Flomeko 2000 - IMEKO TC9 Conference
Salvador, Bahia, BRAZIL
4-8 June, 2000

WET GAS METERING WITH A HORIZONTALLY INSTALLED VENTURI METER

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Abstract

"Wet Gas" Metering is becoming increasingly important to the Natural Gas Production Industry as "Wet Gas" flows are becoming more common in the field and the addition of a field separator is prohibitively expensive. "Wet Gas" is defined here as all flows with a Gas Volume Fractions greater than 95%. There is no agreement in industry to which wet gas metering method is best. Of all the published two-phase flow Differential Pressure (DP) Meter correlations this research has shown seven to be of possible relevance. This paper uses new independent data to compare their performance. Finally, a new correlation is offered.

NOTATION

x	quality (i.e. the ratio of the gas mass flow to the total mass flow)
$\dot{m}_l$ & $\dot{m}_g$	liquid and gas mass flow
D	pipe diameter
$\dot{Q}_l$ & $\dot{Q}_g$	liquid and gas volumetric flow
r_l & r_g	liquid and gas densities
U_{sl} & U_{sg}	liquid and gas superficial velocities
F_{rg} & F_{rg}	liquid and gas Froude Number
K_l & K_g	liquid and gas flow coefficients
ΔP_{tp}	two phase pressure drop across the meter
ΔP_g & ΔP_l	superficial pressure drops across the meter for gas & liquid phases respectively
X	"Modified" Lockhart-Martinelli Parameter (i.e. $X = \sqrt{\Delta P_l / \Delta P_g}$)
d	Root Mean Square Fractional Deviation
n	No. of relevant points

1 INTRODUCTION

Wet Gas Metering has been growing in importance to the Natural Gas Industry over the last few years. Due to the increasing number of wet gas flows being encountered in Natural Gas Production Pipelines there is a strong desire to improve upon the existing technology so meter manufacturers and production companies alike have been taking an active interest in this research topic. There are many general two phase DP Meter Correlations available in the literature but most are unsuitable for Wet Natural Gas Metering for various different reasons. This research considered seven two-phase flow DP Meter correlations potentially suitable for Wet Natural Gas Metering. By use of a Venturi Meter of industry production specifications ($b = 0.55$) supplied by ISA Controls Ltd and the new Wet Gas Loop at NEL new independent data was obtained and these seven correlations compared. Such a comparison of existing correlations was not previously possible as there was no reliable data available which had not been used to create one or more of these seven correlations. Hence, this paper offers the first independent comparison of the available DP Wet Gas Correlations. After the comparison was completed this new data was used to develop a new correlation method.

It should be noted that this paper assumes no errors exist in dry gas metering and all meter errors are due to liquid presence. It should also be noted that all the correlations assume prior knowledge of the liquid flowrate. In industrial situations this is not the case and methods such as the Tracer Dilution method are employed. These are said to have +/- 10% accuracy [1]. Finally, note that no correlation yet accounts for thermodynamic or compressibility effects.

2 THE DEFINITION OF "WET GAS" FLOW

There is no one definition of "Wet Gas" accepted by the Natural Gas Industry. Different organisations have different ideas to what this phrase means. There is only general agreement that "Wet Gas" states the existence of a relatively small quantity of liquid in a gas flow. This meant this research had to gather a wide span of data to encompass all the definitions. The range was from an upper limit of liquid flow was the case of equal gas and liquid mass flowrates (based on one major production companies definition) down to the minimum of as small a liquid flowrate as possible (as some production companies talked of traces of liquid in the gas leaving the separator).

3 THE SEVEN DIFFERENTIAL PRESSURE METER WET GAS CORRELATIONS

There are many two-phase DP Meter correlations in the literature. The majority of these are for Orifice Plate Meters as for years this meter type was the favoured meter in industry. (A good summary of two-phase Orifice Meter correlations is given by Lin in Reference [2].) Most of these are not suitable for metering wet natural gas flows for various reasons. Often the flow conditions of the tests were very different to what would be found in a natural gas production pipeline. In fact it was found that most of these correlations were formed from data sets which did not have any points in the upper range of the required flow qualities. It was therefore found that only five two-phase Orifice Plate Meter correlations were suitable for being included in a correlation performance comparison for wet natural gas flows. Even here, however, the data sets these chosen correlations were derived from were far from ideal for justifying their use in a wet gas natural gas pipeline. They were selected for being the best of the poor choice available and for being the correlations the industry tends to use in practice as it has no alternative. That is, due to the fact that the two existing wet gas Venturi correlations (see below) are so recently created the industry has traditionally had to make do with using Orifice Plate Meter wet gas correlations to try and correct wet gas Venturi readings due to this lack of alternatives. The five Orifice Plate Meter wet gas correlations considered were the Homogenous Equation [2], the Murdock Equation [3], the Chisholm Equation [4], the Lin Equation [5] and the Smith & Leang Equation [6].

