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Paper 7.2

A Discussion on Horizontally Installed Differential Pressure Meter Wet Gas Flow Performances

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Horizontally Installed Differential Pressure Meter Wet Gas Flow Performance Review

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1 INTRODUCTION

The natural gas production industries demand for wet gas flow metering technologies continues to increase and many production facilities now utilize some type of wet gas flow meter and predictions suggest that their use will continue to grow rapidly.

Single phase differential pressure (DP) meters can be used to meter wet gas flows if the liquid flow rate can be obtained from an independent source and a suitable wet gas correction factor is available. As it is not a trivial task to measure the liquid flow rate of a wet gas flow there are wet gas flow metering systems that have been designed to predict both the gas and liquid phase flow rates. A recurring theme with these designs is to use a DP meter as the primary system and some secondary system (e.g. second DP meter, capacitance / conductance devices, radioactive sources, microwave system etc.) to supply the additional information from which the gas and liquid flow rates can be derived. The prediction methods are usually held in commercial confidence and therefore not available for public scrutiny.

Many wet gas and multiphase meters therefore utilize DP meter technologies. Industry is becoming familiar with these new technologies and new field developments could now have wet gas meter technologies integral in the conceptual stage. The potential financial savings of successful wet gas meter installations are substantial. The potential financial losses of unsuccessful wet gas meter installations are also substantial. It is therefore of interest to compare the publicly available wet gas flow DP meter information with new analysis of a previously released Venturi meter data set and new CEESI and BG Group DP meter wet gas data sets. This exercise leads to some interesting questions on DP meter wet gas flow performance and suggests that industry has considerably more work to do before a full understanding of DP meter response to wet gas flows is achieved.

2 DEFINITION OF WET GAS FLOW

Wet gas flow is defined here as any two-phase flow where the Lockhart-Martinelli parameter (X_{LM}) is less or equal to 0.3. That is:

$$X_{LM} = \sqrt{\frac{Superficial\ Liquid\ Inertia}{Superficial\ Gas\ Inertia}} = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}} \leq 0.3 \qquad (1)$$

where $\dot{m}_l$ is the liquid mass flow rate, $\dot{m}_g$ is the gas mass flow rate, ρ_l is the liquid density and ρ_g is the gas density. The term "superficial" can be interpreted as meaning "if the phase flowed alone in the pipe".

3 A BRIEF HISTORY OF DP METER WET GAS FLOW PERFORMANCE RESEARCH

Early attempts at metering two-phase flow assumed the phases to be perfectly mixed (i.e. "homogenised") and therefore the flow was treated as single phase flow. For a known liquid mass flow rate a homogenised wet gas flow can have the gas mass flow rate metered with a DP meter. The gas mass flow rate of a homogenised wet gas flow is traditionally given by equation 2 where the quality/dryness fraction ("x") is given by equation 3:

$$\dot{m}_g = x\left(\frac{\dot{m}_{g_{Apparent}}}{\sqrt{\frac{\rho_g}{\rho_l} + x\left(1 - \frac{\rho_g}{\rho_l}\right)}}\right) \quad \text{---- (2)} \qquad \text{where} \qquad x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} \quad \text{---- (3)}$$

where $\dot{m}_{g_{Apparent}}$ is the uncorrected gas mass flow prediction of the meter when the flow is a wet gas. Substituting equation 3 into equation 2 allows the gas flow rate to be predicted if the liquid flow rate is known. The derivation of equation 2 is given in Appendix 1. An unconventional form of the equation is derived in Appendices 2 and 3. This equation is applicable to all DP meters.

In 1962 Murdock [1] published research on orifice plate meter response to two-phase flows. Increasing the amount of liquid for otherwise set flow conditions caused the meters gas mass flow rate prediction to have an increasing positive error (or "over-reading"). In 1967-77 Chisholm [2,3] published research into DP meter responses to wet gas flow. Like Murdock Chisholm assumed stratified flow but Chisholm also included slip effects in his model. He showed that the over-reading was dependent on the gas to liquid density ratio as well as the amount of liquid flowing with the gas. The Chisholm wet gas correction for orifice plate meters (for $X_{LM}<1$) can be presented as:

$$\dot{m}_g = \frac{\dot{m}_{g_{Apparent}}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{---- (4)} \quad \text{where: } C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{---- (5) and } n = 0.25 \text{ --- (6)}$$

There is a common misperception that Chisholm's equation is wholly theoretically derived and therefore not a correlation. Although the formulation consisted of detailed theoretical arguments the equation relies on an approximation to a parameter justified by the use of data sets [3]. It is therefore a correlation. In order to correct the gas flow rate error with the Chisholm correlation the liquid flow rate must be known.

By the 1990's industry was concentrating on Venturi meter wet gas research with orifice plate meters being perceived as liquid dams and more susceptible to damage. In 1997 de Leeuw [4] presented a seminal research paper on a 4" 0.4 beta ratio Venturi meters wet gas performance. De Leeuw showed that the liquid loading effect (shown by Murdock) and the gas to liquid density ratio effect (shown by Chisholm) on orifice plate meters were also true for Venturi meters. In addition de Leeuw showed that the gas flow rate, for a set liquid loading and gas to liquid density ratio, influences the gas flow rate over-reading magnitude. De Leeuw's correlation is based on Chisholm's mathematical form. That is, de Leeuw still used Chisholm's equations 4 and 5 but altered the exponent "n" to become a function of the gas densiometric Froude number as shown in equations 7a and 7b.

$n = 0.606\{1 - \exp\{-0.746 Fr_g\}\}$ ----(7a) for $Fr_g \geq 1.5$, $n = 0.41$ ----(7b) for $0.5 \leq Fr_g < 1.5$

That is, de Leeuw found from a Trondheim Venturi meter wet gas flow data set that the exponent "n" said by Chisholm to be a constant for an orifice plate meter could be expressed as a constant for stratified flow and a function of the gas densiometric Froude number, Fr_g for annular mist flow. This parameter is a non-dimensional way of describing the gas flow rate. There is also a liquid densiometric Froude number term, Fr_l. They are defined as by equations 8 and 9 (where g is the gravitational constant, A is the pipe cross sectional area, D is the pipe inside bore and diameter and U_{sg} and U_{sl} are the superficial average gas and liquid velocities respectfully).

$$Fr_g = \sqrt{\frac{Superficia\ l\ Gas\ Inertia}{Liquid\ Gravity\ Force}} = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \quad \text{--- (8)}$$

$$Fr_l = \sqrt{\frac{Superficial\ Liquid\ Inertia}{Liquid\ Gravity\ Force}} = \frac{U_{sl}}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l - \rho_g}} = \frac{\dot{m}_l}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_l(\rho_l - \rho_g)}} \quad \text{--- (9)}$$

Since de Leeuw's paper other publications have added to the industries knowledge. Notable papers are Stewart et al. [5] showing V-Cone meters to act in a similar fashion to Venturi meters and that the smaller the beta ratio of a V-Cone meter the larger the over-reading. Stewart [6] later presented a paper showing this beta ratio effect was also true for Venturi meters. This fact then suggested that de Leeuw's correlation would be best suited for 0.4 beta ratio Venturi meters. However, due to lack of alternatives or ignorance of this phenomenon by some Venturi meter users the de Leeuw correlation has been used to correct different beta ratio Venturi meter wet gas errors in industry. The latest published DP meter wet response research indicates that liquid properties [7,8 &10] and diameter [7,8] can affect the differential pressure read by the meter.

The state of the art of wet gas flow metering is now to use a DP meter and either correct the wet gas error using a correlation with a known liquid flow rate obtained from an independent source (such as tracer injection or historical test separator readings) or to use some combination of DP meter and secondary instrumentation with propriety analysis methods to derive the phase flow rates from the combined readings. Both practices require detailed understanding of the DP meters wet gas response. It is therefore important to ask how well understood are wet gas DP meter responses? There are questions to which industry has incomplete answers. For example:

How repeatable are the wet gas flow results of any DP meter? What happens if these DP meter wet gas correlations are extrapolated from their data set ranges to lower and higher values of particular parameters? How large is the error caused by a correlation formed for one beta ratio being used to correct a meter with another? Can a wet gas DP meter correlation formed from data taken from one DP meter type (e.g. a Venturi) give an acceptable correction for a geometrically similar but not identical DP meter type (e.g. a Venturi Nozzle)?

Due to the propriety nature of much of the latest research it is difficult to get any independent answers to these questions. This paper discusses a Joint Industry Project (JIP) sponsored CEESI test on de Leeuw's NAM Venturi meter and a CEESI funded wet gas test on a non-standard Venturi Nozzle type DP meter where the results of using both the de Leeuw and homogenous flow model correction are presented and analysed. In this way an initial attempt at starting to answer at least some these questions is made. First though, to aid later discussions, it is necessary to review flow pattern and flow pattern map terminology.

4 FLOW PATTERNS AND FLOW PATTERN MAPS

The flow pattern is a physical description of how the flowing liquid and gas phases are distributed in the pipe. There are several flow patterns for horizontal two-phase flow. Not all exist with wet gas flow due to wet gas flow having a relatively small volume of liquid compared to the gas volume. The most common horizontal wet gas flow patterns are shown in Figure 1.

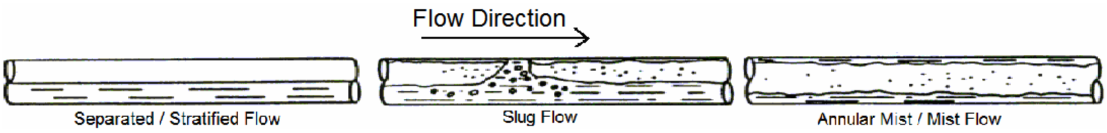

Fig.1 Typical Flow Patterns for Wet Gas Flow

It is not yet possible to theoretically predict flow patterns for set flow conditions. The distribution of the phases in horizontal wet gas pipe flow is dependent on many variables such as pipe diameter, pressure, gas and liquid flow rates and liquid phase properties. There is no general agreement on what to call particular flow patterns so one flow pattern can have several names. The most common names for horizontal wet gas flow patterns are now discussed.

For relatively low pressures (i.e. low gas to liquid density ratios) and low gas velocities (i.e. low gas dynamic forces on the liquid phase) the gravitational force is dominant and the liquid phase tends to be at the base of the pipe with the gas flowing above it. The liquid phase is driven by shear stress on the phase interface. This is often called "stratified flow" or "separated flow". As the pressure and gas flow rate increases waves appear at the interface. If there is enough liquid waves can intermittently block the pipe causing "slug flow". For lower liquid flows as the gas flow rate increases the liquid pushes up the side of the pipe leaving a trough at the centre and liquid droplets begin to be entrained in the gas flow. As the pressure and gas flow rate increases further the entrainment of liquid becomes more pronounced, the average droplet size reduces (as increased gas dynamic forces shatter the larger droplets) and the liquid at the base of the pipe is forced more around the periphery of the pipe creating (due to gravity) a non-symmetrical annular ring. This is often called an "annular-dispersed flow" or "annular-mist flow". As the pressure and gas flow rate continue to rise the percentage of entrained liquid increases, the average liquid droplet size reduces and the liquid film thickness reduces. Finally, the ring effectively disappears (although the pipe wall is always wetted by the droplets impact and re-entrainment) and a fully entrained droplet flow exists called a "mist flow" or "dispersed flow". In reality it is usually not possible to know if the annular ring exists or not so annular-mist flow is a term that is often used to encompass both annular mist and mist flows. If the pressure and gas flow rate continue to increase then the droplets will become so small that effectively the liquid phase is atomized and the flow can in practical terms be considered to be homogenous (i.e. pseudo-single phase) flow. Although increasing gas to liquid density ratio and gas velocity both mutely help drive the flow pattern towards mist flow each are capable of doing this independently of the other. That is, for a set gas to liquid density ratio a high enough gas velocity will create mist flow. The lower the set gas to liquid density ratio the higher the gas velocity required to produce mist flow and vice-versa. In reality the borders between different flow patterns are not distinct but rather they transition between these general descriptions over pressure and flow rate ranges.

