North Sea Flow Measurement Workshop
25-28 October 2011

Venturi Meters and Wet Gas Flow

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ABSTRACT

Wet gas measurement is becoming essential for the oil and gas industry. Venturi flow meters are often used for this purpose. As the produced liquids also contribute to the measured differential pressure a correction is required to determine the actual gas flow rate. Recently, ISO has issued TR 11583 containing a new Venturi wet gas correlation. This paper presents a review of this ISO report. The conclusion of this review is that it is in the interest of the oil and gas industry that this ISO report should be ignored, preferably withdrawn, for several important reasons. In this paper these reasons will be explained. Using this ISO report in real life situations could lead to errors with the equivalent of millions of US$ per application.

1. INTRODUCTION

It has long been recognized that the Venturi flow meter gives reliable flow readings with wet natural gas flow. When used to meter wet gas flows, the Venturi meters gas flow rate reading is known to have a positive bias, induced by the presence of liquids. The wet gas flow correlation, to correct for this bias or so-called over-reading plays a critical role in determining the gas flow rate measurement uncertainty. Although a dedicated correlation is to be preferred, typically a previously published wet gas correlation is used. However, as the published correlations are developed from test facilities with set flow condition ranges that do not always cover all the industry application flow ranges, extrapolation of correlations is common. Extrapolation of correlations can produce significant biases in results.

In 2009 a Venturi meter wet gas correlation was presented at the North Sea Flow Measurement Workshop [1]. This work shortly thereafter was released as an ISO Technical Report [2]. However, the data sets used to create this correlation are relatively limited and heavily based on the single wet gas test facility at NEL. Also, the data sets used to create the correlation include gas with either water only or gas with refined hydrocarbon liquids only, whereas virtually all wells produce gas with water **and** hydrocarbon liquids (condensate). Moreover, until now there has not yet been a comprehensive independent review of the Venturi meter wet gas correlation as proposed in the ISO report. This paper discusses the results of a review undertaken using several independent data sets from various wet gas flow meter test loops and addresses a number of other technical issues.

2. DIFFERENCES BETWEEN CORRELATIONS AND MODELS

In the field of multiphase and wet gas measurement, the use of correlations and models is inevitable. However, in many papers, there is an incorrect use of the terminology. Often, correlation based algorithms are labeled "models", which implies more than the contents provides. This is more than just a semantic discussion as there is a distinct difference between the two:

- Correlations are curve-fits to measured data points. The dependence of the measurand on different parameters and their relation with physics is unknown.
- Models describe the dependence of the measurand by relations based on physics.

When designing correlations, one tries to include the dependence of the measurand on parameters one thinks are of importance. However, no guarantee can be given that all the essential parameters are included and often it is impossible to acquire data points for certain parameters even if these are likely to be of importance. In a test loop, for example, the fluid selection is usually limited. On top of that, no guarantee can be given that the correlation will give correct predictions outside the interval of the data points or when a parameter is changed. This can potentially induce a bias in the results. As each test loop has the potential to have some systematic errors these easily creep into correlations. Therefore, correlations should not be based on data from a single facility.

Models include the physics which govern the measurand results. In building the model, the essential parameters automatically emerge and the contribution of the different mechanisms can be determined. As a result models have predictive power outside the range of data points which have been used for the verification and when essential parameters change.

In our view, the developments in the field of multi-phase and wet gas measurement should shift from a correlation based to a model based approach.

2.1 Comments on experimental data fitting methods

Experiments often produce results where measured parameters appear to be related but no scientific theory exists to understand what the reason for that relationship is. However an empirical data fit to the experimental data is always a possibility. The empirical data fit is just the expression of the experimental data in a mathematical form, and many different mathematical equation forms can be used to express the same data set with similar accuracy. But none has any physical meaning. It is just a convenient method for expressing a set of unexplained experimental results, somewhat more than a repetition of the experimental results with the ability to interpolate and extrapolate the data set.

In other cases, when a limited amount of scientific understanding exists to explain the relationship, an approximation can be used to describe the experimental data. The correlation can then be limited to the approximations in the derived equations. Such a data fit, to unknown values framed around a physical model, is, in this paper, called a "semi-empirical" data fit. With a semi-empirical data fit, the existence of scientific laws allows boundary conditions to be set. That is, rather than being forced to blindly extrapolate an empirical data fit the scientific laws allow some theoretical values to be derived for conditions outside the limits of the available test data. Therefore, these so called theoretical "boundary conditions" offer further structure to a semi-empirical data fit. As a result, semi-empirical data fits are preferable for being more powerful and useful than just empirical fits.

It is possible to use the developed equation to "predict" results between the values of parameters tested (interpolation) or at parameter values in excess of (i.e. both larger and smaller than) the parameter ranges tested (extrapolation). However, in the strictest sense of the word, a correlation does not "predict" anything, interpolation or extrapolation of an empirical data fit only gives a set of numbers from the equation. The operator then assumes[1] that the data fit can correctly produce results outside the range of the experimental data which created it. In general, interpolation tend to give results which are reasonable trustworthy while extrapolation can easily lead to results with large errors.

With both empirical and semi-empirical data fitting a concern is always the possibility of "over-fitting", i.e. when the resulting mathematical expression describes the random noise in the experimental data as well as the underlying parameter relationships. Over-fitting is most prevalent when the data fit is excessively complex, such as having too many parameters relative to the number of observations (i.e. data points). A data fit which has been over-fit will generally have a poor predictive performance as it will likely exaggerate minor fluctuations in the data. A further concern when carrying out either empirical or semi-empirical data fitting is that if the data set is predominantly obtained from one set of test equipment, any test system biases will unknowingly, but falsely, be embedded in the data fit as underlying parameter relationships.

It is in practice impossible to cover all the conditions one will encounter in real-life by correlations, simply because of the huge number of data points required and because one does not know beforehand which parameters are of importance.

3. INTRODUCTION TO THE ISSUES WITH THE ISO TR 11583 REPORT

The industry would welcome a proper standard on the subject of wet gas metering, although many experts feel it is still somewhat premature given the state of the technology. Nevertheless, ISO has issued a report proposing to standardize on a Venturi meter wet gas correlation which is based on a paper published by NEL in 2009 [1]. Unfortunately, the work is considered by many to be a relatively isolated piece of work. The majority of the acknowledged worldwide experts in wet gas metering have not been consulted and they are in fact actively opposing this work being transformed into an International Standard Organisation Technical Report. There are several reasons for these objections:

1. The ISO report, and the NEL paper on which it is based, labels the work as a "model", but it is a correlation.
2. The primary base of the data is a single test facility and its researchers. The data base is a substantial data set from one facility, a single small data set from second facility and some untraceable historical data. This implies that all hidden systematic uncertainties of the primary test facility are included in the developed relationship. We believe that it should be mandatory that any standardised correlation is based on the results of a wide number of test facilities, and preferably substantiated by field experiences, to be acceptable to the industry. Preferably, the conditions should be as close as possible to actual field conditions.
3. The inclusion of the physical properties of the hydrocarbon fluids is incomplete. Gas density, liquid densities, fluid viscosities and surface tensions play a role, as well as the transfer to standard conditions. When these are not addressed, the results will be in error.

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[1] This assumption can be questionable and mathematical equations have an ability to give many individuals a false sense of authority and measurement precision.

