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Paper 4.2

Wet Gas Metering with V-Cone Meters

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1 INTRODUCTION

Wet gas metering is becoming increasingly important in the development of marginal oil and gas fields. Many of these fields are only economically viable if they can be tied back to existing platform infrastructure, reducing the capital expenditure required by a significant margin. In these cases, several fields are often connected to common facilities, requiring each unprocessed stream to be metered before co-mingling.

Wet gas metering can also be a valuable technology in well management, providing on-line information on the production flow and in well testing, reducing the capital expenditure required to investigate potential new wells.

Wet gas metering is at the high gas fraction end of multiphase metering, typically with a gas volume fraction (GVF) above 90%, and mostly above 95%. Standard multiphase meters cannot operate satisfactorily in such conditions. The development of wet gas meters is therefore a key requirement of the oil and gas industry.

At present there are relatively few wet gas meters established in the market, however several manufacturers are currently promoting or developing such meters. In order to develop a wet gas meter, there must be a good understanding of how the constituent components behave in wet gas. Wet gas meters that are based on Differential Pressure (DP) Meter technologies utilize the fact that the presence of liquid in the gas stream will generally cause the DP Meter to “over-read” compared with the gas if it flowed alone.

If the liquid in a wet gas stream is not considered worth measuring, or if the liquid flow can be determined by other means (tracer technique for example), then a dry gas meter can be used, if the effect of liquid is known.

The work presented in this paper provides valuable new information on the performance of the V-Cone flowmeter in wet gas. These results will benefit users wishing to apply the V-Cone meter to wet gas applications or users with existing V-Cone meters that encounter wet gas situations. The findings will also prove beneficial to current efforts to develop a wet gas meter based on the V-Cone meter.

2 WET GAS FLOW MEASUREMENT AT NEL

NEL currently operates a state of the art Wet Gas Test Loop as described in Appendix A. The work presented in this paper was carried out on this system as part of the 1999 – 2002 Flow Programme, supported by the UK’s Department of Trade and Industry (DTI). This project looked at the performance of standard dry gas meters in wet gas flow. The meters tested in this project were: two V-Cone meters (presented in this paper); three Venturis; a Coriolis meter; a Vortex meter and a turbine meter. The results of this work are presented in the final report for Project No. FDMU07. The 2002 – 2005 Flow Programme features another large wet gas project, this time looking at the effect of different fluid properties on the overreading.

3 V-CONE FLOWMETER IN WET GAS FLOW

The V-Cone is a differential pressure meter in which the fluid flows around the outside of a central cone, as opposed to through a central opening. The differential pressure is measured between a tapping in the pipe wall upstream of the cone and a tapping on the downstream end of the cone as shown in Figure 1.

Fig. 1 - V-Cone flowmeter

For a V-Cone Meter the beta value, β, is the square root of the ratio of the minimum cross sectional area through the meter to the inlet cross sectional area. It is calculated by:

$$\beta = \sqrt{1-\left(d_c / D\right)^2} \qquad (1)$$

where d_c is the cone diameter.

The V-Cone is becoming popular in the oil and gas industry in gas and liquid applications and will therefore be considered as an option for wet gas flow measurement. There was very little data on the performance of the V-Cone in wet gas flow with significant quantities of liquid in the gas stream. Consequently, it was decided to test two V-Cones in the 1999 – 2002 DTI Flow Programme project to establish some high quality independent test data.

4 TEST PROGRAM AND RESULTS

Two V-Cone meters, with β values of 0.55 and 0.75, were tested in wet gas at three test pressures, 15 bar, 30 bar, and 60 bar, at a range of gas and liquid flowrates. The different test pressures would allow the effect of gas density to be investigated. The range of flowrates would allow the effect of gas velocity and liquid content to be determined. Although only two β values were tested, this offers the opportunity to investigate any potential β effect on the overreading. The range of test conditions is shown in Table 1 below, expressed by the gas densimetric Froude number, Fr_g and the modified Lockhart Martinelli parameter, X.

Table 1 - Envelope for wet gas V-Cone tests.

β	Pressure (bar)	Fr_g
0.55	15	0.4 – 2.0
	30	0.6 – 2.8
	60	0.8 – 4.0
0.75	15	0.6 – 1.9
	30	0.5 – 2.8
	60	0.9 – 3.5

The maximum modified Lockhart-Martinelli value, X, was 0.3, where achievable, depending on the gas Froude number, pressure and β value.

4.1 Calculation of Over-Reading

Both V-Cones were initially calibrated in dry gas flows at each test pressure to establish a dry gas baseline against which the wet gas results can be compared. When analyzing the subsequent wet gas data, the magnitude of the meter over-reading can be calculated from the ratio $\sqrt{\Delta p_{tp} / \Delta p_g}$. The $\sqrt{\Delta p_g}$ value is calculated using the dry gas calibration data and measured reference gas flowrate and density:

$$\sqrt{\Delta p_g} = \frac{\dot{m}_{g,ref}}{EC_d A_d \varepsilon \sqrt{2\rho_g}} \tag{2}$$

where $m_{g,ref}$ is the gas mass flow read by the reference gas turbine and all other components are as described in Appendix B.

4.2 V-Cone Wet Gas Flow Results

All the wet gas data for the 0.55 Beta V-Cone meter was initially plotted together, as shown below in Fig. 2.

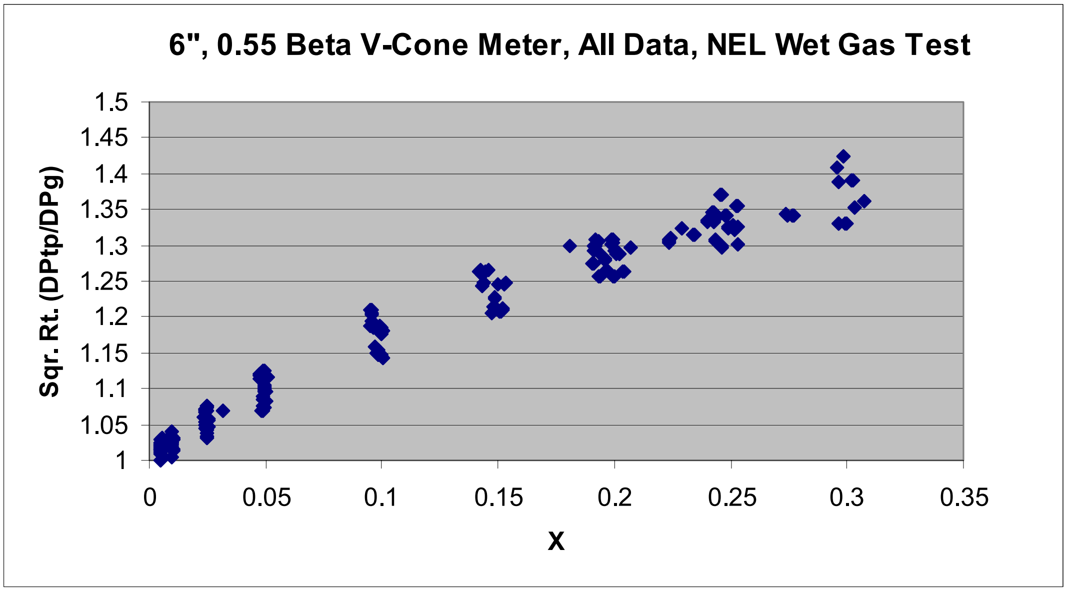

Fig. 2 - Overreading data for 0.55 Beta V-Cone (all data).

It is clear from Fig. 2 that the meter over-reading has a strong dependence on the modified Lockhart Martinelli parameter. However, there is clearly some spread in the data. To investigate the cause of this spread the data from each pressure was plotted separately, as shown in Fig. 3.

