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LIQUID CORRECTION OF VENTURI METER READINGS IN WET GAS FLOW

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SUMMARY

Venturi flow meters can be used to measure the actual gas flow rate in wet gas streams, provided the liquid content is known. An empirical correlation is presented which accurately predicts the effect of the liquid phase on venturi meter readings in wet gas horizontal flow. The correlation is based on a comprehensive experimental data set which was collected in a full scale multiphase flow test facility. The test envelope covers the majority of the wet gas operating conditions encountered in the field. Deviations between the new correlation and the experimental base are better than 2%. The new correlation differs fundamentally from the well known orifice plate correlations of Murdock and Chisholm in that the observed dependence on the gas Froude number is accounted for and the pressure dependence is verified from 15 bar to effectively dense phase conditions. Test results of the overall pressure loss across the venturi meter are also presented. The liquid content of the gas stream can be measured using the tracer dilution method. Field experience with the tracer method over the last couple of years have demonstrated that the flow rates of water and condensate can be determined within the target uncertainty of 10%. At present the tracer method is available to the industry via two licensed contractors.

1. INTRODUCTION

The development costs of gas/condensate fields can be reduced significantly if test separators are replaced by venturi flow meters in each well flow line, and the wetness of the flow is measured periodically, typically 1 to 2 times a year, using a (non-radioactive) tracer method[1,2], see figure 1. The production from different fields can then simply be commingled prior to transporting and processing by shared facilities.

The tracer method involves injection of suitable tracers into the flow line followed by sampling of the liquids. Measurement of the tracer dilution ratio allow the determination of the water and condensate flow rates. Combining these liquid flow rates with the venturi meter readings and the correlation predicting the effect of the entrained liquids on the readings, enable the condensate gas ratio and water to gas ratio to be determined. Using the established CGR and WGR, the raw venturi readings can be interpreted continuously in terms of gas, water and condensate flow rates, until such time that the liquid to gas ratio has substantially changed.

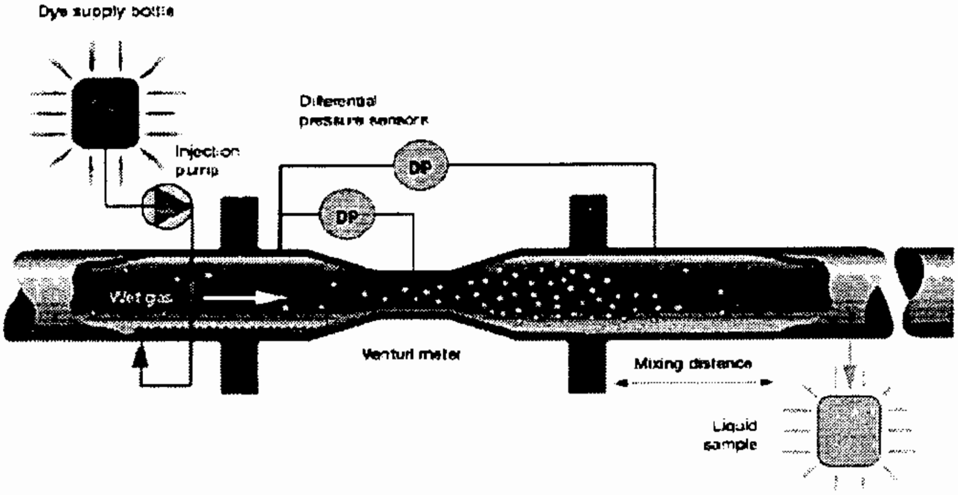

Figure 1. Wet Gas Metering Technique

To date various investigators have proposed expressions to describe the effect of entrained liquid on venturi or orifice meter readings[3]. However, as empirical correlations should only be used within their corresponding experimental range, the applicability of these expressions is limited as they have mainly been established from experiments at low to moderate pressures and flow rates as compared to field conditions. Furthermore, the most well known relationships of Murdock[4] and Chisholm[5] apply to orifice plates only.

Previous experiments at Coevorden[6,7], a field location in The Netherlands, have shown that the overreading of an orifice meter measuring natural gas at pressures around 90 bar and liquid fractions up to 4% by volume closely followed the coinciding predictions by Murdock and Chisholm. However, their apparent similarity at around 90 bar is a coincidence as extrapolation shows that for all other pressures each correlation gives a different predicted overreading. In addition the venturi meter showed a higher overreading than the orifice meter.

The experimental test range covered at Coevorden, however, was still relatively limited. Although natural gas at high pressure could be tested, variations in pressure were limited. The corresponding flow conditions were all located in a small part of the flow map: stratified wavy flow with almost no entrainment. Therefore, a comprehensive experimental data set on the performance of a venturi flow meter in wet gas flow was called for. Such a data set was gathered at the SINTEF Multiphase Flow Laboratory in Trondheim, Norway[8]. The test envelope at this facility covered the majority of the wet gas flow conditions to be encountered in the field. The resulting data set allowed a better correlation to be developed, which is presented in this paper.

2. THE TEST SET-UP

The wet gas venturi tests were conducted at the SINTEF Multiphase Flow Laboratory, located near Trondheim, Norway. The line pressure of this large scale facility could be varied between approximately 15 and 95 bar. The entire system was insulated and heat traced to keep the temperature constant at around 30 °C. The flow loop was equipped with a horizontal, as well as a vertical riser section. The overall length of the loop was about 1 km. Single phase volumetric flow rates could be varied between 26 and 11,000 m^3/d for the liquid and between 1,200 and 35,000 m^3/d actual for the gas. All tests were performed with diesel oil as the liquid and nitrogen as the gas phase. The 4 inch test venturi had an inner pipe diameter of 97.18 mm and a throat diameter of 39 mm, resulting in a beta ratio of 0.401. As the nominal pipe diameter of the test loop was 8 inch, 70 D of 4 inch pipe was installed upstream of the venturi meter and 20 D downstream. This formed a 4 inch test section which had been located in the horizontal section of the test loop, approximately 850 meters from the beginning of the loop and 70 meters upstream from the inlet of the riser.

