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Wet Gas Flow Facility Inter-Comparison

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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 GL is discussed. An ISO 5167-4 compliant 6", 0.6β Venturi meter was wet gas flow tested by CEESI and DNV GL. 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 GL 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 TECHNOLOGY

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. $X_{LM} \leq 0.3$. Note that this definition covers any combination of gaseous and liquid components. The term 'liquid loading' is widely used as a qualitative term to describe the amount of liquid with a gas flow.

The Lockhart-Martinelli parameter is defined as

$$X_{LM} = \sqrt{\frac{\rho_l}{\rho_g}} \frac{u_{sl}}{u_{sg}} \tag{1}$$

where ρ_l and ρ_g are the liquid and gas density, respectively. The superficial velocities of the liquid and and gas are given by

$$u_{sl} = \frac{\dot{Q}_l}{A} \qquad (2)$$
$$u_{sg} = \frac{\dot{Q}_g}{A}$$

where A is the cross-sectional area of the meter inlet and $\dot{Q}_l$ and $\dot{Q}_g$ are the liquid and gas volumetric flow rate at line conditions. For multiphase wet gas flows, the liquid consists of a water and oil/condensate phase, denoted by subscript w and o respectively. For these liquid mixtures the total volumetric flow rate of the liquids need to be considered, i.e. $\dot{Q}_l = \dot{Q}_w + \dot{Q}_o$, and the density is assumed homogeneous

$$\rho_l = WLR \cdot \rho_w + (1 - WLR) \cdot \rho_o, \qquad (3)$$

where $WLR \equiv \dot{Q}_w / \dot{Q}_l$ is the Water Liquid Ratio at line conditions.

In wet gas flow metering two important dimensionless parameters need to be defined. 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 4, is non-dimensional expressions of the gas flow rate, where g is the gravitational constant, D is the meter inlet diameter

$$Fr_g = \frac{u_{sg}}{\sqrt{\tilde{g}D}}, \quad \tilde{g} \equiv g\frac{\rho_l - \rho_g}{\rho_g} \qquad (4)$$

2.1 Wet Gas DP Meters

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, $\dot{m}_{g,Apparent}$ (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.

$$\dot{m}_g = EA_t C_d \varepsilon \sqrt{2\rho_g \Delta P_g} \qquad (5)$$

$$\dot{m}_{g,Apparent} = EA_t C_{d,tp} \varepsilon_{tp} \sqrt{2\rho_g \Delta P_{tp}} \qquad (6)$$

$$OR = \frac{\dot{m}_{g,Apparent}}{\dot{m}_g} = \frac{\varepsilon_{tp} C_{d,tp}}{\varepsilon C_d} \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \qquad (7)$$

$$OR\% = \left(\frac{\dot{m}_{g,Apparent}}{\dot{m}_g} - 1 \right) \cdot 100\% \qquad (7a)$$

3 WET GAS INTER-COMPARISON SETUP

For a wet gas inter-comparison to be successful, several conditions need to be satisfied. The chosen flow meter should reproduce within certain limits, the facilities need to have a statement about the uncertainties of the provided flow rates and the test matrices should have sufficient overlap in the dominant physical parameters, i.e. dimensionless numbers.

3.1 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. Figure 1 shows 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 2 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 (left) and in NEL Wet Gas Facility (right).