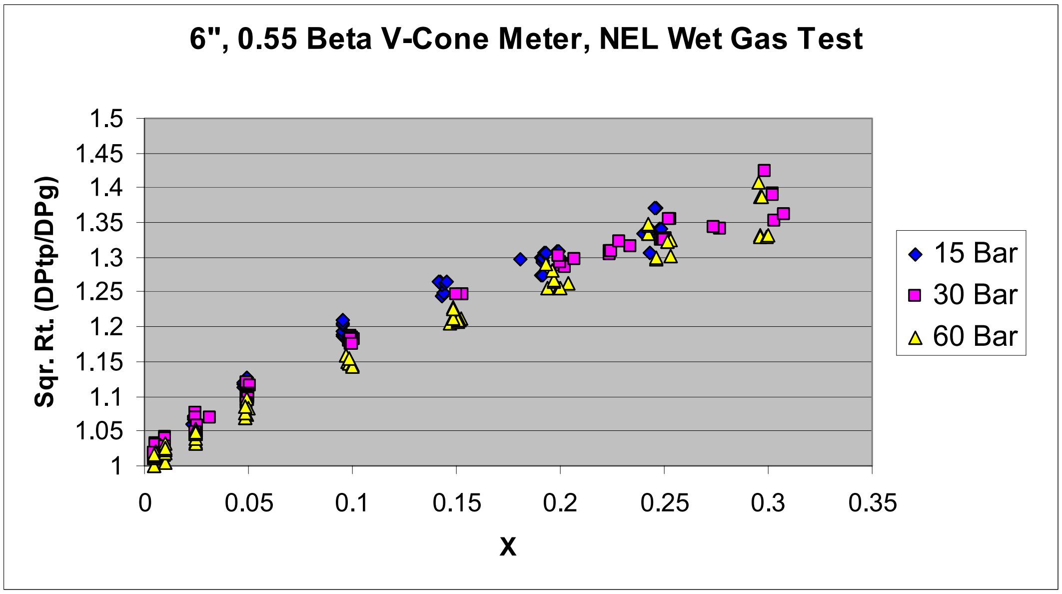

Fig. 3 - Overreading data for 0.55 Beta V-Cone (by pressure).

Fig. 3 shows that there is a pressure effect similar to that discovered for Venturi meters. As the pressure increases the over-reading decreases. However it is clear that there is a spread within the data set for each pressure. To further investigate each of the three pressure sets were plotted separately with the gas densimetric Froude numbers separated out, shown in Figs. 4, 5 and 6.

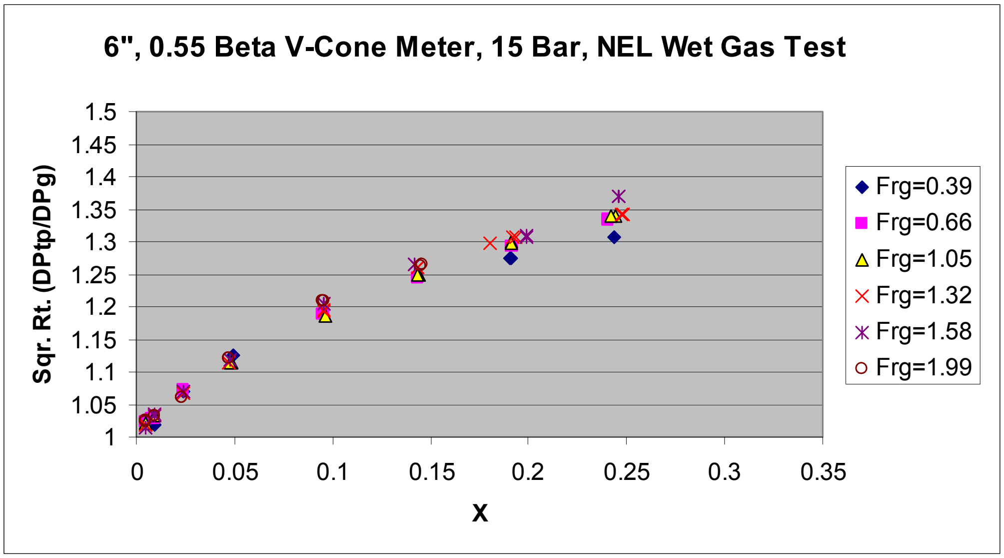

Fig. 4 - Overreading data for 0.55 Beta V-Cone at 15 bar (by Fr_g).

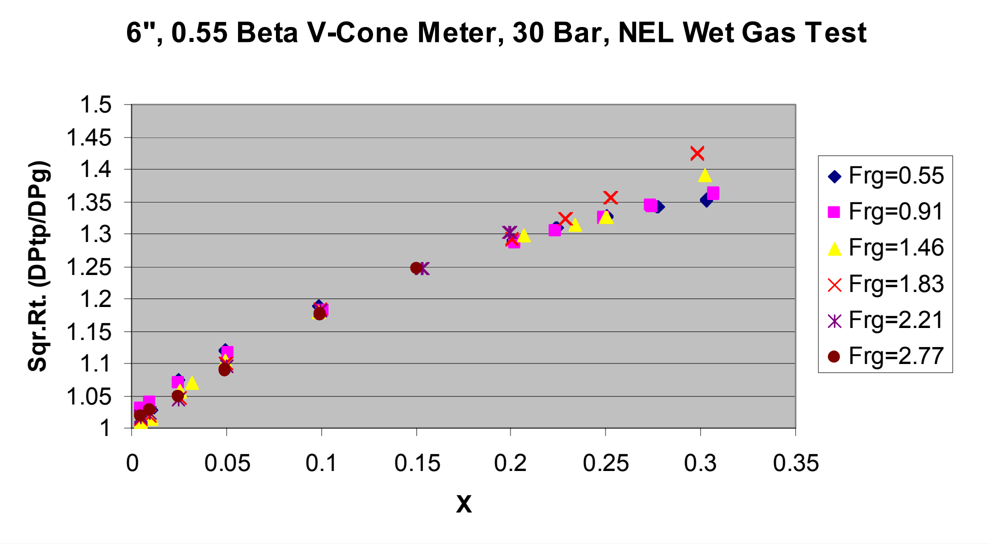

Fig. 5 - Overreading data for 0.55 Beta V-Cone at 30 bar (by Fr_g).

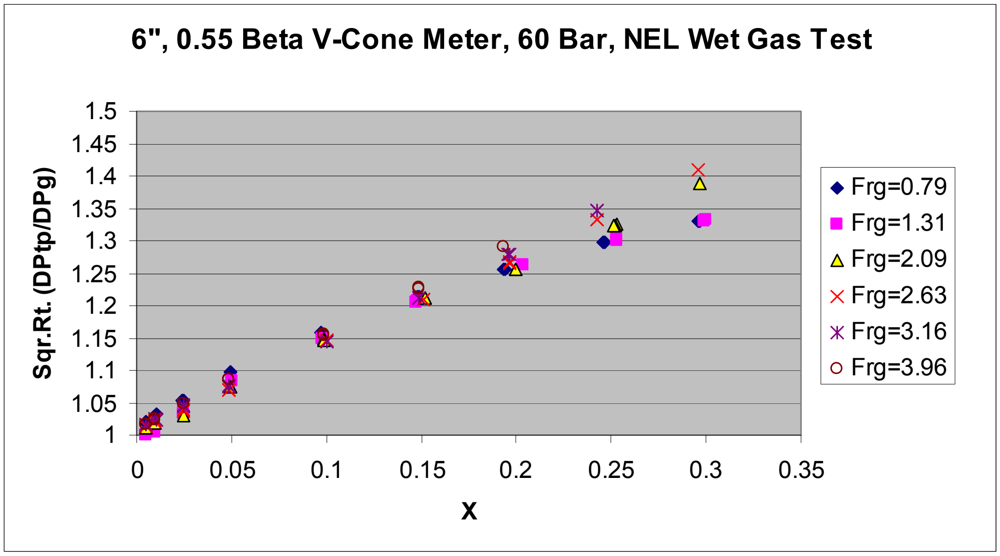

Fig. 6 - Overreading data for 0.55 Beta V-Cone at 60 bar (by Fr_g).

Figs. 4 to 6 show that there is a gas densimetric Froude number effect similar to that discovered for Venturi meters. As the Froude number rises so does the V-Cone meter over-reading. (Note that the Froude number groups are averages across a range as the actual gas flow conditions were set by gas flowrate and pressure. This results in occasional slight discontinuities in the plots especially at higher Froude numbers. Therefore these slight discontinuities are not thought to be due to any physical phenomena but rather a spread in the data set being averaged to give a set Froude number.)

The same procedure was carried out for the 0.75 Beta V-Cone meter. All the wet gas data for the 0.75 Beta V-Cone meter was initially plotted together in Figure 7.

