4”, 0.63 Beta Ratio Cone DP Meter Wet Gas Performance

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1. Introduction

Cone DP meters are often used for unprocessed natural gas flow metering applications. Unprocessed natural gas flows can have entrained water and light hydrocarbon liquids. Hence, it is important to fully understand the wet gas flow response of cone DP meters. One method of metering the gas flow rate of a wet natural gas flow is to estimate the liquid flow rate (usually a mixture of hydrocarbon liquid and water) from an independent source (such as a tracer dilution technique or test separator histories) and then use a wet gas correction factor or “correlation” to correct for the liquid induced gas flow rate error. It is therefore necessary to have a reliable cone DP meter wet gas correlation for wet natural gas flows where the liquid component is a water and / or a light hydrocarbon liquid mixture.

2. The Cone DP Meter

Figure 1 shows a sketch of the generic cone differential pressure (DP) meter geometry. A cone meter is a generic DP meter, i.e. it operates in the same way as any DP meter, e.g. orifice plate, Venturi meters etc.

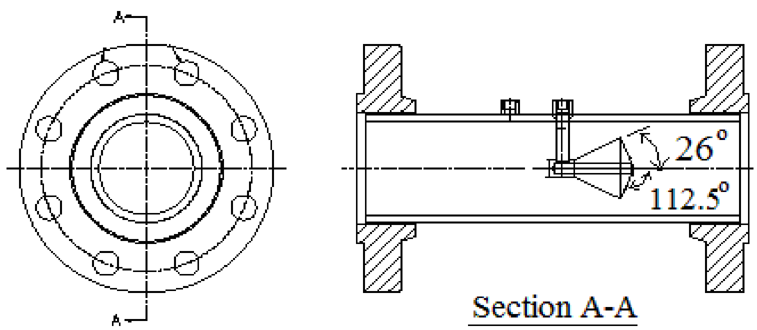

Fig 1. Generic sketch of a cone DP meter assembly.

Generic DP meters all operate by using the principles of conservation of mass and energy and the generic single phase mass flow DP meter equation (used by the cone meter) is shown as equation 1:

$$\dot{m} = EA_t \varepsilon C_d \sqrt{2\rho\Delta P} \quad \text{--- (1)}$$

where $\dot{m}$ is the mass flow rate, E is the “velocity of approach” (a geometric constant), A_t is the minimum cross sectional (or “throat”) area, C_d is the discharge coefficient, ρ is the fluid density ΔP is the differential pressure and ε is the expansibility (i.e. “expansion factor”).

Note that the cone DP meter design being discussed in this paper is the classic design where the low pressure port is located at the centre of the back face of the cone. This papers technical discussion does not extend to the case of cone DP meter designs where the low pressure port is located on the wall of the meter body downstream of the cone assembly.

3. Wet Gas Flow Definitions

Wet gas flow can be considered to be any gas and liquid flow that has a Lockhart-Martinelli parameter, X_{LM}, less than 0.3 [1]. The Lockhart-Martinelli parameter is a non-dimensional method of describing the wetness of a wet gas flow. It is found by equation 2. Note that $\dot{m}_g$ and $\dot{m}_l$ are the gas and liquid mass flow rates and ρ_g and ρ_l are the gas and liquid densities respectively.

$$X_{LM} = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_\ell}} \quad \text{--- (2)} \qquad DR = \rho_g / \rho_l \quad \text{--- (3)} \qquad WLR = \frac{\dot{Q}_w}{\dot{Q}_w + \dot{Q}_{hl}} \quad \text{--- (4)}$$

Cone meters have a wet gas flow response that is dependent on the gas to liquid density ratio, or "DR". The gas to liquid density ratio is shown in equation 3. (This is effectively a dimensionless representation of the pressure for a set water liquid ratio, or "WLR"). The WLR is defined as shown in equation 4. Note that $\dot{Q}_w$ and $\dot{Q}_{hl}$ are the water and hydrocarbon liquid actual volume flow rates at line conditions.

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_\ell - \rho_g}} \quad \text{--- (5)} \quad , \qquad U_{sg} = \frac{\dot{m}_g}{\rho_g A} \quad \text{--- (6)}$$

The gas densiometric Froude number (equation 5) is a non-dimensional method of expressing a wet gas flows gas velocity. Here, g is the gravitational constant, D is the pipe internal diameter and U_{sg} is the superficial gas velocity calculated by equation 6. Note A is the meter inlet area.

$$x_l = \frac{\dot{m}_w}{\dot{m}_w + \dot{m}_{hl}} \quad \text{--- (7)} \qquad \rho_{l\,\mathrm{hom}ogenous} = \frac{\rho_{hl}\rho_w}{\rho_w(1 - x_l) + x_l\rho_{hl}} \quad \text{--- (8)}$$

Note that equations 2, 3 & 5 assume one liquid density. For wet natural gas flows where there is often hydrocarbon liquid and water present there is a question to what liquid density should be used. It is commonly assumed at moderate to high gas flow rates typical of hydrocarbon production the liquids are well mixed and the liquid can be assumed to be a homogenous mix of water and hydrocarbon liquid. In this case an averaged liquid density can be used $\rho_{l\,\mathrm{hom}ogenous}$. This can be calculated by use of equations 7 & 8. Note $\dot{m}_w$ and $\dot{m}_{hl}$ are the water and hydrocarbon liquid flow rates respectively and ρ_w and ρ_{hl} are the water and hydrocarbon liquid densities respectively.

$$OR = \frac{\dot{m}_{g,apparent}}{\dot{m}_g} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \quad \text{--- (9)} \qquad OR\,(\%) = \left(\frac{\dot{m}_{g,apparent}}{\dot{m}_g} - 1\right) * 100\% \cong \left(\sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} - 1\right) * 100\% \quad \text{--- (10)}$$

Finally, cone meters with wet gas flows tend to have a positive bias or "*over-reading"* on their gas flow rate prediction. 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 to actual gas flow rate.

Equations 9 & 10 show the over-reading and percentage over-reading (where ΔP_{tp} and ΔP_g are the actual two-phase or "wet gas" differential pressure and the differential pressure if the gas flowed alone respectively.)

4. Cone DP Meter Wet Gas Research History

ASME [1] describes the history of the DP meter wet gas flow response research. It has been found that all generic DP meters have the same wet gas trends. Therefore, cone meters are known to have the same wet gas flow trends as all other DP meters. Most wet gas flow meter research with cone meters is for horizontally installed meters. In this paper only horizontal wet gas flow is considered.

In 1962 Murdock [2] effectively stated that the orifice plate meter has a wet gas over-reading dependent on the Lockhart-Martinelli parameter. Between 1967-77 Chisholm [3] stated that the generic DP meters had a wet gas over-reading dependent on the Lockhart-Martinelli parameter and the gas to liquid density ratio. In 1997 de Leeuw [4] stated that the Venturi meter had a wet gas over-reading dependent on the Lockhart-Martinelli parameter, the gas to liquid density ratio and the gas densiometric Froude number. In 2002-03 Stewart et al [5,6] showed that Venturi and cone DP meters have wet gas over-reading dependent on the Lockhart-Martinelli parameter, the gas to liquid density ratio, the gas densiometric Froude number ***and*** the beta ratio. (The beta ratio is a DP meter geometric constant. It is defined as the square root of the meters minimum cross sectional area to inlet cross sectional area ratio.) In 2006 Reader-Harris et al [7] and Steven et al [8] showed that liquid properties could, under some flow conditions, have an effect on a DP meters wet gas flow response.

Most cone meter wet gas research has been conducted with 4" & 6" 0.75 beta ratio meters. Figure 2 shows a 4", 0.75 beta ratio cone meters response to Lockhart Martinelli parameter and gas to liquid density ratio. As implied by Chisholm the cone meters over-reading increases with Lockhart Martinelli parameter and as the gas to liquid density ratio increases the over-reading for any given Lockhart Martinelli parameter reduces. Note in Fig 2 that the gas densiometric Froude number is not exactly the same for the two data sets. However, the sensitivity of the over-reading to the gas densiometric Froude number is not enough to cause any significant influence on the gas to liquid density ratio effect. The gas densiometric Froude number effect is seen in Figure 3. For almost identical gas to liquid density ratio values the cone meter has a higher over-reading for the higher gas densiometric Froude number. Figure 4 shows the liquid property influence. The two 4", 0.75 beta ratio cone meter wet gas data sets have almost identical gas to liquid density ratios and gas densiometric Froude numbers. However, the natural gas ("NG") with hydrocarbon liquid (HCL) data has a greater over-reading than the natural gas with water data.

Figure 5 shows Stewart's [5] look at beta ratio influences on cone meter over-readings. Two 6" cone meters were tested, a 0.75 beta ratio and a 0.55 beta ratio respectively. The comparison shows a small but distinct beta ratio affect with the larger beta ratio having the slightly smaller over-reading. Figure 6 was subsequently also presented by Stewart [6]. It shows a very distinct beta ratio effect for Venturi meters. In 2007 CEESI released Joint Industry Project (JIP) wet gas flow data sets for three 4" cone meters. They had beta ratios of 0.45, 0.6 & 0.75 respectively. (This is a typical beta ratio range for cone meters.) The meters were wet gas flow tested at three distinct gas to liquid density ratios, i.e. 0.014, 0.055 & 0.087, as shown in Figures 7 thru 9 respectively. The data is split by gas to liquid density ratio as otherwise this effect can mask any beta ratio effect. (The gas densiometric Froude number effect is too weak to mask a beta ratio effect.) Clearly a beta ratio effect exists.