Recently the Natural Gas Industry has tended to prefer Venturi Meters to Orifice Plate Meters. Only two wet natural gas Venturi correlations are known to this author and only one of these is published. This is the 1997 de Leeuw's correlation [7]. It was unchecked by any researcher with independent data until now and it is still little known or used by the industry. The other wet gas Venturi correlation is the unpublished findings of a natural gas producing company operating in the North Sea. Using field data from a wet gas the Murdock analysis (see Ref. [4]) was repeated and the constant in the correlation altered to suit the Venturi Meter. This author calls this the "Murdock Venturi Equation". This final equation was quoted to the author along with the fact that the wells working pressure was approximately 45 Bar. No other information such as phase flowrates or fluid properties was offered.

The seven correlations considered worthy of comparison are therefore as follows:

1) The Homogenous Equation [2]:

$$\dot{m}_{gas} = \frac{K_g A_t \sqrt{2\, r_g \Delta P_{tp}}}{\sqrt{\left(\frac{r_g}{r_l} + \left(\left(\frac{\dot{m}_{gas}}{\dot{m}_{gas} + \dot{m}_{liquid}}\right)\left(1 - \frac{r_g}{r_l}\right)\right)\right)}} - \dot{m}_{liquid} \tag{1}$$

The Homogenous Equation is the original attempt to correct the error produced in a DP Meter when the a two-phase flow is present. It is based on the idea of averaging the densities to get an equivalent pseudo-single phase flow. No account is taken of the flow pattern. (The flow pattern is now beginning to be understood by more recent researchers as important) Note, that as is the case with all the following correlations the value of the gas mass flowrate must be found by iteration.

2) The Murdock Equation[3]:

$$\dot{m}_{gas} = \frac{K_g A_t \sqrt{2 r_g \Delta P_{tp}}}{1 + 1.26 X} \qquad \text{(2a)}$$

which expands to:

$$\dot{m}_{gas} = \frac{K_g A_t \sqrt{2 r_g \Delta P_{tp}}}{1 + 1.26 \left(\frac{\dot{m}_{liquid}}{\dot{m}_{gas}} \right) \left(\frac{K_g}{K_l} \right) \frac{\sqrt{r_g}}{\sqrt{r_l}}}$$

(2) The Murdock Equation was formed from a wide range of Orifice Plate Meter data including data from wet natural gas production flows and wet steam tests. The flow conditions were wide ranging. Wet gas was not directly considered, the analysis was for all two-phase flows. However, the data does cross into the wet gas range and therefore the correlation is valid here. Murdock formed the equation by creating a model that assumed a stratified flow pattern at all flow conditions.

In equation (2) the "Murdock Constant" of 1.26 can me seen. This is the gradient of the linear line fit found for Murdock's data when plotted on a graph of $\sqrt{\Delta P_{tp} / \Delta P_g}$ vs. X . This gradient is of particular interest in this paper as the Murdock Venturi Equation (equation(7)) is otherwise identical to equation(3), except for this value. Also, the new correlations offered in section (7) have this gradient (denoted as " M ") as a function of pressure and then as a function of pressure and gas flowrate.

3) The Chisholm Correlation[4]:

$$\dot{m}_{gas} = \left(\frac{K_g A_t \sqrt{2 r_g \Delta P_{tp}}}{\sqrt{1 + CX + X^2}} \right) \qquad \text{(3a)}$$

where for X <1:

$$C = \left(\frac{r_{liquid}}{r_{gas}} \right)^{\frac{1}{4}} + \left(\frac{r_{gas}}{r_{liquid}} \right)^{\frac{1}{4}}$$

(3b)