4. The correlation includes at least 10 fit parameters, which carries the danger of "over-fitting", all the more because these parameters have no physical meaning.
5. The risk of erroneous results outside the range of the data on which the correlation is based is severe as the correlation does not give the correct values in the theoretical limiting cases.
6. There is a large knowledge base on wet gas measurement in the industry. We have not been able to discern the "lessons learned" of the past ten or more years in the ISO report. We think this is an unacceptable omission.
7. The discharge coefficient depends on the primary device. Making the C_d dependent on a number of flow parameters would mean a shift from the properties of the meter to the properties of the flow, which is undesirable. As multiphase flow is complex and only understood to a limited extent, we think this is an unattractive, if not incorrect, approach as the dependence in real systems might be quite different from the conditions in a test loop.
8. The ISO report correlation is based on gas and hydrocarbon liquid only, or gas and water only. In practice there are almost always three "phases" present. Experimental data on gas, hydrocarbon liquid and water mixtures show the ISO report correlations gives significant errors.
9. The ISO report correlations include the surface tension using the "*H*" parameter. However as the surface tension is not the same for a test loop kerosene-nitrogen system as for a natural gas-condensate system, the value as prescribed by the ISO paper is likely to be in error for practical, "real life", systems.
10. The ISO report should pay more attention to the Venturi hardware. It should specify the range of (calibrated!) values of the C_d which are acceptable for wet gas measurement as well as the location of the third pressure tap, used for the measurement of the Δp_{loss}. In our view, the Δp_{loss} should be calibrated too as there is, at this moment, insufficient understanding of the phenomena which govern this number. It seems that the relation, presented in the ISO report, contradicts the data in ISO 5167.
11. The use of the tracer dilution method in wet gas flow to determine the liquid flow rates is not as simple as indicated in the few paragraphs in the ISO report. From being closely involved in this technology for over 15 years, the authors believe from their experience that implementation of this technology following the ISO report will be far from sufficient. The ISO report writing could confuse the developers of future applications and prevent them from proper installation. As such the ISO report has the potential to put the successful application of this technology back by years.
12. The presented correlation dismantles the practice to build on the general over-reading equation and takes a step back to a pure empirical data fit. It thus also eliminates the "natural" correct prediction of the limiting cases of LM $\downarrow$ 0 and the dense phase condition.
13. The use of the expansibility factor of dry gas in real wet gas flows is questionable as the gas and hydrocarbon condensate are in thermodynamic equilibrium. Changes in pressure will therefore result in phase and temperature changes, which are currently unpredictable. Therefore, the differential pressure of the Venturi should be kept much smaller than the actual line pressure.
14. The ISO report does not specify any upper boundaries for line diameter, Reynolds number, fluid density ratio, and surface tension and fluid viscosity.
15. The ISO report lower boundary of the gas Froude number in the Venturi throat, stated that it should be above 3, is limiting realistic gas through puts, especially for larger beta values.

The most important of the above considerations will be addressed further in the paper below.

4. BASIC OVERREADING EQUATIONS

As shown in detail in Appendix A, from theory follows the general equation for the overreading as:

$$Overreading = \sqrt{1 + C \cdot LM + LM^2}$$

With the parameter "*C*" equal to:

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

The Lockhart-Martinelli parameter (LM) defined as:

$$LM = \frac{Q_l}{Q_g}\sqrt{\frac{\rho_l}{\rho_g}}$$

in which:

Q_l	=	volumetric liquid flow rate	m^3/s
Q_g	=	volumetric gas flow rate	m^3/s
ρ_g	=	gas density	kg/m^3
ρ_l	=	liquid density	kg/m^3

When expressed in this form, the value of n for specific cases is given by:

- 0 for stratified flow
- 0.25 according to Chisholm
- 0.5 for homogeneous flow
- and ranging between 0.41 – 0.606 according to De Leeuw

Note that this description of the over-reading gives the correct values for the limiting cases of 'dense phase' and zero liquid content.

Recently investigators from NEL proposed a new Venturi wet gas correlation [1], which has been presented in the ISO TC30 technical report TR 11583. However, this correlation is not based on the above general equation. The ISO report equations also modify the discharge coefficient of the meter. We will discuss several consequences regarding this proposal.

4.1 Background to the discharge coefficient

Differential pressure flow meters, as widely used in multiphase and wet gas flow measurements, require the use of a discharge coefficient or "C_d" to calculate the flow rate. An ideal differential pressure flow meter would not require a "discharge coefficient" as the differential pressure would solely be generated by the Bernouilli effect. The requirement for the use of a C_d is to account for the non-ideal flow through the meter. The reason that the measured differential pressure is higher than the differential pressure as predicted by the Bernoulli effect is mainly due that around the meter energy losses occur, dissipation of energy. These losses are larger with an orifice plate than with a Venturi, which is also illustrated by the low pressure recovery of an orifice. A cone flow meter sits somewhere between an orifice and a Venturi. The C_d is thus determined by the geometry of the meter. For optimum performance the Venturi meter C_d is found by calibration.

4.2 Discussion on the "n" value in the equation

By modeling wet gas flows through Venturi meters, Van Maanen showed that the principle of minimum energy for a separated wet gas flow produces a corresponding minimum "*n*" value of zero, as shown in figure 1. The derivation of this boundary condition is shown in Appendix A.

The conditions of Chisholm's tests were at relative low pressure and gas flow rate, so it is to be expected that his flow showed a significant stratification. Knowing that a mist flow has an "*n*" value of 0.5 and an ideal stratified flow an "*n*" value of 0, his choice of 0.25 is not surprising. De Leeuw, on the other hand, used high pressure Nitrogen at higher flow rates, so his flow regime would have been closer to a mist flow than stratified. Therefore it is not surprising that his "*n*" values lay around the value derived for a mist flow. The mist flow model has a theoretical maximum "n" value of 0.5. However, the de Leeuw correlation shows "*n*" values greater that 0.5. The explanation is that there is additional dissipation in the flow, which increases the differential pressure and thus leads to a higher over-reading and therefore a higher "*n*" value. So the value of "*n*" tells us something about the flow condition. The lower the value, the more stratification, the higher, the more entrained liquid and dissipation. However, because the flow regime changes when the fluids move through the Venturi, this is only a qualitative indication.

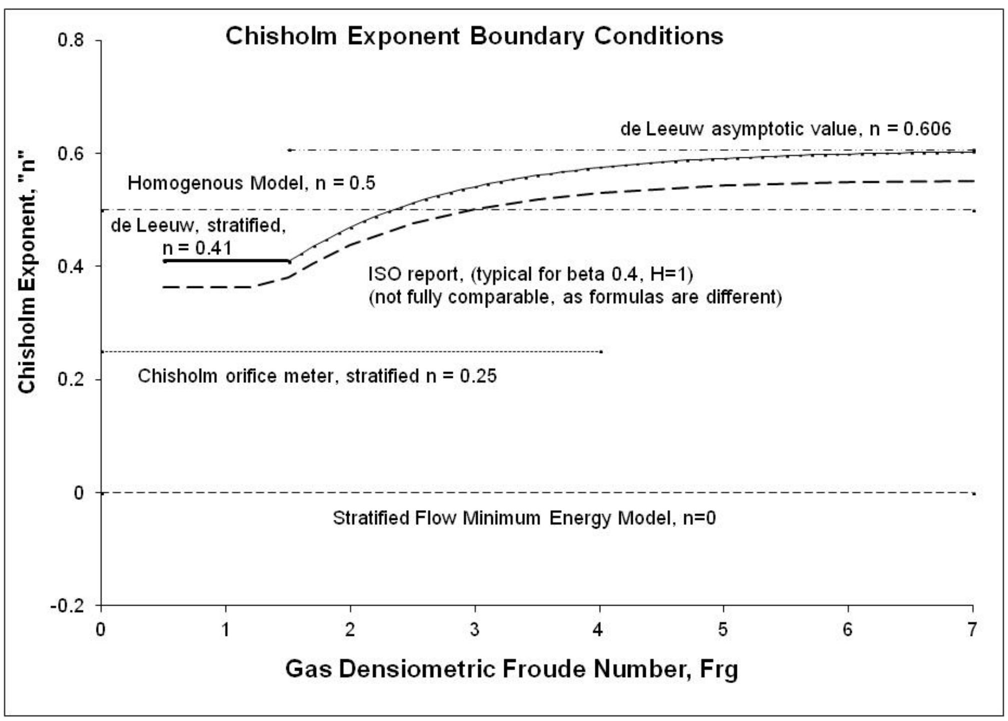

Figure 1: Various "*n*" values.