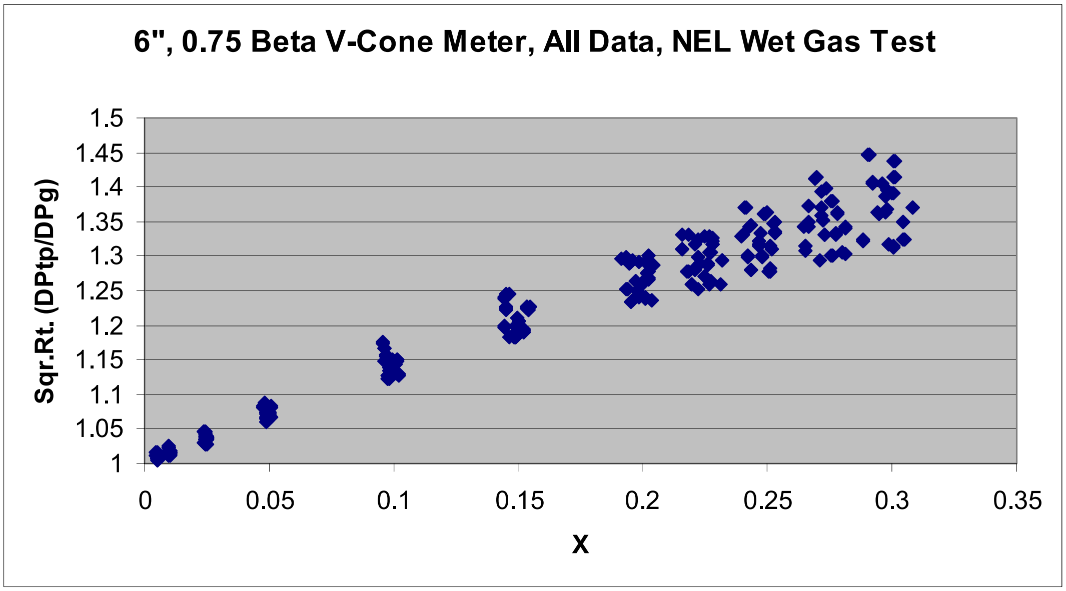

Fig. 7 - Overreading data for 0.75 Beta V-Cone (all data).

Fig. 7 shows that the 0.75 Beta meter over-reading has a strong dependence on the modified Lockhart Martinelli parameter. However, the spread in the data is clearly larger than for the 0.55 beta V-Cone meter. The data is presented in Fig. 8 separated by pressure.

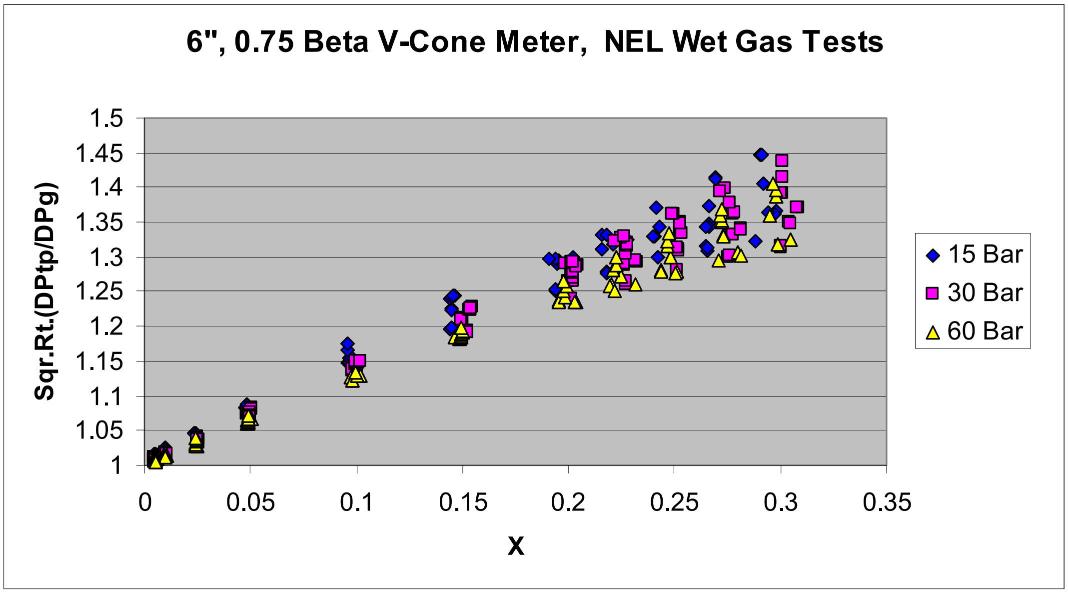

Fig. 8 - Overreading data for 0.75 Beta V-Cone (by pressure).

Clearly there is a pressure effect but there is still a spread in the data for each pressure so, separate pressure graphs with the gas densimetric Froude number sets separated out, were produced, shown in Figs. 9 to 11.

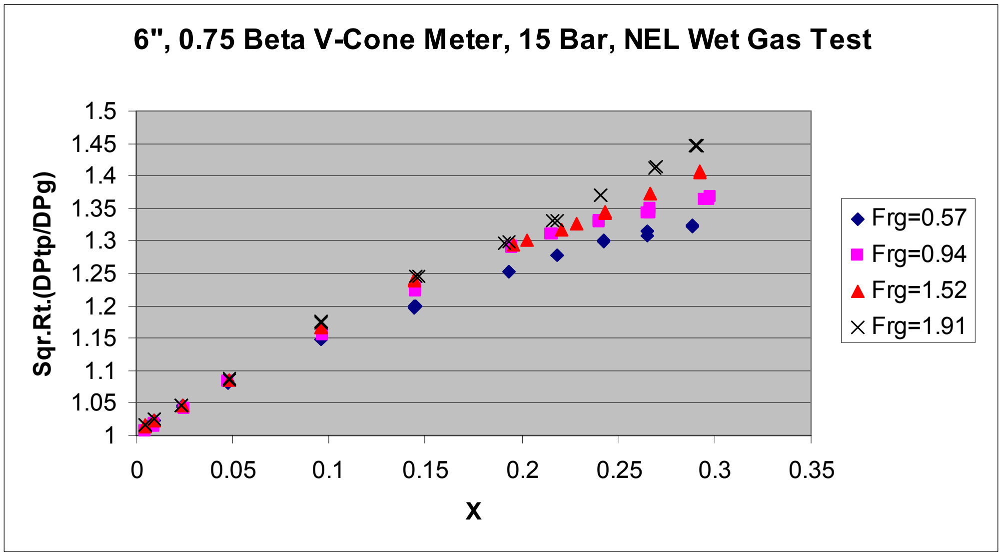

Fig. 9 - Overreading data for 0.75 Beta V-Cone at 15 bar (by Fr_g).

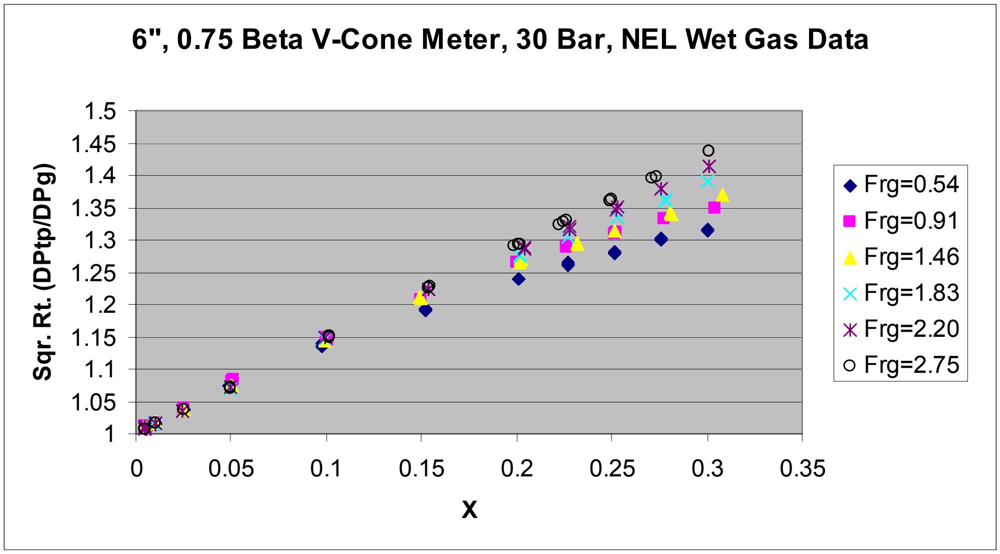

Fig. 10 - Overreading data for 0.75 Beta V-Cone at 30 bar (by Fr_g).