That is:

$$\dot{m}_{gas} = \left(\frac{K_g A_t \sqrt{2 r_g \Delta P_{tp}}}{\sqrt{1 + \left(\left(\left(\frac{r_g}{r_l} \right)^{\frac{1}{4}} + \left(\frac{r_l}{r_g} \right)^{\frac{1}{4}} \right) \left(\frac{\dot{m}_{liquid}}{\dot{m}_{gas}} \right) \left(\frac{K_g}{K_l} \right) \left(\sqrt{\frac{r_g}{r_l}} \right) + \left(\frac{\dot{m}_{liquid}}{\dot{m}_{gas}} \right)^2 \left(\frac{K_g}{K_l} \right)^2 \left(\frac{r_g}{r_l} \right) \right)}} \right)$$

(3)

Chisholm considered general two-phase flow through Orifice Plate Meters and assumed stratified flow. Various data sets were used, including Murdock's. The correlation is therefore valid. This model included more detailed analysis of the shear force at the phase boundary. Note, that from the constant " C " in equation(3b) unlike Murdock in equation(2a), Chisholm indicates the correction depends on the pressure for a given value of X .

4) The Lin Correlation[5]:

$$\dot{m}_{gas} = \frac{K_l A_t \sqrt{2 r_l \Delta P_{tp}}}{\left(\frac{\dot{m}_{liquid}}{\dot{m}_{gas}}\right) q + \sqrt{\frac{r_l}{r_g}}} \qquad (4a)$$

where:

$$q = 1.48625 - 9.26541(r_g / r_l) + 44.6954(r_g / r_l)^2 - 60.6150(r_g / r_l)^3 - 5.12966(r_g / r_l)^4 - 26.5743(r_g / r_l)^5 \qquad (4b)$$

The derivation of Lin's equation is similar to Murdock's equation(2) with the exception that the effect of shear between the phases is stated to be a function of pressure alone as seen in equation (4b). This correlation is formed from Orifice Plate Meter data with wet steam and the refrigerant R-113 across the full range of two-phase flow conditions (including some wet gas flows making it valid here). It must be stated however, that Lin states some of the data was taken from non-standard Orifice Plate Meters. 5) The Smith & Leang Correlation[6]:

$$\dot{m}_{gas} = K_g A_t (BF) \sqrt{2 r_g \Delta P_{tp}} \qquad (5)$$

where BF is the "Blockage Factor":

$$BF = 0.637 + 0.4211x - \frac{0.00183}{x^2} \qquad (5a)$$

The Smith & Leang Equation (5) is formed from a different approach to the problem than taken by the other researchers. A "Blockage Factor" is a corrective value that is introduced to the single phase equation to account for the slow liquid flow partially blocking the fast gas flow. Smith & Leang effectively assume the primary influence of this Blockage Factor to be the flow pattern and this led to the form of equation (5a). Again, the correlation is for two-phase flow but some wet gas data was used making it valid. (Note however, as the quality goes to 100% the Blockage Factor goes to 1.04778, i.e. not unity as it physically must to be correct!)
6) The de Leeuw Correlation[7]:

$$\dot{m}_g = \frac{K_g A_t \sqrt{2 r_g \Delta P_{tp}}}{\sqrt{1 + CX + X^2}} \qquad (3a)$$

where

$$C = \left(\frac{r_l}{r_g}\right)^n + \left(\frac{r_g}{r_l}\right)^n \qquad (6)$$

and $n = 0.606\left(1 - e^{-0.746 Fr_g}\right)$ for $Fr_g \geq 1.5$ i.e. an annular mist flow pattern

$n = 0.41$ for $0.5 \leq Fr_g \leq 1.5$ i.e. a stratified flow pattern

where

$$F_{rg} = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{r_g}{r_l - r_g}}$$

(7)

The de Leeuw correlation is the only published wet gas Venturi Meter correlation and de Leeuw is the first to claim that a correction method must take account of pressure and gas flowrate. The form of the equation is Chisholm's equation (3a). However, equation (6) replaces Chisholm's equation (3b) transforming the equation to a function of pressure and gas flowrate. The data sets used were a Venturi Meter wet gas field data set and a test centre data set (using diesel oil and nitrogen).
7) The Murdock Venturi Correlation:

$$\dot{m}_{gas} = \frac{K_g A_t \sqrt{2 \rho_g \Delta P_{tp}}}{1 + 1.5\left(\frac{\dot{m}_{liquid}}{\dot{m}_{gas}}\right)\left(\frac{K_g}{K_l}\right)\frac{\sqrt{\rho_g}}{\sqrt{\rho_l}}} \tag{8}$$

This is the same equation as the Murdock Equation (2) with the exception that data from a Venturi operating with a production wet natural gas flow (unknown flowrates) at approximately 45 bar has been used to find the constant of 1.5 to replace the orifice constant found by Murdock of 1.26.