The range of "*n*" following from the ISO report is approximately 0.29 - 0.55. This is not fully comparable to the previous values as a component of the ISO report correction factor is a modification of the discharge coefficient. Effectively this modification will slightly increase the value of "*n*".

5. EVALUATION OF THE ISO TECHNICAL REPORT 11583

5.1 The "dense phase" condition

As is shown in Appendix A, the lower limit of the overreading of a Venturi is equal to 1 + *LM*. One condition when this limit is reached is at the "dense phase" condition when the gas and liquid densities are equal, which is approached with increasing line pressure. In this case the overreading should approach the theroretical 1 + *LM* limit. The main already existing correlations do so. The ISO report correlation does not as shown in figure 2 below. Therefore the existing correlations can, with some confidence, be extrapolated from the highest tested pressure to dense phase conditions, whereas the ISO correlation cannot.

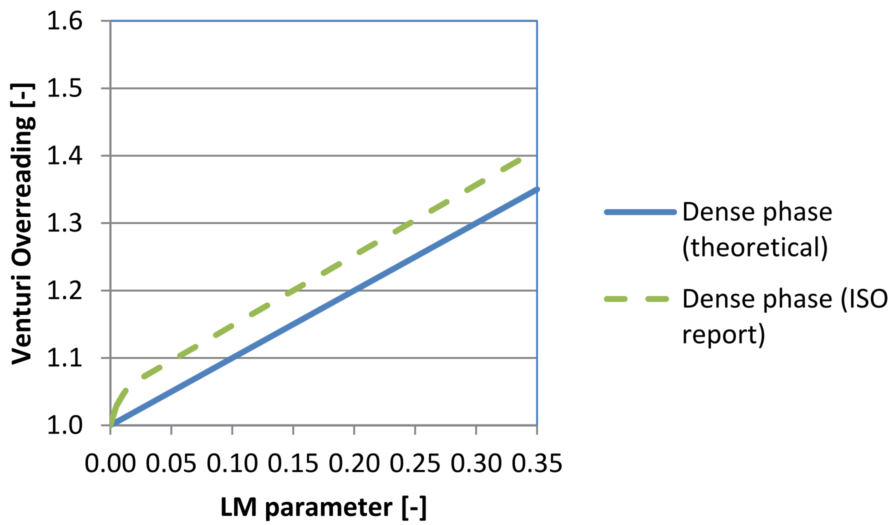

Figure 2: The overreading as predicted for dense phase conditions by theory, and the correlation from the ISO paper.

In the above case, for a β-ratio of 0.75 and gas Froude number of 1.5, the differences are more than 5%. We conclude that the claim of validity in the ISO report to include all pressures above the experimental range is not substantiated and is likely to be incorrect.

5.2 Comparison with other experiments

A first comparison is shown against the independent data gathered at SINTEF to which the De Leeuw equation was fitted.

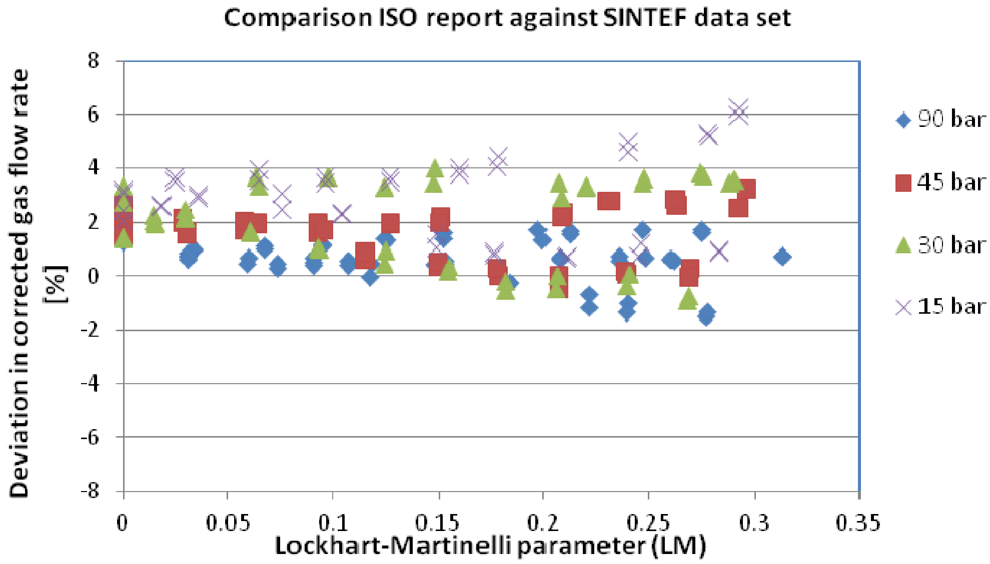

Figure 3: Deviation in the corrected gas flow rate when the SINTEF data is corrected using the ISO report equations.

As can be seen in figure 3 the resulting deviations are above the uncertainty range claimed in the ISO report, 3% for $X_{LM} \leq 0.15$ and 2.5% for $X_{LM} > 0.15$. This is despite the test fluids being similar to the NEL test loop fluids on which the ISO report correlations are mainly based. In addition it can be seen that the uncertainty increases with increasing LM parameter, this is in contradiction to what is mentioned in the ISO report.

Other available data have been obtained from tests at K-lab, Kårsto, Norway. This data contained both single phase liquid as well as liquid mixtures of water and hydrocarbon liquid. The results with the two immiscible liquids will be presented further in the paper. The results of wet gas with only one liquid component are shown in figures 4 and 5 below.

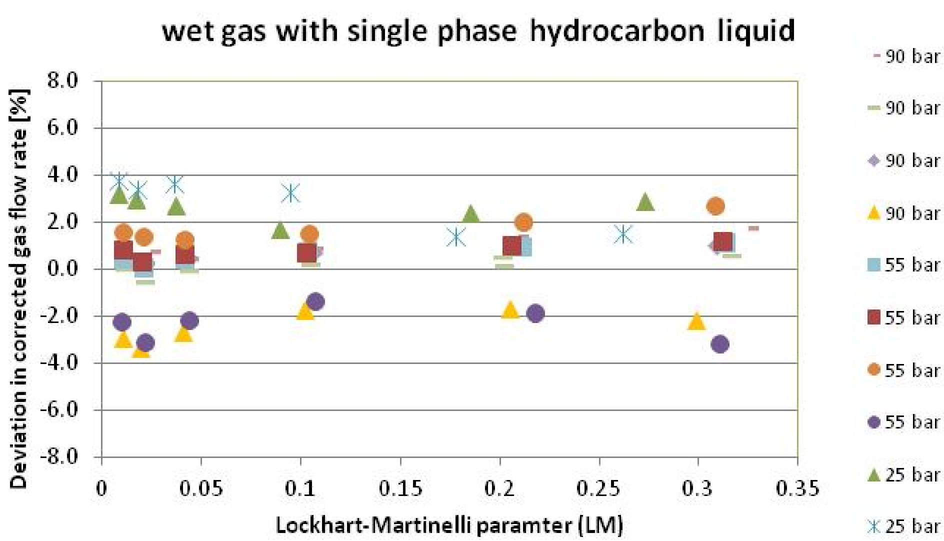

Figure 4: Deviation in the corrected gas flow rate when K-Lab data is corrected using the ISO report equations.