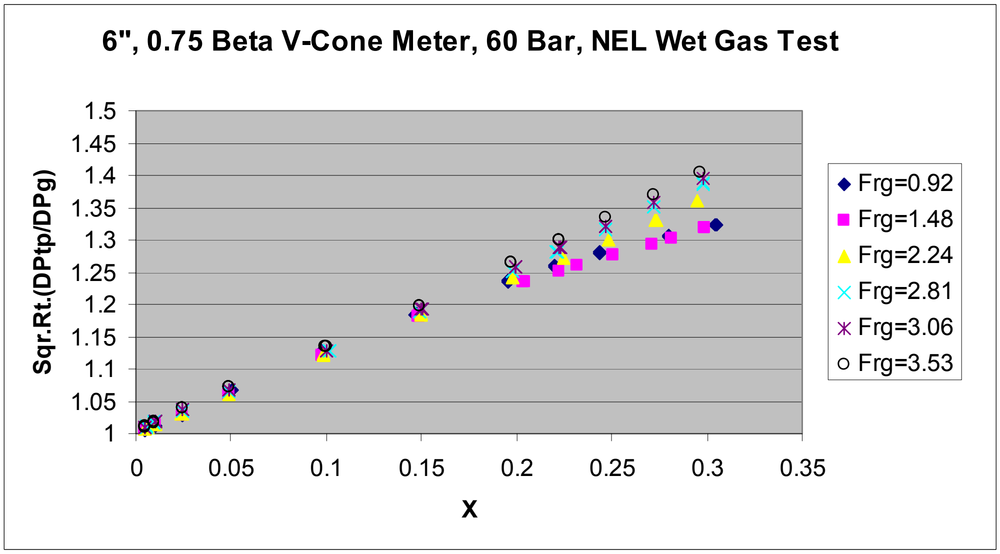

Fig. 11 - Overreading data for 0.75 Beta V-Cone at 60 bar (by Fr_g).

Figs. 9 to 11 show that the same gas densimetric Froude number effect is present for the 0.75 beta V-Cone and for this smaller cone it appears to be more pronounced.

4.3 Investigating the Use of Existing DP Meter Wet Gas Correlations

There are several general two-phase and wet gas correlations published for DP meters. The Orifice Plate meter has the Murdock [1] and Chisholm [2,3] correlations and the Venturi meter has the de Leeuw [4] and the Steven [5] correlations. These are described in Appendix B.

It was considered necessary to check the performance of these existing DP meter wet gas correlations before creating a new V-Cone meter wet gas correlation for each meter. Therefore in lieu of the results the suitability of each of the fore-mentioned correlations was considered.

The Murdock and Chisholm correlations do not account for any gas densimetric Froude number effect which has been seen to be important to the V-Cone meter and hence they are clearly not suitable for use with V-Cone meters. (However, note that this gas densimetric Froude number effect is not greatly noticeable until the modified Lockhart-Martinelli parameter values reach 0.1 and above so for given pressures the Murdock type model could be applied to the situations with modified Lockhart-Martinelli parameter values less than 0.1.)

The de Leeuw and Steven correlations both include a gas densimetric Froude number effect and were therefore applied to these V-Cone meter results. Their performance is given in graphs showing the uncorrected meter over-reading and the error that exists after the respective correlations have been applied for the individual pressures. Tables showing the root mean fractional deviation and maximum percentage errors are also given.

The de Leeuw Venturi Correlation:

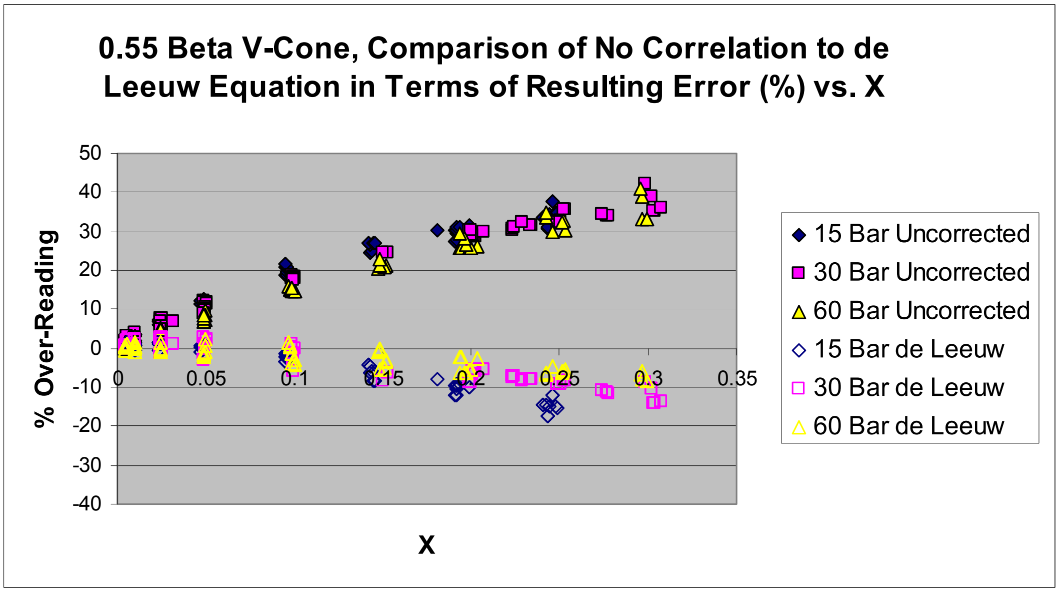

Fig. 12 - The over-reading and the de Leeuw correlation for the 0.55 Beta V-Cone Meter at individual pressures.

Table 2 shows the root mean fractional deviation and maximum percentage errors at the individual pressures for the de Leeuw correlation applied to the 0.55 Beta V-Cone Meter.

Table 2 - The de Leeuw Performance for 0.55 Beta V-Cone Meter.

0.55 Beta	15 Bar	30 Bar	60 Bar	All Pressures
$\pm\delta$	0.066	0.060	0.043	0.055
Max Error %	-17.6	-14.1	-8.3	-17.6

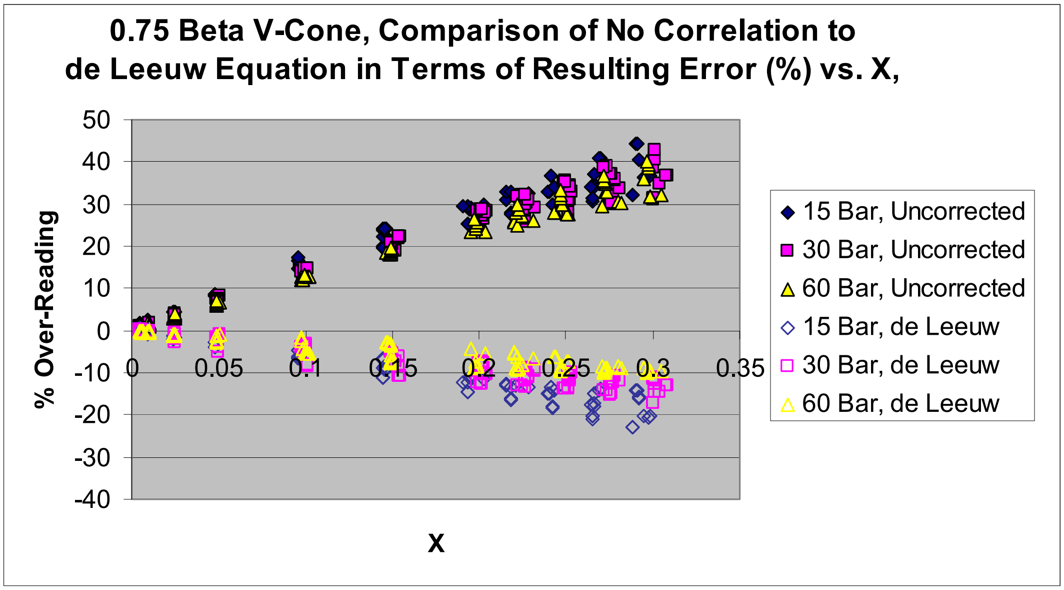

Fig. 13 - The over-reading and the de Leeuw correlation for the 0.75 Beta V-Cone Meter at individual pressures.

Table 3 shows the root mean fractional deviation and maximum percentage errors at the individual pressures for the de Leeuw correlation applied to the 0.75 Beta Meter.

Table 3 - The de Leeuw correlation Performance for 0.75 Beta V-Cone Meter.