The venturi meter was equipped with 4 differential pressure transmitters. Two for measuring the differential pressure over the throat of the venturi, for the flow rate calculation, and two for measuring the overall pressure loss across the meter. Pressure and temperature transmitters were also provided, as well as a single energy gamma densitometer. The densitometer was used to monitor the liquid level in the pipe in order to get an indication when a new flow condition had reached the venturi section. As the total upstream length consisted of approximately 850 meters of 8 inch pipe this could take more than half an hour, depending on the actual flow velocities.

After a flow condition at the venturi section had stabilised two measurements were taken, separated by approximately 5 minutes. An individual measurement consisted of 2 minutes of data logging at a sample rate of 2 samples per second. After the logging period the averages and the standard deviations were calculated and stored.

3. TEST ENVELOPE

The test envelope was chosen to cover the majority of the wet gas operating conditions which can be encountered in the field. This is important as empirical relationships can not be applied outside their corresponding experimental range.

The tests were performed at four different line pressures of 90, 45, 30 and 15 bar, with liquid fractions up to respectively 10%, 8%, 6% and 4%. The wetness of the gas, in LGR terms, varied between 0 and 1000 m^3/million nm^3 at 90 bar, 1500 m^3/million nm^3 at 45 bar, 1800 m^3/million nm^3 at 30 bar, and 2500 m^3/million nm^3 at 15 bar. In Lockhart-Martinelli terms these values correspond to 0 and 0.3 for all conditions. Gas velocities, expressed in terms of the densiometric Froude number, were selected in the range between 1.5 and 4.8. A detailed overview of the test conditions can be found in table 1. In total, about 100 different flow conditions were covered.

Table 1. Summary of the flow conditions at the venturi meter.

Pressure	Gas velocity	Gas Froude number	Liquid velocity	Liquid Froude number	Lockhart-Martinelli parameter	LGR	GVF
[bar]	[m/s]		[m/s]			[m^3/10^6 nm^3]	[%]
90	12	4.8	0 - 1.2	0 - 1.31	0 - 0.3	0 - 1000	100 - 90
	8	3.2	0 - 0.9	0 - 0.97	0 - 0.3	0 - 1000	100 - 90
	4	1.6	0 - 0.4	0 - 0.44	0 - 0.3	0 - 1000	100 - 90
45	11.4	3.2	0 - 0.8	0 - 0.85	0 - 0.3	0 - 1500	100 - 92
	5.8	1.6	0 - 0.4	0 - 0.42	0 - 0.3	0 - 1500	100 - 92
30	14.5	3.2	0 - 0.8	0 - 0.83	0 - 0.3	0 - 1800	100 - 94
	7.3	1.6	0 - 0.4	0 - 0.41	0 - 0.3	0 - 1800	100 - 94
15	17	2.5	0 - 0.7	0 - 0.71	0 - 0.3	0 - 2500	100 - 96
	10	1.5	0 - 0.4	0 - 0.41	0 - 0.3	0 - 2500	100 - 96

The lowest test pressure of 15 bar corresponds to a gas density of approximately 17 kg/m^3. Nitrogen was used as the test gas. This means that the developed correlation should not be used for gas densities much below 17 kg/m^3. The maximum test pressure was 90 bar, corresponding to a gas density of approximately 100 kg/m^3. However, the new correlation is also valid for pressures above 90 bar as the overreading reaches a well defined theoretical limit for conditions at which the gas density equals the liquid density.

The range of the Lockhart-Martinelli parameter from 0 to 0.3 corresponds to different ranges for the gas volume fraction and the liquid to gas ratio depending on the actual pressure. As can be seen from table 1. In fact, the minimum GVF, or the maximum LGR, increases at lower pressures. Basically, parameters like LGR or GVF are not particularly suitable to compare specific flow conditions at different pressures. The relationship between the GVF and the Lockhart-Martinelli parameter (X) can be expressed as:

$$\mathrm{GVF} = \frac{Q_g}{Q_g + Q_l} = \frac{1}{1 + X\sqrt{\frac{\rho_g}{\rho_l}}} \tag{1}$$

The relationship between the LGR and X as:

$$\mathrm{LGR} = \frac{Q_l}{Q_{g,nc}} = X \cdot \frac{\rho_{g,nc}}{\sqrt{\rho_g \cdot \rho_l}} \cdot 1{,}000{,}000 \tag{2}$$

Where 'nc' stand for normal conditions i.e. 0 °C and 101325 Pa. The LGR is commonly expressed in m^3 of liquid per million m^3 of gas at normal conditions. Often standard conditions are used of 15°C and 101325 Pa.

Wet gas flow conditions are best expressed in terms of their gas and liquid densiometric Froude numbers, equations 3 and 4 respectively. These give a more consistent relationship between flow parameters and flow regimes, i.e. corresponding flow regimes are obtained by corresponding Froude numbers.

$$Fr_g = \frac{v_{sg}}{\sqrt{gD}} \cdot \sqrt{\frac{\rho_g}{(\rho_l - \rho_g)}} \tag{3}$$

$$Fr_l = \frac{v_{sl}}{\sqrt{gD}} \cdot \sqrt{\frac{\rho_l}{(\rho_l - \rho_g)}} \tag{4}$$

The ratio of liquid Froude number to gas Froude number is equal to the Lockhart-Martinelli parameter. This parameter has proven itself to be a successful correlation parameter in the area of multiphase flow.

$$X = \frac{Q_l}{Q_g} \cdot \sqrt{\frac{\rho_l}{\rho_g}} \qquad \left(= \frac{Fr_l}{Fr_g}\right) \tag{5}$$

The experimental test envelope as drawn in a Froude number map is illustrated in figure 2. The borders between the various flow regimes, as well as the previous Coevorden test envelope, and a typical gas/condensate field production profile are also indicated. As can be seen, the current experimental envelope covers a large range of conditions in the stratified and annular dispersed flow regimes, close up to the border with the intermittent slug flow regime.