Flow patterns are usually predicted with flow pattern maps that are created from experimental observation and are therefore only valid for that experimental test matrix. In reality extrapolation is often performed. One such map is the Shell Flow Pattern Map [4] (see Figure 2) for 4" two phase flow with nitrogen and diesel oil.

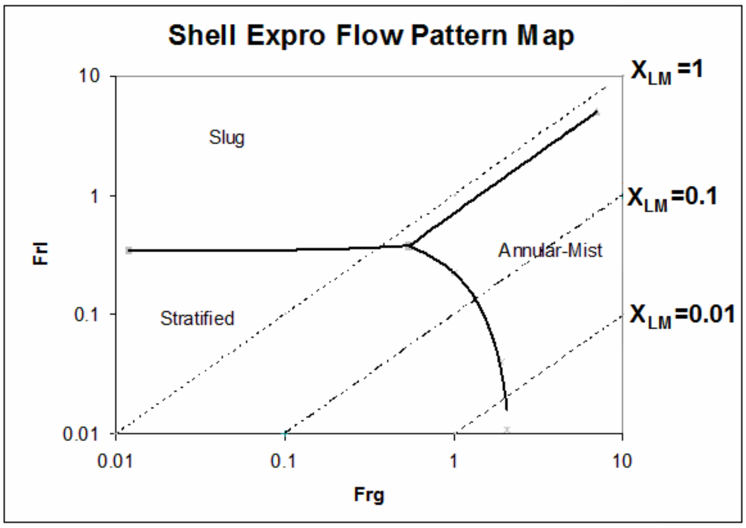

Fig 2. The Shell Flow Pattern Map.

Shell chose to use the gas and liquid densiometric Froude numbers on the abscissa and ordinate of this horizontal flow pattern map which indicates that for wet gas flows (i.e. $X_{LM} \leq 0.3$) at a set liquid densiometric Froude number the flow pattern will be either stratified flow at low gas densiometric Froude numbers or annular mist flow at high gas densiometric Froude numbers. Close to the stratified / annular mist flow border the flow will be in transition between these flow patterns. The further into any region the more pronounced a particular flow pattern will be. As previously stated there is no practical way to know at what flow condition a flow pattern becomes mist flow and when the mist is effectively a homogenised flow. This is why there are no such markings on the flow pattern map. All that is known is that for a set liquid densiometric Froude number the higher the gas densiometric Froude number the less the annular ring flow and the more the mist flow. This point will become relevant to later discussions in this paper. Finally, note that this map is for a set pipe diameter and phase components. Steven [8] discusses how different pipe diameter and phase components may change flow pattern boundaries.

5 THE CEESI WET GAS LOOP

Two data sets presented here were obtained at CEESI. This facility is nominally 4", uses natural gas and a hydrocarbon liquid, has a pressure range of 12 to 75 Bar and a maximum gas flow rate is 650 m^3/hr. The maximum gas flow rate and the maximum Lockhart-Martinelli parameter are related to each other. The lower the Lockhart-Martinelli parameter the higher the available gas flow rate and vice versa. More detailed facility information was presented by Britton [9].

6 DE LEEUW'S VENTURI METER TEST AT TROHNDIEM AND CEESI

Section 3 discussed the de Leeuw wet gas flow correlation for a 4" schedule 80, 0.4 beta ratio Venturi meter (supplied by NAM). This correlation was created from data sets obtained at a field location in the Netherlands (Coevorden) and the Trondheim wet gas test facility in Norway. De Leeuw [4] gives a detailed description of the Trondhiem test facility and test matrix. A sketch of the NAM Venturi meter is shown in Figure 3.

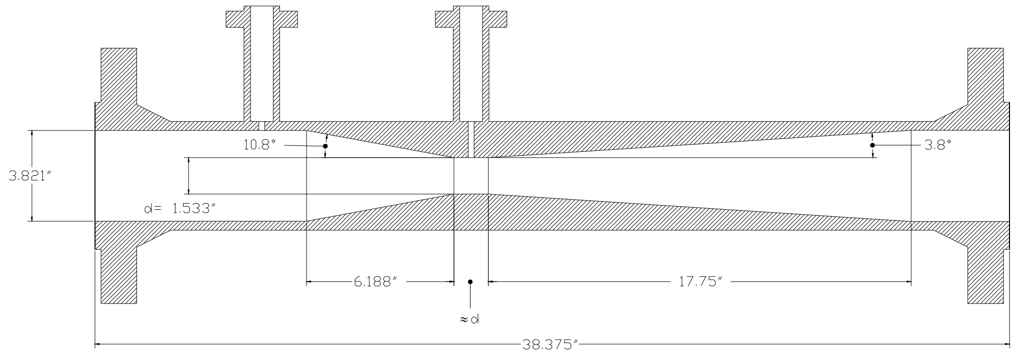

Fig 3. The NAM Venturi Meter Tested at Coevorden, Trondheim and CEESI.

In 2000 CEESI set up a JIP to research wet gas flow metering. Shell was a participant in this JIP and supplied CEESI with the same NAM Venturi as used by de Leeuw. Although this JIP work is held in commercial confidence the JIP allowed the release of this meters test results [9].

Much of the meters combined data sets of Coevorden, Trondheim and CEESI overlap. A notable difference is the fluids used. Trondhiem used nitrogen and diesel oil. CEESI used natural gas and decane. Research from NEL's work for the DTI funded Flow Programme [10] suggests that the type of gas in a wet gas flow has no significant effect on the scale of a DP meters wet gas over-reading but it is suggested by NEL [10] and CEESI [7,8] that the type of liquid can have a significant effect. Much of the data sets gas to liquid density ratios over lap but at the lowest pressures the CEESI gas to liquid density ratio was 0.013 compared to Trondheim's 0.022 (approximately) and at the highest pressures CEESI's maximum gas to liquid density ratio was

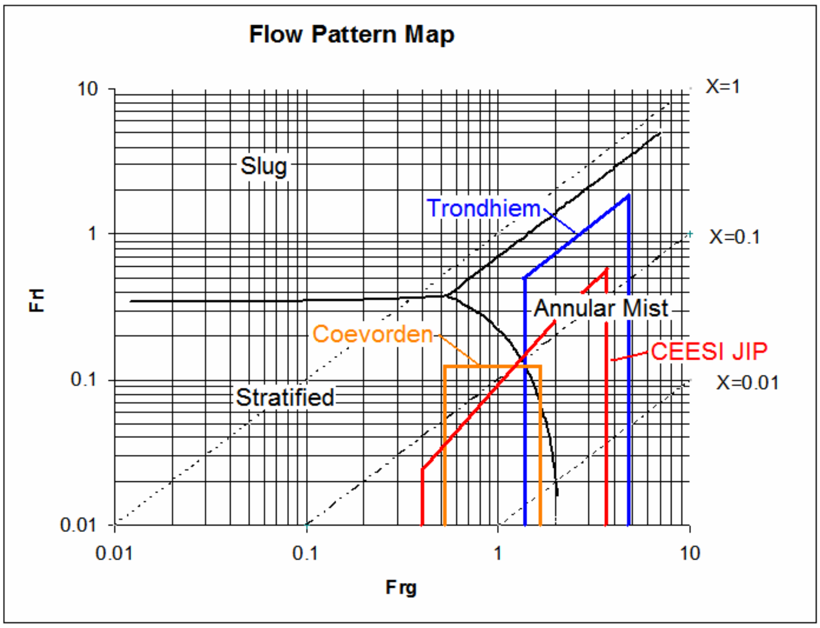

Fig. 4 The Test Matrix for the Coevorden, Trondheim and CEESI NAM Venturi Tests.

0.088 compared to Trondheim's 0.12 (approximately). The comparative densiometric Froude numbers and Lockhart-Martinelli parameters can be seen in Figure 4 where the test ranges of Coevorden, Trondheim and the CEESI JIP tests are shown.

It is evident that the CEESI JIP data has a test matrix that contains the lower part of the Trondhiem Lockhart-Martinelli parameter range. Clearly, most of the densiometric Froude number range at CEESI falls within the Trondheim and Coevorden test matrices. This is a rare chance to investigate the performance of one meter under test at similar conditions at different wet gas test centres. Any difference in results can be related to liquid property differences and/or wet gas test facilities bias.

The NAM Venturi meter CEESI JIP wet gas performance results are reproduced here in Figure 5 as previously presented in 2002 [9] after the permission was granted by the JIP. Figure 5 also shows the result of taking the known liquid flow rate from the test facilities liquid reference meters and applying the de Leeuw correlation.

The CEESI wet gas results shown in Figure 5 show clearly that the over reading relationship with the Lockhart Martinelli parameter and the gas to liquid density ratio (denoted as "DR g/l"). De Leeuw [4] states that the correlation corrected the gas flow rates liquid induced error to within 2% with a few outliers. Figures 6 to 8 show the individual gas to liquid density ratio sets tested with averaged gas densiometric Froude number sets. The low gas to liquid density ratio is well below de Leeuw's data sets minimum of value but it is still largely within the 2% band quoted by de Leeuw. The higher gas to liquid density ratio data sets show the de Leeuw correlation working as specified by de Leeuw [4].

The results shown in Figures 5 to 8 confirm that de Leeuw's correction technique works well for the meter it was created for when tested at a different location. No significant liquid property effect or test facility bias was found. (The possibility that liquid property and test facility bias cancelled each other out is considered remote.) However, the liquids are both light hydrocarbons and therefore similar. All that is said here is wet gas flows with light hydrocarbon liquids may have similar characteristics. Note that NEL [10] and CEESI [7,8] have stated that noticeable differences were found when testing DP meters with wet gas flow when a hydrocarbon liquids are present and then water was present as the liquid phase. It is therefore unlikely that the de Leeuw correlation would have worked as well if the liquid phase was water.

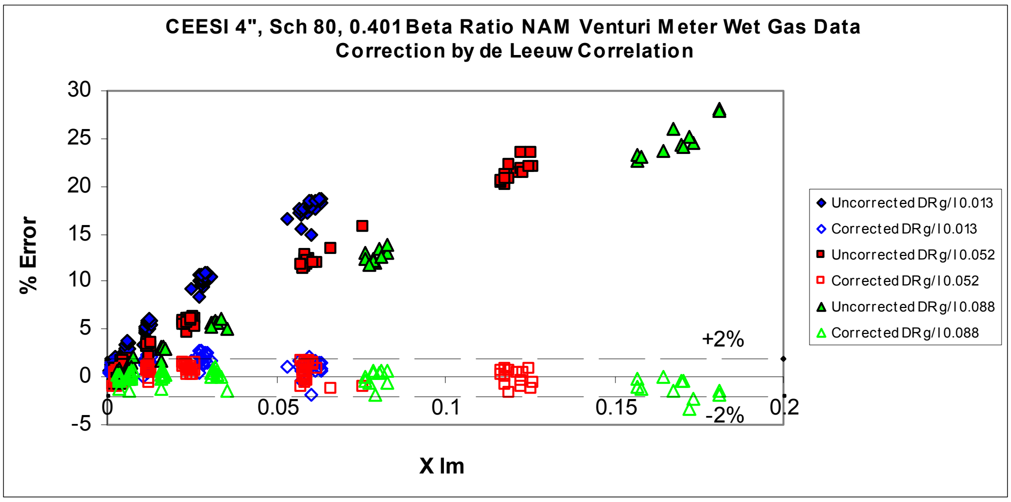

Fig 5. The Uncorrected and de Leeuw Correlation Corrected CEESI NAM Venturi Meter Results.