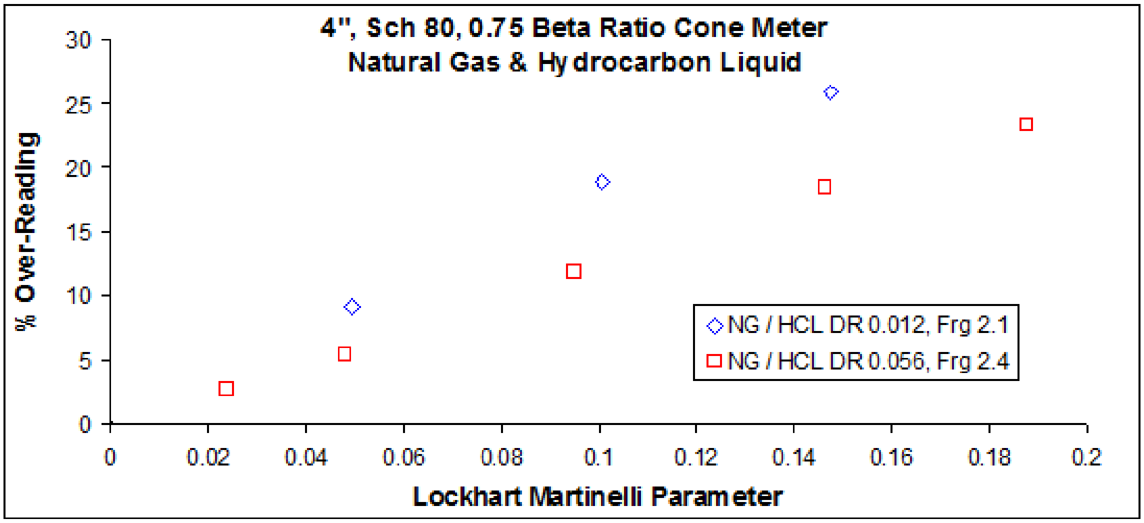

Fig 2. 4", 0.75 beta cone meter gas to liquid density ratio affect.

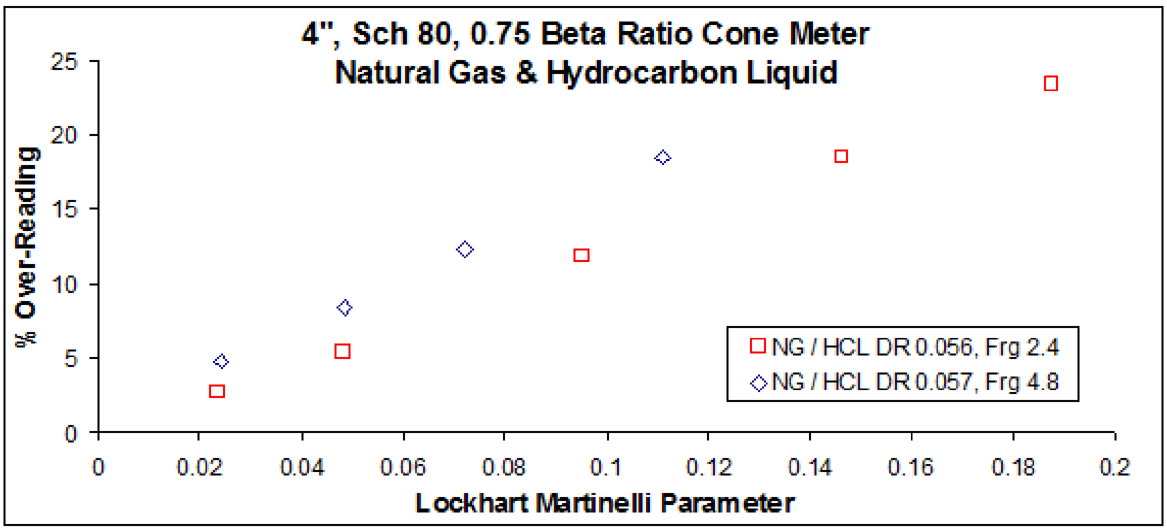

Fig 3. 4", 0.75 beta cone meter gas densiometric Froude number affect.

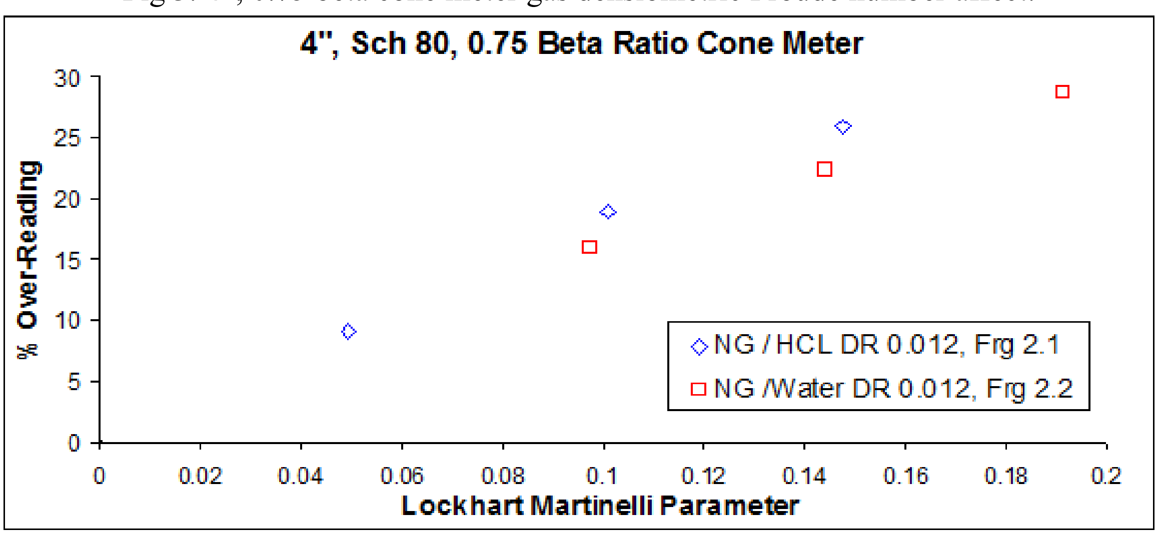

Fig 4. 4", 0.75 beta cone meter liquid property affect.

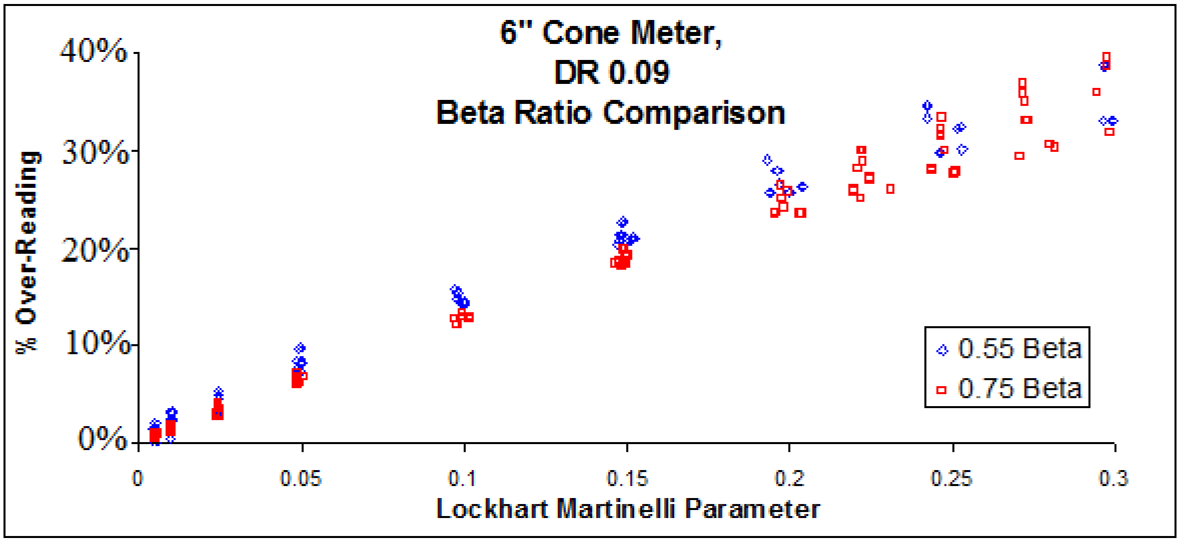

Fig 5. 2002 data showing the wet gas responses of different beta ratio cone meters.

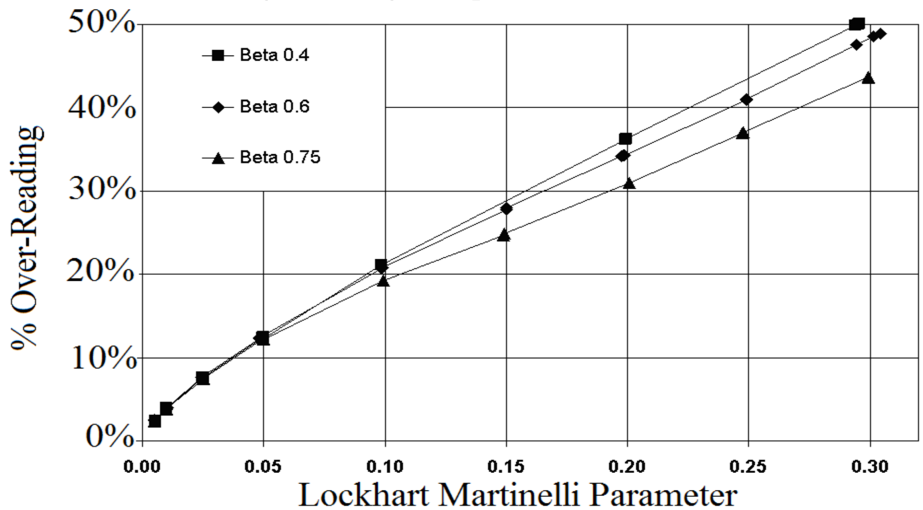

Fig 6. 2003 data showing the wet gas responses of different beta ratio Venturi meters.