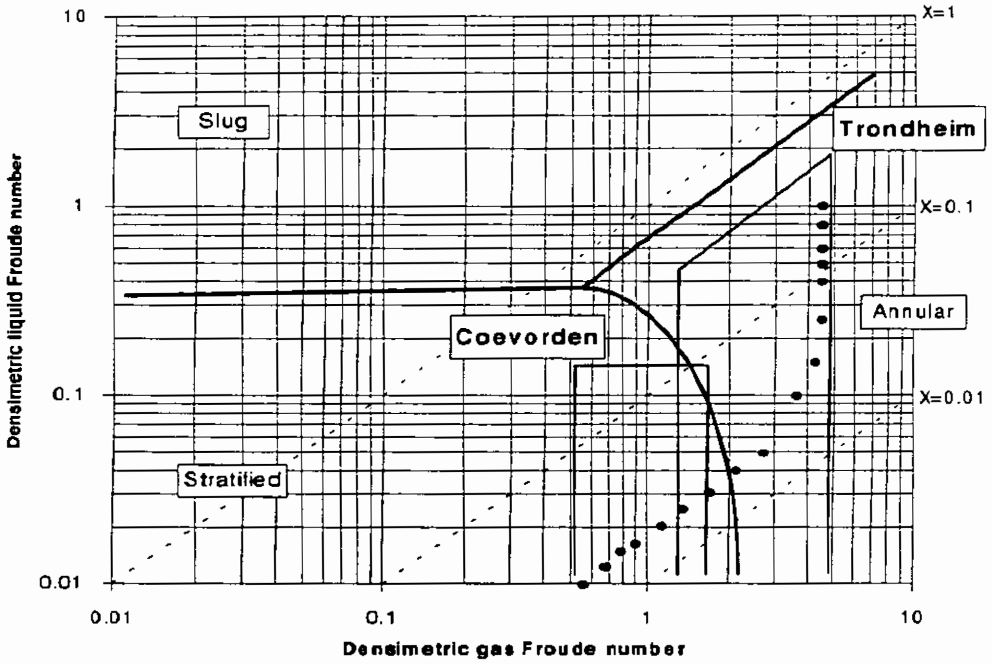

Figure 2. Flow map showing the Trondheim test envelope (various pressures), compared to Coevorden (90 bar only), and a typical production profile.

4. TEST RESULTS AND PRESENTATION OF THE NEW CORRELATION

4.1. Venturi flow rate overreading

The presence of liquid in the gas stream causes the differential pressure over the venturi meter to increase with respect to the case when only the gas is flowing. This larger differential pressure results in a larger calculated gas flow rate, hence the venturi meter is said to "over-read". In the following the term overreading will refer to the ratio $Q_{tp}/Q_g = (\Delta P_{wet}/\Delta P_{dry})^{1/2}$.

Some typical test results are shown in figure 3. In this figure the venturi meter overreading is plotted against the liquid fraction expressed in terms of the Lockhart-Martinelli parameter. The dependence of the overreading on the actual line pressure, or better on the gas density, can clearly be seen. The lower the pressure the higher the overreading. At 15 bar and a Lockhart-Martinelli parameter of around 0.3 a venturi meter overreading of almost 1.8 is reached.

Figure 3 also shows the theoretical limit line. This line represents the condition for which the density of the gas phase equals that of the liquid. Consequently, the overreading can never go below this line. Therefore, overreading curves for pressures above 90 bar have to lie between the 90 bar and the theoretical curve. The theoretical line has been taken into account during the development of the correlation.

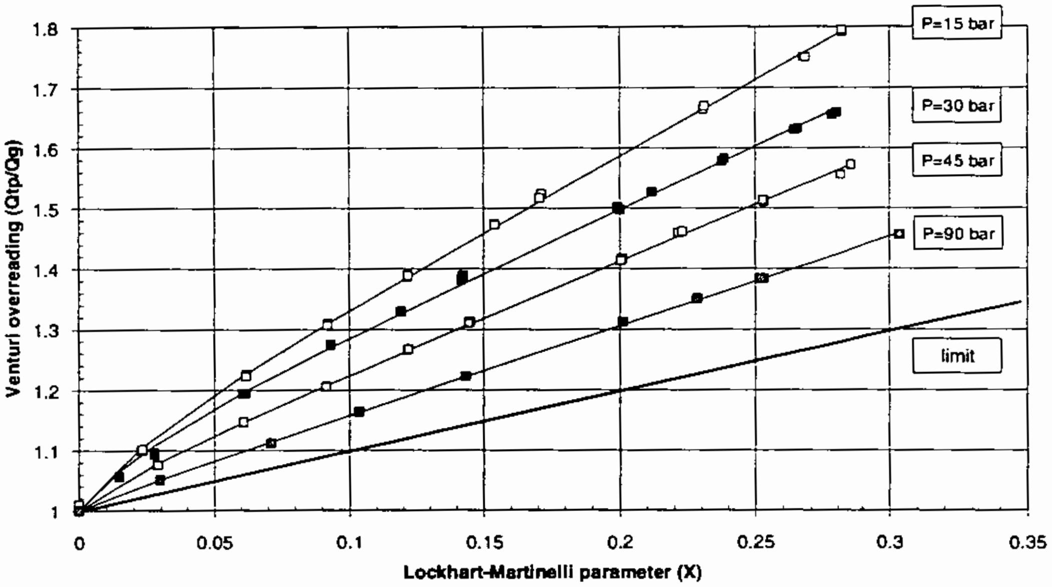

Figure 3. Trondheim test results showing venturi overreading against liquid fraction, expressed as the Lockhart-Martinelli parameter. Frg = 3.2

