Wet Gas Flow Facility Inter-Comparisons

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Abstract

Many wet gas meters have their performance characterized or acceptance tested at one of the few available wet gas test facilities. The inherent assumption is that a wet gas meter tested at any wet gas flow test facility will have the same performance as at any other wet gas test facility, and the same performance as in the field. An inter-laboratory comparison would be beneficial in helping prove this. However, compared to single phase flow facilities there is a dearth of wet gas flow test facility inter-comparisons. In this paper such an inter-comparison is discussed. After reviewing some previous evidence, the results of a horizontally installed 6", 0.6β ISO compliant Venturi meter tested at the CEESI and DNV GL multiphase wet gas test facilities are reviewed. The two data sets are compared to each other and to the published Venturi meter wet gas correction factor published by TUVNEL (and adopted by ISO). As a correlation represents a data set in the form of an equation, this TUVNEL correlation effectively indicates the wet gas performance of Venturi meter's at TUVNEL. Hence, this exercise achieves a rare inter-wet gas flow facility comparison. Along with this laboratory inter-comparison, the CEESI and DNV GL wet gas data points which lie outside the ISO correlation give interesting lessons on the effect of extrapolating the ISO correlation.

1. Introduction

Multiphase wet natural gas flow metering is required throughout the natural gas production industry. However, there are only a few industrial grade multiphase wet gas flow test facilities worldwide. Industry practice tends to be to test and / or characterise multiphase wet gas meters at one of these test facilities. The inherent assumption is that all multiphase wet gas test facilities give the same result and the same result as the meter's subsequent performance in the field.

However, there has been no concerted attempt to prove the reproducibility of results for any one meter between different multiphase wet gas flow facilities. There is some anecdotal evidence that a DP meters response is reproducible amongst the multiphase wet gas test facilities, but there has never been a dedicated attempt to prove the assumption.

In this paper anecdotal evidence known to the authors is discussed. Then a basic wet gas test facility inter-comparison between CEESI and DNV is discussed. An ISO 5167-4 compliant 6", 0.6β Venturi meter was wet gas flow tested by CEESI and DNV. This particular meter was chosen for two reasons. The first was it is a typical size and design for what is used by industry for wet gas flow metering. The second was that ISO TR 11583 has adopted and published a TUV NEL Venturi meter wet gas correlation that covers this meter size. As a correlation is a fit to the source data, this ISO correlation is effectively a mathematical expression of the NEL data sets. Hence, the CEESI and DNV data can not only be directly compared, but indirectly compared to the equivalent NEL results, meaning an effective three laboratory check for reproducibility was achieved.

2. Wet Gas Meter Terminology

A wet gas flow is defined by ISO [1, 2] & ASME [3] as any two-phase (liquid and gas) flow where the Lockhart-Martinelli parameter (X_{LM}) is less or equal to 0.3, i.e. $X_{LM} \leq 0.3$. This definition covers any combination of gaseous and liquid components.

The Lockhart-Martinelli parameter (equation 1) indicates the relative amount of total liquid with the gas flow. Note that m_g & m_l are the gas and liquid mass flow rates respectively (where m_l is the sum of the liquid component flow), and ρ_g & ρ_l are the gas and liquid densities respectively.

$$X_{LM} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}} \quad \text{--- (1)}$$

The term 'liquid loading' is widely used as a qualitative term to describe the amount of liquid with a gas flow.

The gas to liquid density ratio ($DR = \rho_g / \rho_l$) is a non-dimensional expression of pressure. The gas densiometric Froude number (Fr_g), shown as equation 2, is non-dimensional expressions of the gas flow rate, where g is the gravitational constant, D is the meter inlet diameter and A is the meter inlet cross sectional area.

$$Fr_g = \frac{m_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \quad \text{---- (2)}$$

Single liquid component wet gas flows have one liquid density. Multiphase wet gas flows have two liquid densities, i.e. water and liquid hydrocarbon, 'LHC'. In this paper light liquid hydrocarbon will be called 'oil'. In this case the liquid density used to calculate the gas to liquid density ratio and the gas densiometric Froude number is the average liquid density.