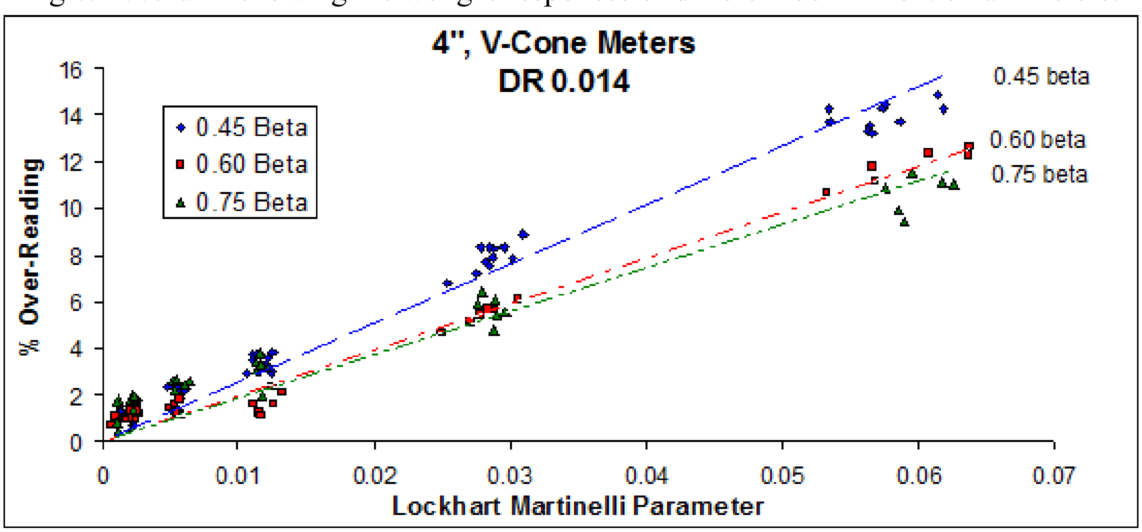

Fig 7. 2007 data showing the wet gas responses of different beta ratio cone meters at DR 0.014.

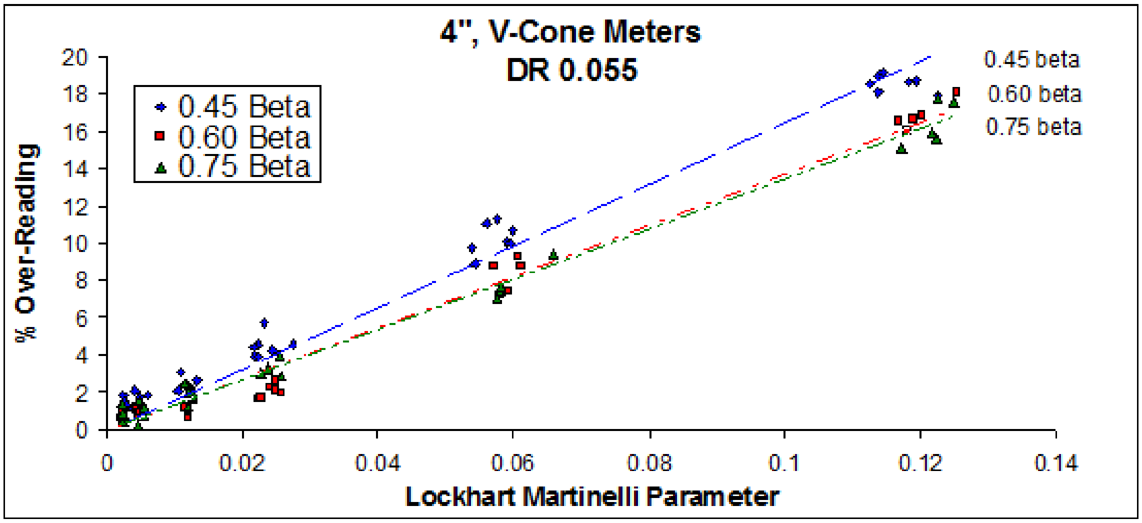

Fig 8. 2007 data showing the wet gas responses of different beta ratio cone meters at DR 0.055.

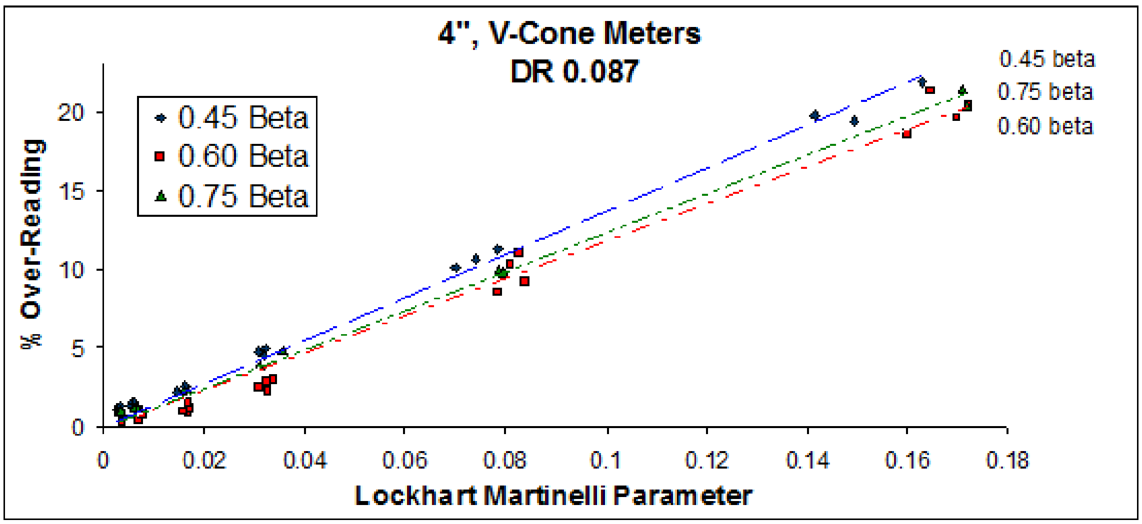

Fig 9. 2007 data showing the wet gas responses of different beta ratio cone meters at DR 0.087.

In all three Figures the 0.45 beta ratio has a distinctly higher gradient. However, there is very little difference between the 0.6 and 0.75 beta ratio meters (as indeed there is only a small difference for the 0.55 & 0.75 beta ratio data shown in Figure 5). Figures 5, 7 & 8 suggest that the smaller the beta ratio the larger the over-reading. However, the difference is not great between the mid and high beta ratio meters. Both have similar over-readings compared to the 0.45 beta ratio. It appears from Figures 7 thru 9 that the cone meter beta ratio effect on wet gas over-readings is not linear. Whereas the 0.45 beta ratio cone meter has a distinctly higher over-reading the difference between the 0.6 and 0.75 beta ratio data is so small that in Figure 9 the high gas to liquid density ratio data set shows the 0.6 beta ratio with a smaller over-reading than the 0.75 beta ratio cone meter. However, in Figure 9 this is considered to be caused by both slight differences in the 0.75 & 0.6 beta ratio data sets gas densiometric Froude number range and simply data scatter. Error bars for each data set (not shown here to maintain clarity) over lap each other. It is now generally accepted amongst researchers, if not amongst meter users, that DP meter wet gas response depends on the beta ratio. The larger the beta ratio the larger the wet gas flow over-reading. Due to this beta ratio effect DP meter wet gas flow correction factors (or "correlations") are typically stated to be only valid for specific beta ratios.

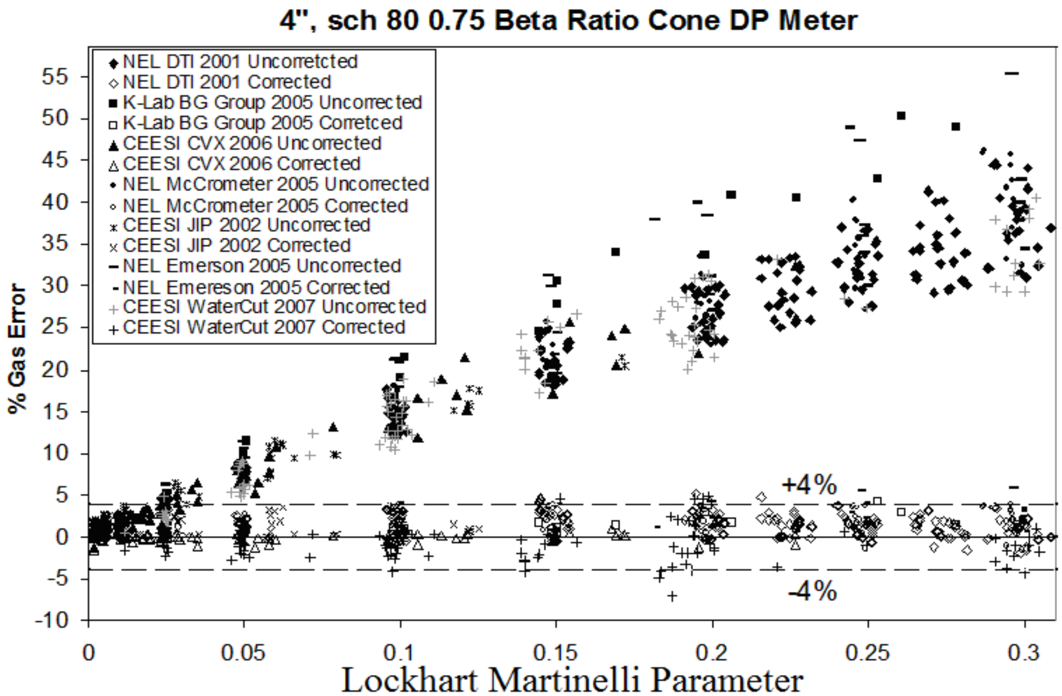

Fig 10. 4" & 6", 0.75 beta ratio cone meter.