4 PREVIOUS TWO-PHASE FLOW CORRELATIONS COMPARISONS

No wet gas Venturi Meter correlation comparison has previously been published. In fact, only three general two-phase Orifice Plate Meter correlation comparisons exist (Ref.[6], Ref.[2] & Ref.[8]) and these are not independent of each other. All suffer from a lack of independent data in which to judge the correlation performances. The conclusions in these paper are therefore of limited value. It is clear what is required is a rig capable of giving independent data in which to test the correlations. This now exists at NEL.

5 EXPERIMENTAL APPARATUS

The data used for this papers comparison was obtained by this author on the newly commissioned NEL Wet Gas Loop using a standard ISA Controls Ltd. ($\beta = 0.55$) Venturi. This facility has a 11.2m^3 separator holding the fluids nitrogen and kerosene (which were chosen as the best acceptable choice to simulate wet natural gases after the latter was deemed too hazardous to meet legal requirements). The gas flows in a six inch (schedule 40, i.e.154mm inside bore) gas pipeline that has a 200kW Howden centrifugal blower capable of supplying up to 1100 m^3/hr in dry gas flows. This dry gas flow is metered by an Instromet reference gas turbine meter upstream of the liquid injection point. The gas flow is cooled by a Bi-Water HP Air Cooler directly downstream of the blower. The liquid pump is an eleven stage Ingersoll-Dresser pump which supplies up to 60 m^3/hr of kerosene via a bank of liquid reference turbine meters to the control valves that dictate the quantity of liquid injected. The injector was for some data points an open pipe and for others a nozzle attached to this open pipe. (It was discovered during commissioning that the injector type did not matter as flow pattern equilibrium was reached prior to the inlet of the test piece.) Directly upstream of the test piece was a Tritech Ltd. "Sea Spy" high pressure camera installed to allow viewing of the flow pattern during testing. This camera allowed the system operator to check that the flow pattern was not stratified flow but was indeed annular-mist as was predicted to exist in both the actual production pipelines and the NEL facility by both the Shell Expro empirical flow pattern map and the leading academic prediction method, the semi-empirical Taitel & Duckler Method. Finally, the upstream pressure and the Venturi Differential Pressure was measured by Yokogawa pressure transducers.

For all three pressures tested (20,40 & 60 bar) the maximum gas flowrate was capped at 1000 m^3/hr due to the calibration limit of the reference gas turbine meter.(The minimum gas flowrate tested was chosen to be 400 m^3/hr). This upper capping was required for the smaller liquid flowrates as the system was capable of more. However, with higher liquid flowrates the extra resistance in the system meant that the blower could not deliver 1000 m^3/hr. Hence for the higher gas flowrates the values of X are less than for the lower gas flowrates.

6 THE INDEPENDENT COMPARISON

The method of comparison of the seven correlation performances was chosen to be by comparison of the root mean square fractional deviation (as was done in Ref.[6] & Ref.[8]). That is:

$$d = \sqrt{\left[\frac{1}{n}\Sigma\left(\frac{\dot{m}_{gas}\left(predicted\right) - m_{gas}\left(actual\right)}{\dot{m}_{gas}\left(actual\right)}\right)^2\right]}$$

(9)

In total 243 points were taken in the test matrix. The range of liquid and gas flowrates and the corresponding value of the "modified" Lockhart Martinelli Parameter (X) are given in Table 1 below.

Table 1. The Flowrate Range at the Three Pressures Tested

Pressure Qg (m^3/hr)	20 Bar X range	40 Bar X range	60 Bar X range
400	0.0032 to 0.1559	0.0012 to 0.2299	0.0011 to 0.3086
600	0.0021 to 0.1536	0.0008 to 0.2192	0.0007 to 0.2716
800	0.0015 to 0.1174	0.0006 to 0.2102	0.0006 to 0.2756
1000	0.0012 to 0.0175	0.0005 to 0.0562	0.0004 to 0.0816

This data was used to find the root mean square fractional deviation for each correlation for all the data and then for each pressure. The results are shown in Table 2 below.

Table 2. The Results of the Root Mean Square Fractional Deviation for All Pressures Together and then Individual Pressures.