"Water cut" is the ratio of the water to <u>total</u> liquid (i.e. the sum of water and LHC) volume flow rates when the fluid is at ***standard*** conditions. In this paper "water to liquid mass ratio" (or "WLMR") is defined as the ratio of the water to total liquid ***mass*** flow rates. The use of mass flow removes the requirement to define the flow conditions. The WLR_m is shown as equation 3, where m_w is the water mass flow rate and m_{lhc} is the LHC mass flow rate.

$$WLR_m = \frac{m_w}{m_w + m_{lhc}} \quad \text{--- (3)}$$

The average density of a two component liquid mixture is the total combined liquid mass per unit liquid volume. It is commonly assumed that two liquid components will be homogenously mixed. This homogenous liquid phase ($\rho_{l,\mathrm{hom}}$) is calculated by equation 4. Note that ρ_w & ρ_{lh} are the water and LHC densities respectively. For multiphase wet gas flows it is this liquid mixture density that is used to calculate the wet gas flow parameters.

$$\rho_{l,\mathrm{hom}} = \frac{\rho_w \rho_{lh}}{(\rho_{lh}\, WLR_m) + \rho_w (1 - WLR_m)} \quad \text{--- (4)}$$

Equation 5 shows the generic DP meter gas mass flow equation, where E is the velocity of approach (i.e. a geometric constant), A_t is the minimum cross sectional area, C_d is the discharge coefficient, ε is the expansibility factor and ΔP_g is the differential pressure (DP). Wet gas flow conditions tend to cause a DP meter to have a positive bias in the gas flow rate prediction. This is often called an "over-reading" and denoted as "OR". The DP created by a wet gas (ΔP_{tp}) is different to when that gas flows alone (ΔP_g). The result is an erroneous, or "apparent", gas mass flow rate prediction, $m_{g\ apparent}$ (see Equation 6). The over-reading is expressed either as a ratio (equation 7) or percentage (equation 7a) comparison of the apparent to actual gas mass flow rate.

$$m_g = E A_t C_d \varepsilon \sqrt{2 \rho_g \Delta P_g} \quad \text{---(5)}$$

$$m_{g\ apparent} \approx E A_t C_d \varepsilon \sqrt{2 \rho_g \Delta P_{tp}} \quad \text{--- (6)}$$

$$OR = \frac{m_{g\ Apparent}}{m_g} = \frac{\varepsilon_{tp} C_{d,tp}}{\varepsilon C_d} \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \quad \text{--- (7)}$$

$$OR\% = \left(\frac{m_{g\ Apparent}}{m_g} - 1 \right) * 100\% \quad \text{--- (7a)}$$

3. Existing Evidence of Reproducibility

There are a few published data sets that imply that multiphase wet gas meters give reproducible meter results. ISO TR 12748 gives an orifice meter multiphase wet gas flow correction factor for horizontally installed meters (adopted from Steven et al [4]). This correlation was formed with a large data set consisting of tests at two test facilities (CEESI & NEL) over two decades. Figures 1 & 2 show sample photographs of such orifice meter test at the CEESI & NEL wet gas test facilities.

These tests were largely uncoordinated, carried out by two Joint Industry Projects (JIPs), various meter end users, and meter manufacturers. The orifice meters tested were from various manufacturers and consised of paddle plate and chambered orifice meter designs. All data agreed to a remarkable extent. As the data from the different orifice meters at the different test facilities were found to be very reproducible, it was possible to create a mathematical expression of the response, i.e. a orifice meter wet gas correction factor. Figure 3 shows the ISO traceable data and the effect of applying the associated correction factor for a known liquid loading.

Fig 1. Orifice Meter Installed
in CEESI Wet Gas Facility.

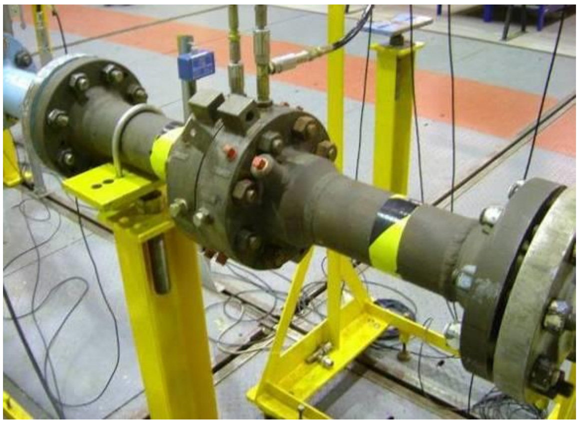

Fig 2. Orifice Meter Installed
in NEL Wet Gas Facility.