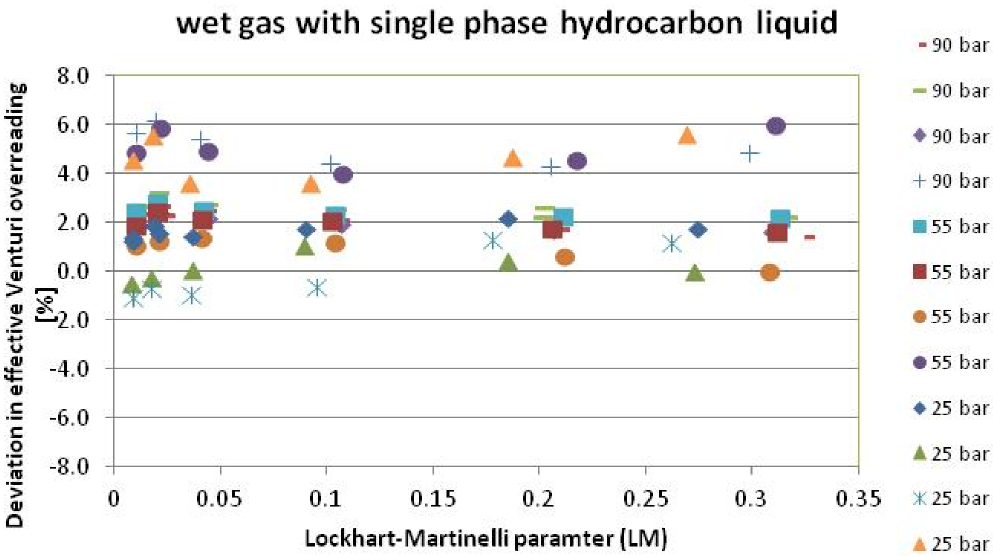

Figure 5: Deviation in the corrected gas flow rate when K-Lab data is corrected using the ISO report equations, when the calibrated C_d is applied instead of the value of C_d =1 as stated by the ISO report.

The deviations in the corrected gas flow rate, as seen in figure 4, may superficially appear reasonable with the claims in the ISO report, 3% for $X_{LM} \leq 0.15$ and 2.5% for $X_{LM} > 0.15$. However, the calibrated C_d for this Venturi meter was 0.975. This is different from the ISO report where the C_d value is stated to be 1. This implies that for dry gas conditions the ISO report equations will result in a 2.5% error. In this case the incorrectly assumed ISO discharge coefficient of 1 will artificially improve the correlations performance by coincidence. However, it is important to note that this inappropriate discharge coefficient can just as easily be detrimental to the correction factor. If we compare the effective over-reading between the ISO report and the K-Lab data, i.e. excluding the effect of the differences in the C_d, the deviations between the ISO prediction and the wet gas over-reading data are larger. This is shown in figure 5. It should be noted that the deviation in over-reading and corrected gas flow rate error is of opposite sign; e.g. a 10% too high an over-reading prediction results in a 10% too low gas flow rate.

6. A RECENT REAL LIFE TEST

A 12” nominal size wet gas Venturi meter was tested at the NEL wet gas facility. This is the same facility of which most of the data on which the ISO report correlations are based have been gathered.

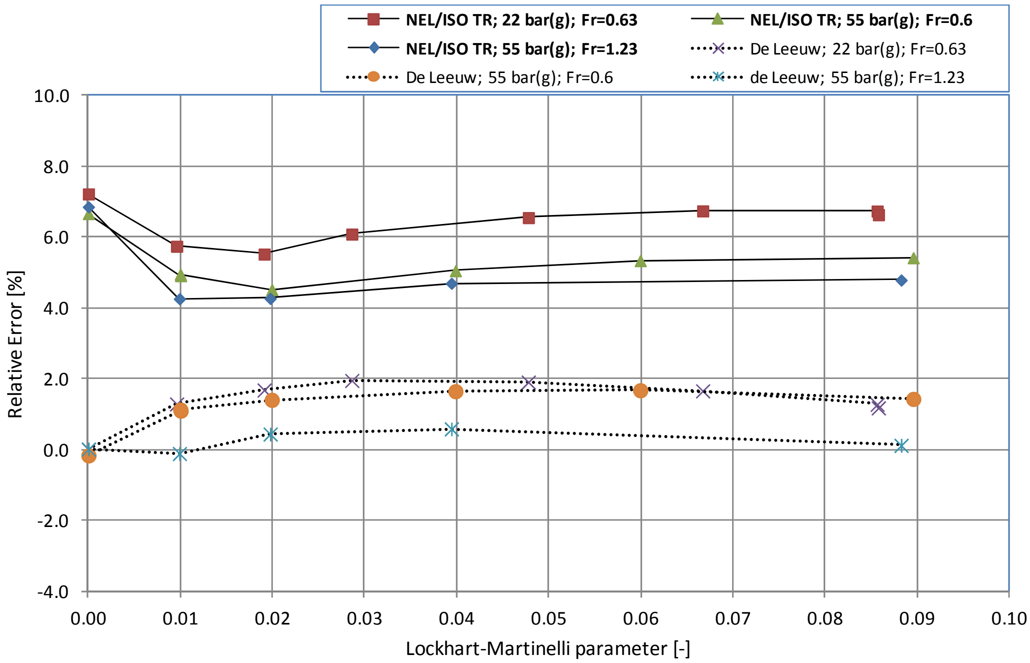

Figure 6: Resulting deviations of a 12” meter test at NEL.

The performance of the ISO report correlation for this case is shown in figure 6. Across the pressure, gas Froude number and the Lockhart-Martinelli parameter ranges tested, the deviations using the ISO report correlations fall in the range from 7.6% to 4.2%. For comparison purposes, an existing correlation performed better in this case as it uses the actual discharge coefficient.

It is acknowledged that the dry gas discharge coefficient of the Venturi tube was on the low side, i.e. 0.936. However, most operating companies would not scrap a costly 12” wet gas Venturi meter just because the discharge coefficient does not fit within the ISO report. Moreover, as the ISO report states a fixed discharge coefficient without a calibration requirement, a deviation in the real discharge coefficient will not even be spotted when following this report. This implies that deviations as occurred above go unnoticed.

As in many cases wet gas Venturis are used outside the range of Reynolds numbers as specified in ISO 5167, calibration is recommended. As the results in figure 7 show [5], the discharge coefficient at high Reynolds number can vary considerably from Venturi to Venturi. This is furthermore acknowledged by ISO 5167 which states, for a Reynolds number greater than 2 million, that a C_d of 1.01 with an uncertainty of 3% in case meters are not calibrated. To stay within the specified accuracy ranges as claimed in the ISO report, 3% for $X_{LM} \leq 0.15$ and 2.5% for $X_{LM} > 0.15$, this would mean that the wet gas correction would need to have no uncertainty to meet its stated uncertainties.

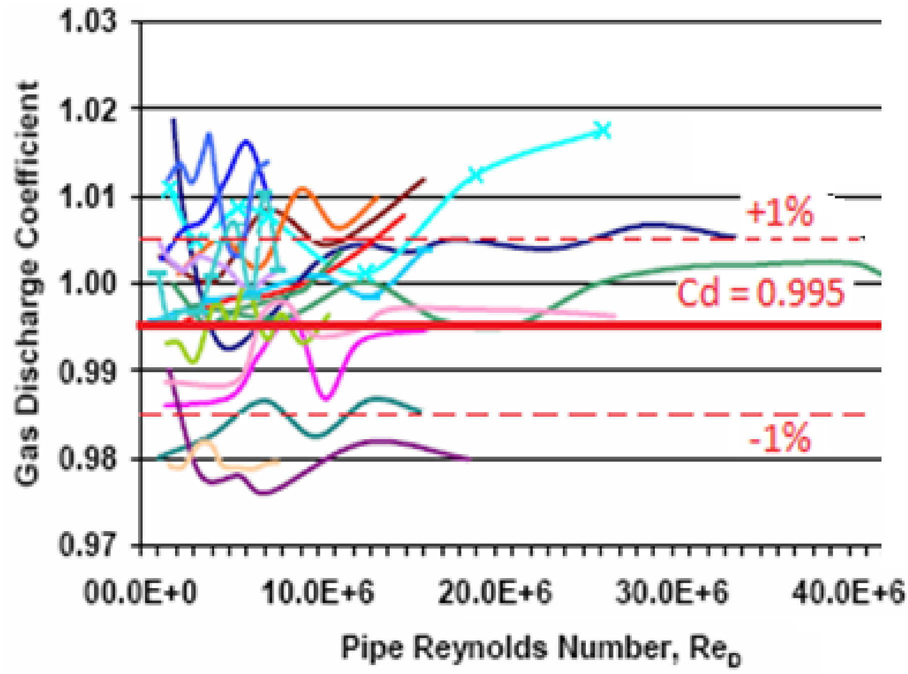

Figure 7: Eighteen Venturi meter data sets [5].