0.75 Beta	15 Bar	30 Bar	60 Bar	All Pressures
± δ	0.114	0.086	0.059	0.086
Max Error %	-23.1	-17.3	-9.9	-23.1

The Steven Venturi Correlation:

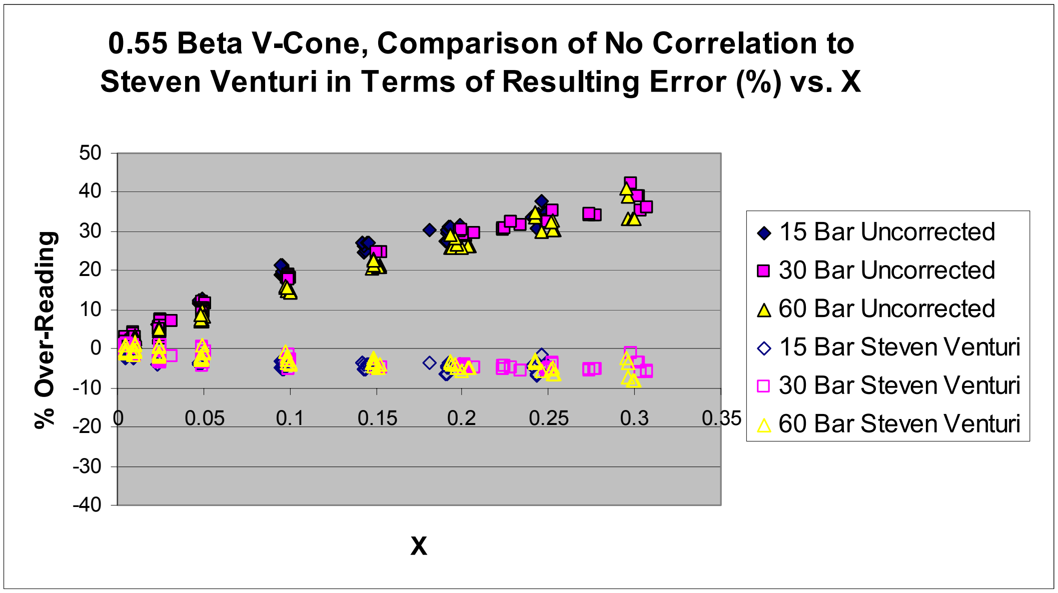

Fig. 14 - The over-reading and the Steven Venturi correlation for the 0.55 Beta V-Cone Meter at individual pressures.

Table 4 shows the root mean fractional deviation and maximum percentage errors at the individual pressures for the Steven correlation applied to the 0.55 Beta V-Cone Meter.

Table 4 - The Steven Venturi Correlation Performance for 0.55 Beta V-Cone Meter.

0.55 Beta	15 Bar	30 Bar	60 Bar	All Pressures
± δ	0.036	0.036	0.035	0.035
Max Error %	-6.7	-6.1	-8.1	-8.1

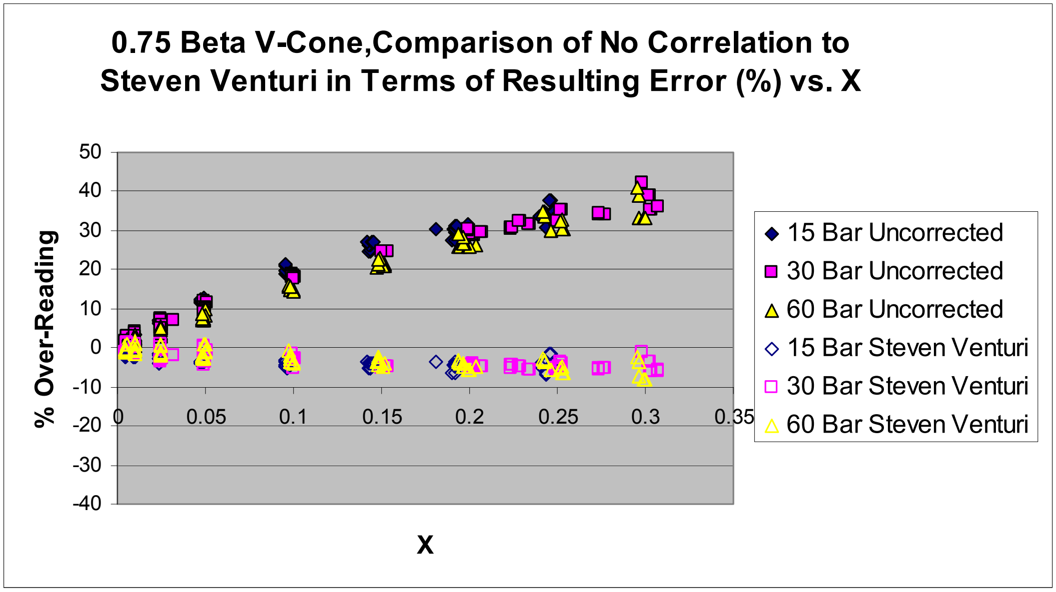

Fig. 15 - The over-reading and the Steven Venturi correlation for the 0.75 Beta V-Cone Meter at individual pressures.

Table 5 shows the root mean fractional deviation and maximum percentage errors at the individual pressures for the Steven correlation applied to the 0.55 Beta V-Cone Meter.

Table 5 - The Steven Venturi Correlation Performance for 0.75 Beta V-Cone Meter.

0.75 Beta	15 Bar	30 Bar	60 Bar	All Pressures
± δ	0.054	0.056	0.052	0.054
Max Error %	-9.6	-9.1	-9.4	-9.6

The preceding tables and graphs show that the Venturi correlations are giving better results than if no correlation is used but they are in no way accurate when applied to V-Cone meters.

This exercise has shown that the Venturi Meter wet gas correlations are over correcting the liquid induced V-Cone meter error. This is an indication that the V-Cone meter has a lower over-reading than Venturi meter for a given wet gas flow condition. To check this conclusion the NEL data sets for 60 Bar wet gas tests on a 0.55 Beta Venturi meter [5] and for the 0.55 Beta V-Cone meter were plotted together in Fig. 16.

This comparison confirms that for the same wet gas flow conditions the V-Cone meter has a lower overreading than the Venturi meter. Another point of interest shown in Fig. 16 was that the gas densimetric Froude number effect is more pronounced for the V-cone meter than the Venturi Meter. This is seen in the larger spread of the data when the test data is not split into gas densimetric Froude number groups as in Figs. 4 to 6. It was also considered interesting to plot the two different V-Cone meter data sets on the same graph to see the effect of the beta ratio. A sample plot showing the 60 Bar data sets is shown in Fig. 17. (The 15 Bar and 30 Bar data sets showed the same relationship.) It was found that the larger cone / smaller Beta had a greater over-reading than the smaller cone / larger Beta. This follows theory as the larger cone accelerates the gas flow to a higher velocity and hence the energy losses to the liquid would be proportionally higher than for the smaller cone and slower gas velocity. However it can be seen that the pressure and gas densimetric Froude number effects still cause the data to overlap.

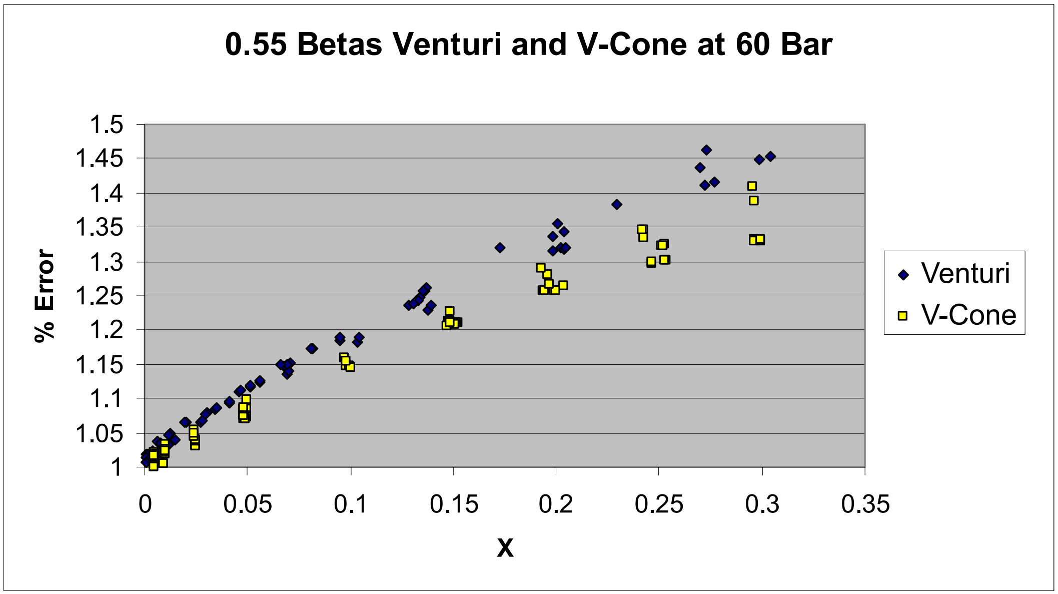

Fig. 16 - A comparison of the V-Cone and Venturi meters at the same wet gas flow conditions.