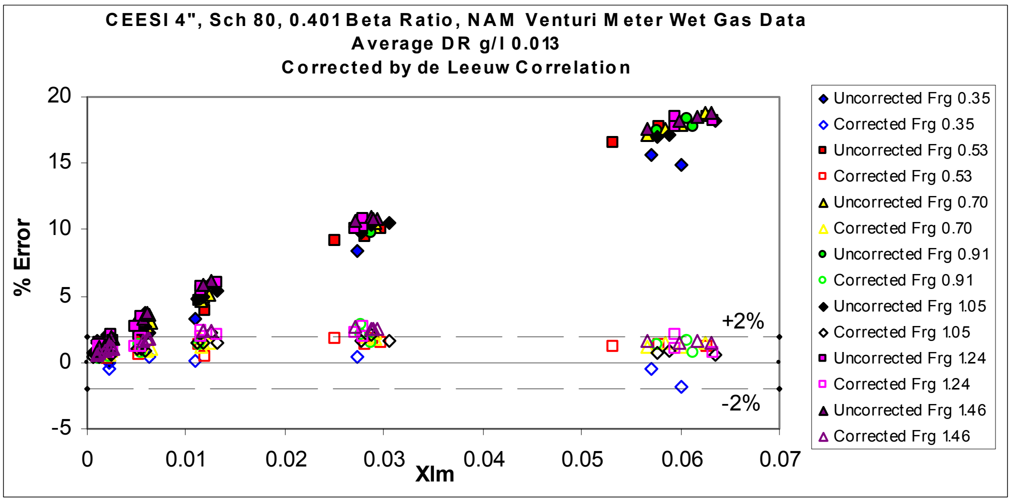

Fig 6 The Uncorrected and de Leeuw Correlation Corrected CEESI NAM Venturi Meter Results for an Average Gas to Liquid Density Ratio of 0.013.

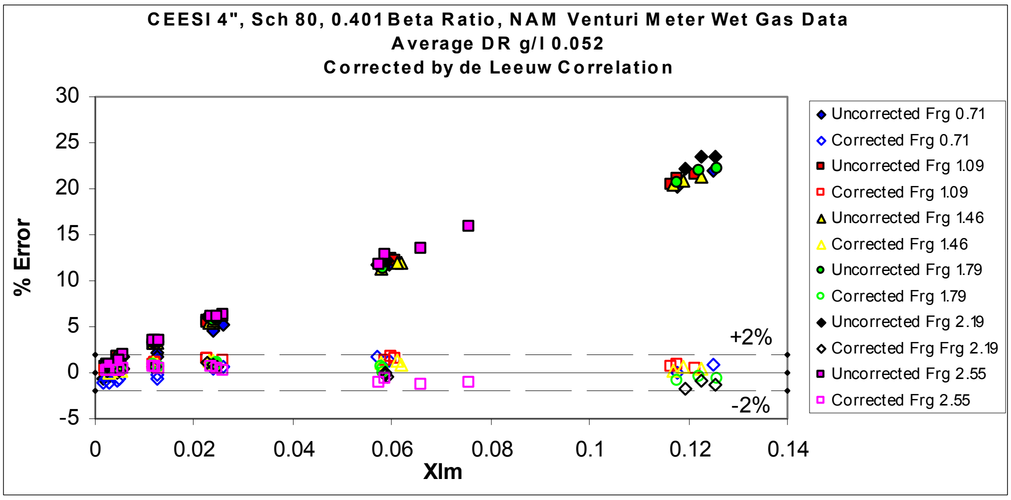

Fig 7 The Uncorrected and de Leeuw Correlation Corrected CEESI NAM Venturi Meter Results for an Average Gas to Liquid Density Ratio of 0.052.

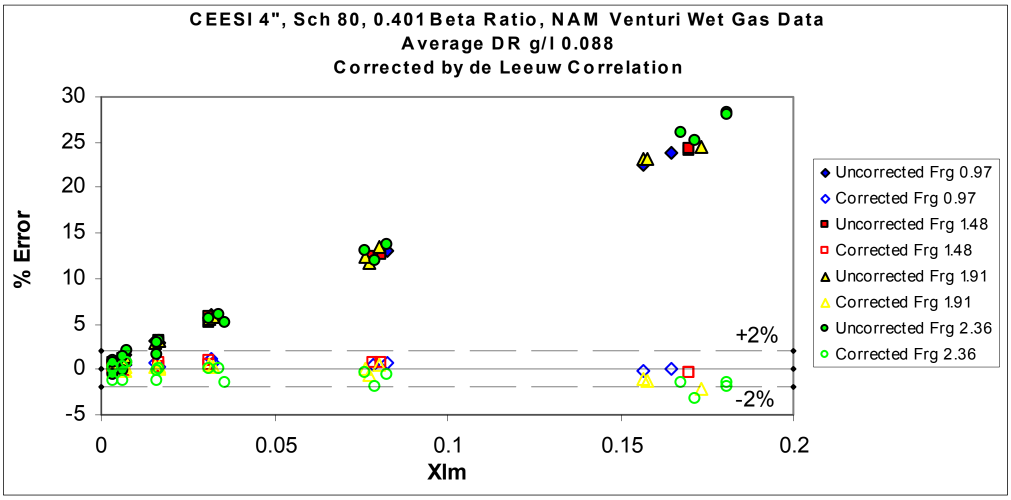

Fig 8 The Uncorrected and de Leeuw Correlation Corrected CEESI NAM Venturi Meter Results for an Average Gas to Liquid Density Ratio of 0.088.

7 THE NON-STANDARD VENTURI NOZZLE METER WET GAS TEST

CEESI wet gas tested a non-standard Venturi-Nozzle type DP meter (see Figure 9). With industries habit of applying particular wet gas correlations formed for specific DP meter geometries to other geometries of DP meter it is of interest to see how applicable de Leeuw's Venturi correlation is to this particular meter.

It was first necessary to check this non-standard DP meters dry gas performance. A set value for the flow coefficient of 0.9847 was found to fit the data across a ten to one turndown to within +/- 0.6% This result was viewed as satisfactory for use as a dry gas base line in order to investigate the meters wet gas response.

Figure 10 shows the CEESI wet gas test data set range superimposed on the Shell flow pattern map with the Coevorden and Trondheim data set ranges used in creating the de Leeuw Venturi wet gas correlation. (It should be noted that here CEESI used Stoddard solvent (i.e. mainly C9-C12) for the liquid phase.) This CEESI data set is different that of the JIP (see Figure 4) as the maximum gas densiometric Froude number is considerably higher here. However these elevated gas flow rates limited the maximum Lockhart Martinelli parameter that could be reached at higher pressure tests. Table 1 shows the test matrix.

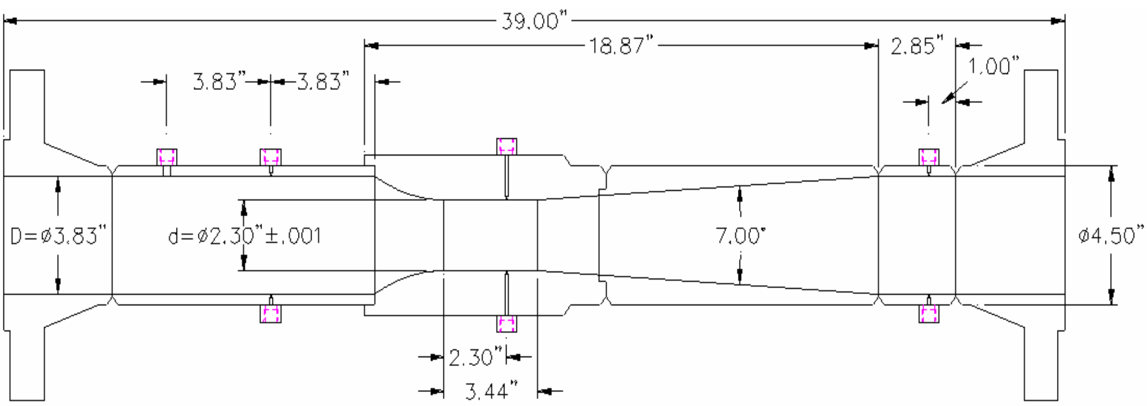

Fig 9. The Non-Standard 4", Schedule 80, 0.6 Beta Ratio Venturi Nozzle Type DP Meter Tested with Wet Gas Flow by CEESI.

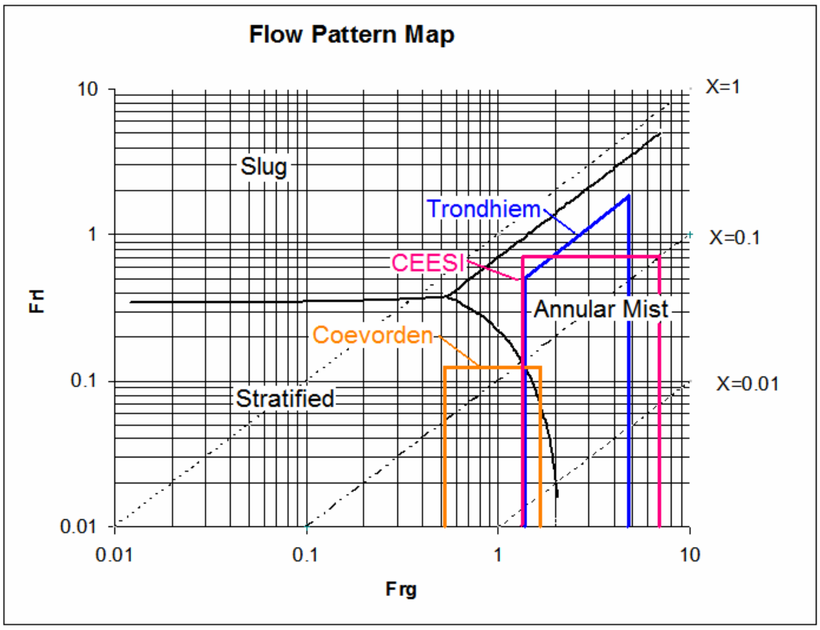

Fig. 10. The Test Matrix for the Coevorden, Trondheim and CEESI Non-Standard Venturi Nozzle Meter Wet Gas Flow Tests.

Note that wet gas flow data sets with gas densiometric Froude numbers greater than five are rare. Figure 10 shows the maximum gas densiometric Froude number tested at Trondheim was five. Figure 4 shows the maximum gas densiometric Froude number tested by CEESI for the JIP was less than four. NEL generally publishes wet gas test loop data that has a maximum gas densiometric Froude number of five. Here, CEESI has taken the maximum gas densiometric Froude number to nearly seven (although at these elevated flow rates the maximum Lockhart Martinelli parameter is less than 0.1). It is therefore likely that the flow pattern at these conditions is closer to mist / homogenized flow than most previously published data sets.

Approximate Pressure (Bara)	Average Gas to Liquid Density Ratio	Gas Densiometric Froude Number	Maximum Lockhart-Martinelli Parameter
14	0.0133	1.55	0.2
		2.30	0.2
		2.84	0.2
45	0.0481	1.42	0.3
		3.52	0.17
		5.27	0.11
71	0.0786	1.81	0.3
		3.66	0.18
		5.53	0.08
		6.83	0.08

Table 1. The CEESI Non-Standard Venturi Nozzle Meter Wet Gas Flow Data Set.

Figure 11 shows the relationship between over-reading and the Lockhart-Martinelli parameter for the three gas to liquid density ratios tested. The increase of the Lockhart-Martinelli parameter shows an increase in over-reading and the higher over-reading for lower gas to liquid density ratios is evident as would be expected. Figures 12 shows for the set gas to liquid density ratio of 0.013 the individual gas flow rate (i.e. gas densiometric Froude number) effect on the over-reading and the result of using the de Leeuw equation for a known liquid flow rate. Figure 13 magnifies the de Leeuw correction result of Figure 12. Figures 14 and 15 are a similar pair of Figures for the case of the set gas to liquid density ratio of 0.048 and Figures 16 and 17 are a

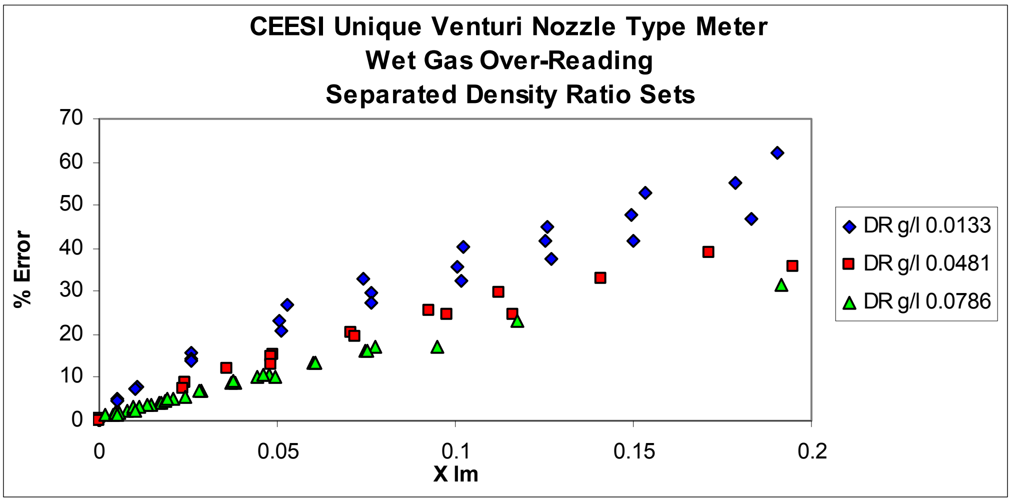

Fig 11. All Wet Gas Data with Separated Pressure from CEESI Venturi Nozzle Type DP Meter.