7. WET GAS FLOWS WITH WATER AND CONDENSATE.

In real life applications within the natural gas industry the liquid fraction in wet gas flow will almost always consist of a mixture of water and hydrocarbons, the latter called condensate. Small amounts of water are always present, as all reservoirs are water vapour saturated, and additional formation water may be produced. But neither the ISO report nor the NEL paper on which it is based provide guidance on the appropriate value of *H* in case of other than single phase liquids (*H* = 1 for hydrocarbon liquids, and 1.35 for water at ambient temperature). Also, in many wells the temperature is significantly above ambient and it is unclear what the effect of temperature is on the value of *H*.

When the ISO report correlations are only applicable in the case of single component liquids, i.e. only water (at ambient temperature) or only condensate, this would practically mean that the ISO report is inapplicable to natural gas applications, as explained above. To prevent engineers applying the ISO report by mistake, we have the opinion that already for this reason the ISO report should be ignored by the natural gas industry. It would be better to withdraw the report.

There is currently only limited experimental data for water/condensate mixtures as the liquid phase. The results available, however, indicate that it is not sufficient to use a flow rate weighted density for the liquid and to chose one or the other of the two values for H offered by the ISO report for water only and hydrocarbon liquid only to obtain the correct overreading. This can be seen from a collection of results shown in figure 8.

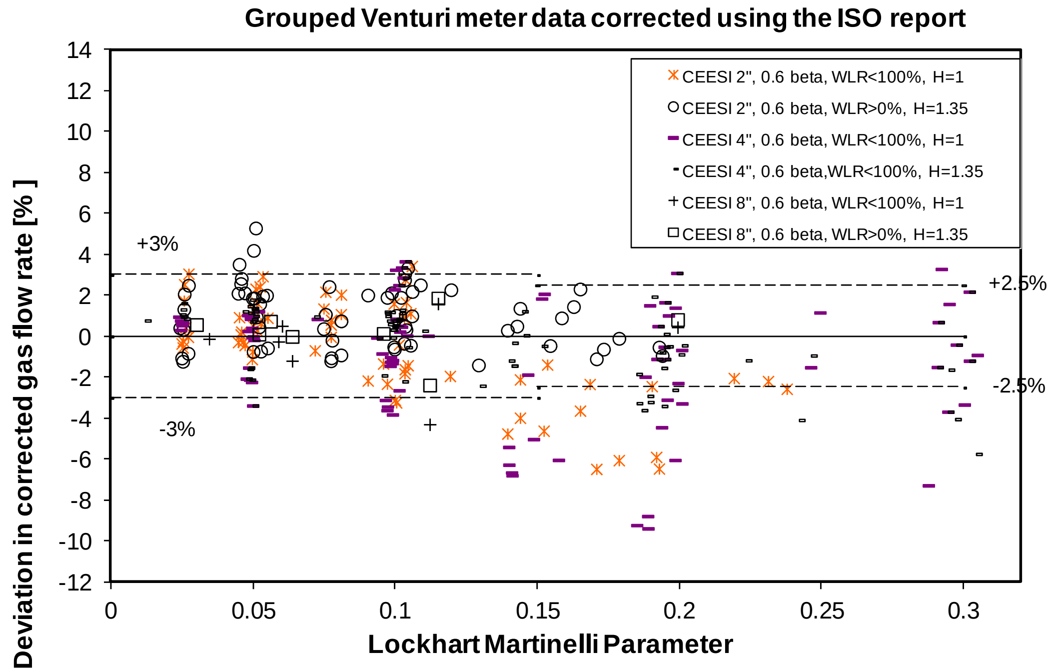

Figure 8: Deviation in the corrected gas flow rate, when the liquid phase consists of a mixture of water and hydrocarbon liquid.

The ISO report gives no guidance on how to treat the formula when the liquid is a mixture of water and hydrocarbon liquid. It is clear from figure 8 that the uncertainty specification in the ISO report is not met in realistic conditions.

Other available data have been obtained from tests at K-lab, Kårsto, Norway, shown in figures 9 and 10.

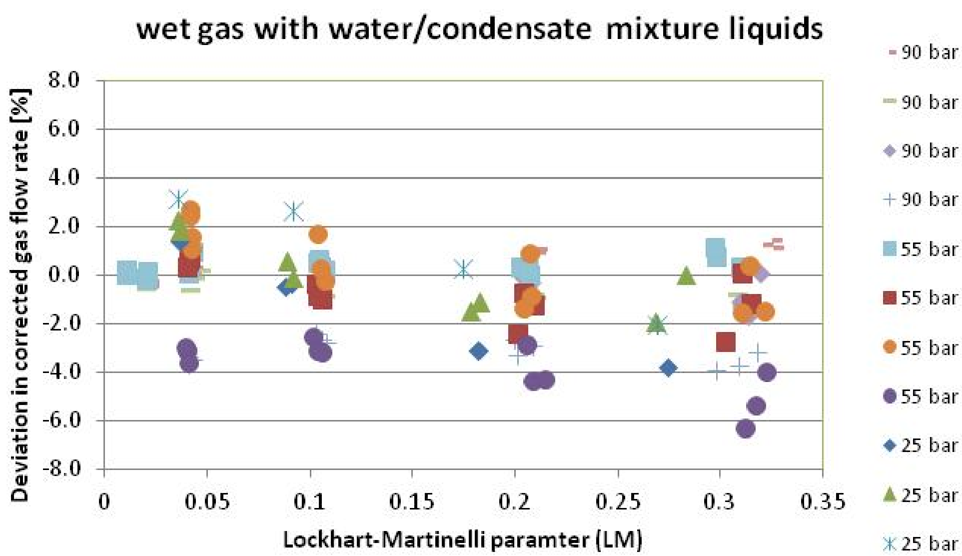

Figure 9: Deviation in the corrected gas flow rate when K-Lab data is corrected using the ISO report equations.

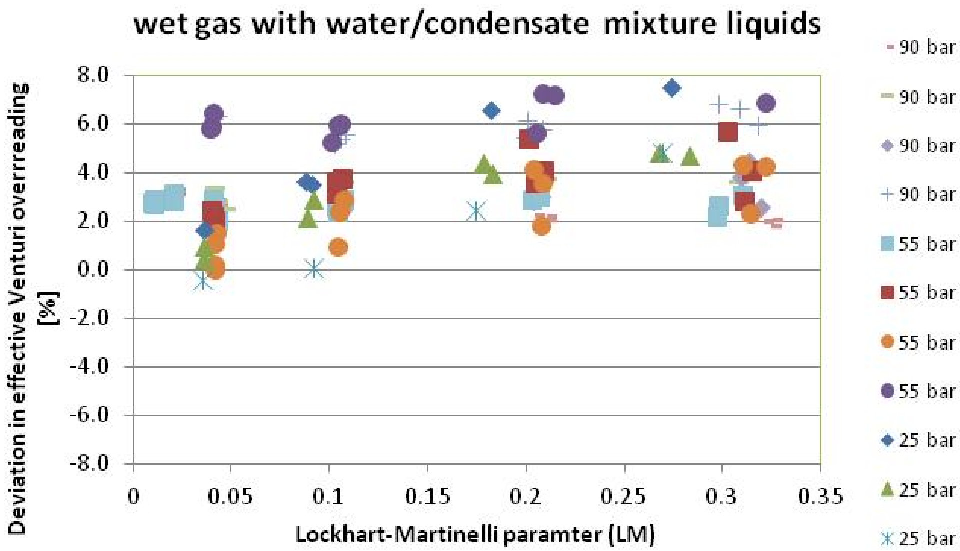

Figure 10: Deviation in the corrected gas flow rate when K-Lab data is corrected using the ISO report equations, when the calibrated C_d is applied instead of the value of $C_d = 1$ as stated by the ISO report.