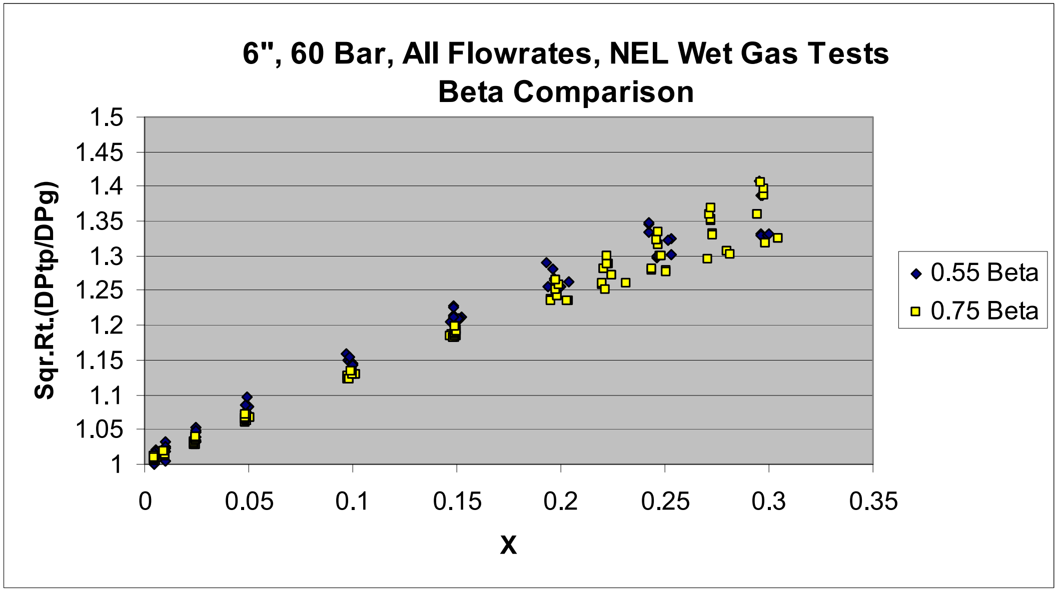

Fig. 17 - A comparison of the two V-Cones at 60 bar.

5 NEW CORRELATIONS

Clearly a wet gas V-Cone Meter correlation was required as the performances of the existing DP meter correlations were not acceptable. The de Leeuw and Steven Venturi correlation mathematical forms were examined for use with the V-Cone meter wet gas data. Unfortunately the de Leeuw form (which has the simplicity of having only two free parameters) did not fit the data. The Steven Venturi correlation mathematical form (with six free parameters) did. Therefore for each V-Cone meter the data for each pressure was plotted on a 3 dimensional graph of $\sqrt{\Delta p_{tp}/\Delta p_g}$ vs. X vs. Fr_g. For each graph the values of A, B and C (see Equation (13)) were found by use of the software TableCurve 3D. Then the software

TableCurve 2D was used for to find the functions relating the values A, B and C to the gas to liquid density ratio (i.e. the pressure). The results are as follows:

V-Cone Meter Wet Gas Correlation:

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{\left(\frac{1+AX+BFr_g}{1+CX+BFr_g}\right)} \qquad (3)$$

0.55 Beta V-Cone Meter

$$A = 1.224 + \frac{0.141}{\left(\frac{\rho_g}{\rho_l}\right)} \qquad (4a)$$

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

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

0.75 Beta V-Cone Meter

$$A = -0.0013 + \frac{0.3997}{\sqrt{\frac{\rho_g}{\rho_l}}} \qquad (5a)$$

$$B = 0.0420 - \frac{0.0317}{\sqrt{\frac{\rho_g}{\rho_l}}} \qquad (5b)$$

$$C = -0.7157 + \frac{0.2819}{\sqrt{\frac{\rho_g}{\rho_l}}} \qquad (5c)$$

Notice that equations 4a, 4b and 4c and 5a, 5b and 5c are selected to give the correct values of A, B and C within the test pressure range and to continue to give sensible likely values when the pressure is extrapolated to “dense phase conditions” (i.e. extremely high pressures where the gas density approaches that of the liquid density).

Figs. 18 to 21 show the new 0.55 Beta and 0.75 Beta correlation performances. Tables 6 and 7 shows the root mean fractional deviation and maximum percentage errors at the individual pressures for the new 0.55 Beta and 0.75 Beta correlations.

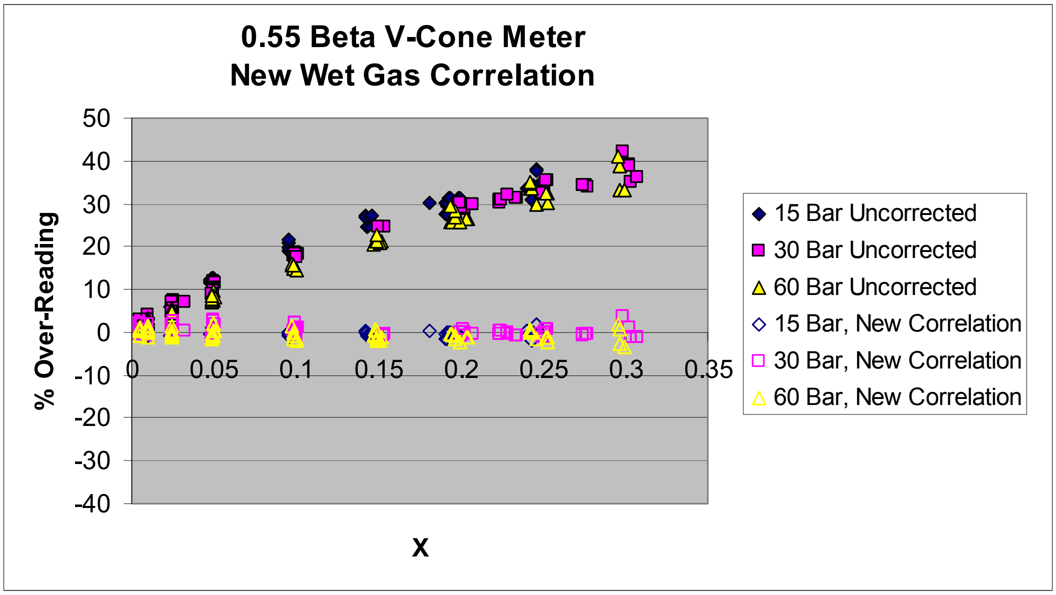

Fig. 18 - The Over-Reading and the New 0.55 Beta V-Cone Meter Correlation Performance at Individual Pressures.

Table 6 - The New 0.55 Beta V-Cone Meter Correlation Performance.

0.55 Beta	15 Bar	30 Bar	60 Bar	All Pressures
± δ	0.007	0.012	0.013	0.011
Max Error %	-1.90	+3.59	-3.47	+3.59

Expanding the new 0.55 Beta V-Cone correlation performance to percentage error plot gives Fig. 19.

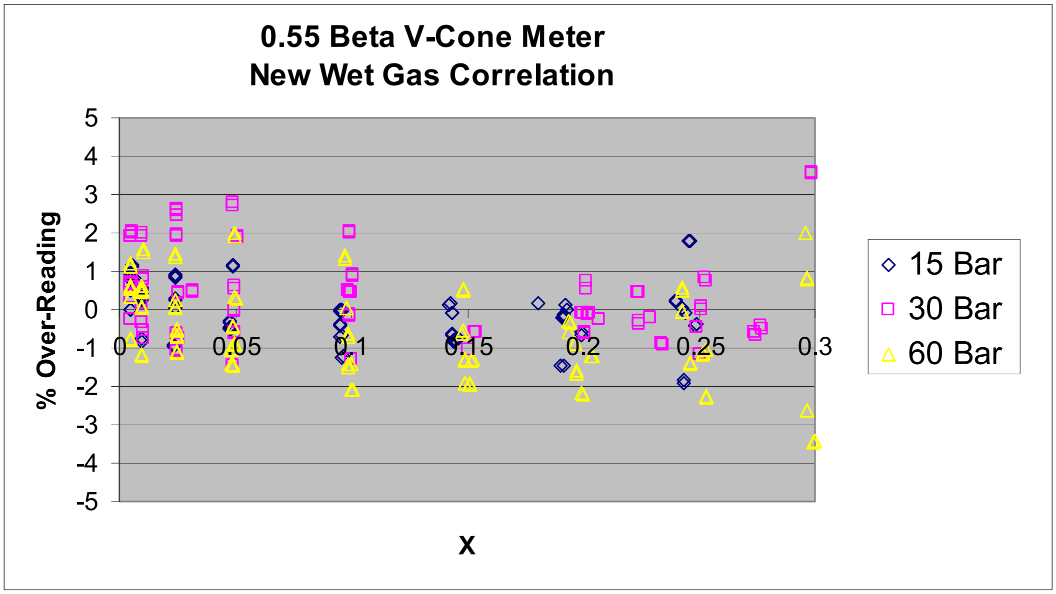

Fig. 19 - The Percentage Error of the New 0.55 Beta V-Cone Meter Correlation Performance at Individual Pressures.

Fig. 19 shows that the majority of the points are below 2% with the exception of some outliers.