The test results furthermore show that the venturi meter overreading is dependent on the actual gas velocity, or gas Froude number. This is illustrated in figure 4, where the overreading is plotted for a single line pressure, but for two different gas velocities, i.e. 12 m/s and 6 m/s, corresponding to gas Froude numbers of approximately 3.2 and 1.6, respectively. Without showing the similar graphs for all other pressures, it can be said that the lower the pressure the larger the spread. This dependence of the venturi meter overreading on the gas Froude number has not been reported in any earlier publication. Hence, all previous reported correlations are limited in their validity as none of them take this dependence into account.

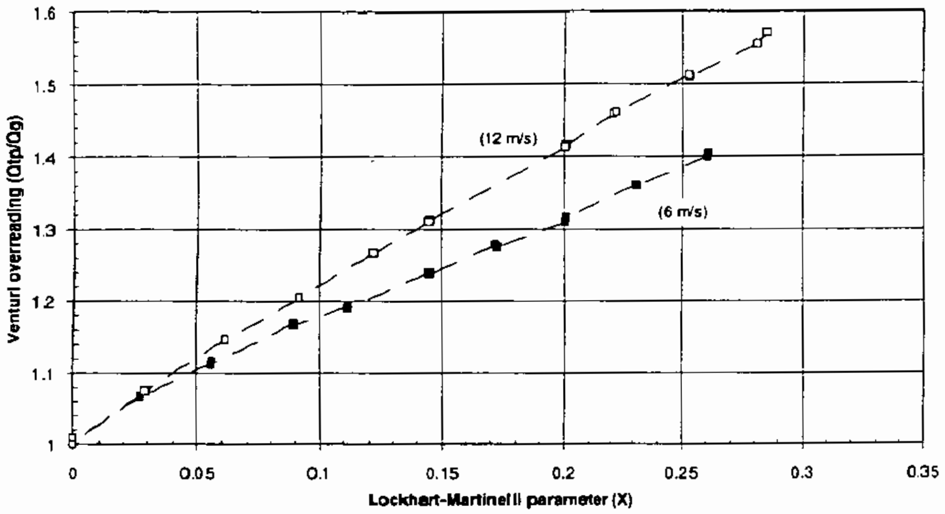

Figure 4. Typical test results showing the venturi meter overreading at 45 bar and two different gas velocities.

In particular, the experimental data shows that the well known relationships of Murdock and Chisholm do not predict the correct venturi overreading. The reason being, apart from the fact that they were originally developed for orifice plates, is that the Murdock equation neither takes the pressure nor the gas Froude number dependence into account, while the Chisholm equation does not include the gas Froude number dependence.

4.2. Venturi overreading correlation

Based on the experimental data a new correlation for use with venturi meters has been developed. The final relationship is given by equation 8. A more detailed derivation can be found in Appendix A.

$$\frac{Q_{tp}}{Q_{go}} = \sqrt{1 + CX + X^2} \qquad \text{where:} \quad C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$$

$$\left.\begin{array}{llll} \text{and} & n = 0.606\left(1 - e^{-0.746 \cdot Fr_g}\right) & \text{for} & Fr_g \geq 1.5 \\ & n = 0.41 & \text{for} & 0.5 \leq Fr_g < 1.5 \end{array}\right\} \qquad (8)$$

Above relationship is valid for gas densities above 17 kg/m^3 (up to the liquid density), gas Froude numbers above 0.5, and Lockhart-Martinelli parameters up to 0.3.

A measure of how well the new venturi correlation describes the experimental data is shown in figure 5. This figure shows the absolute difference between the correlation and the actual test points. It can be seen that the difference stays within approximately ±2%. The standard deviation of the difference is only 1%. Furthermore, the individual differences have a zero mean and are normally distributed.

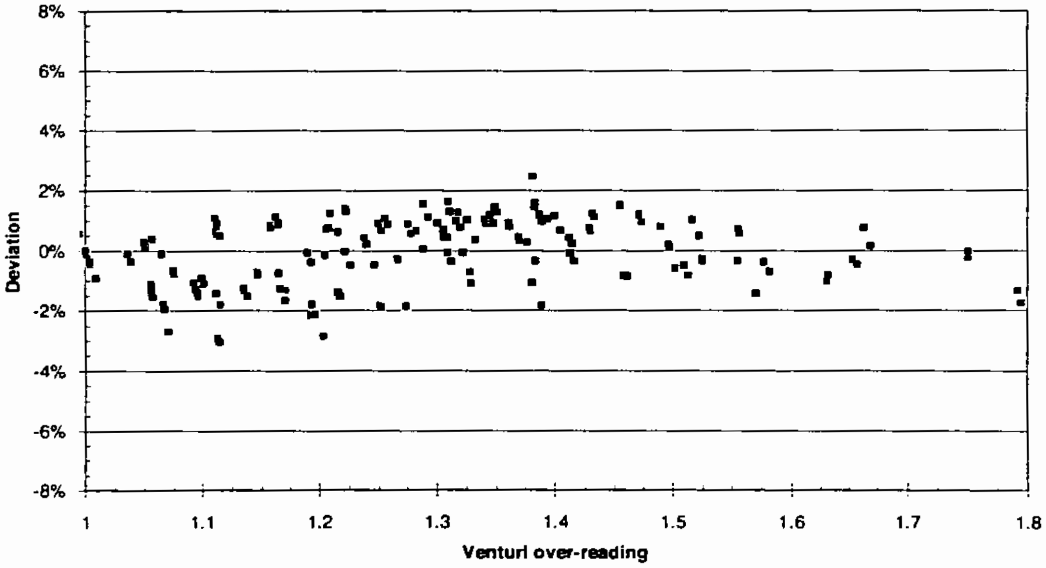

Figure 5. Plot of the difference between the developed correlation and the experimental data expressed in percentage overreading. The results are plotted as a function of the actual overreading.