By far the most common cone meter geometries tested with wet gas flow are 4" & 6" 0.75 beta ratio meters. Therefore the most comprehensive cone meter wet gas correlation released is for this meter geometry. (It is as yet unknown what effect significant diameter changes have on cone meter wet gas performance.) The current 4" to 6", 0.75 beta ratio cone meter wet gas flow correlation (from Steven [9]) is shown as the following equation:

$$\dot{m}_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \text{ ---(11)} \quad \text{where} \quad C = \left(\frac{\rho_g}{\rho_\ell}\right)^n + \left(\frac{\rho_\ell}{\rho_g}\right)^n \text{ --- (12)}$$

for $Fr_g \leq 0.5$ $\quad n = 0.143$ --- (13a)

for $Fr_g > 0.5$

$$n = \frac{1}{2}\left(1 - \left(\frac{0.83}{\exp(0.3 * Fr_g)}\right)\right) \text{ --- (13b)}$$

Note that this correlation form is based on Chisholm's correlation [3] and de Leeuw's Venturi meter correlation [4]. The parameter denoted as "n" is Chisholm's exponent. It has been shown (Steven [10]) that Chisholm's exponent should tend to ½ when extrapolated to high gas densiometric Froude numbers.

Figure 10 shows the massed 4" & 6", 0.75 beta ratio cone meter wet gas flow data sets. Both the meters uncorrected gas flow rate error and the corrected gas flow rate after application of the correlation are shown. Note that in order to perform the wet gas correction the liquid flow rates of oil and water must be supplied from an external source. As stated earlier this is typically found in natural gas production flows by either tracer dilution techniques or test separator histories. This information is then fed into equations 2 thru 8 and these equations are then used with the wet gas equation set 11 thru 13b. This leaves the gas flow rate as the only unknown and this can be found by iteration. If the liquid flow rates are known accurately then the correction factor predicts the gas flow rate to ±4% to 95% confidence. Largely due to ignorance or lack of alternatives some in the natural gas production industry have been known to apply this geometry specific cone meter correlation to different geometries, e.g. different beta ratios. The effect this has on metering accuracy is not well understood. In this paper we shall now discuss this with use of a CEESI 4”, 0.63 beta ratio cone meters wet gas data set.

5. New 4”, 0.63 Beta Ratio Cone DP Meter Multiphase Wet Gas Flow Data

The CEESI wet gas loop conducts client research and verification tests on wet gas flow equipment. However, during maintenance flow runs, commissioning of system upgrades or commercial jobs where not all the test section length is being utilized by the customer, CEESI can choose to add equipment to complete the loop and gather data on chosen devices. Figure 11 shows a carbon steel 4”, schedule 80, 0.63 beta ratio cone meter installed at the end of the CEESI wet gas loops test section. Note that the inlet pressure and the traditional DP are being measured. (It is also noticeable that the permanent pressure loss is being measured. This was for extra research out with the scope of this technical paper.) This meter has been installed periodically downstream of various tests with various wet gas flow test matrices between 2008 and 2010.

Fig 11. 4”, 0.63 beta ratio cone meter installed at CEESI’s wet natural gas loop.

This 4”, 0.63 beta ratio cone meter was never tested with a dedicated test matrix designed to investigate its wet gas performance. The range of the wet gas flow test data sets recorded were always dictated by the other equipment installed upstream of this meter. Nevertheless, due to the multiple tests of varied test matrices there is now enough data to discuss its performance over a considerable wet gas flow range.

Figure 12 shows the meters gas flow performance. Note that the CEESI wet gas loop is not a dry gas calibration facility. It is specifically designed for wet gas flow research. Therefore, unlike the CEESI gas flow meter calibration facilities, the wet gas flow loop running dry has a master gas meter (a turbine meter) only rated to give an uncertainty of 0.75%. Therefore, the cone meter has been “calibrated” here against this master turbine meter. Figure 12 shows that a constant discharge

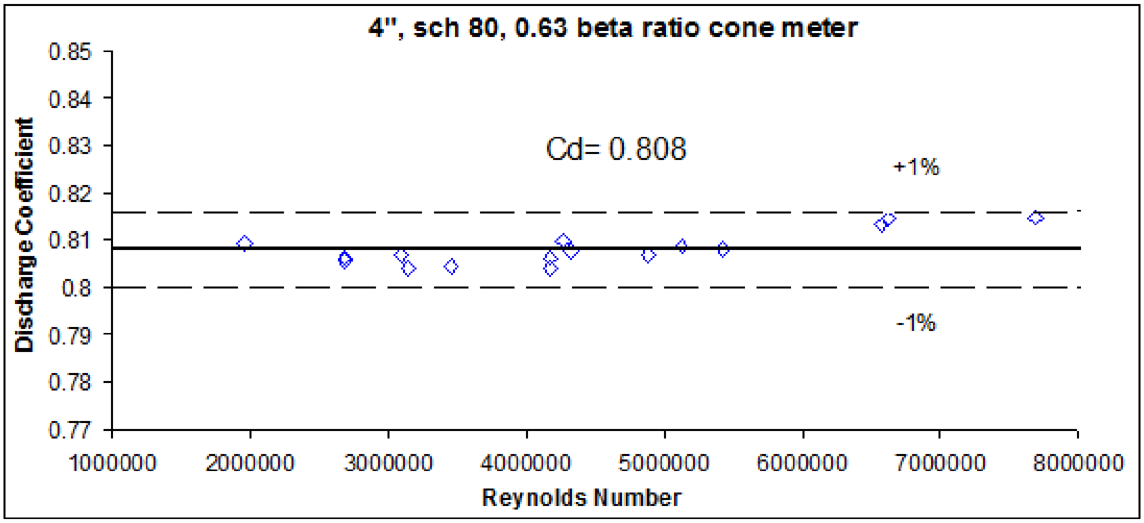

Fig 12. 4", 0.63 beta ratio cone meter dry gas performance.

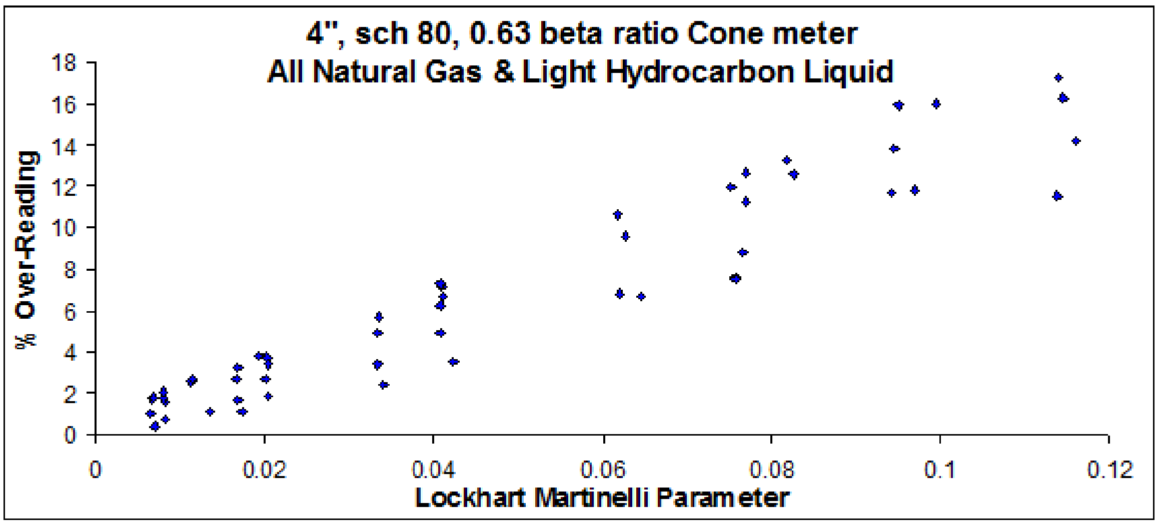

Fig 13. All 4", 0.63 beta ratio cone meter gas with HCL data.

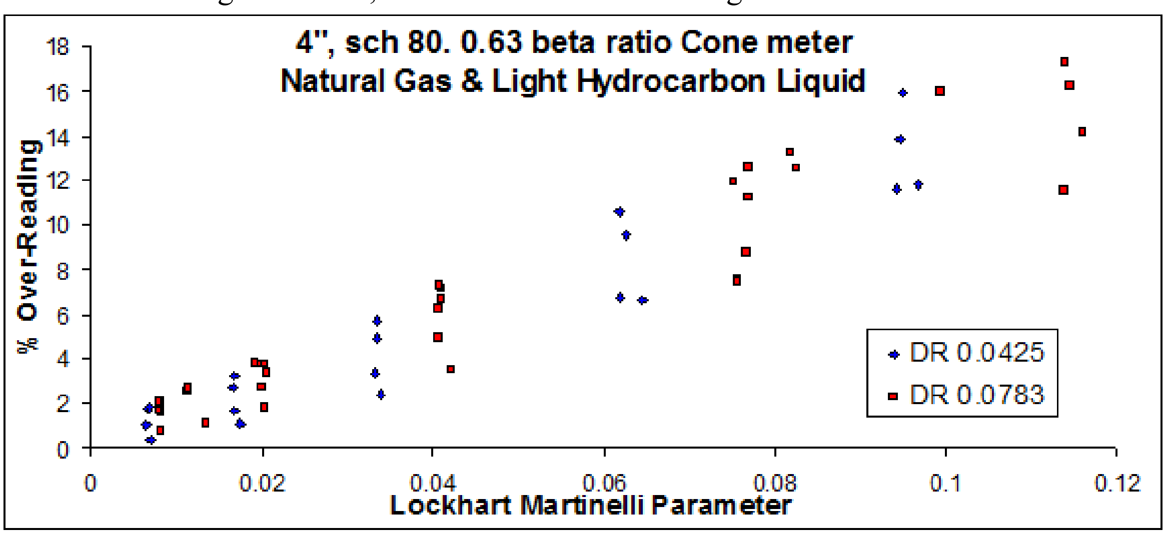

Fig 14. 4", 0.63 beta ratio cone meter gas with HCL data, with separated DR.