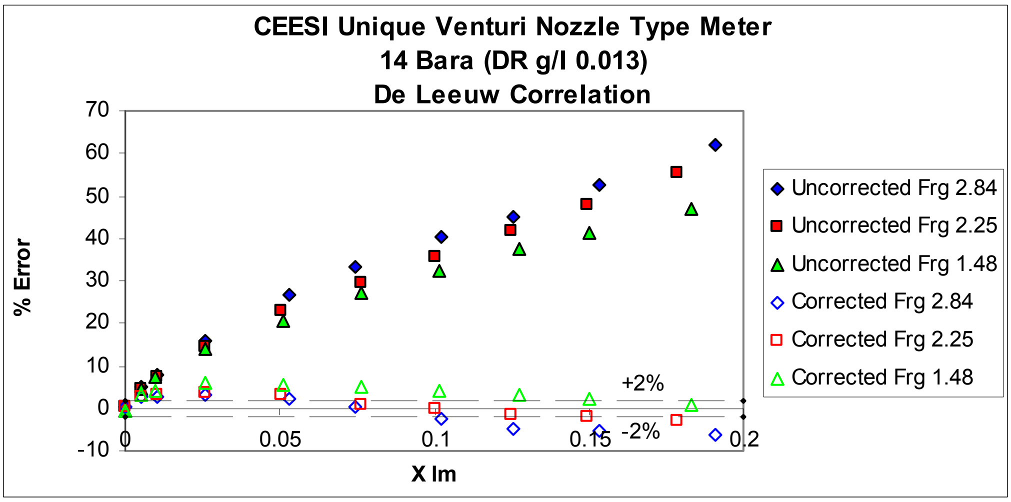

Fig 12. 14 Bar Wet Gas Data Uncorrected and Corrected with the de Leeuw Correlation.

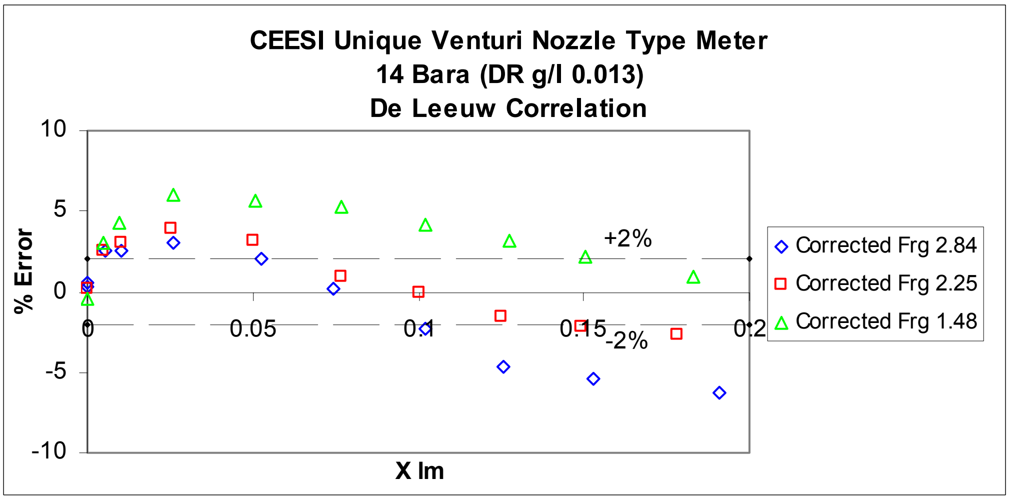

Fig 13. 14 Bar Wet Gas Data Corrected with the de Leeuw Correlation.

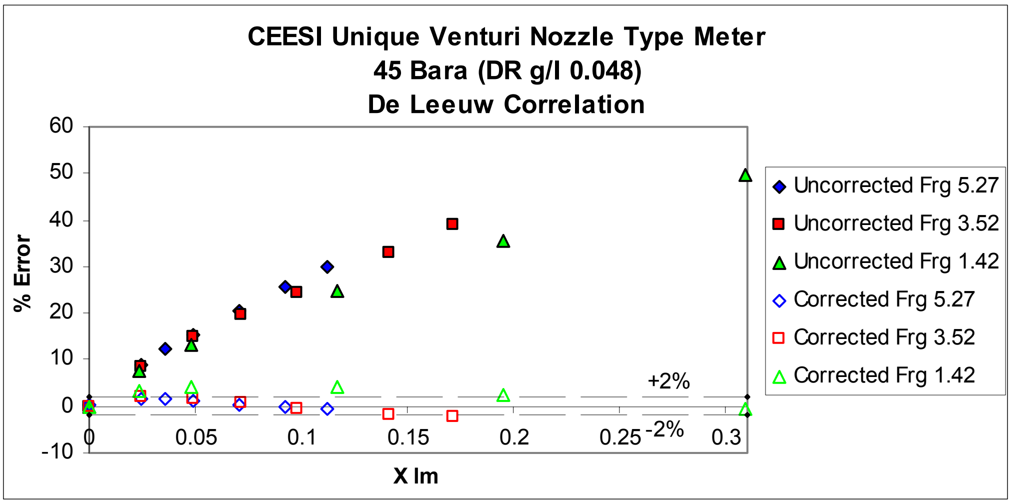

Fig 14. 45 Bar Wet Gas Data Uncorrected and Corrected with the de Leeuw Correlation.

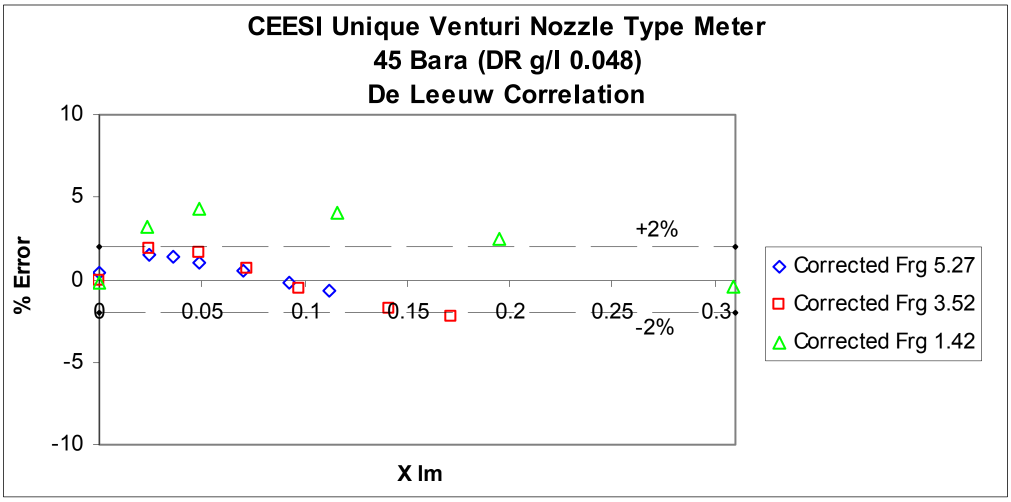

Fig 15. 45 Bar Wet Gas Data Corrected with the de Leeuw Correlation.

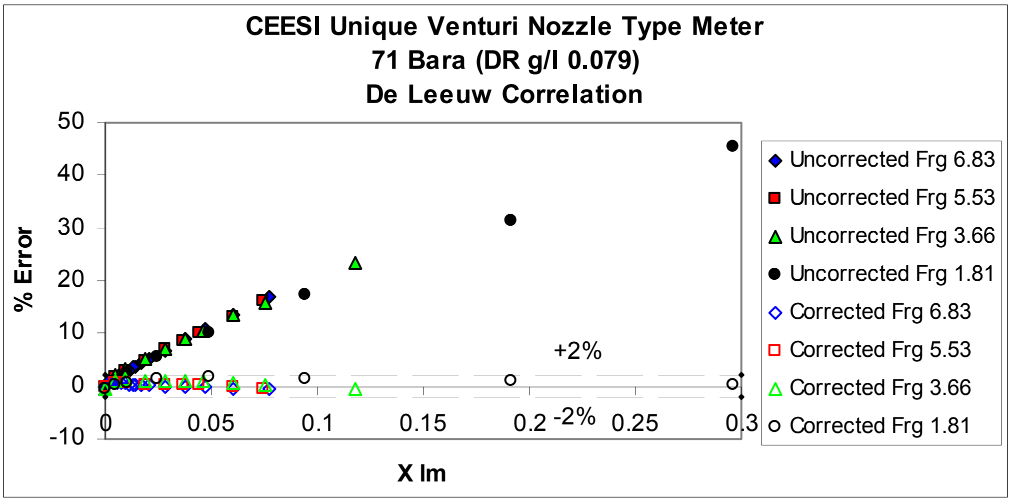

Fig 16. 71 Bar Wet Gas Data Uncorrected and Corrected with the de Leeuw Correlation.

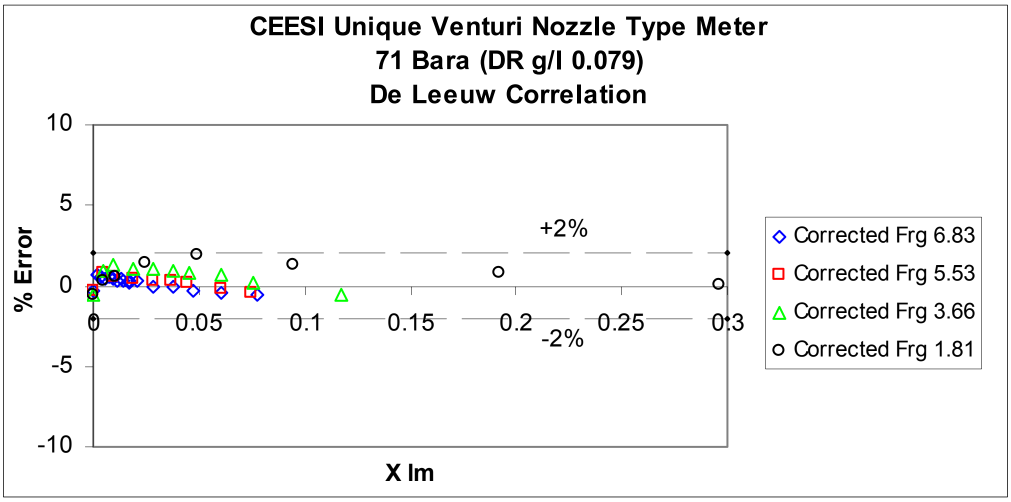

Fig 17. 71 Bar Wet Gas Data Corrected with the de Leeuw Correlation.

similar pair of Figures for the case of the gas to liquid density ratio of 0.088. As previously published for other DP meter tests the higher the gas densiometric Froude numbers for other parameters held constant the greater the over-reading. It is also visible here that as higher gas to liquid density ratios are held constant the difference in the over-reading to Lockhart Martinelli parameter gradient for changing gas densiometric Froude numbers reduces. This is also in line with what has been previously reported for DP meters. It is interesting to note that in Figure 16, which shows gas densiometric Froude number data at higher values than has previously been reported, the gas densiometric Froude number effect appears to have been diminished to the point where it appears further increases in the gas to liquid density ratios will make the effect disappear. At the highest gas to liquid density ratios tested here there is no significant difference in the gas densiometric Froude number sets up to a Lockhart Martinelli parameter of 0.08 and the very little data at or above this value suggests only a small gas densiometric Froude number effect still exists. Previously, it has been verbally postulated amongst researchers that at high enough gas to liquid density ratios the gas densiometric Froude number effect will fade away.