To illustrate the difference between the new venturi correlation and the Murdock and Chisholm expressions, a plot has been made, see figure 6, for a typical condition for which the gas density is 80 kg/m^3 and the liquid density 700 kg/m^3. As mentioned earlier, the Murdock and Chisholm relationships do not differ too much at this condition. In contrast the new correlation predicts a different overreading for different gas Froude numbers, which leads to significant differences.

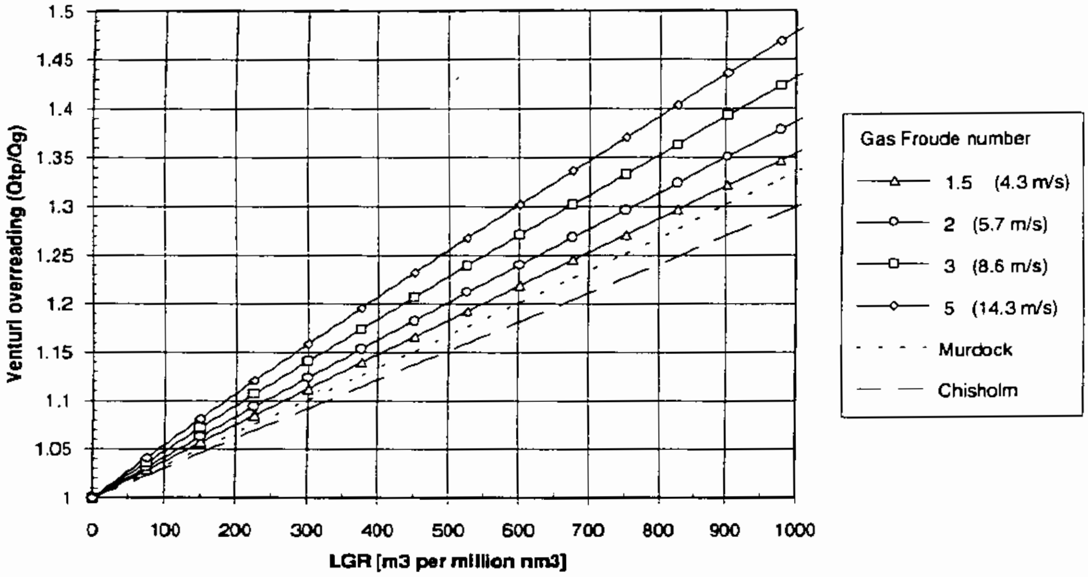

Figure 6. Illustrative comparison between the new venturi correlation and the Murdock and Chisholm orifice relationships, for the case ρ_l=700 kg/m^3 and ρ_g=80 kg/m^3.

4.3. Venturi pressure loss ratio

The pressure loss across a venturi meter is larger in two-phase flow than in single phase flow. Part of the energy which is transferred from the gas to the liquid phase when flowing through the inlet and throat sections, is not recovered in the diffuser section.

Some typical 90 bar test results are shown in figure 7, in which the venturi pressure loss ratio is plotted against the Lockhart-Martinelli parameter. The pressure loss ratio is defined as the ratio between the overall pressure drop across the meter divided by the differential pressure over the throat. The results show that the pressure loss ratio depends on the actual liquid content. Similar to the venturi meter overreading, the pressure loss ratio also depends on the actual gas velocity or gas Froude number.

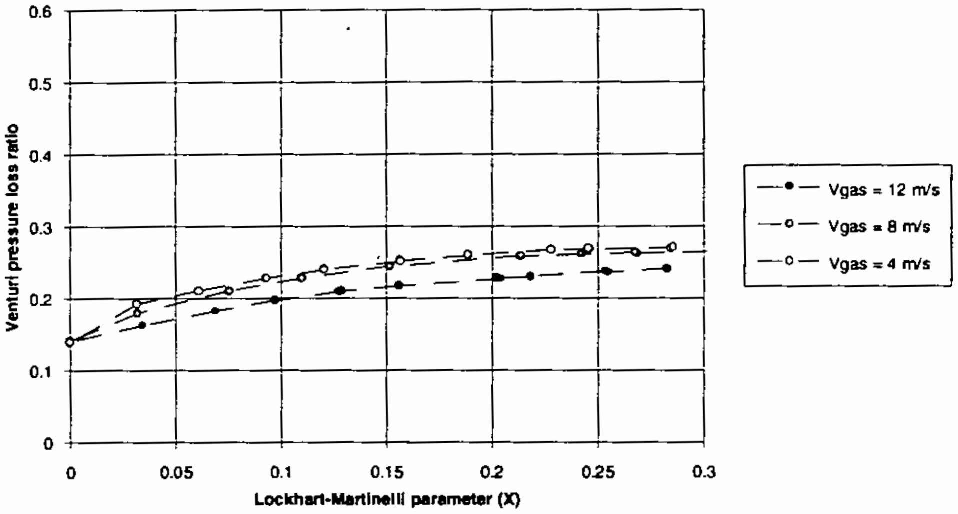

Figure 7. Test results at 90 bar showing the venturi pressure loss ratio against the Lockhart-Martinelli parameter for various gas velocities.