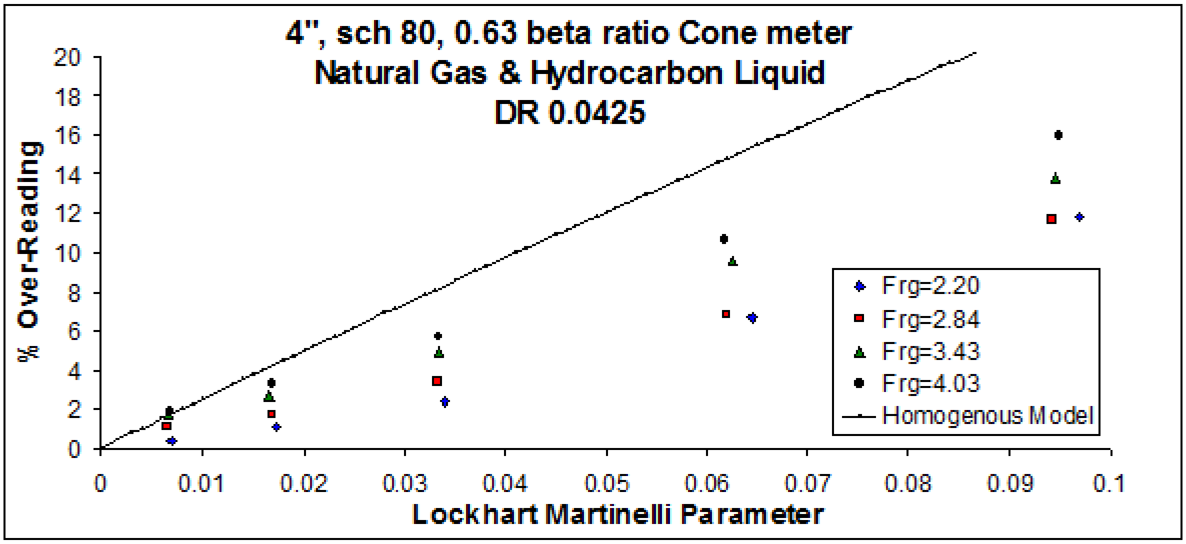

Fig 15. 4”, 0.63 beta ratio cone meter gas with HCL data, set moderate DR, with separated Frg.

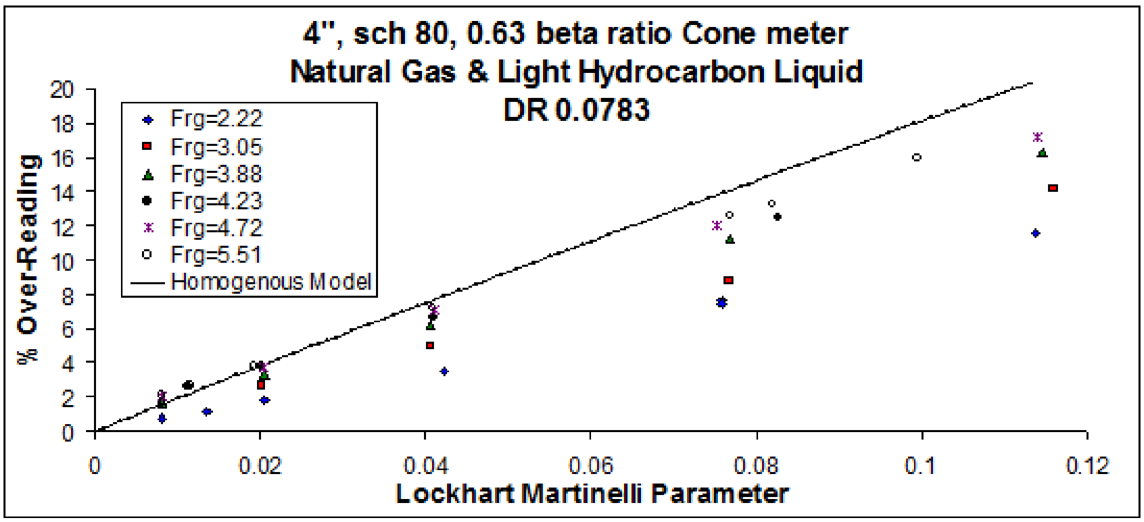

Fig 16. 4”, 0.63 beta ratio cone meter gas with HCL data, set higher DR, with separated Frg.

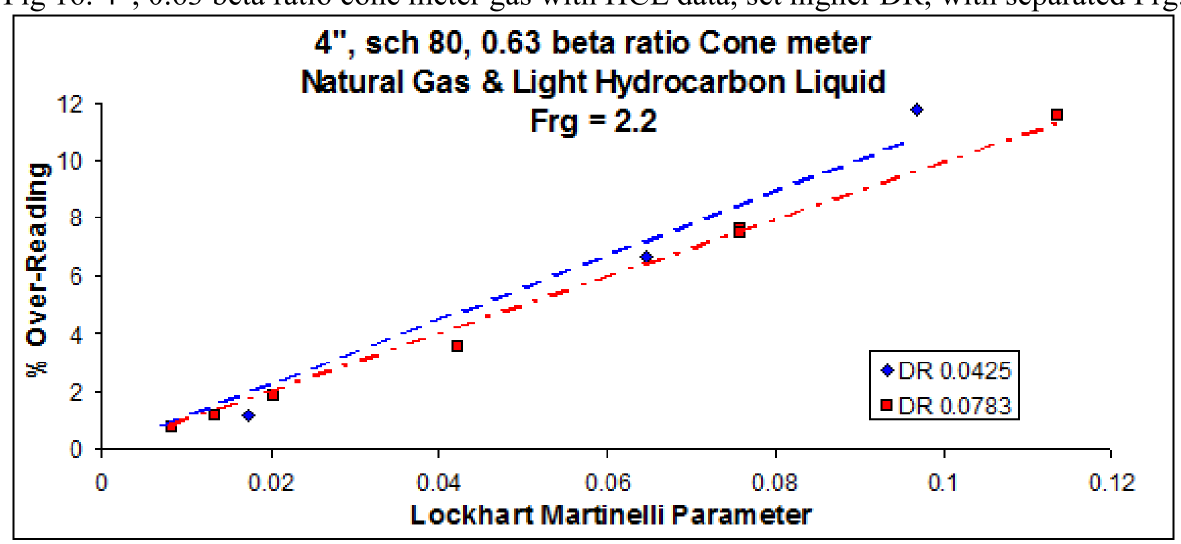

Fig 17. 4”, 0.63 beta ratio cone meter gas with HCL data, set Frg, with separated DR.

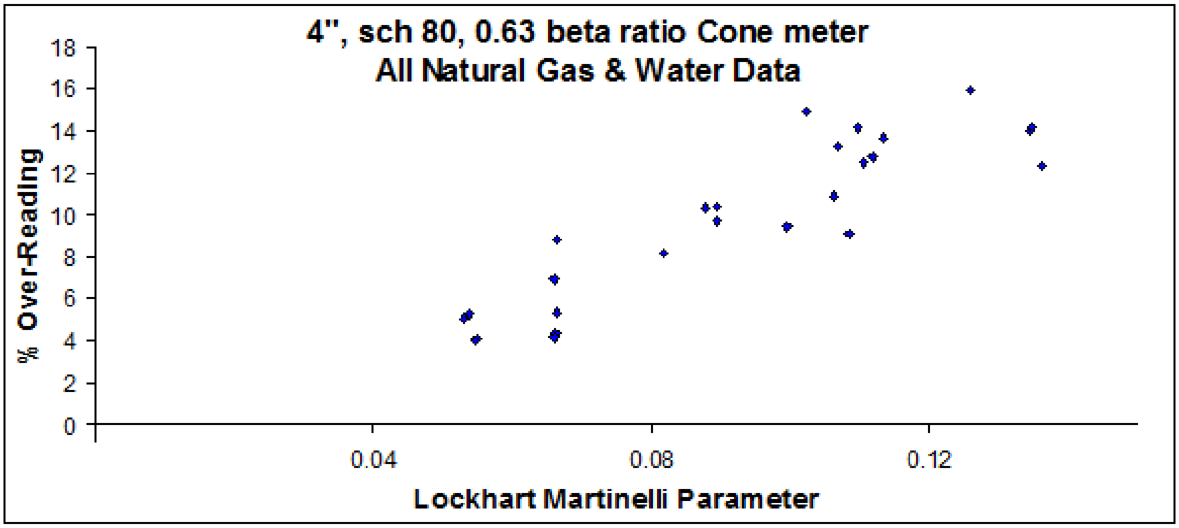

Fig 18. All 4”, 0.63 beta ratio cone meter gas with water data.

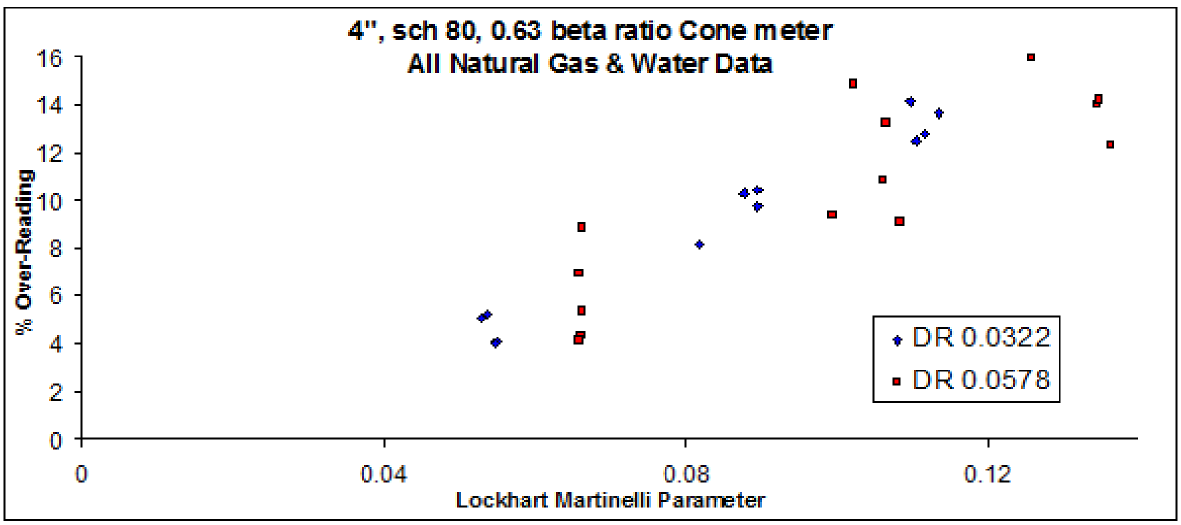

Fig 19. 4”, 0.63 beta ratio cone meter gas with water data, with separated DR.