The 14 Bar data (Figures 12 and 13) shows de Leeuw's correlation is correcting the gas flow rate to ±6%. The 45 Bar data (Figures 14 and 15) show the de Leeuw's correlation is correcting the gas flow rate to ±5%. The 71 Bar data graphs (Figures 16 and 17) shows the de Leeuw's correlation is correcting the gas flow rate to ±2%. These results indicate that while it is considerably better to use the de Leeuw correlation rather than no correction, when used in situations where there are several extrapolations on de Leeuw's data set (e.g. in this case different converging / diverging section geometries, different beta ratio and an extrapolation of the upper limit of the gas densiometric Froude number) it should not be expected to offer ±2%. The de Leeuw correlation did not correct this DP meter particularly well. Due to the results of testing the NAM Venturi meter at CEESI it is assumed unlikely that the slight difference in liquid properties and test facility bias are contributors to this result. (Note that de Leeuw never claimed his correlation was suitable for extrapolation to other meters.) However, this analysis indicated that the higher the pressure and the higher the gas flow rate the better de Leeuw's correlation corrected this DP meter.

8 FLOW PATTERN INFLUENCES ON DP METER WET GAS PERFORMANCE

With the CEESI non-standard Venturi Nozzle meter data set having higher gas densiometric Froude numbers than has commonly been tested before it is clear from Figure 10 that the flow pattern for these high gas densiometric Froude numbers is further into the annular mist region than has been discussed in earlier papers. The transition region within annular mist flow where the flow becomes atomized (i.e. homogenous flow) is not known and therefore it is of interest to apply the homogenous correction to this data to review its performance. (The homogenous correction is shown in equations 4 and 10). The derivation of equation 10 is given in Appendix 2.

$$\dot{m}_g = \frac{\dot{m}_{g\,Apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \text{ ---- (4)} \qquad \text{where:} \qquad C = \left(\frac{\rho_g}{\rho_l}\right)^{\frac{1}{2}} + \left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{2}} \text{ ----- (10)}$$

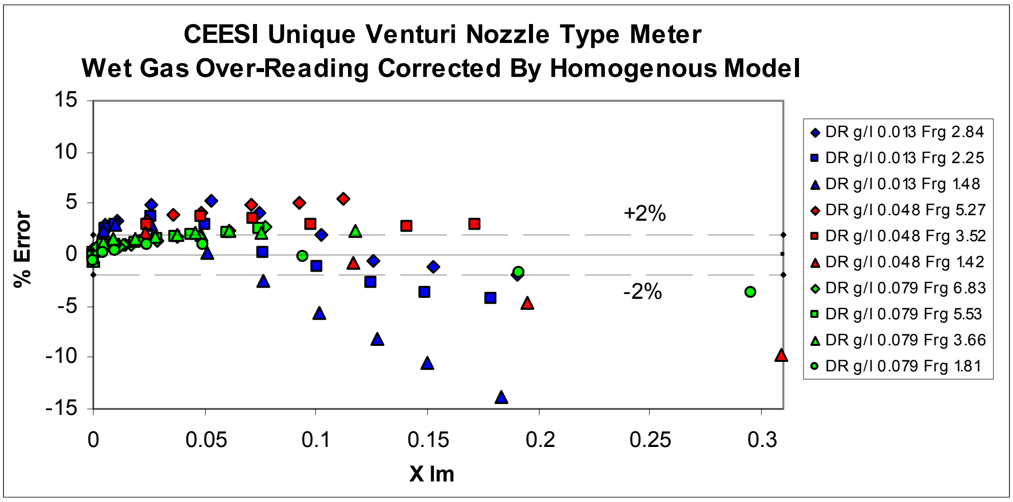

Fig.18. The CEESI Non-Standard Venturi Nozzle Meter Data Homogenous Model Correction.

Figure 18 shows the results of applying the homogeneous model correction (for a known liquid flow rate). At the low pressure the correlations performance is poor. However, as expected for the set 14 Bar data as the flow rate (Fr_g) increases (i.e. the flow moves from stratified flow towards annular mist flow) the performance significantly improves. At 45 Bar the result is significantly better than for 14 Bar. However, contrary to theoretical considerations there is no clear improvement of the performance as flow rates increase. At 71 Bar the homogenous model performs considerably better than at the lower pressures (as expected). In line with the result in Figure 16 at 71 Bar there is little difference in the different gas flow rate (or "Fr_g") results. As the homogenous model does not give results scattered around the zero error line it is concluded that although the flow is annular mist it is not yet under these test conditions completely homogenised.

The de Leeuw correlation was better than the homogenous model at correcting this high pressure data. At gas densiometric Froude numbers greater than approximately 2.337 de Leeuw predicts the exponent 'n' to be greater than 0.5. However, as the gas densiometric Froude number continues to increase for any set pressure a homogenised flow will finally be reached and here, by theory (see Appendix 2), the exponent 'n' must equal 0.5. De Leeuw [4] states that equation 5 has a natural limit as when pressure is increased until the gas to liquid density reaches unity (which could be considered to be a homogenous flow) C=2 and then this homogenous flow equation shall be:

$$\dot{m}_g = \frac{\dot{m}_{g\,Apparent}}{\sqrt{1 + 2X_{LM} + X_{LM}^2}} \qquad (11)$$

This is true, but it only discusses homogenous flow resulting from density ratio considerations. However, as discussed in section 4 homogenous flow can also be approached at values of gas to liquid density ratio less than unity if the gas flow rate is sufficiently high. Here then de Leeuw's equation 7a is asymptotic to the constant value 0.606 for increasing flow rates when theory suggests it should be asymptotic to the value 0.5. (Note however that at flow rates below the homogenous flow region some experimental evidence exists to suggest that the value of the exponent 'n' should not necessarily be capped at 0.5.) Chisholm [3] stated that the exponent 'n' for orifice plate meter stratified flow was 0.25. This value was obtained by a mix of theory (orifice plate meter stratified flow modeling), data analysis and approximation. In his equation derivation [3] Chisholm discussed the average gas to liquid velocity (or "slip") ratio (K) being solely a function of the gas to liquid density ratio according to orifice plate meter experimental data analysis (for $X_{LM} < 1$). Chisholm claimed:

$$K = \frac{\bar{U}_g}{\bar{U}_l} = \sqrt{\left(\frac{\rho_l}{\rho_g}\right)} \tag{12}$$

However, it has not been subsequently shown that equation 12 holds for all DP meters with various parameter ranges and hence the fact that de Leeuw set the exponent 'n' at 0.41 for a Venturi meter with stratified flow (see equation 7b) does not then contradict any theory.

It is interesting to note that NEL have published a wet gas Venturi meter research report [10] where values of the de Leeuw exponent "n" are plotted versus gas densiometric Froude number. In this report wet gas test results are discussed for a 4" 0.75 beta ratio standard Venturi meter, a 4" 0.6 beta ratio standard Venturi meter and a 4" 0.75 beta ratio non-standard Venturi meter (due to a convergent angle 10.5^0). These meters were tested with different fluid combinations at set gas to liquid density ratios of 0.024 and 0.046. NEL reported that changing the gas component had no significant effect on the meters wet gas performances but there was a significant difference caused by switching to water from kerosene. (This report is in line with CEESI papers [7,8] on the wet gas response of a 2" Venturi meter when the liquid component was varied between water and Stoddard solvent.) For each meter, the exponent 'n' vs. gas densiometric Froude number, Fr_g was plotted and at the gas densiometric Froude number value of 1.5 the data varied between $0.35 < n < 0.41$ (i.e. a similar result to that which de Leeuw [4] reported at Trondheim). It is also interesting to note that these three NEL data sets have a maximum gas densiometric Froude number less than 5 but two indicate the data is becoming asymptotic to the exponent 'n' value 0.5 as the gas densiometric Froude number increases (as Appendix 2 suggests is a physical requirement). The third meter (the 0.6 beta ratio meter) has 'n' values slightly greater than 0.5 at the highest gas densiometric Froude numbers tested. As stated earlier there is no known reason why the exponent 'n' can not be greater than 0.5 in non-homogenous flow. (It is postulated here though that as the gas densiometric Froude number continues to increase homogenous flow will be approached and the exponent 'n' will tend to 0.5).

NEL [10] and CEESI [7] have both previously shown the following results. At relatively low pressures and gas flow rates there is no appreciable difference between a DP meters reaction to wet gas with hydrocarbon liquid and a wet gas with water. Both cases will cause the meter to over read the gas flow in a similar way. At relatively high pressures and gas flow rates there is an appreciable difference between a DP meters reaction to wet gas with hydrocarbon liquid and a wet gas with water. The gas / water flow has a lower over-reading vs. Lockhart Martinelli parameter gradient than the gas / hydrocarbon liquid. NEL [10] has also shown as pressures and flow rates increase further this difference in gradient diminishes.

Four graphs from the NEL report [10] are reproduced here. Figure 21 to 23 (NEL reports [10] Figure 17, 18, 20) show data for a 4" Sch 80 0.75 beta ratio ISO 5167 compliant Venturi meter at a gas to liquid density ratio of 0.046 and gas densiometric Froude numbers of 1.5, 2.5 and 4.5 respectively. The flow pattern prediction at these conditions is predicted by the Shell Flow Pattern Map in Figure 19. Here the fact that the borders between flow patterns are not exact but rather transition zones is shown by the inclusion of estimated transition zones. (These are not to be taken as precise.) Hence the NEL data [10] is predicted here to be predominantly stratified flow with transition to annular mist taking place at higher liquid loadings (Frg=1.5), predominantly

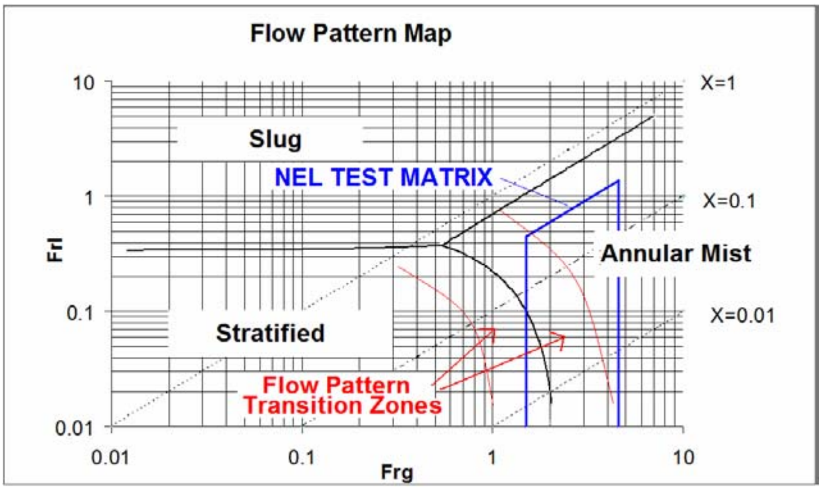

Figure 19. NEL 4" Conditions During the 4" Venturi Meter Wet Gas Liquid Property Effect Tests.

annular mist flow with some stratification at lower liquid loadings (Frg=2.5) and annular mist flow (Frg=4.5).

It must be remembered that this flow pattern map was formed from 4" gas / hydrocarbon liquid data. No gas / water data was used. It is generally assumed that water will have different flow pattern boundaries to hydrocarbon liquids [8] due to water being more viscous and having a greater surface tension than light hydrocarbon liquids. This would mean it would take a greater gas flow rate (i.e. more gas dynamic force) to change a gas / water flow from stratified to annular mist and to produce any stated average droplet size in an annular mist flow than it would for a gas / hydrocarbon liquid flow. If this is so the Shell flow pattern maps boundaries could be expected to shift as sketched in Figure 20. The broken lines represent the borders of the respective transition zones. (Again, these are not intended to be taken as precise.)