FOR ALL PRESSURES:	d +/-	FOR 20 BAR DATA:	d +/-
Murdock (M=1.5)	0.02616	de Leeuw	0.025416
de Leeuw	0.032227	Murdock (M=1.5)	0.03133
Murdock (M=1.26)	0.035413	Chisholm	0.039514
Chisholm	0.036555	Lin	0.044897
Homogeneous	0.04262	Murdock (M=1.26)	0.045684
Lin	0.046235	Homogeneous	0.053765
Smith & Leang	0.082111	Smith & Leang	0.067016

FOR 40 BAR DATA:	d +/-	FOR 60 BAR DATA:	d +/-
Murdock (M=1.5)	0.020899	Murdock (M=1.26)	0.02388
de Leeuw	0.03015	Murdock (M=1.5)	0.02531
Homogeneous	0.034929	Chisholm	0.032862
Murdock (M=1.26)	0.033905	Homogeneous	0.03707
Chisholm	0.037192	de Leeuw	0.039131
Lin	0.044785	Lin	0.04787
Smith & Leang	0.080903	Smith & Leang	0.095114

The results are shown graphically over the page.

It can be seen that as would be expected the new Venturi correlations do very well. However, as the Murdock Venturi Equation was formed from data with only one pressure and a relatively constant value of X , while the de Leeuw Equation was formed from a wide span of data, the fact that with the exception of the 20 bar case the Murdock Venturi Equation was more accurate was very surprising. Especially surprising was the poor performance of the de Leeuw Equation at 60 bar as this is well inside this correlations range. On the whole it can be seen that for applications in which there would be different pressures the Murdock Venturi Equation is the best choice. For applications in the 20 bar range the de Leeuw equation is best. For applications in the 40 bar range the Murdock Venturi Equation is best. Another unexpected result at 60 bar was the good performance of the original Murdock Equation. However, it will be shown in the section(7) that the general good performance of the Murdock Venturi Equation and the good performance of the original Murdock Equation at 60 Bar is actually coincidental to the NEL data range and is not as surprising as at first glance.

Of the five Orifice Plate Meter Equations the Smith & Leang Equation has got the poorest performance. Clearly, the constants found by Smith & Leang from their non-standard Orifice Plate Meter data set are not of use for the case of Venturi Wet Gas Metering. Likewise, the Lin Equation was formed from some non-standard orifice Plate Meters and included data with R-113 as the flowing fluid and here too a relatively poor accuracy was found when it was applied to Venturi Wet Gas Metering. As would be expected the Homogenous Equation was one of the poorer correlations. However, it is interesting to note that although for the all pressure comparison it was the third least accurate for 40 and 60 bar it was mid-table. This indicates that although it is now known that parameters such as the flow pattern, fluids type and DP Meter type are important to accurately predicting the required correction applied to a meters reading, if a correlation formed with data from one set of these parameters is applied to the case of a flow with another different set of parameters the correction may actually be less accurate than simply using the traditional homogenous method! The Chisholm Equation can at best be said to be of average performance. This is not surprising given Chisholm's statement in Ref.[4] that for Orifice Plate Meter performance the correlation was "…unsatisfactory with the values from the remaining two [data sets]-James and Murdock. This requires further study." In fact these two data sets were the only two Chisholm had for the lower values of X that are dealt with in this paper. Finally, it must be said that the original Murdock Equation, the correlation best known and probably the most used by industry, is actually reasonably accurate compared to the other Orifice Plate Meter Correlations. Perhaps this is partially due to a greater percentage of the data used to form it being from wet natural gas flows compared to the others that use far more wet steam data. Of course the overall good performance of this correlation for the all pressures case is boosted from the fact that it is the most accurate at 60 bar for what will be shown to be a coincidence in section(7).