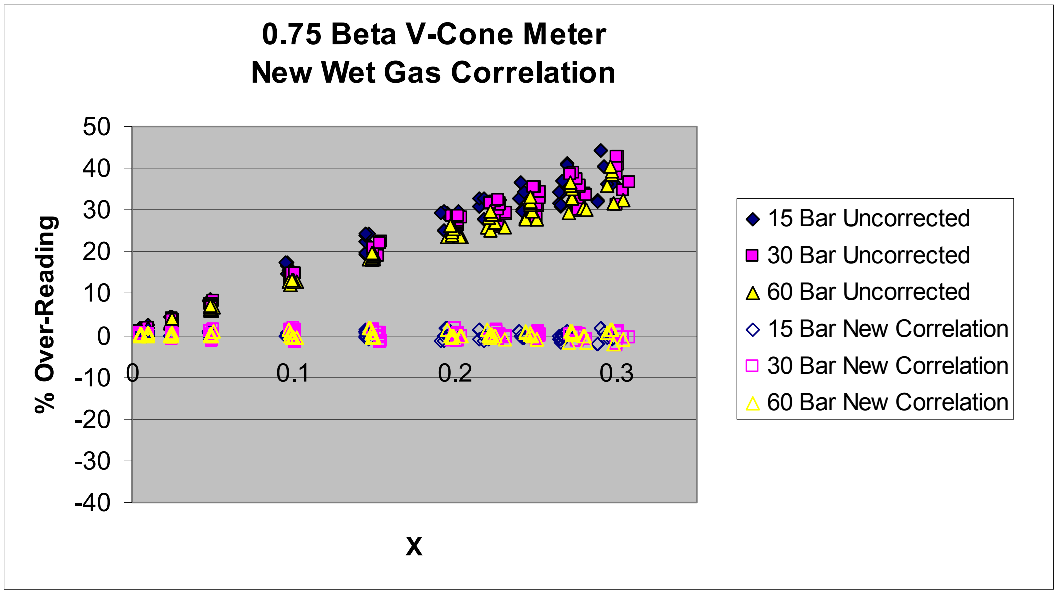

Fig. 20 - The Over-Reading and the New 0.75 Beta V-Cone Meter Correlation Performance at Individual Pressures.

Table 7. The New 0.75 Beta V-Cone Meter Correlation Performance.

0.75 Beta	15 Bar	30 Bar	60 Bar	All Pressures
± δ	0.008	0.008	0.007	0.008
Max Error %	-2.3	-2.4	-2.3	-2.4

Expanding the new 0.75 Beta V-Cone correlation performance to percentage error plot gives Fig. 21.

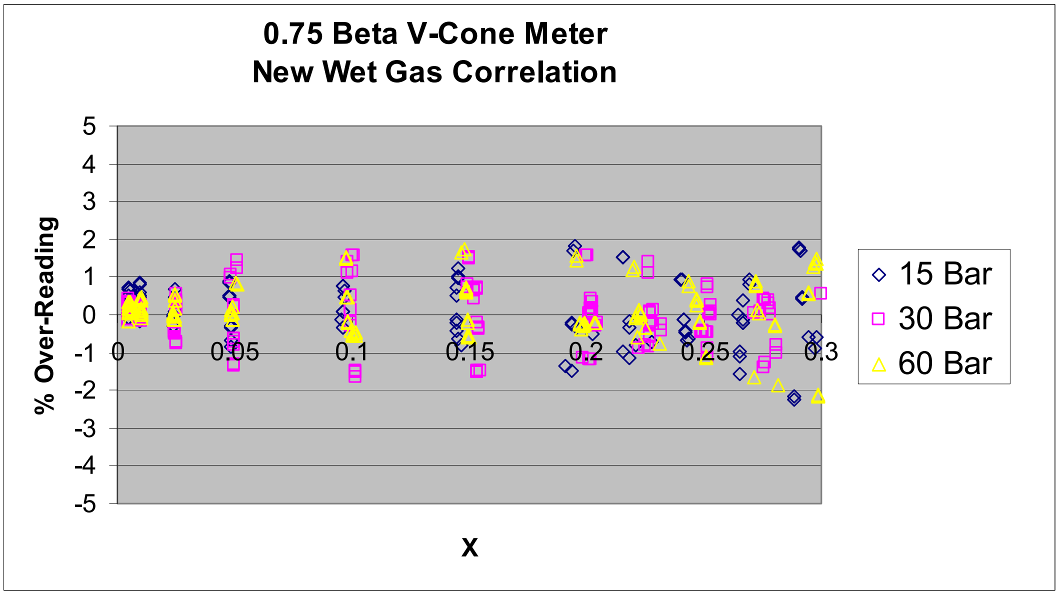

Fig. 21 - The Percentage Error of the New 0.75 Beta V-Cone Meter Correlation Performance at Individual Pressures.

Fig. 21 shows that the majority of the points are below 2% with the exception of some outliers.

6 CONCLUSIONS

The NEL Wet Gas Loop was proven to be capable of conducting detailed wet gas performance testing of the two V-Cone meters over a wide range of flow conditions and reliable repeatable data was obtained.

The V-Cone meters were found to be capable of metering wet gas flows.

The liquid component entrained in the gas flow had a clear and repeatable effect on the V-Cone meters. The V-Cone meters over-read the gas mass flowrate when exposed to wet gas flows. This over-reading was dependent on the amount of liquid present, the pressure of the flow and the gas flowrate itself.

It was found that for the same wet gas flow conditions the V-Cone meter has less error than the Venturi meter.

Correlations were created for the V-Cone meters that correct for the liquid induced error and the uncertainty of these correlations is 2% with the exception of a few outlying points.

The NEL wet gas tests and the resulting data analysis discussed here has created a basis for further wet gas V-Cone meter development which is an on going process.

7 ACKNOWLEDGEMENT

The work described in this paper has been carried out as part of the 1999 – 2002 Flow Programme, funded by the UK Department of Trade and Industry’s National Measurement Systems Directorate.

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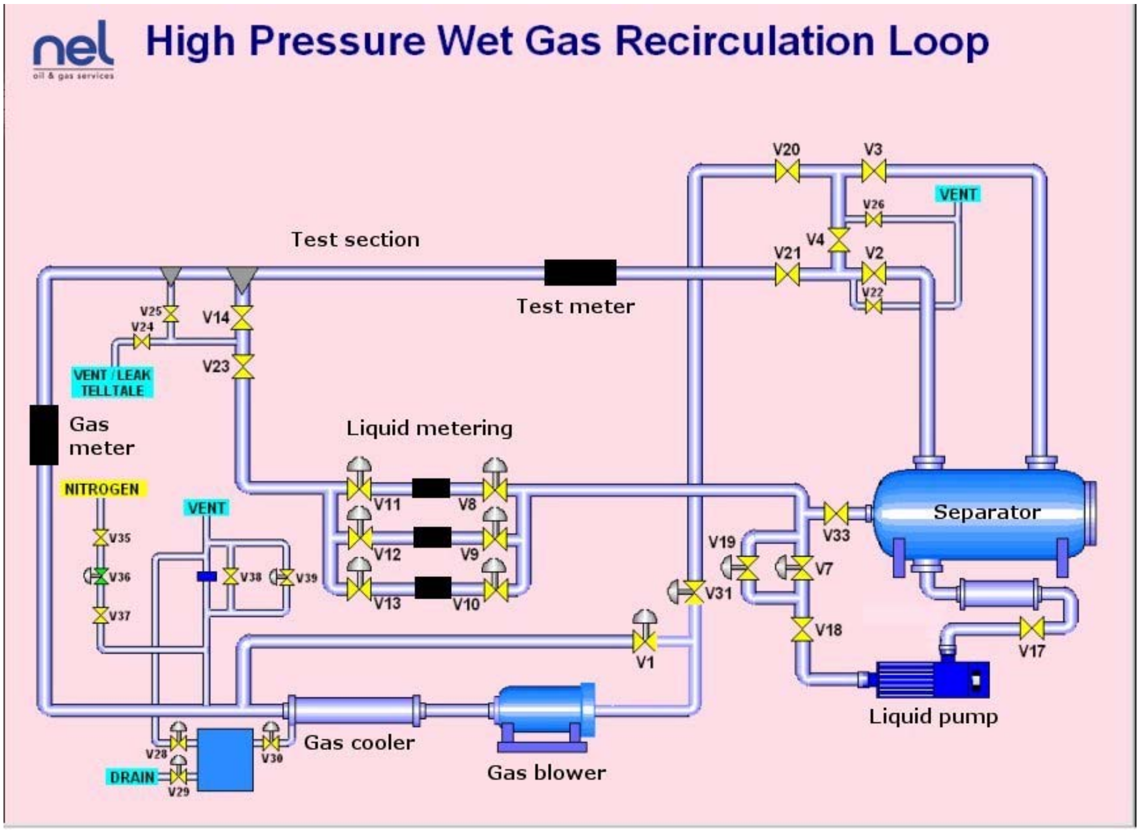
[6] Steven. R.N., “Wet Gas Metering”. PhD Thesis, Department of Mechanical Engineering,University of Strathclyde, UK, April 2001.