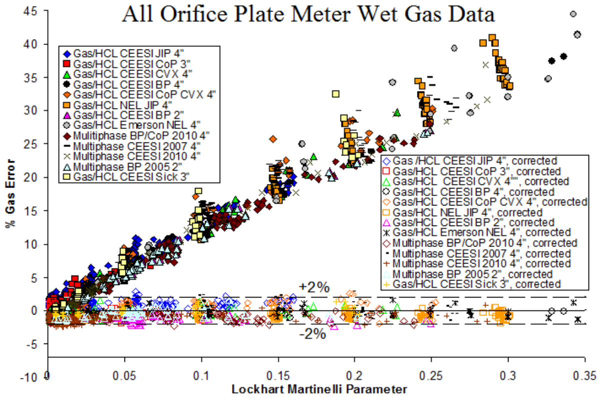

Fig 3. ISO TR 12748 Orifice Meter Reproducible Data Set.

Figure 3 shows the remarkable reproducibility of the orifice meter performance at the different test facilities tested over a wide period of time. This of course is a testament to both the reproducibility of the orifice meter in wet gas applications, as well as the ability of the different test facilities to create reproducible results. This orifice meter wet gas research produced in effect an inter-lab comparison between CEESI & NEL and for the orifice meter at least, the result is that both facilities give the same results.

In 2006 CEESI (Steven [5]) released a 4", 0.4β Venturi meter wet gas data set tested at CEESI as part of a JIP. Figure 4 shows the meter installed at CEESI. This meter was donated to this JIP by Shell after they had previously been tested it with wet gas flow at the Trondheim wet gas flow facility. De Leeuw [6] of Shell had previously published this Tondheim data set with an associated correlation. As a correlation is a fit to the source data, this Shell correlation is effectively a mathematical expression of the Trondheim data sets.

Fig 4. Shell's 4", 0.4β Venturi Meter at CEESI.

Figure 5 shows the CEESI JIP wet gas data and the effect of correcting the data for a known quantity of liquid using de Leeuw's correlation. The dotted lines represent the uncertainty claim of de Leeuw. Clearly the correlation works within the stated uncertainty, showing that the performance of the meter at Trondheim was reproduced at CEESI.

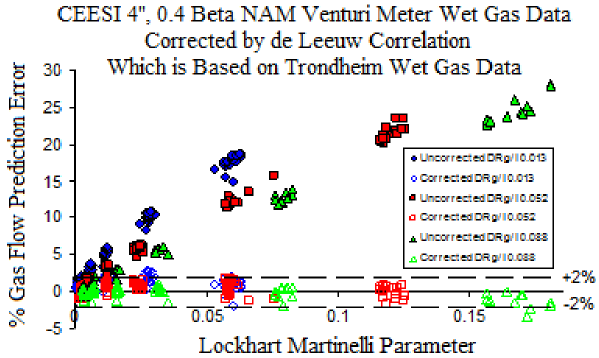

Fig 5. CEESI Wet Gas Data From Shell 4", 0.4β Venturi Meter Previously Tested at Trondheim.

4. CEESI, DNV, & NEL Inter-Comparisons

In 2009 Reader-Harris et al [7] released a Venturi meter wet gas correction factor applicable over a wide range of meter geometries and a wide range of wet gas flow conditions. The correction factor is shown in the box below. This correlation was subsequently adopted by ISO TC30 in the TR 11583.

$$\dot{m}_g = \frac{EA_t\varepsilon_{tp}C_d^*\sqrt{2\rho_g\Delta P_{tp}}}{\sqrt{1+CX_{LM}+X_{LM}^2}} \quad \text{--- (1)}$$

$$C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{--- (2)}$$

$$C_d^* = 1 - \left(0.0463 * \left[\exp\left(-0.05 * Fr_{g,th}\right)\right] * \left\{\min\left(1, \sqrt{\frac{X_{LM}}{0.016}}\right)\right\}\right)$$