As stated earlier the calibrated C_d for this Venturi meter was 0.975. This is different from the ISO report where the C_d value is stated to be 1. This implies that for dry gas conditions the ISO report equations will result in a 2.5% error. In this case again the incorrectly assumed ISO discharge coefficient of 1 will artificially improve the correlations performance by coincidence. However, it is important to note that this inappropriate discharge coefficient can just as easily be detrimental to the correction factor. If we compare the effective over-reading between the ISO report and the K-Lab data, i.e. excluding the effect of the differences in the C_d, the deviations between the ISO prediction and the wet gas over-reading data are larger. This is shown in figure 10.

As a further remark, the test fluids so far described are considered stable fluids. In real life applications the fluids are in thermodynamic equilibrium and thus transfer between the gas and liquid phases occurs with pressure changes. The effects of these real life conditions on the results are currently unknown (see also section 10), and therefore the uncertainty of the ISO report correlations, which is based on experimental data fits with stable fluids, is also unknown.

8.1 The tracer dilution technique

As the over-reading correlations require input of the liquid flow rate, the tracer dilution technique has been developed as one of the options. A number of papers have been published on the practical aspects of the tracer dilution method [6-12]. In addition one oil company is known to have captured the practical details in a 38 page document devoted to its correct implementation. This illustrates that the technique is not as straightforward as it might seem at first sight and easily can lead to erroneous results. As an example some of the many sources of error ignored by the ISO report are:

- The requirements for the stability of the tracer solution injection flow rate
- The requirements for sufficient mixing of the tracer solution with the target phase
- Effects of fluctuations in the liquid flow rate with time scales shorter than the sampling time
- Effects of shrinkage of the samples when taken form flow line conditions to atmospheric for analysis
- Considerations for the choice of solution solvent for the injection solutions make up, and laboratory analysis

• As the determined liquid flow rate is proportional to the injection flow rate, any error in the latter shows up directly in the first. A stable injection skid is therefore crucial.
• In stratified flow, for example, the turbulence in the liquid layer can be very low. As a consequence, mixing might be hampered or even almost absent. The often quoted 150D which is also referenced in the ISO report is insufficient under these conditions.
• Because the tracer concentration is inversely proportional to the liquid flow rate, fluctuations in the latter will lead to systematic errors as the average of the inverse is not equal to inverse of the average.
• Well flow lines at high pressures lead to hydrocarbon liquids (condensate) containing a significant fraction of light hydrocarbons. When such a sample is brought to atmospheric conditions for analysis, the light hydrocarbons evaporate, reducing the volume of the sample (shrinkage). This can be up to 40%. The concentration of tracer is subsequently increased by the inverse. If this is not taken into account, obviously severe errors will occur. The determination of this so-called shrinkage needs to be made experimentally as no theoretical prediction is accurate enough. This requires that a sample is taken in a calibrated volume at line conditions using a specialized sampling device.
• The choice of fluids in the laboratory can influence the results, as these should be stable at laboratory conditions.

Our opinion therefore is that the ISO report description of the tracer method is far too simplistic as well as incomplete. Such a description is likely to lead to incorrect applications.

8. THE USE OF THE PRESSURE LOSS (RATIO) IN WET-GAS FLOW MEASUREMENT

The total pressure loss ratio of a Venturi is sensitive to the liquid loading of the gas flow and it has been proposed by earlier researchers that this measurement can potentially be used to determine the liquid fraction [5]. However, so far it has not been unambiguously described by a correlation or a model.

As a base line, the ISO report correlates the pressure loss ratio in single phase conditions. The correlation given does, however, not correspond to the results presented in ISO 5167 where the pressure loss ratio decreases with increasing beta ratio. Also experimental data for a number of Venturi meters show different as well as variable results. In figure 11 the pressure loss ratio is plotted for a number of various different Venturi meters.

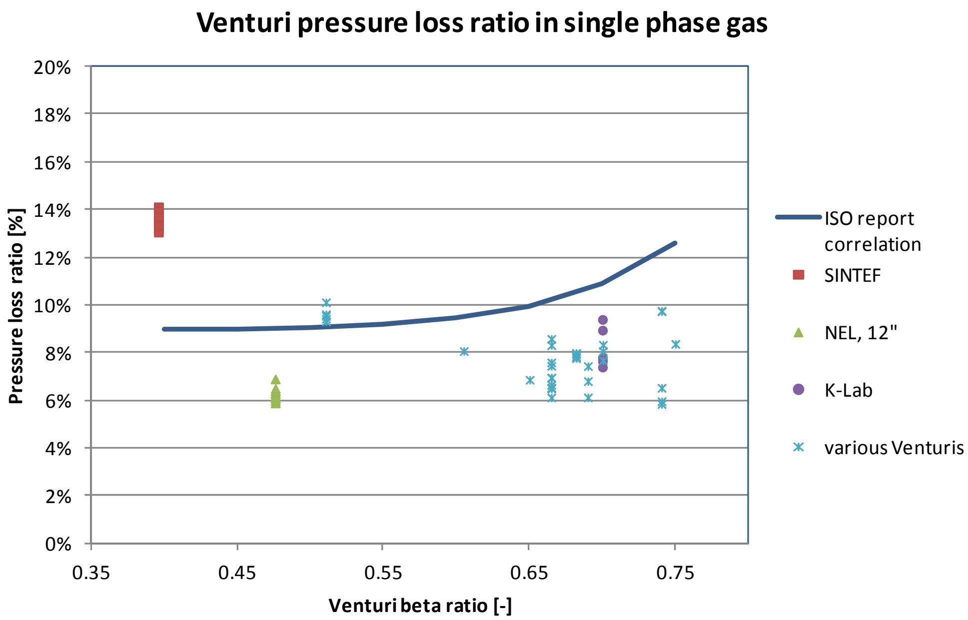

Figure 11: Venturi pressure loss ratio in single phase gas flow.

The ISO TR 11583 report includes correlations which claim to describe the use of the pressure loss ratio to determine the value of the Lockhart-Martinelli parameter. As the pressure loss ratio in dry gas is incorrectly described, this prediction will most likely be highly inaccurate.

Using the same example as in section 6, the predicted Lockhart-Martinelli parameter using the ISO report formula is used to determine the over-reading and hence the gas correction factor as per ISO report description. It can be clearly seen from figure 12 that application of the ISO report method results in significant errors in the corrected gas flow rate.

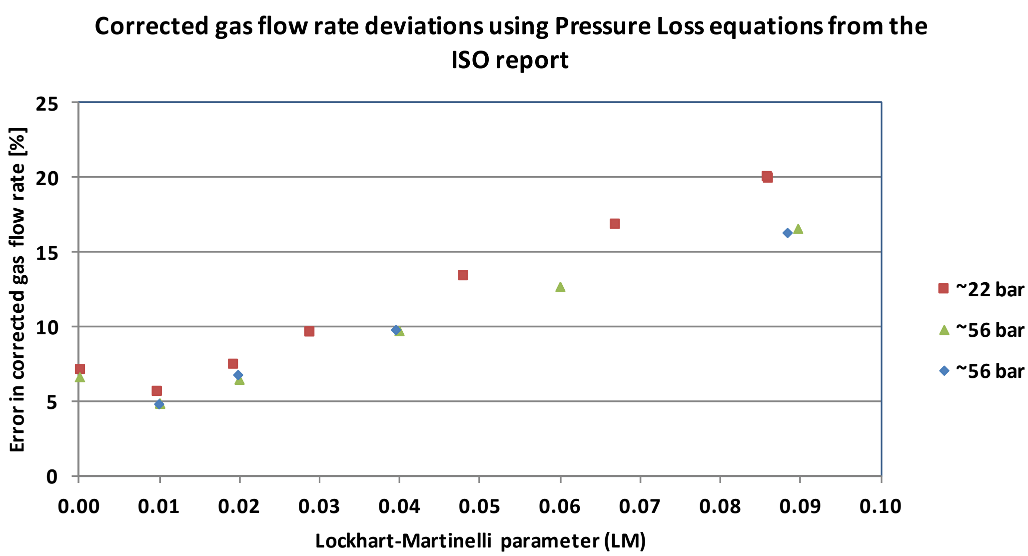

Figure 12: The error, introduced by the estimation of the Lockhart-Martinelli parameter, based on the ISO report correlations.