The potential for the pressure loss measurement is to use it as a means to determine the liquid content of the flow, from which the overreading factor can be determined accordingly. In essence this would form a simple two-phase flow meter. To date, however, no acceptable correlation formula has yet been found which would relate the pressure loss ratio to the actual liquid content and the overreading. Additional experiments might be required.

Although the exact behaviour is not yet known, the pressure loss ratio can still be used to monitor changes in the liquid content. This can be an important feature when using the tracer dilution technique for measuring the liquid content. Only when the pressure loss ratio has indicated a significant change in the liquid content, tracer measurements have to be organised.

The sensitivity of the pressure loss ratio to the actual liquid content is not constant, but varies depending on the actual wetness and line pressure. The sensitivity, which is equal to the slope of the curves, is adequate in the lower wetness range, but decreases with increasing wetness. The change in sensitivity with pressure can be seen in figure 8 where the pressure loss ratio measurements at 45 bar are shown. In this case the pressure loss ratio becomes virtually independent of the liquid content for Lockhart-Martinelli parameters larger than approximately 0.15.

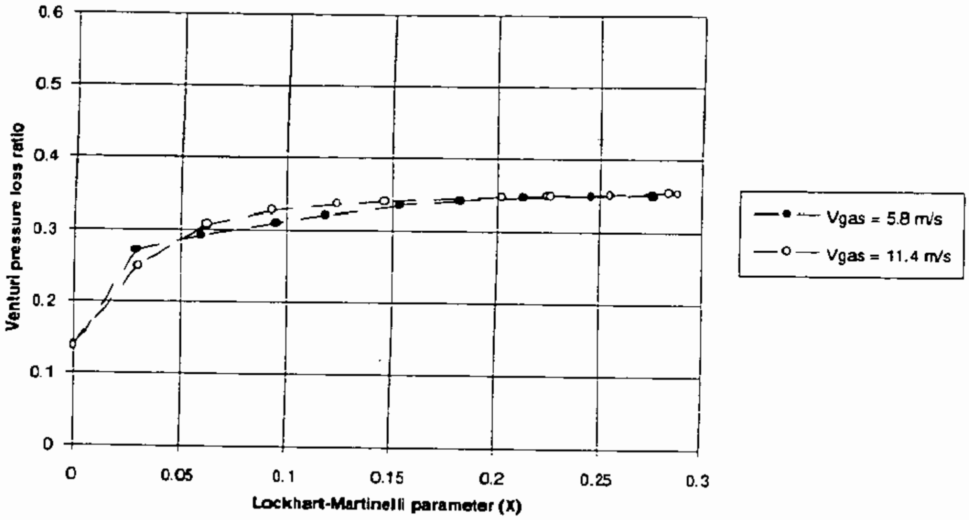

Figure 8. Test results at 45 bar showing the venturi pressure loss ratio against the Lockhart-Martinelli parameter.

5. TRACER METHOD STATUS

To determine the liquid content of the gas stream a method based on the tracer dilution technique has been developed, which was the subject of an earlier paper[4] presented at the North Sea Flow Measurement workshop in 1994. A schematic of the technique is included in figure 1. A suitably chosen tracer is injected into the flowing stream at a precisely metered rate. Downstream of the injection point, where the tracer has mixed thoroughly with the fluid, a liquid sample is taken. From the tracer dilution ratio and the injection rate the liquid flow rate can be determined.

Using different tracers the water and condensate flow rates can be measured at regular intervals. As the wetness is expected to change only gradually with time once or twice a year is expected to be sufficient. More regular measurements, however, could be required during the beginning of the field to establish the wetness behaviour over time.

Over the last number of years various field trials with the tracer method have been done to prove the technique under actual conditions. An overview of the test results is given in figure 9, which shows the deviation between the tracer and the reference measurements. It can be seen that the deviations are well within the target range of 10%. Taking into account that the plotted deviation is in fact the combined uncertainty of the tracer method and the reference measurements, the uncertainty of the tracer method itself is even better.

After the field trials the tracer technology was licensed to SGS Redwood at Ellesmere Port, UK, and Petrotech a.s. at Haugesund, Norway, making the tracer method commercially available to the industry.

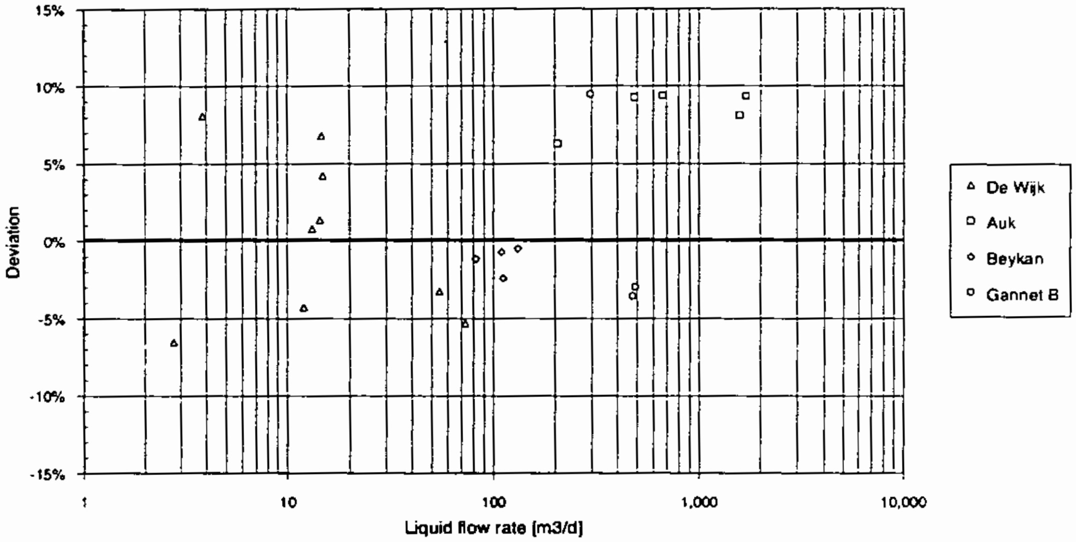

Figure 9. Overview of the various field tests, showing the deviation between the tracer method and reference measurements.