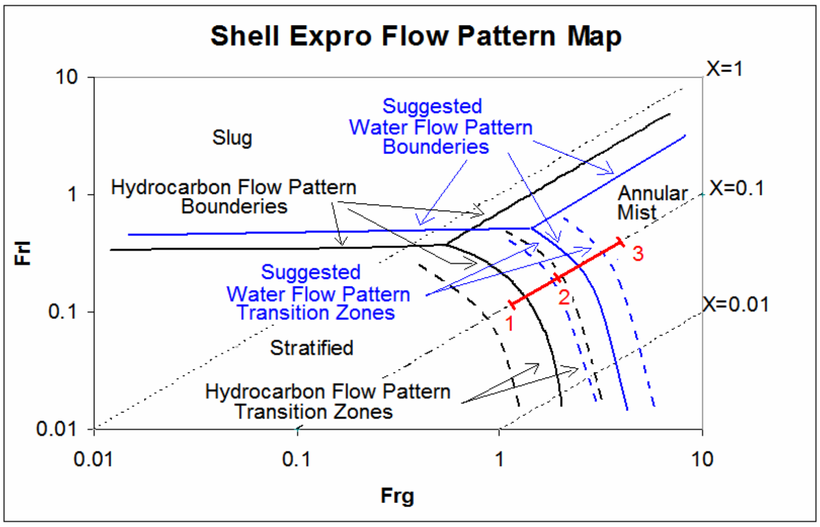

Figure 20. The Postulated Shift in Boundary Positions in the Shell Flow Pattern Map for the Case of Gas/Water Flows Instead of Gas/Liquid Hydrocarbon Flows.

It is postulated in Figure 20 that wet gas liquid properties can shift the transition zones between flow patterns and hence for a set Lockhart-Martinelli parameter and gas densiometric Froude number different liquid properties can mean different flow patterns. Stratified flow for different liquids is not likely to be greatly different with only slight differences in liquid height produced by different viscous and interfacial tension forces acting with the gas dynamic shear force. However, when the gas dynamic forces are great enough to transition the liquid hydrocarbon wet gas flow but not an equivalent water wet gas flows the meter will see different flow patterns for the same Lockhart Martinelli parameter and gas densiometric Froude number parameters. Even when the gas dynamic forces are strong enough to assure that both a liquid hydrocarbon wet gas flow and a water wet gas flow are annular mist flow it will not be a similar situation to both being stratified flow as for the same gas dynamic force water would have less entrainment and larger droplets than liquid hydrocarbon wet gas flows. Hence once the stratified flow pattern condition has been departed from a liquid hydrocarbon wet gas flow could be expected to be always more entrained in the gas phase than a water wet gas flow for set conditions. The limiting factor is when the gas dynamic forces get strong enough to fully atomise both types of liquid component wet gas flows. Here, both flows could be considered homogenous flows (i.e. pseudo single phase flows). This is the behaviour repeatedly evident in NEL's results [10]. Below we examine one example.

Note that NEL reported no effect when the gas component was changed. For the Figure 21 data the flow pattern map (Figure 20) suggests that the flows for Frg=1.5 (e.g. point 1 in Figure 20 for X_{LM}=0.1 case) are stratified for natural gas / water and in the early stratified / annular mist transition zone for natural gas / kerosene. Note that there is no significant difference in the meters wet gas over-reading results between the kerosene and the water wet gas flow. Only at the highest Lockhart Martinelli parameter value does the natural gas / kerosene flow have a marginally higher over-reading (which is where in Figure 20 the flow is becoming annular flow). At a Lockhart Martinelli parameter of 0.3 the over-reading for natural gas / kerosene is approximately 42% and the over-reading for natural gas / water is approximately 40%.

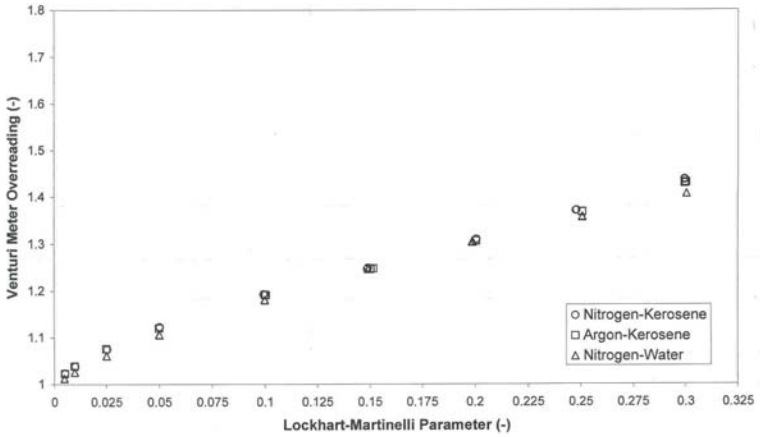

Figure 21. NEL 4", Sch 80, 0.75 Beta Ratio Venturi Meter, Gas to Liquid Density Ratio of 0.046, Gas Densiometric Froude Number of 1.5.

For the Figure 22 data (e.g. point 2 in Figure 20 for X_{LM}=0.1 case where Frg=2.5) the flow pattern map (Figure 20) suggests that the kerosene wet gas flow is well into the transition zone between stratified and annular mist flow but the water wet gas flow is still stratified flow (or at least substantially further back in its particular stratified to annular mist flow transition zone). Here we see that the water wet gas flows over-reading at a Lockhart Martinelli parameter of 0.3 is approximately 47%. That is, the over reading for this flow that has a relatively small amount of entrained water has increased by a significantly smaller amount from the Figure 21 stratified data compared to the kerosene wet gas flow that is now according to Figure 20 becoming close to fully annular mist and has a relatively large quantity of entrained kerosene. The kerosene wet gas flow here has an over-reading at a Lockhart Martinelli parameter of 0.3 of approximately 55%. That is, it has increased by a relatively large amount from the Figure 21 stratified data and it is now clearly different to the water wet gas data.

For the Figure 23 case of Frg=4.5 the flow pattern map (Figure 20) suggests that the kerosene wet gas flow is fully annular mist while the water wet gas flow which is in the upper region of the stratified to annular mist flow transition zone. Hence, the water wet gas flow is becoming close to

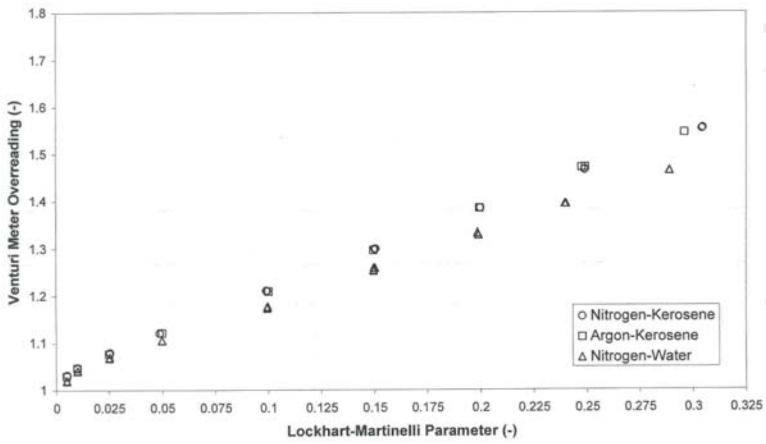

Figure 22. NEL 4", Sch 80, 0.75 Beta Ratio Venturi Meter, Gas to Liquid Density Ratio of 0.046, Gas Densiometric Froude Number of 2.5.

fully annular mist and has a relatively large quantity of entrained water. Both flows are therefore largely annular mist flows but the water will have a larger average droplet size. Here we see that the water wet gas flows over-reading at a Lockhart Martinelli parameter of 0.3 is approximately 58%. We also see that the kerosene wet gas flow has an over- reading at a Lockhart Martinelli parameter of 0.3 of approximately 60%. That is, it has had a modest increase since the gas densiometric Froude number of 2.5 data and now the water wet gas flow is catching up as both flow patterns tend towards, what could in practical terms be called, homogenised flow.

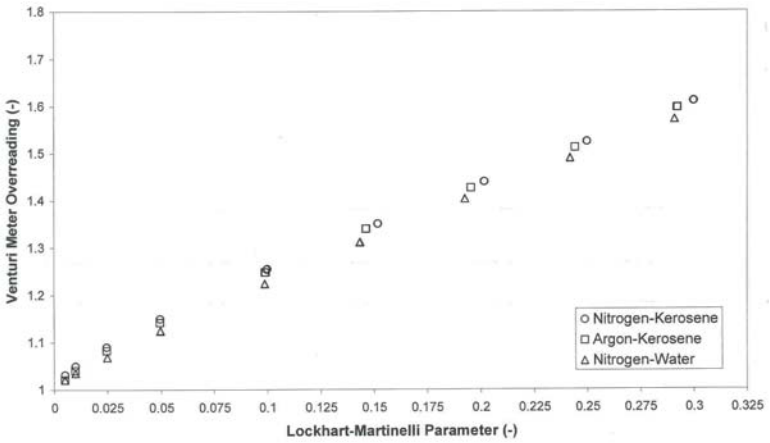

Figure 23. NEL 4", Sch 80, 0.75 Beta Ratio Venturi Meter, Gas to Liquid Density Ratio of 0.046, Gas Densiometric Froude Number of 4.5.

It is now interesting to note what over-reading a fully homogenised wet gas flow would give for this gas to liquid density ratio (0.046) at a Lockhart Martinelli parameter values of 0.3. When equation set 4 and 10 is applied the resulting over-reading is 59.78%. So this suggests that the kerosene wet gas flow data at a gas densiometric Froude number of 4.5 is in practical terms homogenised flow. However, the water wet gas flow data set with its X_{LM}=0.3 over-reading of approximately 58% is not as close as the lower liquid viscosity and surface tension kerosene wet gas flow to being homogenised although it looks like it will reach this state at a slightly higher gas flow rate than the kerosene wet gas flow. This theory is further backed by NEL's plot of this meters de Leeuw exponent 'n' vs. the gas densiometric Froude number in Figure 24 (i.e. NEL's [10] Figure 43). All the data sets in this Figure 24 appear to be approximately asymptotic to n=0.5 as required by the homogenous flow model (or slightly above). The water wet gas over reading has a smaller value of 'n' (i.e. smaller over-reading) at any given set of wet gas flow parameters.

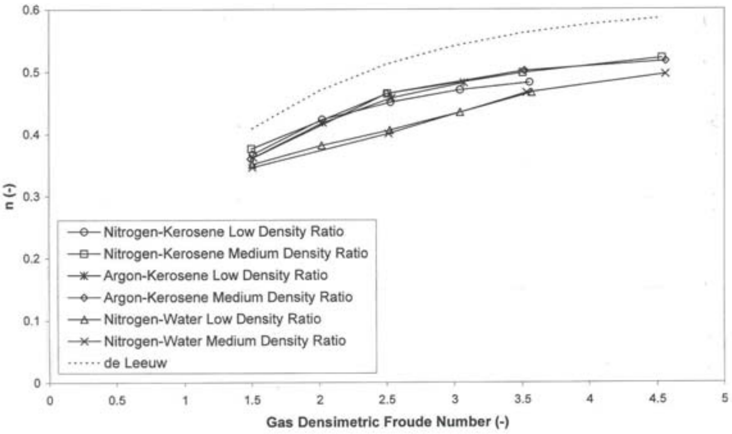

Fig 24. NEL 4” 0.75 Beta Ratio Venturi Meter Exponent ‘n’ vs. Gas Densiometric Froude Number.

The kerosene wet gas data at the high flow rates appears to be asymptotic to a constant value of approximately 0.5 (or slightly above). The water wet gas exponent value “n” lags the kerosene wet gas data exponent value but these water wet gas flow results can be extrapolated to the exponent 0.5 value at some higher gas densiometric Froude number than the kerosene wet gas flow. It is noted here that one of the three meters NEL tested (the 0.6 beta ratio meter) appears to have an exponent asymptotic to a value higher than 0.5.