Furthermore, as shown in figure 13, the K-Lab data as discussed in section 8 above also reveals that the pressure loss ratio is significantly dependent on the WLR of the liquid. This effect is ignored by the ISO report thereby making it not applicable to real life gas/condensate applications.

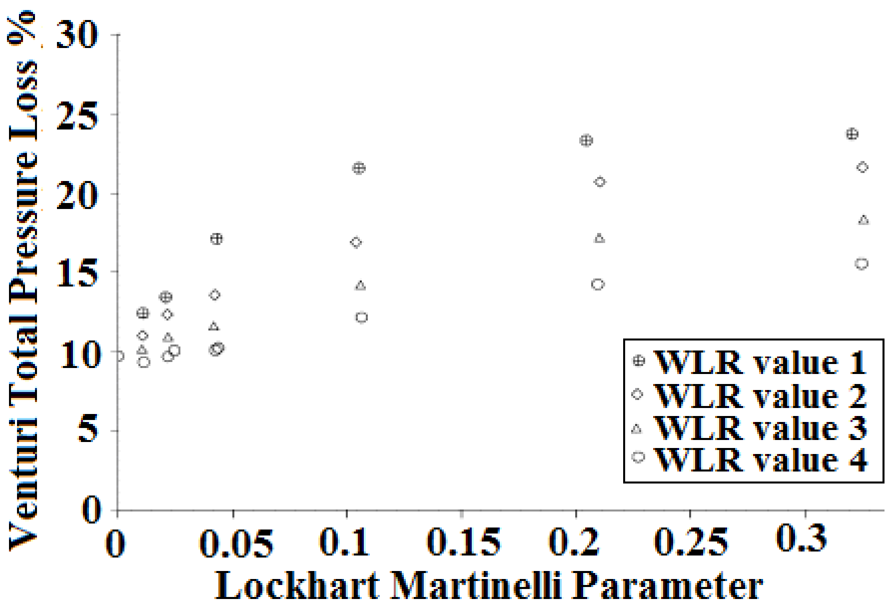

Figure 13: The pressure loss ratio for 4 different WLR values, at a set line pressure and gas Froude number, shows a significant dependence on the WRL.

Based on the above results it is demonstrated that the ISO report correlations neither align with other available experimental results nor describe realistic situations in which the liquid phase consists of condensate and water.

The difficulties are further enhanced by a demonstrated sensitivity of the pressure loss to the actual internal diameter of the pipe section where the pressure loss tapping is located. Certainly in practical implementations where the actual internal diameters of flow lines vary, this easily leads to significant changes in the total pressure loss ratio. The mitigation is to calibrate the meter in a test loop with the pressure loss tapping pipe section attached and not to be disconnected after calibration when the total pressure loss ratio is to be used for the estimation of the liquid loading. Practical aspects like this example above are ignored by the ISO report.

All aspects above lead to the conclusion that the statements made on the pressure loss ratio in the ISO report are incomplete and in some aspects incorrect. This supports the view of the authors that the current ISO report should be ignored by the natural gas industry and preferably be withdrawn.

9. COMMENTS ON THE EXPANSIBILITY FACTOR IN WET-GAS

In real-life well streams, the gas and liquid are in thermodynamic equilibrium. As a consequence changes in the line pressure or temperature will lead to a shift in the gas-liquid split of the fluid. When a wet gas fluid mixture moves through a differential pressure flow meter, the pressure will change and consequently a shift between gas and liquid will occur, which results in an increase in the gas fraction and a temperature drop. Because of the transfer of matter between the phases and the temperature changes, the common equation for the expansibility factor for dry gas is incorrect as this equation does not include mass transfer.

Figure 14 below, shows that this is a real-life phenomenon. The flow is from right to left. The white cover on the flow line is frost which coverage is indicative of the internal temperature. Note that the fluids are significantly cooler when these have passed through the Venturi as the downstream flanges are frozen.

As it is extremely difficult to predict fluid phase change in real-life systems, the best solution is to minimize the problem by keeping the differential pressure small compared to the actual pressure. The value of expansibility may then be assumed to stay sufficiently close to 1 so that deviations can be ignored.

Figure 14: Illustration of thermodynamic behavior of wet gas well flow.

10. CONCLUSIONS AND RECOMMENDATIONS

1. Venturi meters are widely used as wet gas meters. Therefore the uncertainty of the available wet gas overreading correlations is of great importance. A universal applicable Venturi meter correlation that covers all meter geometries, flow conditions and fluid properties is very desirable. However, it is concluded that any newly proposed Venturi meter correlation must be subjected to an independent review.

2. The authors have conducted an independent review of the Venturi meter wet gas correlation proposed by ISO TC30 TR 11583. The authors have presented material in this paper which challenges many statements made in this ISO report. Issues range from fundamental considerations, such as the modification of the fundamental meaning of the discharge coefficient, data fitting anomalies, independent experimental evidence, including a recent test at the facility on which the majority of the data is based, to unsupported and incomplete technical statements.

3. However, with no other international standard document currently available it is a practical reality that many in industry who are in search of detailed guidance on this subject will therefore use this published ISO report as a "de facto" standard. Using the ISO report for wet gas flow measurement in real life situations could lead to very significant errors with the equivalent of many millions of US$ per application.

4. It is recommended, that for the best results in the future, correlations should be fitted to as wide a range of experimental tests as possible.

5. It is good scientific practice to use modeling instead of empirical data fits whenever possible. Modeling provides a better understanding of the relevant mechanisms governing the over-reading of a Venturi flow meter in wet gas flow. This may in the future provide better confidence in applying the relationship outside the covered experimental range.

6. This review has come to the conclusion that the ISO TC30 TR11583 is very inappropriate for the requirements of the oil and gas industry. As the only practical use of the report is for the oil and gas industry (as the power industry does not apply this technology in any significant scale) this review concludes that it is only reasonable that ISO withdraws this Technical Report.

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APPENDIX A. Basic equations for venturi overreading.

When using Venturi flow meters in wet gas the presence of liquids leads to an increase in the differential pressure. In accordance with the literature, we will define the overreading, of a differential pressure flow meter as:

$$Overreading = \sqrt{\frac{\Delta p_{tp}}{\Delta p_{go}}}$$

in which:

Δp_{tp}	=	Differential pressure of the Venturi in two or three phase flow	Pa
Δp_{go}	=	Differential pressure of the Venturi if only the gas would flow	Pa

The Lockhart-Martinelli parameter (LM) defined as:

$$LM = \frac{Q_l}{Q_g}\sqrt{\frac{\rho_l}{\rho_g}}$$

in which:

Q_l	=	volumetric liquid flow rate	m^3/s
Q_g	=	volumetric gas flow rate	m^3/s
ρ_g	=	gas density	kg/m^3
ρ_l	=	liquid density	kg/m^3

To provide some insight to the overreading we will first derive two basic equations for the overreading.

A.1 The overreading of a homogeneous mixture

One approximation that can be made is to consider the gas and liquid to flow as a homogenous mixture. Here it is assumed that there is no velocity slip between the gas and liquid phases, e.g. the flow regime is "mist" and that both the gas and liquid phases move with the same velocity because the liquid is dispersed as small droplets. Under this assumption the overreading can be mathematically calculated because macroscopically the fluid behaves the same as if it were a single phase, but with a higher density than the gas alone. The calculation of the overreading is then as follows.