--- (3)

$$Fr_{gas,th} = {Fr_g}\big/{\beta^{2.5}} \quad \text{--- (4)}$$

$$n = \max\left(\left(0.583 - 0.18\beta^2 - 0.578\exp\left(-0.8 * Fr_g/H\right)\right), 0.392 - 0.18\beta^2\right)$$

--- (5)

H is 1 for light hydrocarbon liquid
H is 1.35 for water at ambient temperature
H is 0.79 for water at elevated temperatures

Stated Limits of Use:

$0.4 \le \beta \le 0.75$ $\quad 0 < X_{LM} \le 0.3$
$Fr_{gas,th} > 3$ $\quad DR > 0.02$

Stated Uncertainties:

Gas flow prediction uncertainty for $X_{LM} \le 0.15$: 3%
Gas flow prediction uncertainty for $X_{LM} > 0.15$: 2.5%

This correction factor was created from an extensive wet gas Venturi meter data set from NEL, a single data set from CEESI, and some older untraceable data from larger Venturi meters. Hence, it is heavily based on NEL data.

This fact is useful when it comes to a wet gas flow facility inter-comparison. As a correlation is a fit to the source data, this ISO / NEL correlation is effectively a mathematical expression of the NEL data sets. Hence, in effect, any 3rd party wet gas facility Venturi meter data set can be compared to this ISO / NEL correlation to create a facility inter-comparison.

The ISO adoption of this NEL wet gas Venturi meter correlation was at the time controversial. There were two main issues. The first issue was that some in industry believed it was premature for ISO to adopt this correlation before significant 3rd party independent data was available to confirm its accuracy. Although it was probable the correlation would be proven sound, it was seen by some as good practice (and the proper scientific method) to have independent verifications. The second issue was that the correlation was restricted to gas with water **or** gas with oil. There was no allowance for the most common natural gas field flow conditions of gas with water **&** oil. The effect of the technically straight forward application of a fluid property extrapolation to account for these common field fluid compositions was unknown.

In response to the need for more wet gas flow facility inter-comparisons, and the controversy over the ISO TR 11583 correlation not having enough independent checks, CEESI & DNV agreed to wet gas test the same ISO compliant 6", 0.6β. Figures 6 & 7 show the same meter installed at the CEESI & DNV wet gas test facilities respectively. Both test facilities tested this meter by installing it in the respective facilities during a 3rd party commercial test of unrelated equipment. Therefore the data sets were restricted to both the range of the facilities, and the test matrix set by the 3rd party equipment tests.

The CEESI data set had the range:

$$0 \le X_{LM} \le 0.16$$
$$0.015 \le DR \le 0.085$$
$$0.7 \le Fr_{g,th} \le 25.5$$
$$0\% \le WLR \le 100\%$$

The DNV data set had the range:

$$0 \le X_{LM} \le 0.35$$
$$0.0125 \le DR \le 0.065$$
$$1.3 \le Fr_{g,th} \le 10.5$$
$$0\% \le WLR \le 100\%$$

$Fr_{g,th}$ denotes the gas densiometric Froude number using the Venturi meter throat diameter, i.e. equation 4.

Figure 8 shows the combined data from CEESI and DNV where the data was within the ISO TR 11583 correlations range (inclusive of gas with oil or gas with water data only). Also shown is the result of applying the ISO TR 11583 correlation for a known quantity of liquid. The dashed lines represent the ISO stated uncertainty values. The CEESI & DNV data agree with each other and the combined data corrected by the NEL / ISO TR 11583 correction falls within the stated uncertainty bands.