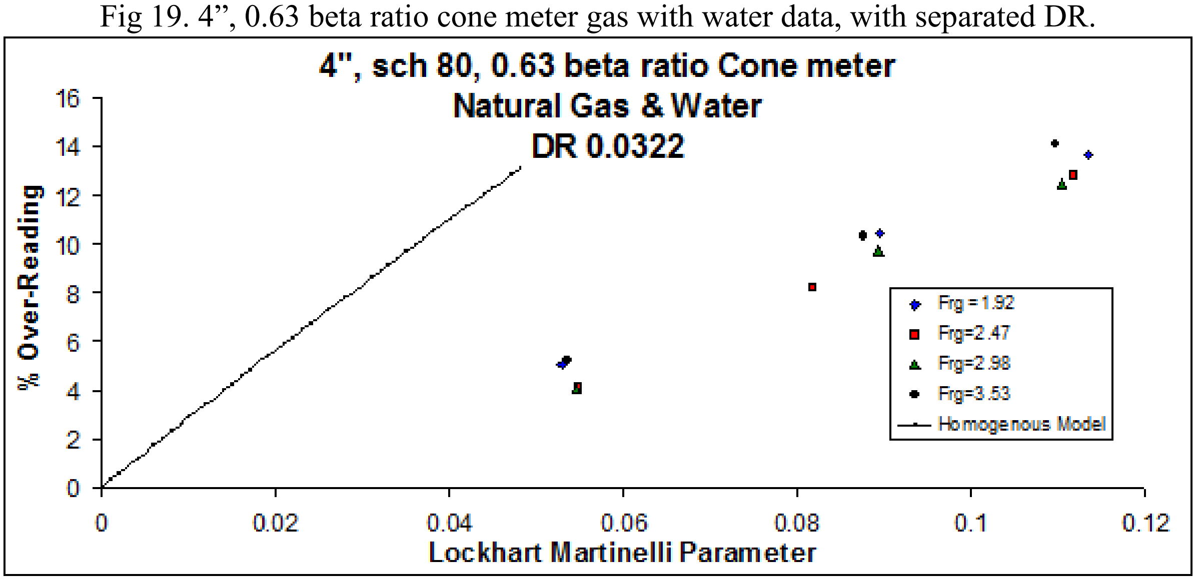

Fig 20. 4”, 0.63 beta ratio cone meter gas with water data, set moderate DR, with separated Frg.

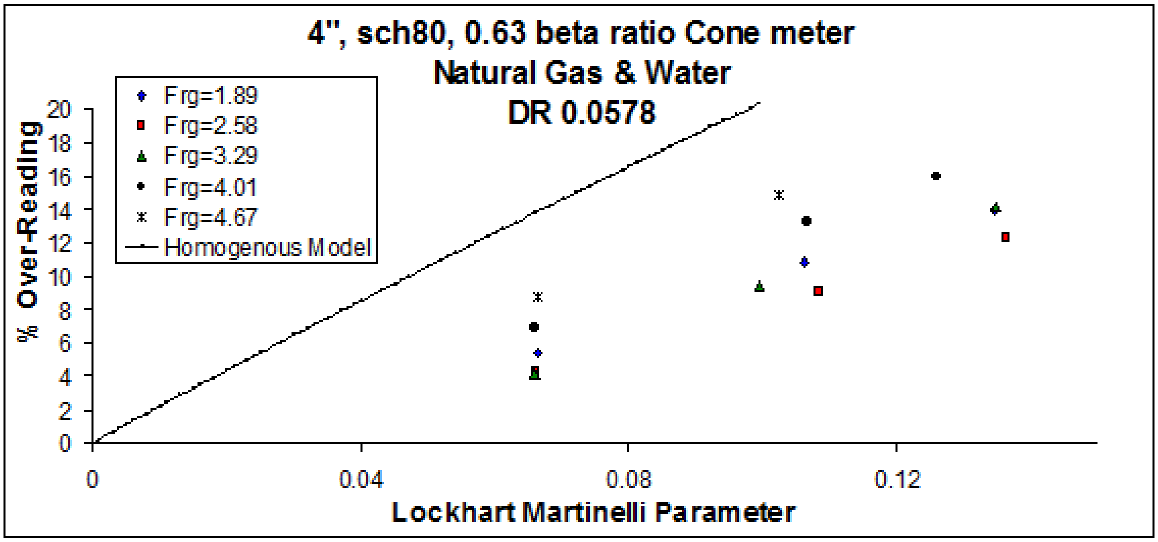

Fig 21. 4", 0.63 beta ratio cone meter gas with water data, set higher DR, with separated Frg.

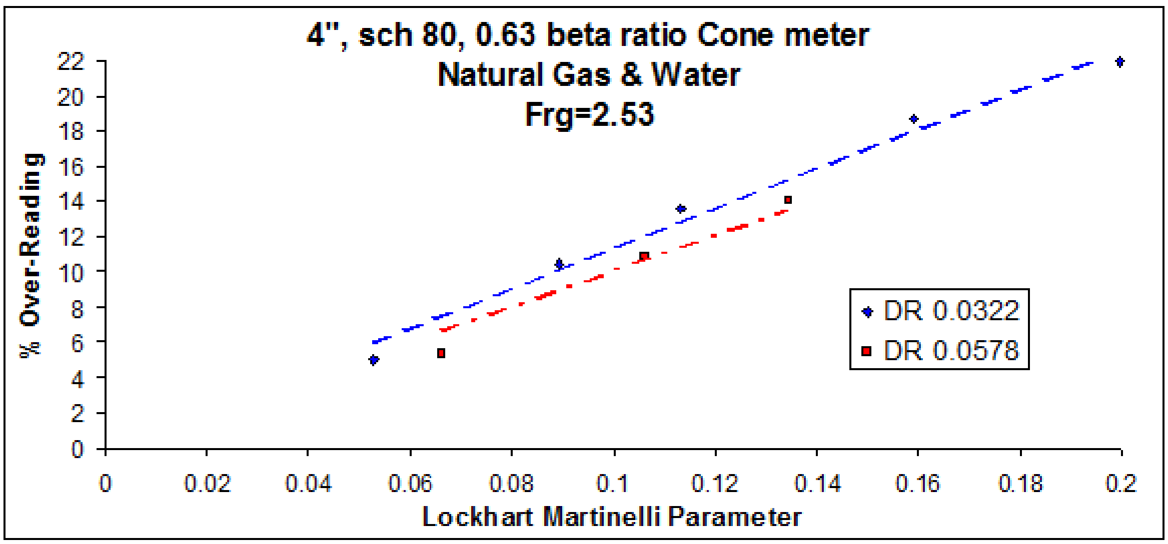

Fig 22. 4", 0.63 beta ratio cone meter gas with water data, set Frg, with separated DR.

coefficient gives the gas flow rate to within 1%. This is an acceptable gas calibration for wet gas flow service (as wet gas data scatter can be greater than this). This then is the dry gas baseline from which all other research extends.

Figure 13 shows all the natural gas and hydrocarbon liquid (HCL) data. As expected the Lockhart Martinelli parameter is seen to have a direct significant influence on the gas flow rate prediction. Figure 14 shows the same data set with the two gas to liquid density ratio sets separated. No clear relationship can be seen. However, it is noteworthy that both data sets have a wide range of gas densiometric Froude numbers that can mask such an effect. Figures 14 & 15 show these two individual gas to liquid density ratio sets independently with the ranges of gas densiometric Froude numbers shown on each graph respectively. Clearly for all other parameters held constant as the gas densiometric Froude numbers increases the over-reading increases. Both show a tendency for the over-reading of a set a set Lockhart Martinelli parameter and gas to liquid density ratio wet gas flow to increase towards the homogenous flow model with a rising gas densiometric Froude number. The homogenous model is the theoretical condition where the liquid phase is so well mixed in the gas flow that the fluid can be considered a pseudo-single phase flow. Naturally for any given gas to liquid density ratio, as the gas densiometric Froude number (i.e. the gas velocity) increases the wet gas flow tends to be more mixed. Therefore, these results follow other DP meter findings and make physical sense. It is noteworthy that for the two gas to liquid density ratio sets obtained each have a data sub-set of a gas densiometric Froude number of approximately 2.2. This pair of data sets can therefore be used to show the gas to liquid density ratio effect on wet gas flow over-readings. Figure 17 shows that for all other wet gas flow parameters held constant as the gas to liquid density ratio increases the over-reading reduces.

Figure 18 shows all the natural gas and water data obtained. Clearly there is less data gathered here than for the gas / HCL wet gas flows. However, from Figure 18 we can see that again, as expected, the Lockhart Martinelli parameter is seen to have a direct significant influence on the gas flow rate prediction. Figure 19 shows the same data set with the two gas to liquid density ratio sets separated. Again, no clear relationship can be seen. However, as both data sets have a wide range of gas densiometric Froude numbers any gas to liquid density ratio influence could be masked here. Figures 20 & 21 show these two individual gas to liquid density ratio sets independently with the ranges of gas densiometric Froude numbers shown on each graph respectively. There is a slightly more complicated relationship between the over-reading and the gas densiometric Froude number when the liquid is water. In both Figures 20 & 21 we see that as the gas densiometic Froude number increases initially from low values there is no clear relationship. However, from a moderate gas densiometric Froude number onwards the same trend as seen for gas with HCL exists, i.e. the larger the gas densiometric Froude number the larger the over-reading, and the over-reading tends to the homogenous model.