It should be remembered that the value of the gas densiometric Froude number required to homogenise any wet gas flow depends on the gas to liquid density ratio, as by theory, the higher the gas to liquid density ratio (i.e. the less weight effect on the liquid phase) the lower the required gas dynamic forces required to disperse the liquid phase. This is not clearly shown in Figure 24 (while the other plots in the NEL report [10] give somewhat clearer indications that this is indeed the case) but it can be best seen here on comparing the nitrogen – kerosene low and medium density ratio plots. The low density ratio can clearly be seen to be taking a shallower approach to the n = 0.5 homogenous value.

Note that there is an issue the author regards as unresolved with regards to matching theory to data sets. If we consider only the fluids that created the Shell Flow Pattern map (and hence avoid issues regarding the liquid properties effects) the flow pattern prediction is set for set pairs of gas densiometric Froude number and Lockhart Martinelli parameter. That is, the map effectively states that the gas to liquid density ratio affect is accounted for within the gas densiometric Froude number and it therefore does not independently influence the flow pattern. If the conjecture that the flow pattern solely controls over-reading scale for set Lockhart Martinelli parameters is true then we should see the same over-reading for set Lockhart Martinelli parameters and gas densiometric Froude numbers regardless of the gas to liquid density ratio. Examination of wet gas DP meter data sets suggests this is not the case. A postulated remedy to this irregularity is that as the map is an approximation from observations, the flow pattern borders may be found to shift along a third axis where the gas to liquid density ratio is plotted.

To summarise, there is little in the literature for anybody searching for an explanation to why different liquid properties could cause different wet gas over readings when all other parameters are equal. The following is a postulation on what phenomena causes these NEL [10] and CEESI [7] results offered in an attempt to stimulate open debate on this topic. It has long been suggested that the flow pattern can affect a DP meters over-reading. The available data sets and theory for wet gas DP meters indicate that increasing the gas densiometric Froude number for otherwise set conditions increases entrainment and therefore the over-reading of the meter. It could therefore be argued that increasing the liquid entrainment in a wet gas flow of set conditions (which can be done by changing liquid properties) increases the over-reading and it is the flow pattern that has caused the shift in the over-reading. Therefore, liquid properties that influence the flow pattern will influence the over-reading and it would then be expected that liquids with properties that require relatively low gas dynamic forces to entrain the liquid (e.g. non-viscous and low interfacial tension liquids) would have more entrainment at set Lockhart Martinelli parameter, gas to liquid density ratio and gas densiometric Froude numbers than liquids with properties that require larger gas dynamic forces to entrain the liquid in the gas phase (e.g. more viscous and high interfacial tension liquids). If greater entrainment of liquid causes a greater over-reading then the conclusion would be that more viscous and higher interfacial tension liquids will always have less entrainment and therefore less over-reading for all parameters except liquid properties remaining equal. With water being significantly more viscous with a higher interfacial tension than kerosene this is precisely what is shown in the NEL report [10] and CEESI paper [7].

9 UPPER BOUNDARY CONDITIONS OF ALL WET GAS FLOW METER CORRELATIONS

The homogenous flow model could be applied to any generic DP meter design if the meter operator knows the wet gas flow is homogenised. As far as this author is aware there are no DP meter wet gas flow data sets released that have a combination of gas to liquid density and gas densiometric Froude number parameters that are known to produce a flow that could be considered approximately homogenised flow. However, there is one data set that approaches these conditions that has never been released until now. In 2005 BG Group tested a DP meter at K-Lab under extreme wet gas flow conditions that appear when plotted on the Shell flow pattern map to approach homogenised flow. The meter was a 6”, schedule 160, 0.75 beta ratio V-Cone meter. The test fluids were natural gas and condensate. BG Group supplied the test data to CEESI on request in 2006 and has given permission for the results to be shown (see Table 2).

Density Ratio (gas to liquid)	Xlm	Frg	Actual Gas Flow Rate Over-Reading Error (%)	Homogenous Equation Correction (%)
0.0418	0.051	6.75	11.56	-0.67
0.0422	0.102	6.74	21.44	-1.67
0.0429	0.169	6.80	34.10	-2.18
0.0430	0.150	6.78	30.59	-2.07
0.0437	0.206	6.90	40.96	-2.10
0.0450	0.261	6.52	50.39	-1.96
0.0584	0.253	4.29	42.78	-3.14
0.0583	0.198	4.37	33.61	-3.20
0.0595	0.049	4.38	8.10	-2.00
0.0601	0.098	4.39	16.70	-2.5
0.0591	0.144	4.43	24.50	-3.07
0.0580	0.227	7.56	40.60	-1.79
0.0596	0.278	7.73	48.92	-1.50
0.0595	0.050	8.65	9.97	-0.34
0.0605	0.100	8.75	19.00	-0.91
0.0605	0.150	8.79	27.81	-1.12

Table 2. The 6”, Schedule 160, 0.75 Beta Ratio V-Cone Meter, K-Lab Wet Gas Flow Test Results.

Figure 25 shows the small but rare test matrix on the Shell flow pattern map with comparison to the previously discussed data sets. (Note that the axis is logarithmic.) Although the pressure is moderate the gas densiometric Froude numbers are considerably higher in the K-Lab data set than studied before. Therefore, it can be seen here that the test matrix is further into the annular

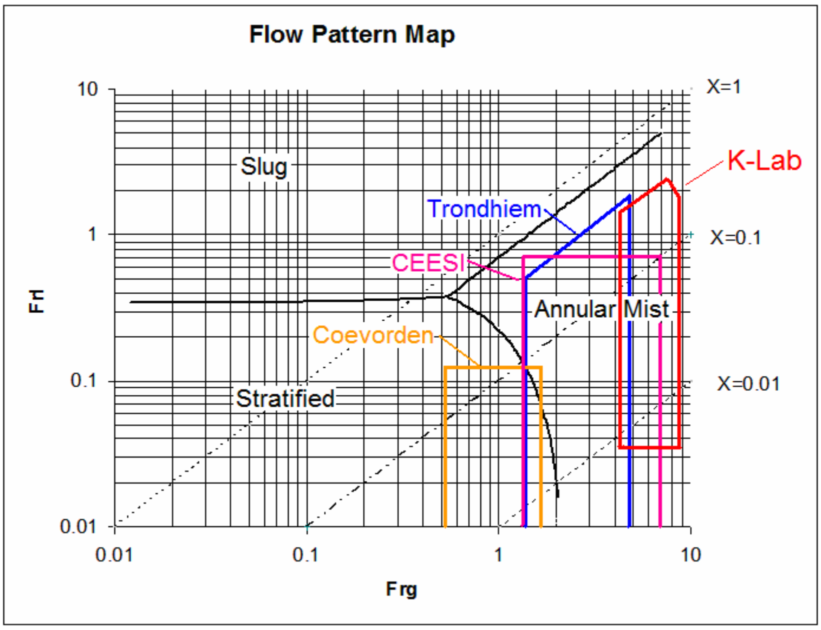

Figure 25. The K-Lab Wet Gas Test Matrix Sketched on the Shell Flow Pattern Map for a 6", Schedule 160, 0.75 Beta Ratio V-Cone DP Meter.

mist flow than the earlier discussed flows. It is closer to being true homogenous flow.

Table 2 shows the comparison of the experimentally found over-reading of the gas flow rate and the homogenous models over-reading of the gas flow rate prediction. Figure 26 shows the data in graphical form. Figure 27 highlights the affect of applying the homogenous model.

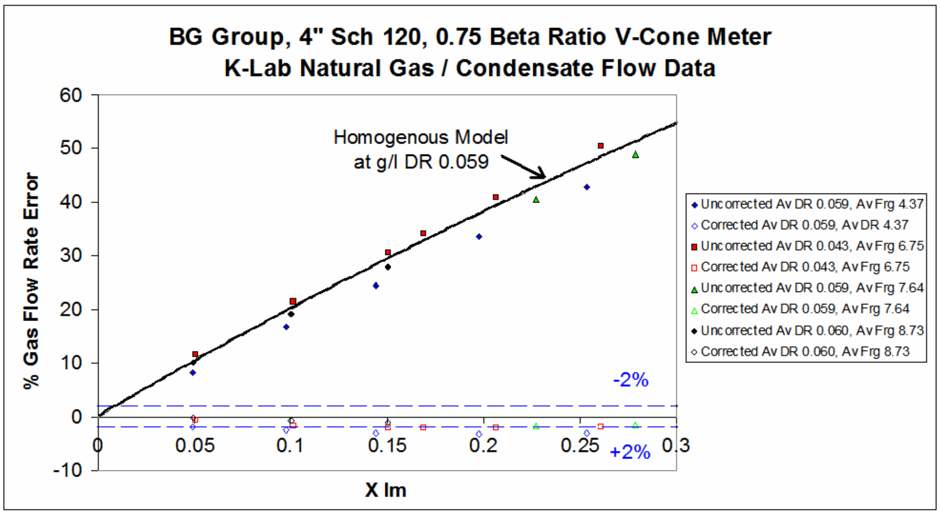

Figure 26. The K-Lab 6", Schedule 160, 0.75 Beta Ratio V-Cone DP Meter Wet Gas Test Data Over-Reading to Lockhart Martinelli and Correction with the Homogenous Model.

The lowest gas to liquid density ratio data (i.e. 0.043) had a moderately high gas densiometric Froude number of (i.e. 6.75). The homogenous model over corrected the liquid induced error by up to approximately 2.2%. The other three data sets all have approximately the same gas to liquid density ratio (i.e. 0.059). It is clear that as the gas densiometric Froude number increases from 4.37 to 7.64 and to 8.73 the homogenous models predictions keep improving. Whereas the low gas densiometric Froude number of 4.37 has errors in the correction of up to approximately 3.2% by the gas densiometric Froude number of 7.64 it has improved to approximately 1.8%. By

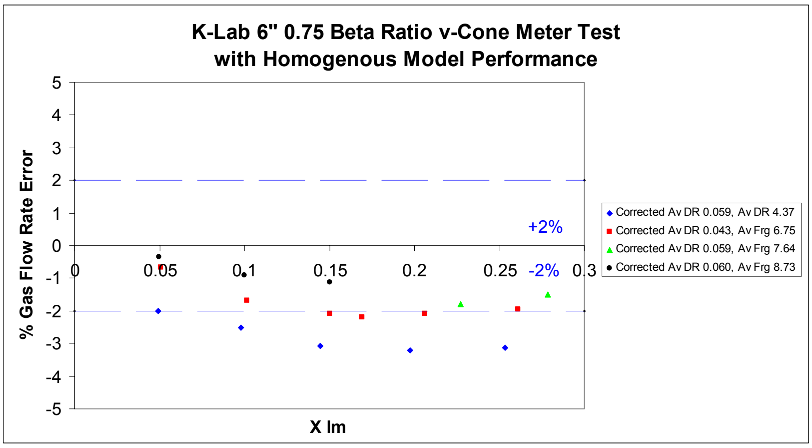

Figure 27. The K-Lab 6”, Schedule 160, 0.75 Beta Ratio V-Cone DP Meter Wet Gas Test Data Corrected with the Homogenous Model.

the gas to liquid density ratio of 0.06 and high gas densiometric Froude number of 8.73 the homogeneous model is predicting the data to well within 2% which is the stated uncertainties of most DP meter wet gas flow correlations. Therefore, at the gas to liquid density ratio of 0.06 and the gas densiometric Froude number of 8.73 this natural gas / condensate wet gas flow is in practical terms a homogenous flow.

With the theory suggesting that wet gas flow with high gas to liquid density ratios and/or gas densiometric Froude numbers tend towards homogenous flow and DP meter wet gas data from CEESI, NEL and K-Lab generally agreeing with this theory it is suggested by this author that all DP meter wet gas flow correlations should be created in a mathematical form that when extrapolated they should tend towards a homogenous model correction. This is currently not typical. The author has not previously used this theoretical boundary condition for the creation of DP meter wet gas flow correlations but in hindsight this should perhaps have been done.