Fig 6. 6", 0.6β venturi Meter at the CEESI Wet Gas Test Facility

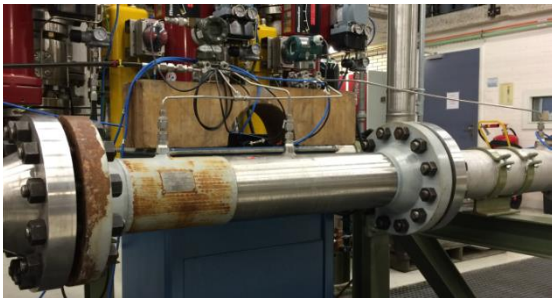

Fig 7. 6", 0.6β venturi Meter at the DNV Wet Gas Test Facility

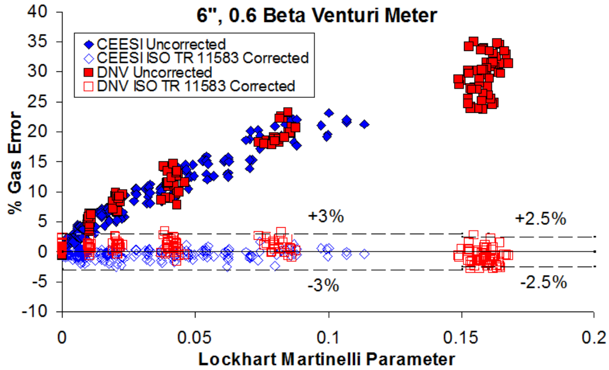

Fig 8. CEESI & DNV 6", 0.6β Venturi Meter Wet Gas Data within ISO TR range.

Figures 9 & 10 show the CEESI & DNV individual data sets respectively, split into gas with oil and gas with water. (The DNV data shows a token multiphase wet gas data set, i.e. gas with water & oil.)

In effect this results show that NEL, DNV, & CEESI produce the same Venturi meter wet gas flow performance.

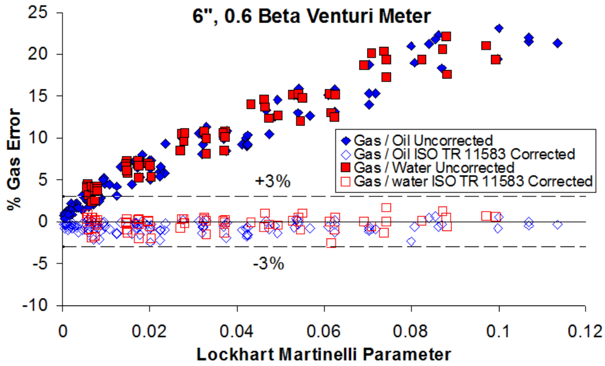

Fig 9. CEESI Data within Range of ISO TR 11583

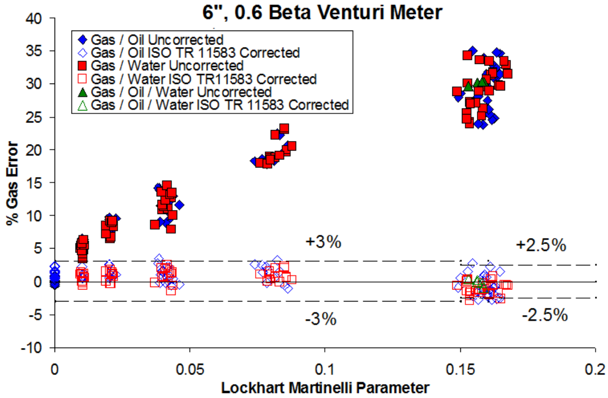

Fig 10. DNV Data within Range of ISO TR 11583 (Plus a Small Multiphase Wet Gas Data set)

5. Extrapolation ISO TR 11583's Correlation

It is useful to know the effects of extrapolating a correlation. Figure 11 shows the effect of using the ISO TR 11583 with the multiphase wet gas CEESI data (i.e. gas with oil and water) where all other parameters are within the correlations stated flow condition range. The correlation corrects the gas flow rate prediction to within the correlations stated uncertainty, however, this data set is only for $X_{LM} \leq 0.12$.