The density of the homogeneous mixture is:

$$\rho_{mix} = \frac{Q_g\rho_g + Q_l\rho_l}{Q_g + Q_l} = \frac{Q_g\rho_g + Q_l\rho_l}{Q_{mix}}$$

in which:

ρ_{mix}	=	Weighted average density of the mixture	kg/m^3
Q_g	=	Gas volumetric flow rate	m^3/s
ρ_g	=	Gas density	kg/m^3
Q_l	=	Liquid volumetric flow rate	m^3/s
ρ_l	=	Liquid density	kg/m^3

and $Q_{mix} = Q_g + Q_l$

in which:

Q_{mix} = Total volumetric flow rate of the mixture m^3/s

Using the above equations and the common equation for Venturi flow calculation, we obtain:

$$\Delta p_{mix} = \frac{Q_{mix}^2 (1-\beta^4)\rho_{mix}}{2C_d \varepsilon \beta^4 A_D^2} = M \cdot Q_{mix}^2 \rho_{mix}$$

in which:

Δp_{mix}	=	Differential pressure of the Venturi generated by the mixture	Pa
β	=	ß-ratio of Venturi (= internal throat diameter / internal pipe diameter)	
C_d	=	Venturi discharge coefficient	
ε	=	Expansibility factor	
A_D	=	Internal cross sectional area of the pipe	m^2
M	=	Constant which includes Venturi geometric properties	m^{-4}

Note. We will assume that $\Delta p_{mix} \ll p$ (the actual line pressure) and therefore the value for ε is close to 1. It will therefore be ignored in the rest of the derivation.

It is now straightforward to calculate the differential pressure under the "gas only" condition. The result is:

$$\Delta p_{go} = \frac{Q_g^2 (1-\beta^4)\rho_g}{2C_d \beta^4 A_D^2} = M \cdot Q_g^2 \rho_g$$

in which:

Δp_{go} = Differential pressure of the Venturi if only gas would flow Pa

The *Overreading* now is:

$$Overreading = \sqrt{\frac{\Delta p_{tp}}{\Delta p_{go}}} = \frac{Q_{mix}}{Q_g}\sqrt{\frac{\rho_{mix}}{\rho_g}} = \frac{v_{mix}}{v_g}\sqrt{\frac{\rho_{mix}}{\rho_g}}$$

With some reprocessing, this results in:

$$Overreading = \sqrt{1 + C \cdot LM + LM^2}$$

The parameter "*C*" is equal to:

$$C = \sqrt{\frac{\rho_g}{\rho_l}} + \sqrt{\frac{\rho_l}{\rho_g}} = \left(\frac{\rho_g}{\rho_l}\right)^{\frac{1}{2}} + \left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{2}}$$

Or when "C" is expressed more general this is equal to:

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

With $n = {}^1/_2$ for homogeneous mist flow.

A.2 The overreading at minimum energy

The lowest value of the flowing energy is the idealized situation for a horizontal wet-gas flow. It is approximated when the flow regime is stratified-smooth with negligible dissipation due to viscous friction. It is possible to calculate the *Hold-Up* and the *overreading* under such a condition. This will be done below.

In a stratified-smooth flow, the liquid will move slower as the liquid density is higher than the gas density. The flowing (specific) energy of the flow is:

$$E = \tfrac{1}{2}\rho_g v_g^2 \cdot A_g + \tfrac{1}{2}\rho_l v_l^2 \cdot A_l$$

in which:

E	=	Specific energy of the flow	Pa
v_g	=	Actual gas velocity	m/s
A_g	=	Fraction of cross-sectional area taken up by the gas	
v_l	=	Actual liquid velocity	m/s
A_l	=	Fraction of cross-sectional area taken up by the liquid	

N.B. Note that $A_l + A_g = 1$

As we are looking for the value of A_g where the system flows with minimum energy, we will calculate the first derivative to A_g and put this to zero. This leads, using the substitutions:

$$p = \rho_g v_{sg}^2$$

$$q = \rho_l v_{sl}^2$$

to

$$A_g = \frac{\sqrt{p}}{\sqrt{p} + \sqrt{q}}$$

$$A_l = \frac{\sqrt{q}}{\sqrt{p} + \sqrt{q}}$$

A_l is also the *Hold-Up*, so this can be found by substituting the equations for p and q into the equation above:

$$\frac{\sqrt{q}}{\sqrt{q} + \sqrt{p}} = \frac{v_{sl}\sqrt{\rho_l}}{v_{sl}\sqrt{\rho_l} + v_{sg}\sqrt{\rho_g}} = \frac{1}{1 + \frac{v_{sg}}{v_{sl}}\sqrt{\frac{\rho_g}{\rho_l}}} = \frac{1}{1 + \frac{1}{LM}} = \frac{LM}{1 + LM}$$

The now obtained values for A_g and A_l can be used to calculate the *overreading*. The specific energy of the flow in the pipe is, using the results for A_l and A_g and substituting these in the equation for the specific energy:

$$E_p = \tfrac{1}{2} \cdot (p + q + 2\sqrt{pq})$$

in which:

E_p	=	Specific flowing energy in the pipe	Pa

As long as the densities of the fluids remain unchanged (either incompressible fluids or the differential pressure « actual pressure, see above), the *LM* value in the throat is the same as in the pipe. Knowing that under this condition and still assuming minimum flowing specific energy it is easy to see that:

$$v_{sgt} = \frac{v_{sg}}{\beta^2} \text{ and } v_{slt} = \frac{v_{sl}}{\beta^2}$$

in which:

v_{sgt}	=	Superficial gas velocity in the throat	m/s
v_{slt}	=	Superficial liquid velocity in the throat	m/s
β	=	ß-ratio of Venturi (= internal throat diameter / internal pipe diameter)	

Using this equation, the determination of the overreading yields:

Overreading = 1 + *LM*

Rewriting this equation in the following way:

$$1 + LM = \sqrt{1 + 2LM + LM^2}$$

$$2 = (\frac{\rho_g}{\rho_l})^0 + (\frac{\rho_l}{\rho_g})^0$$

or when "*C*" is expressed more general this is equal to:

$$C = (\frac{\rho_g}{\rho_l})^n + (\frac{\rho_l}{\rho_g})^n$$

With $n = 0$ for stratified flow.

As the underlying requirement is that the flow is at minimum specific energy, the *overreading* can indeed never be lower than $1 + LM$.

A.3 Correlations based on experimental data

It is therefore not surprising that others have used the general shape of the equation above to design their correlation. Well-known examples are the correlations of Chisholm and De Leeuw. Chisholm's correlation is:

$$C = (\frac{\rho_g}{\rho_l})^{0.25} + (\frac{\rho_l}{\rho_g})^{0.25}$$

De Leeuw introduced an extension in the form of:

$$C = (\frac{\rho_g}{\rho_l})^n + (\frac{\rho_l}{\rho_g})^n$$

$n = 0.41$ $\quad 0.5 < Fr_g < 1.5$ and

$n = 0.606 \cdot (1 - e^{-0.746 Fr_g})$ $\quad Fr_g > 1.5$

So we have now one equation with an essential parameter "*n*", which has several distinct values: 0 for stratified flows, 0.25 according to Chisholm, 0.5 for homogeneous flow and in the range 0.41 – 0.606 according to De Leeuw.

The range of "*n*" following from the ISO report is approximately 0.29 - 0.55. This is not fully comparable to the previous values as some of the over reading is "moved" by the modification of the discharge coefficient. Taking the modified discharge coefficient into account the effective "*n*" value by the ISO report will slightly increase.

A.4 The overreading at the dense phase condition

A further limiting case is the dense phase condition where effectively the gas and liquid densities are equal so the fluids behave as a single phase fluid. Substituting this condition in the "universal equation above yields $C = 2$ for any value of *n*. So it can be concluded that the overreading = $1 + LM$.

Note that this is in agreement with almost all published correlations for the overreading of Venturis in wet-gas, except for the recent ISO report proposed correlation. This correlation does not converge to this theoretical limit at dense phase conditions due to that fact that the discharge coefficient is modified.