20 Bar

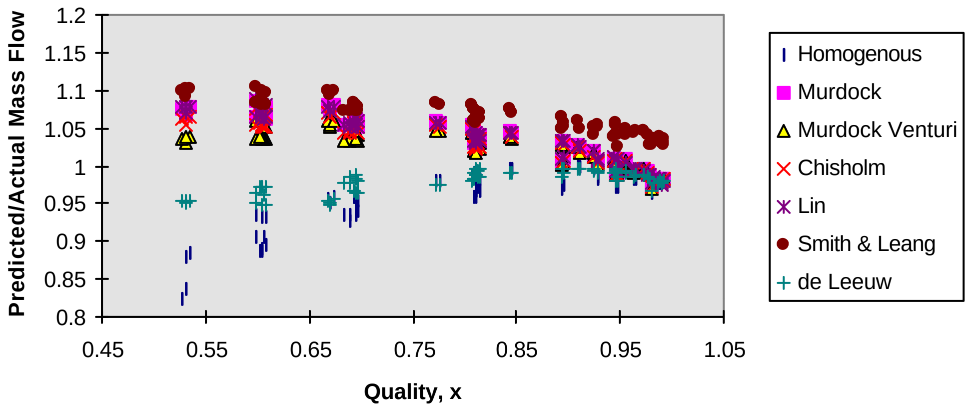


Figure 1. Comparison of all seven correlations using 20 bar data.

40 Bar

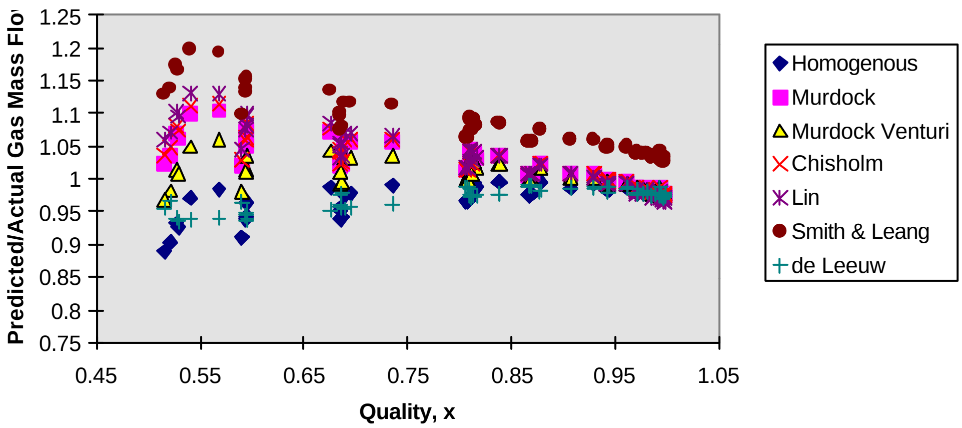


Figure 2. Comparison of all seven correlations using 40 bar data.

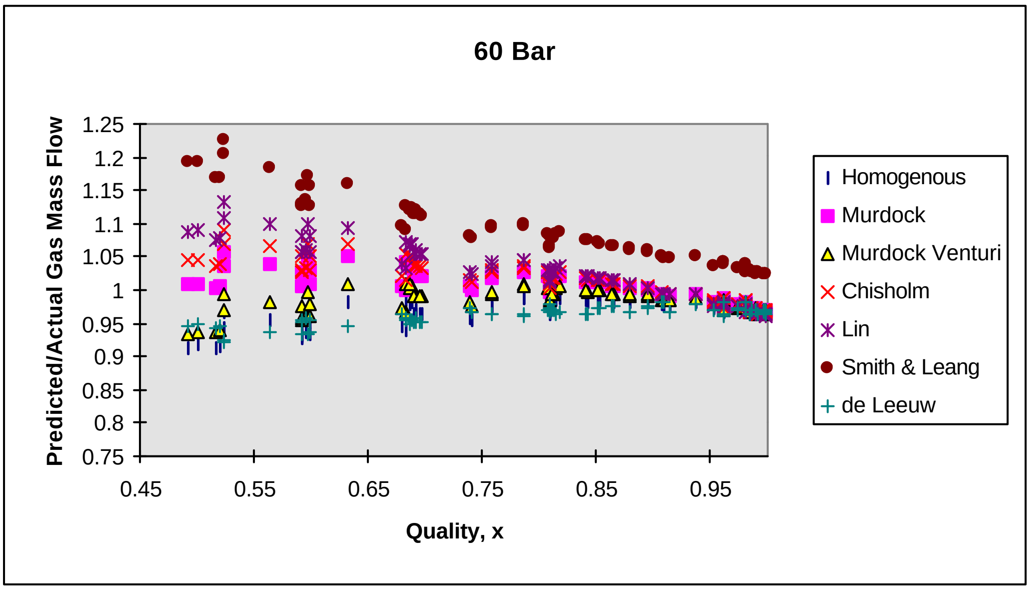


Figure 3. Comparison of all seven correlations using 60 bar data.