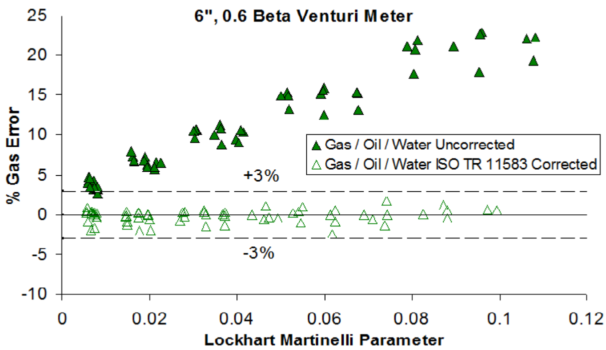

Fig 11. CEESI Multiphase Wet Gas Data

Figure 12 shows gas with oil CEESI data where the density ratio and / or the throat gas densiometric Froude number were marginally outside the correlation range. The CEESI data shown in Figure 12 has the ranges $0.7 < Fr_{g,th} < 3$ and $0.016 < DR < 0.02$. The ISO TR 11583 correlation performs well.

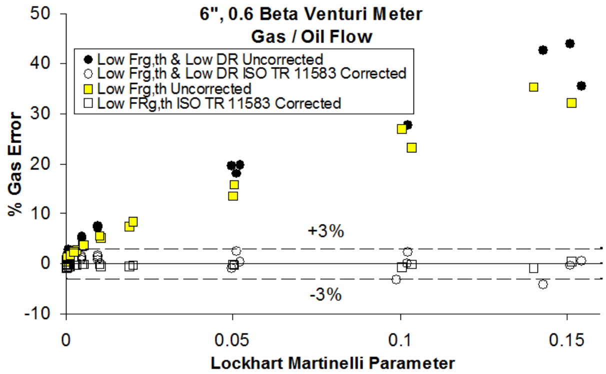

Fig 12. CEESI Gas with Oil Wet Gas Data with Density Ratio & / or $Fr_{g,th}$ Outside ISO TR 11583 Range.

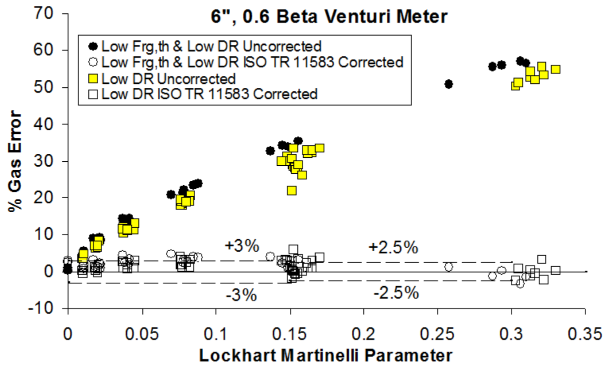

Fig 13. DNV Gas with Oil or Water Wet Gas Data with $Fr_{g,th}$ & / or Density Ratio Outside ISO TR 11583 Range.

Figure 13 shows gas with oil or water DNV data where the density ratio and / or the throat gas densiometric Froude number were marginally outside the correlation range. The DNV data shown in Figure 13 has the ranges $1.3 < Fr_{g,th} < 3$ and $0.012 < DR < 0.02$. In this case the ISO TR 11583 correlation performs well.

However, it is a limited data set and it was noted that there was no multiphase wet gas flow data for the higher liquid loadings. Further data sets show the effect of such an extrapolation of the ISO TR 11583 correlation.

5. Independent Checks on ISO TR 11583 Venturi Meter Wet Gas Correlation

CEESI has two independent sets of multiphase wet gas Venturi meter data. One data set consists of multiphase wet gas ISO compliant 2", 4", 6", & 8" 0.6β Venturi meters. Figures 14 thru 17 show these meters under test at CEESI. Table 1 shows the test range compared to the TR 11583 range of applicability.

Although the ISO TR 11583 correlation is published as only applicable to gas with oil **or** water it is a simple procedure to interpolate the factor 'H' (relative to the water cut) to produce a correlation for use with gas with oil **&** water. Such a procedure is of course out with the scope of ISO TR 11583 and is not guaranteed to work within the correlations stated uncertainty. Figure 18 shows the results. For a known liquid flow rate, **within** the specified range of the ISO correlation, i.e. for gas with oil **or** water, the ISO correlation predicted the gas flow through all four Venturi meters to within the stated uncertainty of the correlation. However, for the higher Lockhart-Martinelli parameter values ($X_{LM} > 0.15$) the ISO TR 11583 correlation slightly over-corrects the multiphase wet gas flow data. This result has been repeatedly found.