This is generally attributed to the liquid dispersion in the pipe, or the "flow pattern". For any given gas to liquid density ratio at low gas velocities (i.e. gas densiometric Froude numbers) the flow pattern is stratified, i.e. the liquid runs along the base of a horizontal pipe. As the gas velocity increases the liquid becomes entrained in the gas, i.e. it flows in droplets. This is often called mist flow. Whilst the flow pattern is stratified the gas densiomteric Froude number has little effect. However, once the liquid starts transition from stratified flow to a mist flow the gas densiometric Froude number has a significant influence on the meters wet gas flow over-reading. The same is considered true of the gas with HCL flows. However, with the significantly less interfacial tension between HCL and gas compared to water and gas it is known that at the conditions tested here the gas / HCL flows were never stratified, even at the lowest gas densiometric Froude number. (This is not so for the lowest gas with water flows.)

Finally, note that Figures 20 has a gas densiometric Froude number of 2.58 and Figure 21 has a gas densiometric Froude number of 2.48. As these are similar values we can compare the data sets looking for any gas to liquid density ratio effect. Figure 22 shows this comparison. Again, as we saw for gas with HCL, the gas with water wet gas flow through the cone meter has a gas to liquid density ratio effect. The larger the gas to liquid density ratio for all other wet gas flow parameters held constant the lower the meters gas flow rate over-reading.

Figure 23 shows all the wet gas data taken at CEESI for the 4", 0.63 beta ratio cone meter. This includes the gas with HCL only flows, the gas with water only flows and the gas with both HCL and water flows (sometimes called "multiphase wet gas" flows). The liquid mix of water and HCL is denoted in the Figures legend as "WLR" (for water liquid ratio – an indication that this data set has more WLR values than just 0% for HCL only or 100% for water only). Clearly the multiphase wet gas flow causes the cone meter to have a similar reaction to when the wet gas flow has only one liquid component with the gas. However, it was found that although there may be some relatively small WLR effect on the meters wet gas over-reading it does not appear to be linear and as yet this phenomenon is not fully understood. Therefore, for a horizontally installed 4" cone meter with a set beta ratio, a wet gas correction factor should account for the Lockhart Martinelli parameter, gas to liquid density ratio and the gas densiometric Froude number. It could be argued that it should also account for the WLR. However, including a WLR effect in any wet gas cone meter correlation is difficult as the effect WLR has on a wet gas over-reading has is not well understood. Therefore, as suggested by Steven [9] for the existing 4" & 6", 0.75 beta ratio wet gas correlation, currently the practical way for industry to deal with any WLR influence on a cone meters wet gas flow performance is to understand that the effect is relatively small and therefore it can be considered to be simply scatter in the data set. This was done by Steven [9] for the 4", 0.75 beta ratio multiphase wet gas correlation (i.e. equation set 11 thru 13b).

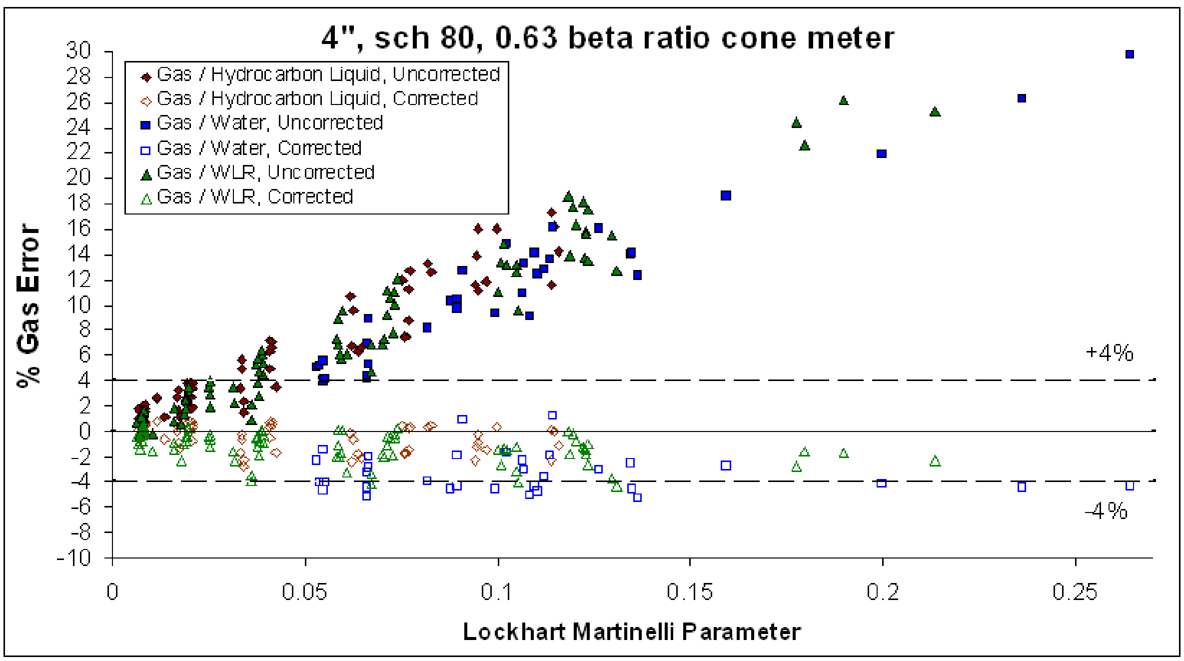

Fig 23. All CEESI 4", 0.63 beta ratio cone meter data uncorrected & corrected with the existing 4" & 6", 0.75 beta ratio data.

Figure 23 shows this 4" 0.75 beta ratio correlation being applied to the 4", 0.63 beta ratio cone meter data set. As we have seen, there is thought to be a beta ratio effect on the wet gas flow performance of cone meters. Hence, it could be reasonably argued that this correlation is being inappropriately applied. However, due to lack of alternatives (or possibly ignorance) this type of DP meter wet gas correlation extrapolation happens often in the natural gas production industry. Therefore this is an interesting valid research exercise. The results were surprising.

Figure 23 shows that when the 4", 0.75 beta ratio multiphase wet gas correlation was applied to the 4", 0.63 beta ratio cone meters multiphase wet gas data set, the corrections not surprisingly did not fall within the correlations stated uncertainty of 4%. What was very surprising however, is that the correction was too much, not too little. The general understanding of the cone meter beta ratio effect is that the bigger the beta ratio the smaller the over-reading. Hence, one could expect under the same wet gas flow conditions for the 4", 0.75 beta ratio meter to produce a smaller over-reading than a 4", 0.63 beta ratio cone meter. In this case, it follows that a 4", 0.75 beta ratio cone meter correlation should predict a smaller over-reading than exists for a 4", 0.63 beta ratio cone meter and therefore fail to correct for all the 0.63 beta meters error. But that is not what is found here. In fact the 0.75 beta correlation has predicted too great an error and therefore "over-corrected" the error. The resulting under prediction of the actual gas mass flow rate can be seen in Figure 23.

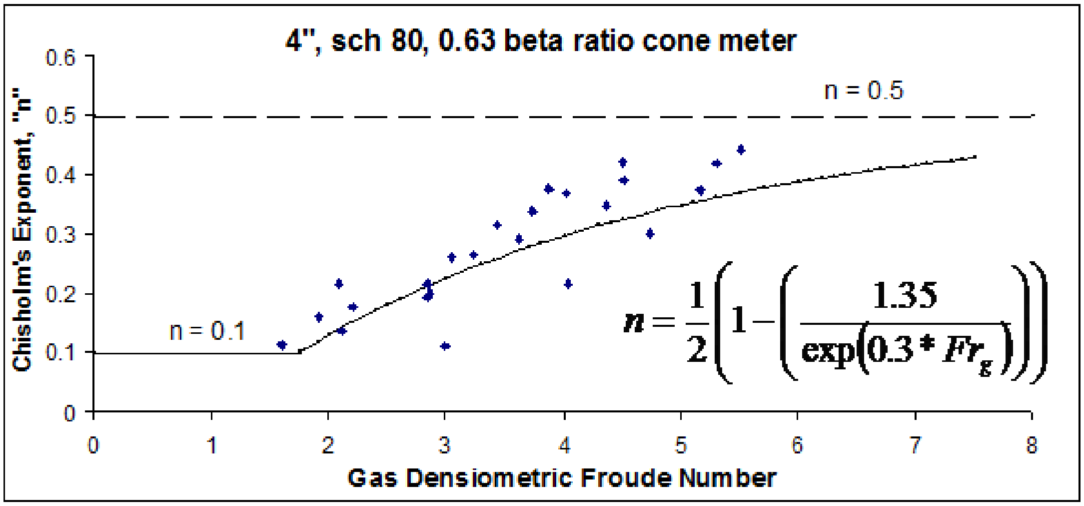

Figure 24. Data fit of the 4", 0.63 beta ratio cone meter wet gas data set.

Due to the existing 4", 0.75 beta ratio cone meter correlation being inapplicable to the 4", 0.63 beta ratio cone meter data a new correlation was fitted for the 0.63 beta ratio data set. That data fit is shown in Figure 24. The new correlation is:

$$\dot{m}_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1+CX_{LM}+X_{LM}^2}} \text{ --- (11)} \quad \text{where} \quad C=\left(\frac{\rho_g}{\rho_\ell}\right)^n+\left(\frac{\rho_\ell}{\rho_g}\right)^n \text{ --- (12)}$$

for $Fr_g \leq 1.75$ $\qquad$ $n = 0.1$--- (14a)

for $Fr_g > 1.75$ $\qquad$ $$n=\frac{1}{2}\left(1-\left(\frac{1.35}{\exp(0.3*Fr_g)}\right)\right) \text{ --- (14b)}$$

Figure 25 & 26 show that the uncertainty of this correlation is 3% to 95% confidence. It is noticeable in Figure 26 (which shows the corrected results only) that there is a *general* trend for the gas with HCL data to tend to the 0 to +3% range and the gas with water to tend 0% to -3%. This again is evidence of the liquid property effect as shown earlier in Figure 4.