One interesting and important point that must be mentioned is the fact that not all the data points had the meter over-reading. That is, it is generally assumed in all two-phase/wet gas DP Meter papers that the liquid presence will cause a greater pressure drop across the meter due to the liquid being forced along by energy exerted by the gas, a situation that would result in the meter over estimating the gas flow. However, it was found during the NEL / ISA Venturi tests that this is not always the case. For the case of very small liquid quantities compared to the gas flow rate, i.e. very small X values, a meter under-reading occurred. (See Fig.4 As an example). This under-reading existed for all three pressures and all gas flowrates. For each case it was noted that as the gas flowrate reduced so did the amount of liquid capable of producing a meter under-reading. In all previous papers it appears the minimum value of X tested was above the value required to see this phenomenon. A consequence of this is that none of the existing correlations are of a form that even allows an under-reading to be corrected. This finding could be of significance to the case of under-sized or inefficient separators which leave a trace of liquid in the post separator "dry gas" line where the metering is traditional carried out. (It should be noted that in Ref.[9] Ting et al. indicated that an Orifice Meter had under-read in field tests. However, no explanation or correlation was offered). It is postulated by this author that the reason for this under-reading is in fact the "back effect" phenomenon. This phenomenon is named and studied by researchers interested in solid particle/ gas flows and it describes how small solid particles in a gas flow effect the turbulence by damping it down. It is therefore possible that for two-phase liquid/gas flows with a dispersed flow pattern a similar phenomenon could occur.

7 A NEW CORRELATION

The first use of this new data after the comparison was complete was to repeat Murdocks method (Ref.[3]) of finding the gradient of a linear fit of all data together on a $\sqrt{\Delta P_{tp}/\Delta P_g}$ vs. X graph. This gradient, generally denoted as " M " and found to be equal to 1.26 by Murdock when using his Orifice Plate Meter data, was found to be 1.5163 (see Figure 4).

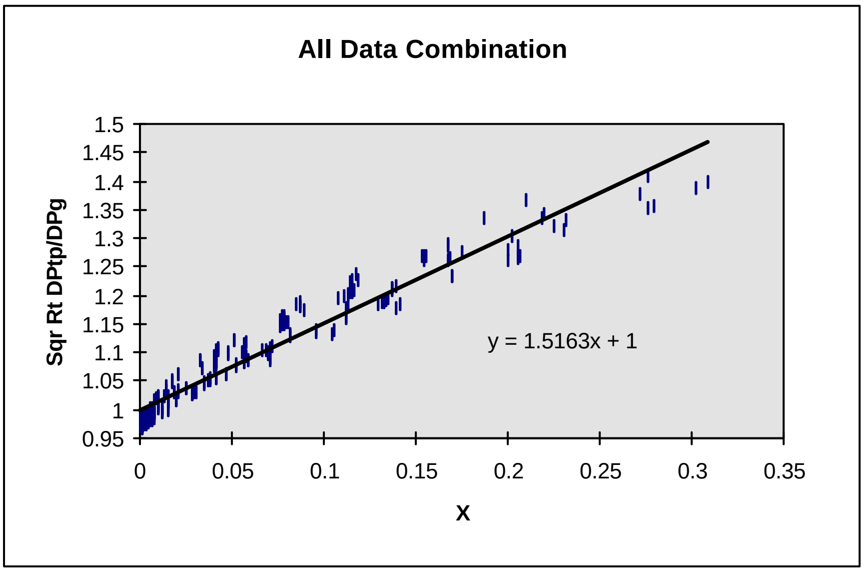
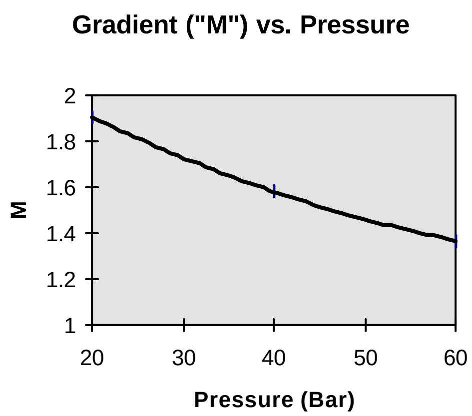


Figure 4. A Murdock Type Graph with Venturi Data

It is therefore clear why the Murdock Venturi Equation (with $M = 1.5$) did so well in the above comparison. But as this value of M was found from one pressure of 45 bar the next investigation was to find how this gradient varied for the three pressures. Graphs were created for each of the three pressures data points and the gradient found. The results were plotted on a Gradient (M) vs. Pressure graph and a line was fitted. (See figure 5 below).