6. CONCLUSION

An empirical correlation to determine the overreading effect of the liquid phase on venturi meter readings in wet gas horizontal flow has been derived, which is in part similar to the Chisholm equation for orifice plates. The correlation is based on an extensive experimental data set, gathered at the SINTEF Multiphase Flow Laboratory in Trondheim, Norway, covering a wide range of wet gas flow conditions. The developed correlation describes the experimental data set better than ±2% absolute with a standard deviation of 1%, using only two free parameters. The theoretical overreading limit occurring at the (high) pressure for which the gas density equals the liquid density is exactly predicted. The relationships originally developed by

Murdock and Chisholm for orifice plates do not predict the venturi overreading correctly.

The experiments at SINTEF were done using a 4 inch venturi meter with a beta ratio of 0.4. Test fluids used were nitrogen and diesel oil. As the new relationship is empirical, different venturi dimensions and fluid properties should in principle be studied for their effect. However, these effects are expected to be minimal. Experiments by earlier investigators[9] with orifice plates showed no significant effect of the beta ratio. Moreover, the effect of different dimensions is basically accounted for as dimensionless Froude numbers are used. The data from the previous Coevorden tests, beta ratio 0.4, nominal line size 3 inch, and natural gas and water as test fluids, overlap with the SINTEF data for similar flow conditions.

The liquid content of the gas stream can be determined by means of the tracer dilution technique. Field trials at a number of different locations have demonstrated that the water and condensate flow rate can be measured within the target uncertainty of 10%. Using the new correlation this means that the gas flow rate can be corrected to within approximately 2% to 4%, depending on the actual liquid content. At present, the tracer method is commercially available through two licensed service companies, Petrotech a.s. in Norway and SGS Redwood in the UK. Continuous monitoring of variations in the liquid content can be done by measuring the venturi pressure loss ratio.

7. LIST OF SYMBOLS AND UNITS

β	venturi beta ratio (= d/D)	[-]
C	variable defined in eq. 4	[-]
D	internal pipe diameter	[m]
Fr_g	densiometric gas Froude number	[-]
Fr_l	densiometric liquid Froude number	[-]
g	gravitational constant	[m/s^2]
LGR	Liquid to Gas Ratio	[m^3/10^6 nm^3]
n	variable defined in eq. 5	[-]
P	pressure	[Pa]

Q_l	liquid flow rate	[m^3/s]
Q_g	gas flow rate	[m^3/s]
Q_{tp}	gas flow rate calculated using the two-phase pressure drop	[m^3/s]
ρ_l , ρ_g	liquid, gas density	[kg/m^3]
v_{sl} , v_{sg}	liquid, gas superficial velocity	[m/s]
X	Lockhart-Martinelli parameter	[-]

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APPENDIX A DERIVATION OF THE VENTURI CORRELATION

The experimental data presented in this paper shows that the well known relationships of Murdock and Chisholm do not predict the correct venturi overreading. The reason being, apart from the fact that they were developed for orifice plates, is that the Murdock equation neither takes the pressure nor the gas Froude number dependence into account, while the Chisholm equation does not include the gas Froude number dependence. This can be seen clearly if the Murdock and Chisholm relationships are written in terms of the Lockhart-Martinelli parameter (X).

Murdock's relationship:

$$\frac{Q_{tp}}{Q_g} = 1 + 1.26X \qquad \text{(A-1)}$$

Chisholm's relationship:

$$\frac{Q_{tp}}{Q_g} = \sqrt{1+CX+X^2} \qquad \text{where } C = \left(\frac{\rho_l}{\rho_g}\right)^{0.25} + \left(\frac{\rho_g}{\rho_l}\right)^{0.25} \quad (\text{for } X<1) \qquad \text{(A-2)}$$

It shows that the overreading predicted by the Murdock equation only depends on the Lockhart-Martinelli parameter. The effect of pressure and gas Froude number on the overreading, as illustrated in the figures 3 and 4, can therefore not be predicted. The Chisholm equation does take the line pressure into account via the C parameter which contains the gas density, but the explicit gas Froude number dependence shown in figure 4 is not predicted.

The general shape of the Chisholm curve, however, closely resembles those of the experimental curves. In particular the observed small curvature at low liquid fractions is well predicted. In fact, the experimental data for a single gas Froude number and line pressure can be described very well by the Chisholm equation by tuning the C factor.

Furthermore, it was found that a general form of Chisholm's relationship for parameter C,

$$C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n \qquad \text{(A-3)}$$

could be used to describe the pressure effect for a specific gas Froude number by selecting the right magnitude for parameter *n*. This is illustrated in figure A1. A fixed value for *n* thus describes the overreading curves for a single gas Froude number but for the whole pressure range.