Parameter	CEESI Test Range	ISO TR 11583 Stated Limits
Pressure	14.8 to 77 bara	N/A
Gas to Liquid DR	0.016 < DR < 0.085	DR > 0.02
Fr_g range	$0.25 < Frg < 7.13$	$Fr_g > 3\beta^{2.5}$
X_{LM}	$0 \le X_{LM} < 0.28$	$X_{LM} < 0.3$
Inlet Diameter	1.939” ≤ D ≤ 7.981”	D ≥ 2”
Beta	0.600	$0.4 \le \beta \le 0.75$
Gas / Liquid phase	Gas /Oil/ Water	Gas / Oil or Gas / Water

Table 1. CEESI 2” to 8” Venturi Meter Wet Gas Test Data Shown in Figure 18 & the ISO TR 11583 Venturi Meter Wet Gas Flow Correlation Flow Ranges.

Fig 14. 2”, 0.6β Venturi Meter at CEESI

Fig 15. 4”, 0.6β Venturi Meter at CEESI

In a separate project CEESI multiphase wet gas tested seven nominally identical 6”, 0.6β Venturi meters. Figure 19 shows four of these meters under test at the CEESI wet gas flow facility. Figure 20 shows the combined data set from these seven meters. Figure 21

Fig 16. 6”, 0.6β Venturi Meter at CEESI

Fig 17. 8”, 0.6β Venturi Meter at CEESI

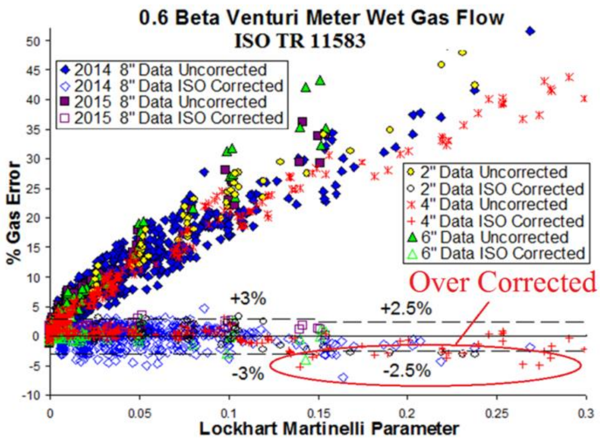

Fig 18. 2”, 4”, 6”, & 8” ISO Compliant Venturi Meter Wet Gas Data From CEESI, Corrected by TR 11583.

shows the corrected data only. Again, as with the data shown in Figure 18, at higher Lockhart-Martinelli parameter values ($X_{LM} > 0.15$) the ISO TR 11583 correlation slightly over-corrects the multiphase wet gas flow data.

TUVNEL, which created the correlation adopted by ISO using gas with oil or water data, have also now produced multiphase wet gas Venturi meter data that again shows this issue. NEL published (Graham et al [8]) 4” Venturi meter data that shows for gas with oil or water the ISO TR 11583 correlation worked within its

Fig 19. Four Out of Seven 6", 0.6β Venturi Meters at CEESI

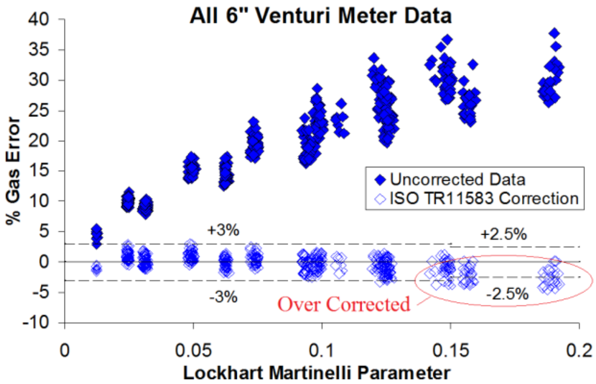

Fig 20. CEESI Massed 6" Venturi Meter Multiphase Wet Gas Uncorrected & TR 11583 Corrected Data