6. <u>Discussion of Results</u>

This new correlation is evidentely better for use with this particular 4" 0.63 beta ratio cone meter than the existing 4", 0.75 beta ratio cone meter correlation. That in itself is not surprising as the correlation was fitted to that data set. However, what is surprising is that the 0.63 beta data set

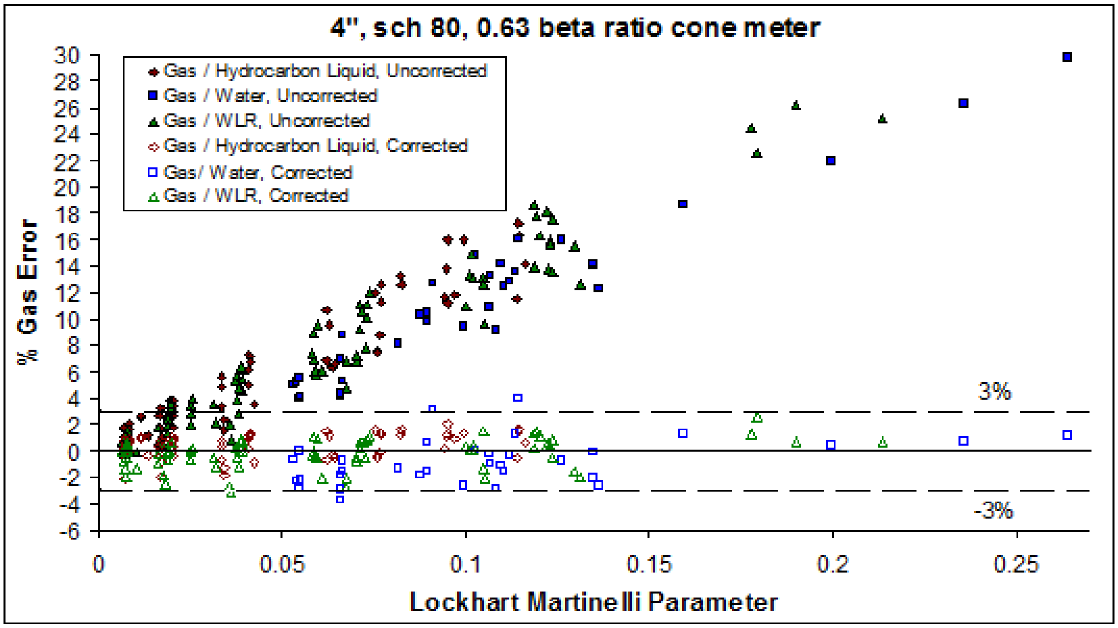

Fig 25. All CEESI 4", 0.63 beta ratio cone meter data uncorrected & corrected with the new 4", 0.63 beta ratio data.

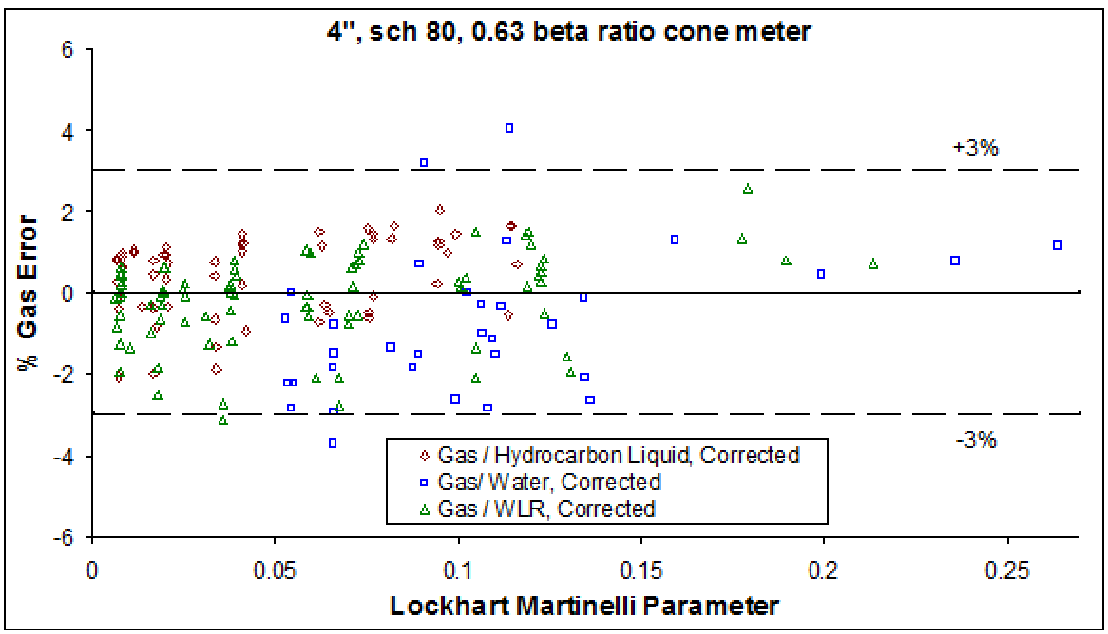

Fig 26. All CEESI 4", 0.63 beta ratio cone meter data corrected with the new 4", 0.63 beta ratio data.

showed a lower over-reading than the 0.75 beta ratio meter. The generally accepted relationship between the over-reading and the beta ratio has not been seen here. Figure 27 shows the comparison of the two correlation predictions at a randomly chosen wet gas flow condition. Clearly the 0.63 beta ratio correlation has a lower over-reading prediction than the 0.75 beta ratio correlation. There is no confirmed reason for this result. It is true that earlier research has shown the difference between a 0.6 & 0.75 beta ratio cone meter to be small enough that the data scatter can show a 0.75 beta to have a slightly higher over-reading than a 0.6 beta ratio (i.e. Figure 9). However, the difference between the two correlations shown in Figure 27 seems too great to be accounted for solely in this way.

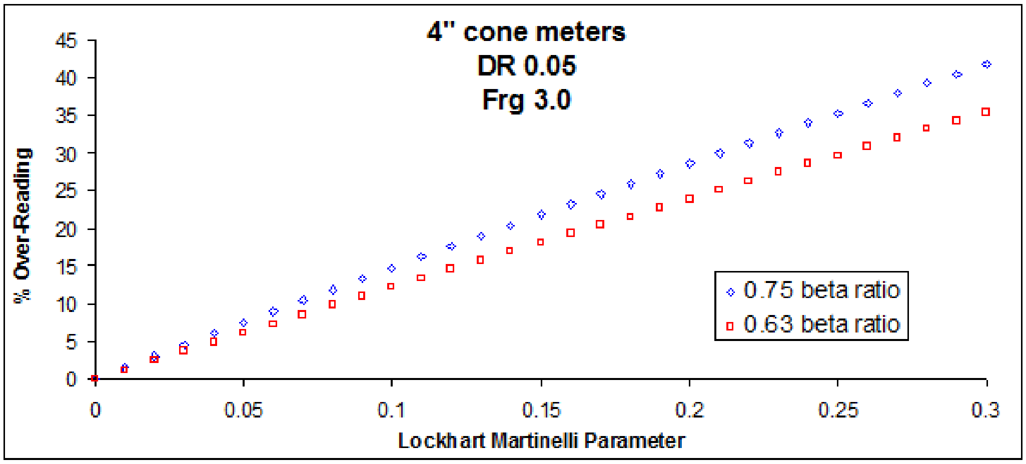

Fig 27. A comparison of the 0.75 & 0.63 beta ratio correlations, at a random wet gas flow condition.

It is noteworthy that the 0.63 beta ratio data set is skewed towards the lower end of the wet gas flow range with most of the data at Lockhart Martinelli parameters less than 0.15. A larger data set with more data with higher liquid loads may somewhat reduce the difference between the two data sets. However, as yet no conclusive statement can be made to why the 4", 0.63 beta ratio cone meters wet gas over-reading is lower than the 4", 0.75 beta ratio cone meters wet gas over-reading. All that can be stated with certainty is that applying the 0.75 beta ratio correlation to the 0.63 beta ratio cone meter gave results outside the correlations stated uncertainty. However, the wet gas flow data from the 4", 0.63 beta ratio cone meter could be fitted to produce a dedicated wet gas correlation.

6. <u>Conclusions</u>

Cone meters are sturdy, simple reliable DP meters. When properly calibrated cone meters can meter dry gas flows to 0.5% uncertainty. Cone meters can be economical multiphase wet gas flow meters. When a cone meter is wet gas flow tested it can be shown to give a repeatable wet gas performance. A wet gas flow correlation can be created from data fitting a cone meters wet gas flow test result. This resulting wet gas flow correlation will predict the gas flow rate through the meter if the liquid flow rate is known from an external source.

The CEESI wet gas flow test of the 4", 0.63 beta ratio meter showed that the meter performed according to the known wet gas flow trends for all DP meters. Increasing Lockhart Martinelli parameter caused an increase of the over-reading. Increasing gas to liquid density caused a reduction of the over-reading. Increasing gas densiometric Froude number caused an increase of the over-reading. Higher interfacial tension liquids reduce the over-reading. The result of the CEESI wet gas flow test of the 4", 0.63 beta ratio meter was a correlation for that particular meter where for known water and hydrocarbon liquid flow rates the gas flow rate could be corrected to within 3% at 95% confidence.

Applying a correlation designed for another cone meter geometry is not advisable. This may lead to a bias in the gas flow rate prediction. The only sure way to know a cone meters wet gas performance is to wet gas flow test the meter in question.

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