The three points had a line fitted by the software TableCurve 2D. The equation is:

$$M = EXP\left(1.0958067 - 0.100878\sqrt{P}\right) \quad (9)$$

where P is the pressure in bars.
(Applied to data set used to form equation the root mean fractional deviation is 0.021)

Figure 5. The relationship between the Murdock Gradient and Pressure.

Note that in order to maintain a reasonable approximation to the gradient found for a linear fit of the data on a $\sqrt{\Delta P_{tp} / \Delta P_g}$ vs. X graph it was necessary to ignore the data of the flows at 1000 m^3/hr as most of this data was for very small liquid flowrates and hence much of it was too close to the origin to give a reasonable gradient estimate. From equation (9) it is found that at 45 bar the gradient "M" is 1.52. This is very close to the value of 1.5 used in the Murdock Venturi Equation. Furthermore, it should be noted at 60 bar equation (9) predicts a gradient of 1.37 which resolves the problem of the surprising result at the 60 bar correlation comparison of the original Murdock Equation being more accurate than the Murdock Venturi Equation. That is, as 1.37 is closer to 1.26 than 1.5 the fact that the original Murdock Equation was more accurate than the Murdock Venturi Equation is no longer surprising, it is just shown to be a coincidence. Finally, as at 20 Bar equation (9) gives a gradient of 1.91 the reason for the poor result of the original Murdock Equation compared to the Murdock Venturi Equation is understood.

Equation (9) effectively updates Murdocks original method to the statements of Chisholm and Lin that any meter correction needs to account for pressure and this new equation has the added advantage that it is formed from Venturi data. However, de Leeuw suggested that the correction should in fact take into account both pressure and gas flowrate for given fluid properties. On investigating the relationship of the Murdock Gradient (M) at each pressure with varying gas flowrates it was indeed found that the gradient changed. Hence, for each pressure and gas flowrate (excluding the 1000 m^3/hr for the fore mentioned reason) graphs of $\sqrt{\Delta P_{tp} / \Delta P_g}$ vs. X were created and the gradient found for each case. The software TableCurve 3D was then used to find the gradient as a function of pressure and gas flowrate. The resulting equation obtained shown below.

$$M = \frac{1.45964 - 0.005(P) - 0.00583\left(\dot{Q}_g\right) + 0.00000433\left(\dot{Q}_g\right)^2}{1 - 0.00562(P) - 0.00379\left(\dot{Q}_g\right) + 0.00000294\left(\dot{Q}_g\right)^2}$$

(10)

where P is in bar and $\dot{Q}_g$ is in cubic metres per hour. (Applied to data set used to form equation the root mean fractional deviation is 0.015).

Equations (9) &(10) simply need to be substituted into the place of the Murdock constant ($M = 1.26$) and the equation iterated. The range of their application is:

$$20Bar \leq \Pr essure \leq 60Bar$$

$$400m^3 / hr \leq \dot{Q}_g \leq 800m^3 / hr$$

$$0.012 \leq X \leq 0.3^*$$

where * indicates some extrapolation may be required depending on the data (see table 1).

8 CONCLUSIONS

There are several conclusions that can be drawn from this research. The first is that of the existing wet gas correlations the little known Murdock Venturi Equation is the best for wet gas Venturi Meters over the experimental range used in this paper. However, from the subsequent investigation of the relationship between the Murdock gradient, pressure and gas flowrate it was discovered that a considerable improvement in accuracy can be obtained by swapping the constant in the Murdock Venturi Equation with equation(9) to make it a simple function of pressure and a further smaller improvement is possible if this constant is swapped with equation (10) making it a more complex function of pressure and gas flowrate. It should of course be noted that these correlations do not account for the very small liquid flowrates producing Venturi meter under-readings. It therefore stands that these correlations should not be used for $X < 0.012$. Current work at the NEL includes the creation of a new correlation capable of predicting both the under and over-readings of a wet gas Venturi Meter and this should be published in the near future.

ACKNOWLEDGEMENTS

The author would like to thank Dr. A. Gilchrist of Strathclyde University for the academic support supplied, ISA Control Ltd. for their supply of a production standard Venturi Meter (and for information on industrial practices) and Dr. D. Hodges for his assistance during the NEL testing program.

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