It is also note worthy to mention that in these high pressure, high gas densiometric Froude number wet gas flows where the flow can be effectively modeled as homogenous flow it is acting like a pseudo-single phase fluid. In this situation all wet gas flow metering concepts that rely on measurement of wet gas phase flows by the relative difference of two or more DP readings will not see any relative difference in any measurement between the dry gas base line and the homogenous flow. This is because the homogenous flow is a pseudo-single phase fluid and therefore the wet gas meter system would act like the meter is encountering a single phase. This then is a theoretical limitation on such devices. Curiously though, different DP meter primary elements interact with the flow in different ways. Some appear to affect the flow pattern in such a way as to require higher gas to liquid density ratios and gas densiometric Froude numbers than others to give the generic DP meter homogenous over-reading. Fortunately, the majority of the real world flows can not be modeled as homogenous flow and as long as the data set for the stratified / annular mist flow that created the correlation in question is not extrapolated they should work within the data set boundaries.

10 CONCLUSIONS

It is important that the wet gas flow characteristics of the most popular wet gas flow meter type, i.e. the Differential Pressure meter, be fully understood.

The NAM 4”, Sch 80, 0.4 beta ratio Venturi meter tested with wet gas by Shell at Trondheim gave similar results when tested at the CEESI wet gas test loop. There was no evidence of facility bias or a liquid property effect between the different hydrocarbon liquids tested (i.e. diesel oil and decane). As NEL [10] have shown that gas component does not have a significant effect on the wet gas over-reading this suggests that the different light hydrocarbon liquids did not have a significant effect on the wet gas over-reading. The de Leeuw wet gas correlation corrected the CEESI wet gas over-reading for a known liquid flow rate to within 2% with a few outliers which is the performance claimed by de Leeuw [4].

The de Leeuw correlation worked well for the meter from which it was created. However, theoretical considerations suggest that large gas densiometric Froude number extrapolations of this correlation could possibly lead to errors as the value of the de Leeuw exponent does not converge on the theoretical value that is required by the homogenous flow model.

A non-standard Venturi Nozzle DP meter was tested at CEESI and the same wet gas flow trends as published for other DP meters were observed. This test matrix included higher gas densiometric Froude numbers than other wet gas test matrices previously published and confirmed previous postulations that this parameters effect continues to diminish with increasing gas to liquid pressure ratio.

The de Leeuw equation created from the Trondheim NAM Venturi meter wet gas data did not perform as well with the CEESI non-standard Venturi Nozzle DP meter as it did on the NAM Venturi meter. A 6% uncertainty for a known liquid flow rate was found. This suggests DP meter wet gas correlations should be applied to other DP meter geometries with caution. It was noticed however that as the pressure and flow rate increased for the CEESI non-standard DP meter the performance of the de Leeuw correlation and the homogenous model improved considerably.

CEESI and NEL have both independently shown that using water instead of a liquid hydrocarbon as the liquid component on a wet gas phase has little effect on wet gas flow over-readings for low gas to liquid density ratio and gas densiometric Froude numbers and a significant effect on wet gas flow over-readings for high gas to liquid density ratio and gas densiometric Froude numbers. NEL has shown if these parameters are increased further this difference diminishes and then disappears. This paper postulates that the possible cause is the flow pattern.

As wet gas metering has such potential to help industry and DP meters are at the core of many wet gas and multiphase meter designs it is clear that much research and wet gas meter testing still needs to be done to improve wet gas flow DP meter understanding. This paper discusses a theory regarding DP meter wet gas response but more work is required in this field.

The next generation of wet gas flow metering Joint Industry Project (JIP) is testing DP meters with different liquid components to improve understanding of the liquid property effect. As the financial rewards to industry of successfully advancing these technologies are clear manufacturer and user financed research on this topic is likely to continue.

10 ACKNOWLEDGMENTS

CEESI would like to again thank the JIP members for having given permission in 2002 for the NAM Venturi meter wet gas data to be released. Members of the JIP (as they were titled in 2002) are Aramco, BP Amoco, ChevronTexaco, Enron Transportation Services, Gas Research Institute, NOVA Research & Technology Corp., Oryx Energy, Shell Canada, Shell International, Trans Canada Pipeline and Union Pacific Resources.

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CEESI would like to thank the BG Group for their kind permission allowing the presentation of their unique wet gas DP meter research data.

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APPENDIX ONE

The homogenous flow model assumes the gas and liquid phases flow at the same velocity and are perfectly mixed together so as they flow as a single phase flow with an averaged fluid density. This then allows the application of the single phase DP meter equation. The algebraic steps to develop the homogenous model are as follows. Let ν be the specific volume, and ρ the density. Subscripts denote the phases. Let M be mass and V be volume. M_{total} be the total mass of a homogenous mix held in a volume V_{total}.

$$\nu_{homogenous} = \frac{1}{\rho_{homogenous}} \quad \text{---- (A.1.1)} \quad \text{then} \quad \nu_{homogenous} = \frac{V_{total}}{M_{total}} = \frac{V_{liquid}+V_{gas}}{M_{total}} = \frac{V_{liquid}}{M_{total}} + \frac{V_{gas}}{M_{total}} \quad \text{---- (A.1.2)}$$

The flow quality /dryness fraction (x) definition is:

$$x = \frac{\dot{m}_{gas}}{\dot{m}_{gas} + \dot{m}_{liquid}} = \frac{\dot{m}_{gas}}{\dot{m}_{total}} \quad \text{---- (3)} \qquad \text{and} \qquad 1 - x = \frac{\dot{m}_{liquid}}{\dot{m}_{gas} + \dot{m}_{liquid}} = \frac{\dot{m}_{liquid}}{\dot{m}_{total}} \quad \text{---- (A.1.3)}$$

For a unit time a set mass of liquid and gas flows so the flow rate symbol is dropped here. Substitution of equations 3 and A.1.3 into equation A.1.2 for a unit of time therefore gives:

$$\nu_{homogenous} = \frac{V_l}{\left(\dfrac{M_l}{1-x}\right)} + \frac{V_g}{\left(\dfrac{M_g}{x}\right)} = \frac{1}{\rho_{homogenous}} = x\frac{V_g}{M_g} + (1-x)\frac{V_l}{M_l} \quad \text{---- (A.1.4) , i.e.:}$$

$$\frac{1}{\rho_{homogenous}} = \frac{x}{\rho_g} + \frac{1-x}{\rho_l} \quad \text{---- (A.1.5)} \qquad \text{i.e.} \qquad \rho_{homogenous} = \frac{\rho_l \rho_g}{\rho_l x + \rho_g (1-x)} \quad \text{---- (A.1.6)}$$

For a homogenized flow this density value is applied to the single phase DP meter equation along with the actual two-phase DP read. That is:

$$\dot{m}_{total} = EA_tK\sqrt{2\rho_{homogenous}\Delta P_{tp}} \quad \text{---(A.1.7)} \quad \text{and so:} \quad \dot{m}_g = x\dot{m}_{total} = xEA_tK\sqrt{2\rho_{homogenous}\Delta P_{tp}} \quad \text{--- (A.1.8)}$$

Or substituting equation A.1.6 into equation A.1.8 and re-arranging gives:

$$\dot{m}_g = x\left(\frac{EA_tK\sqrt{2\rho_g\Delta P_{tp}}}{\sqrt{\dfrac{\rho_g}{\rho_l} + x\left(1 - \dfrac{\rho_g}{\rho_l}\right)}}\right) = x\left(\frac{\dot{m}_{g\,Apparent}}{\sqrt{\dfrac{\rho_g}{\rho_l} + x\left(1 - \dfrac{\rho_g}{\rho_l}\right)}}\right) \qquad (2)$$

Note that when the gas is dry (i.e. the quality (x) is unity) the homogenous equations reduce to the single phase equations.

Due to the assumption of fully mixed flow it is usually considered only appropriate when the gas to liquid density ratio is high, flow rates are very high and the flow pattern is mist flow. It is difficult to know in practical situations when the gas and liquid phases are in a homogenous mix and when they are not.

APPENDIX TWO

Note that equation 1 defines the Lockhart-Martinelli parameter and by substituting equation 3 and equation A.1.3 into equation 1 gives:

$$X_{LM}=\frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}}=\frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}} \text{ ---- (A.2.1)} \quad \text{i.e.} \quad x=\frac{1}{1+\left\{X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}\right\}} \text{ ---- (A.2.1.a)}$$

Substituting equation A.2.1.a into equation 2 gives the homogenous model in terms of the Lockhart-Martinelli parameter.

$$\dot{m}_g=\frac{EA_tK\sqrt{2\rho_g\Delta P_{tp}}}{\left(1+X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}\right)\sqrt{\frac{\rho_g}{\rho_l}+\frac{\left(1-\frac{\rho_g}{\rho_l}\right)}{\left(1+X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}\right)}}} \text{ --- (A.2.2)}$$

Rearranging gives:

$$\dot{m}_g=\frac{EA_tK\sqrt{2\rho_g\Delta P_{tp}}}{\sqrt{\left\{\left(1+X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}\right)^2\frac{\rho_g}{\rho_l}\right\}+\left\{\left(1+X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}\right)\left(1-\frac{\rho_g}{\rho_l}\right)\right\}}} \text{ ---- (A.2.3)}$$

This in turn can be expanded out and after terms cancel the remaining expression can be expressed as:

$$\dot{m}_g=\frac{EA_tK\sqrt{2\rho_g\Delta P_{tp}}}{\sqrt{1+\left\{\sqrt{\frac{\rho_g}{\rho_l}}+\sqrt{\frac{\rho_l}{\rho_g}}\right\}X_{LM}+X_{LM}^2}}=\frac{\dot{m}_{g\,Apparent}}{\sqrt{1+CX_{LM}+X_{LM}^2}} \text{ ---- (A.2.3.a)}$$

where: $C=\sqrt{\frac{\rho_g}{\rho_l}}+\sqrt{\frac{\rho_l}{\rho_g}}$ ---- (A.2.4) i.e.: $C=\left(\frac{\rho_g}{\rho_l}\right)^n+\left(\frac{\rho_l}{\rho_g}\right)^n$ ---- (A.2.4.a) and $n=\frac{1}{2}$.

Chisholm derived n=0.25 using a stratified flow model. Here it is shown that for a homogenized wet gas flow n=0.5.

APPENDIX THREE

Chisholm [2, 3] developed an orifice plate meter two phase flow correction based on a stratified flow pattern. This was shown earlier as equations 4 to 6. The authors has not found in any of Chisholm's research papers an expression for the parameter C if the flow pattern is homogenous flow. However, from the stratified flow derivation Chisholm expresses the slip ratio at the orifice plate meters vena contracta (K_{vc}) as equation (A.3.1).

$$K_{vc} = \frac{U_{g2}}{U_{l2}} = \frac{1}{Z}\sqrt{\frac{\rho_l}{\rho_g}}$$

(A.3.1)

Where "Z" is defined by Chisholm as a "Shear Force Function" and U_{g_2} and U_{l_2} are the average gas and liquid flow velocities at the orifice plate meter vena contracta. Chisholm then defined the parameter "C" by equation A.3.2.

$$\mathrm{C} = \mathrm{Z} + \frac{1}{\mathrm{Z}}$$

(A.3.2)

Therefore Chisholm stated:

$$C = \frac{1}{K}\sqrt{\frac{\rho_l}{\rho_g}} + K\sqrt{\frac{\rho_g}{\rho_l}}$$

(A.3.2.1)

Now, if we state the flow is homogenous instead of stratified then we are stating that U_{g_2} and U_{l_2} are equal as homogenous flow has a slip ratio of unity. Here then, from equation A.3.1 and equation A.3.2.1 we have stated that for homogenous flow we have:

$$C = \sqrt{\frac{\rho_g}{\rho_l}} + \sqrt{\frac{\rho_l}{\rho_g}}$$

(A.3.2.2)

Therefore we have reduced Chisholm's definition of C to being the same as equation A.2.4 as required.