APPENDIX A - NEL HIGH-PRESSURE WET GAS TEST FACILITY

The NEL Wet Gas facility has been operational since 1999, and has been heavily used for research, testing and calibration work since. The facility is a recirculating loop based around a 12m^3 gas/liquid separator. The test section is nominally four or six inch, but sizes from 2-inch to 8-inch can be accommodated. The fluids used are oxygen-free nitrogen (density range 2 to 70 kg/m^3) and a kerosene substitute (Exxsol D80; approximate density of 800 kg/m^3). The facility operates at ambient temperatures of approximately 20°C at pressures up to 62 barg.

Gas is drawn from the top of the separator and driven round the loop by a 200 kW gas blower up to a maximum dry gas flowrate of 1400 m^3/hr. Liquid is injected through an injection spool over 50D upstream of the test section. The gas and liquid temperatures are both controlled with heat exchangers to maintain equal temperatures in the test section. The gas and liquid reference flowrates are measured using traceable calibrated reference turbines. The expanded uncertainty on the gas mass flowrate is ±0.35% and ±0.15% for the liquid mass flowrate (both at the 95% confidence level). All temperature and pressure measurements are taken using traceable calibrated instrumentation. A modified subsea video camera can be used to monitor the two-phase flow in the test section. The camera view allows the transition from stratified flow to annular/mist flow to be observed.

A schematic of the NEL Wet Gas Facility is shown below, displaying the key equipment and general layout.



APPENDIX B - DIFFERENTIAL PRESSURE FLOWMETER HISTORY IN WET GAS

There have been several general two-phase and wet gas specific DP Meter publications in the last fifty years. All indicate that when differential pressure meters are used to meter wet gas flow the measured differential pressure is higher than it would be if the gas phase flowed alone. It is believed that this is caused by energy losses at the gas liquid interface(s) as the gas drives the liquid through the meter. The exact amount of additional pressure loss will depend on the several parameters, including the geometry of the meter, the amount of liquid present, pressure, gas velocity, liquid density, viscosity and surface tension, and the flow regime in the pipe. This additional pressure drop produces an over-reading in the apparent gas mass flowrate, compared with what would be measured without any liquid present. This difference must be corrected by using some form of over-reading correlation.

Several correlations have been proposed over the years for Orifice Plate Meters, e.g. Murdock [1], Chisholm [2, 3] and for Venturi Meters, e.g. de Leeuw [4], and Steven [5]. Homogenous models have also been traditionally used for general DP Meters with two-phase flows. Steven gives a good background on these correlations [6].

The standard DP meter equation is used for V-Cones metering dry gas. That is:

$$\dot{m}_g = C_d E \varepsilon A_d \sqrt{2\rho_g \Delta p_g} \tag{1a}$$

For wet gas flows the apparent gas mass flowrate is given by:

$$\dot{m}_{g(tp)} = C_d E \varepsilon A_d \sqrt{2\rho_g \Delta p_{tp}} \tag{2a}$$

where $\dot{m}_{g(tp)}$ is the apparent gas mass flowrate determined by the meter from the two-phase flow differential pressure.

C_d is the discharge coefficient of that meter from a dry gas flow calibration.

E is the velocity of approach factor $\left(1/\sqrt{1-\beta^4}\right)$

ε is the gas expansibility factor.

A_d is the minimum cross sectional area through the meter.

Δp_{tp} is the measured two-phase differential pressure.

β is the square root of the ratio of the minimum flow cross sectional area through the meter to the inlet cross sectional area.

All DP meter correlations express the corrected gas mass flowrate, $\dot{m}_g$, as

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{\text{CorrectionFactor}} \tag{3a}$$

Murdock's original correction factor was based on several sets of orifice plate data from different sources. It uses a correction factor that was solely a function of a parameter Murdock denoted as "X". Due to a confusing repeated use of this letter by other researchers it is denoted here as X_{Murdock}. This parameter is the square root of the superficial liquid Differential Pressure to the superficial gas Differential Pressure. It is calculated by:

$$X_{Murdock} = \sqrt{\frac{\Delta p_l}{\Delta p_g}} = \frac{C_{d_g}\varepsilon}{C_{d_l}} \frac{\dot{m}_l}{\dot{m}_g} \sqrt{\frac{\rho_g}{\rho_l}} \tag{4a}$$

where C_{d_l} is the discharge coefficient at the liquid superficial Reynolds number,
C_{d_g} is the discharge coefficient at the gas superficial Reynolds number,
$\dot{m}_l$ and $\dot{m}_g$ are the liquid and gas mass flowrates,
Δp_1 and Δp_2 are the liquid and gas superficial differential pressures, and
ρ_l and ρ_g are the liquid and gas densities.

The Murdock Correlation is

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{1 + 1.26X_{Murdock}} \tag{5a}$$

Chisholm used a correction factor that was a function of pressure (although in fact the phase density ratio was used to keep the correction factor dimensionless) and a parameter which is the square root of the ratio of the superficial liquid inertia to the superficial gas inertia. Industry has since erroneously called this as the Lockhart-Martinelli parameter. In fact it is not the original Lockhart-Martinelli parameter which is the ratio of a two-phase flows superficial liquid to gas friction pressure drop along a unit length of pipe. Therefore this parameter is called the "modified" Lockhart-Martinelli parameter in this paper and denoted by the letter X.

$$X = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}} \tag{6a}$$

The Chisholm correlation is

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{\sqrt{1 + CX + X^2}} \tag{7a}$$

where

$$C = \left(\frac{\rho_l}{\rho_g}\right)^{1/4} + \left(\frac{\rho_g}{\rho_l}\right)^{1/4} \tag{8a}$$

de Leeuw and Steven both carried out wet gas tests using Venturi meters and found that both the Murdock and the Chisholm correction factors were not suitable for Venturis. For Venturis, de Leeuw and then Steven used correction factors that were functions of; the pressure; the modified Lockhart-Martinelli parameter and the gas flowrate. Again this was non-dimensionalised by the use of the gas densimetric Froude number usually denoted by "Fr_g". This is defined as the square root of the ratio of the liquid gravity force to the gas inertial force. It is:

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \tag{9a}$$

where U_{sg} is the superficial gas velocity which is calculated by:

$$U_{sg} = \frac{\dot{m}_g}{\rho_g A} \tag{10a}$$

and A is the meter inlet cross sectional area.

g is the gravitational constant (9.81 m/s^2)
D is the inlet diameter.

The de Leeuw correlation is based on the Chisholm correlation form. The data from a 4”, 0.401 beta Venturi Meter. It is:

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{\sqrt{1+CX+X^2}} \tag{7a}$$

where

$$C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n \tag{11a}$$

and $n = 0.41$ for $0.5 \le Fr_g \le 1.5$ (12a)

$$n = 0.606\left(1 - e^{-0.746\ Fr_g}\right) \textbf{ for } Fr_g \ge 1.5 \tag{13a}$$

The Steven correlation is based on data from a 6” 0.55 beta Venturi Meter tested at NEL. It was not possible to fit this data to the Chisholm / de Leeuw equation form. The resulting Steven correlation is:

$$\dot{m}_g = \frac{\dot{m}_{g\,(tp)}}{\left(\dfrac{1+AX+BFr_g}{1+CX+DFr_g}\right)} \tag{14a}$$

where

$$A = 2.085 + \left(0.0060 \Big/ \left(\frac{\rho_g}{\rho_l}\right)^2\right) \tag{15a}$$

$$B = -0.08 + \left(0.0001 \Big/ \left(\frac{\rho_g}{\rho_l}\right)^2\right) \tag{16a}$$

$$C = 0.548 + \left(0.0042 \Big/ \left(\frac{\rho_g}{\rho_l}\right)^2\right) \tag{17a}$$

$$D = -0.079 + \left(0.00009 \Big/ \left(\frac{\rho_g}{\rho_l}\right)^2\right) \tag{18a}$$

Note that this Steven Venturi wet gas correlation is an updated an final version to that previously published [5]. Similarly to the de Leeuw equation it has an uncertainty of 2% with a few outlying points.

At present the only way to ensure an accurate correction for a differential pressure meter in wet gas operation is to test a meter in a wet gas test facility prior to installation in the field or in situ against a reliable and traceable reference. Whilst de Leeuw and Steven both published improved correction factors for Venturis based on their own data, it is clear that further work is required in this area to provide a larger, more reliable data set on which to base further improved correction factors.