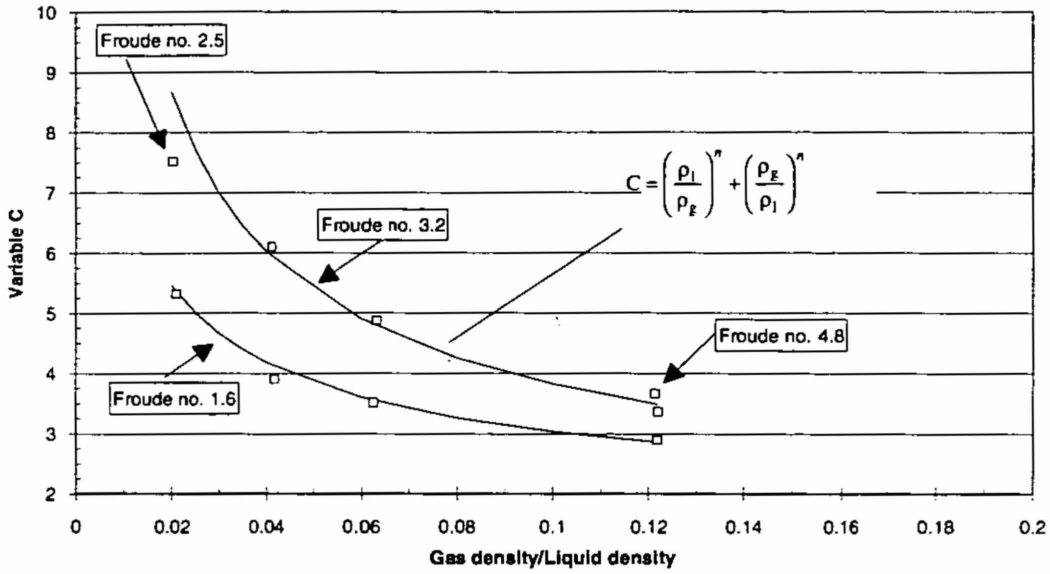

Figure A1. Resulting C values for the complete data set as a function of the density ratio and gas Froude number.

The theoretical limit condition is included automatically. When the gas density equals the liquid density C is equal to 2, independently of n. With C equal to 2, equation A-2 and A-3 exactly describe the theoretical line which holds for dense phase conditions, i.e. very high pressures.

All the resulting values for n, which are obtained by fitting equation A-3 to the data, are shown in figure A2. These values were fitted with the following empirical relationship:

$$n = 0.606\left(1 - e^{-0.746 \cdot \mathrm{Fr}_g}\right) \qquad \text{for} \quad \mathrm{Fr}_g \geq 1.5 \qquad \text{(A-4)}$$

The complete SINTEF data set has now been described by using only two free parameters, i.e. 0.606 and 0.746.

The value of n for gas Froude numbers between 0.5 and 1.5 is derived from the previous Coevorden data set and was found to be 0.41. As indicated in figure A2, the Coevorden test envelope partly overlaps with the SINTEF one, but extends further down to lower gas Froude numbers.

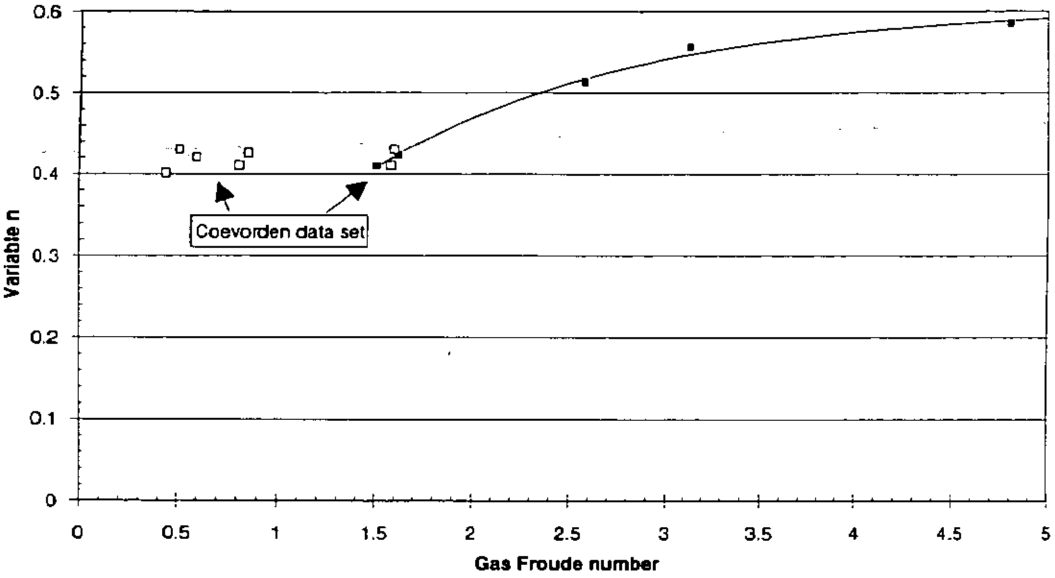

Figure A2. Resulting n values for both the Trondheim and Coevorden data.

The overlapping conditions are well predicted by the new correlation. However, the Coevorden results for Froude numbers below 1.5 show that the value of n does not decrease any further and stays constant at about 0.41. This effect is attributed to the fact that the Coevorden flow conditions were all in the stratified flow regime with a constant, but almost zero entrainment. At higher Froude numbers n increases as the entrainment increases.

The final relationship to calculate the venturi meter overreading is given by formula A-5. The relationship is valid for gas densities above 17 kg/m^3 (up to the liquid density), gas Froude numbers above 0.5, and Lockhart-Martinelli parameters up to 0.3.

$$\frac{Q_{tp}}{Q_{go}} = \sqrt{1 + CX + X^2} \qquad \text{where:} \quad C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$$

$$\left.\begin{array}{lll} \text{and} \quad n = 0.606\left(1 - e^{-0.746 \cdot Fr_g}\right) & \text{for} & Fr_g \geq 1.5 \\ n = 0.41 & \text{for} & 0.5 \leq Fr_g < 1.5 \end{array}\right\} \qquad \text{(A-5)}$$