that the difference between the NEL and CEESI's meter diameter and liquid properties has a negligible effect on the over-readings. Hence with these assumptions in place we can compare the beta ratio effect between the NEL 0.55 beta ratio meter and the CEESI 0.60 beta ratio meter directly.

Figure 21 shows the two data sets for NEL's 0.55 beta ratio V-Cone meter and CEESI's 0.60 beta ratio V-Cone meter. If the beta ratios were the same it would be expected that the 50 Bar CEESI tests would fall between the NEL 30 and 60 Bar tests. However, the beta ratios are not equal and with the known DP meter, beta ratio, wet gas effect, discussed above, it was expected that with the diameter and liquid property effects small, the CEESI meter with the bigger beta ratio (i.e. larger “throat”) should have a smaller magnitude of over-reading. This is in fact what is seen. The two separate wet gas loops at NEL and CEESI therefore appear to agree with each other.

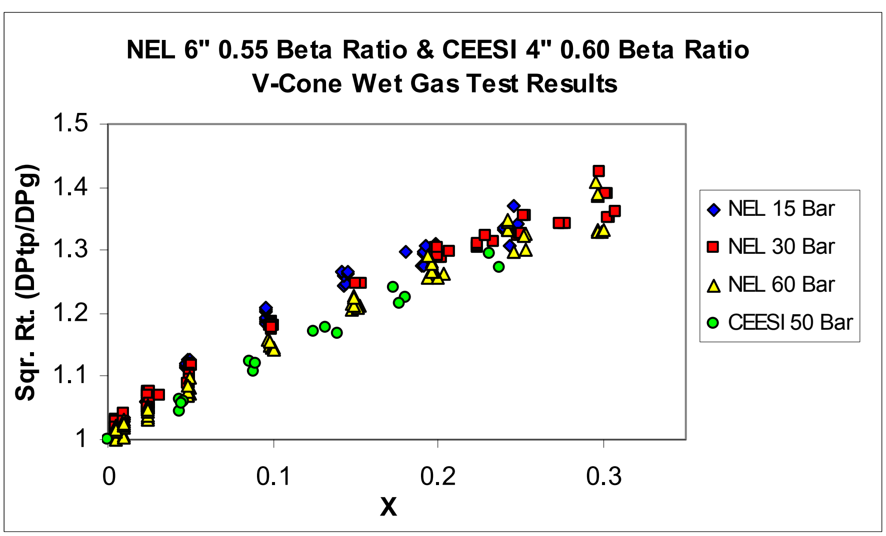

Fig 21 – The NEL 6” 0.55 Beta Ratio and CEESI 4” 0.75 Beta Ratio Comparison.

The practical implications of the fact that DP meters have a known beta ratio effect with wet gas flows is that users should plan to use set beta ratios with published correlations. These correlations are typically formed from data sets obtained with concentrated wet gas flow testing on a particular beta ratio. Hence the correlations are typically aimed at these specific beta ratio values and have the lowest uncertainty at that beta ratio. Failure to select a meter with a beta ratio with a wet gas flow correlation, adds an avoidable uncertainty to the overall metering system. McCrometer currently offers two beta ratio choices for wet gas metering, a 0.55 beta ratio V-Cone meter for relatively low flowrates, and a 0.75 beta ratio V-Cone meter for relatively high flowrates.

6 Conclusions

6.1. The repeat NEL tests of the 6” 0.55 beta ratio V-Cone meter have shown that the meter is repeatable with wet gas flows.

6.2 A significant obstruction ten diameters upstream of the V-Cone meter inlet appeared to have no significant effect on the meters performance.

6.3 The 6” 0.55 beta ratio V-Cone meter therefore has a wet gas correlation available for use in industry for cases where the liquid loading in a wet gas flow can be estimated and the Lockhart-Martinelli parameter is less or equal to 0.3 (i.e. $X \leq 0.3$). The uncertainty of this correlation is 2% with a few outliers.

6.4 It was shown that the meter continued to work in larger liquid loading two-phase flows up to a Lockhart-Martinelli parameter is less or equal to 0.5. A correlation is available for use in cases where the liquid loading in a wet gas flow can be estimated and the Lockhart-Martinelli parameter is less or equal to 0.5. The uncertainty of this correlation is 5% with a few outliers. This would be implemented in cases where the Lockhart-Martinelli parameter is between 0.3 and 0.5

6.5 There is an advantage when metering wet gas flows with V-Cone meters (or any other DP meter types) to use a beta ratio with known data sets and published wet gas correlations as this eliminates one of the several possible sources of uncertainty that exist in this challenging metering situation.

6.6 Although there were significant differences in the wet gas test loops run by NEL and CEESI the V-Cone meter wet gas test results from NEL and CEESI were found to be similar. Nevertheless, further research on the effect of meter diameter and fluid properties on DP meter wet gas flow over-readings is required by industry to complete the understanding of DP meters with wet gas flows.

Notation

X The Lockhart-Martinelli parameter

$\dot{m}_g$ The actual gas mass flowrate

$\dot{m}_l$ The actual liquid mass flowrate

$\dot{m}_{g(tp)}$ 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 densiometric Froude number

U_{sg} The superficial gas velocity

g The gravitational constant

D The meter inlet diameter

A The meter inlet cross sectional area

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