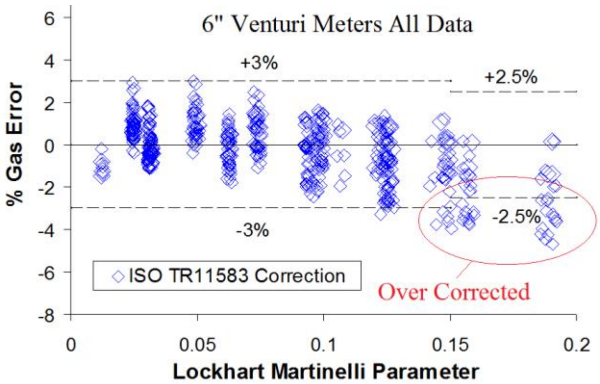

Fig 21. CEESI Massed 6" Venturi Meter Multiphase Wet Gas TR 11583 Corrected Data

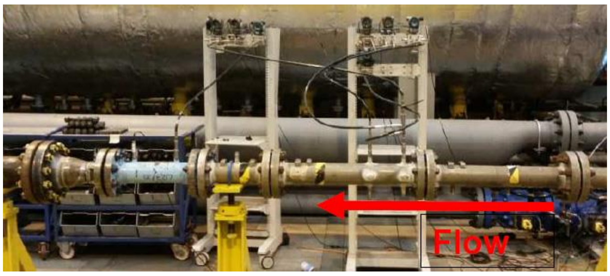

Fig 22. NEL 4" Venturi Meter During Multiphase Wet Gas Flow Testing.

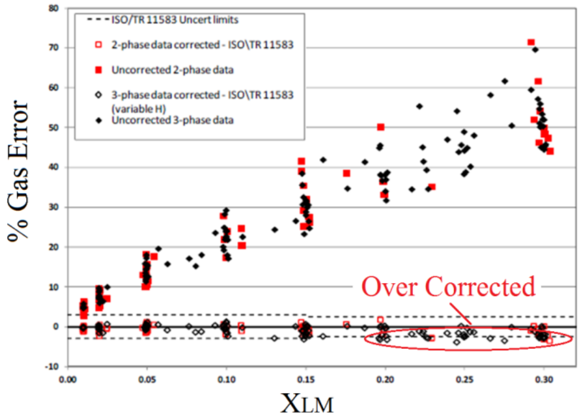

Fig 23. NEL 4" Venturi Meter Wet Gas Uncorrected & TR 11583 Corrected Data.

stated uncertainty, but for gas with oil and water at $X_{LM} > 0.15$ the TR 11583 correlation slightly over corrects the data. Figure 23 reproduces the NEL graph. This is essentially the same result as independently found by CEESI on two different projects.

This result has been reproduced in different facilities, using different equipment and different times. This is another indicator that the different industrial grade wet gas test facilities do produce the same results as each other.

8. Conclusions

The available evidence backs the assumption that a Venturi meter (and therefore by extension a generic DP meter) has a reproducible wet gas performance at different wet gas flow test facilities. As Venturi (& DP) meters are the most popular choice for economic wet gas metering this fact is important to industry. It means that DP meters tested in one wet gas test facility have a known wet gas performance in other test facilities, and far more importantly by extension, a known performance in the field. Also by extension, a DP meter wet gas correlation (such as the Venturi meter wet gas correlation TR 11583) created with data from one facility should be applicable within the stated meter geometry and wet gas flow condition range in the field.

However, this examination of the available multiphase wet gas Venturi meter data clearly shows that the old adage "…you extrapolate a correlation at your own risk" holds. The ISO TR 11583 correlation is not developed for multiphase (gas, oil, & water) wet gas flow, only gas with oil or water wet gas flow. Subsequently, use of this correlation with multiphase wet gas flow at higher liquid loadings (i.e. $X_{LM} > 0.15$) will lead to a slight negative bias in the gas flow rate prediction.

An ISO Venturi meter correlation applicable over a wide range of Venturi meter sizes is very useful to industry.

It would be to industries benefit for a multiphase wet gas Venturi meter correlation to be created. However, although one test facility should produce data that is reproducible in other test facilities and in the field, it is still best practice that such a correlation should either be formed with data from multiple test facilities (ideally more than two), or the correlation formed with data from one test facility should be independently checked by 3rd parties at other multiphase wet gas flow test facilities before being generally adopted by the standards boards.

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