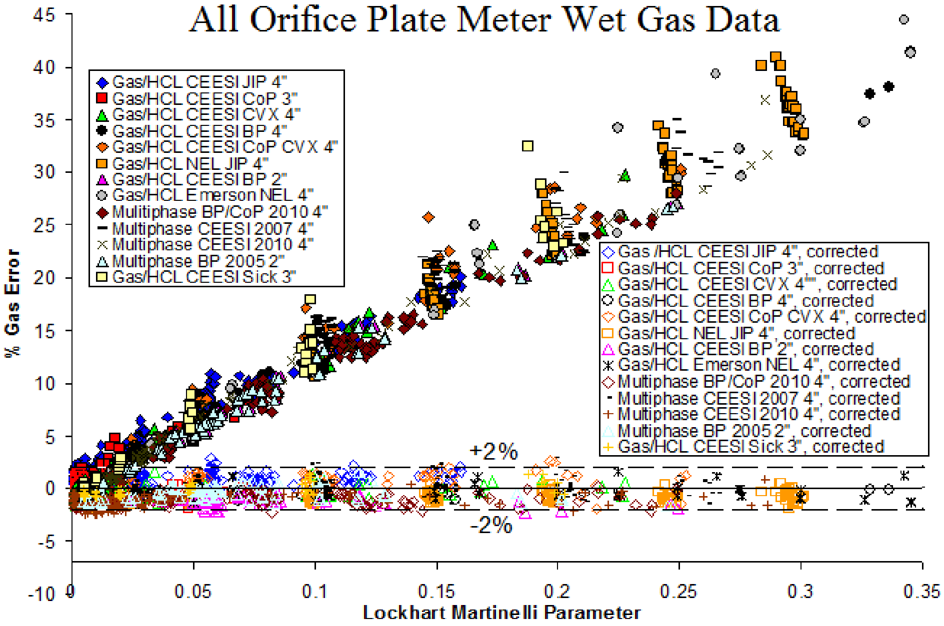

Fig. 2 - ISO TR 12748 orifice meter reproducible data set.

Figure 2 shows the remarkable reproducibility of the orifice meter performance at the different test facilities tested over a long 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 one of these JIPs. Figure 4 shows the meter installed at CEESI. This meter was donated to this JIP by Shell after they had previously tested it with wet gas flow at the Trondheim wet gas flow facility. De Leeuw [6] of Shell had 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. 3 - Shell’s 4”, 0.4β Venturi Meter at CEESI.

Figure 4 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 essentially reproduced at CEESI.

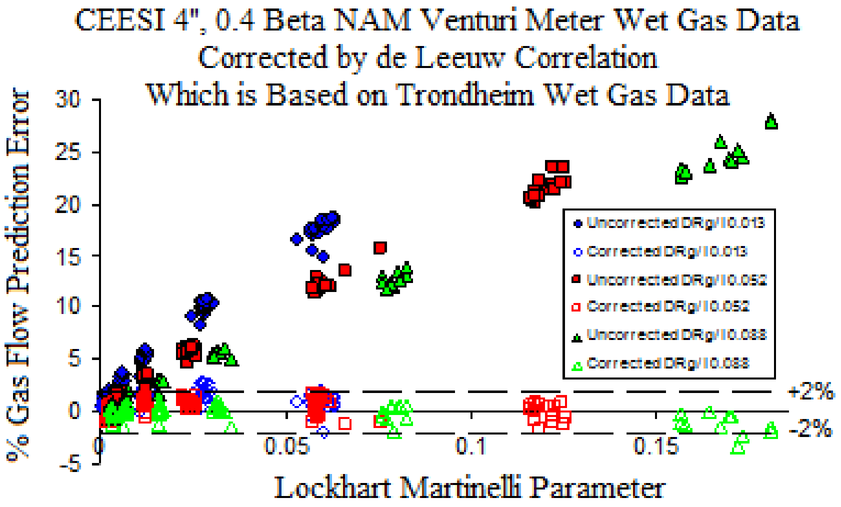

Fig. 4 - CEESI Wet Gas Data From Shell 4", 0.4β Venturi Meter Previously Tested at Trondheim.

3.2 Uncertainty of the Wet Gas Test Facilities

The reference gas volumetric flow rate at the CEESI wet gas test facility is measured by an ultrasonic flow meter and a turbine meter. The liquid flows are measured by means of a Coriolis mass flow meter. The DNV GL facility uses a ultrasonic flow meter as gas flow reference meter and also a Coriolis mass flow meter for the liquids. Both facilities are operated in a closed loop configuration. The claimed relative expanded uncertainties (k=2) of the CEESI and DNV GL facility are given in Table 1.

Table 1 – Claimed reference uncertainties of CEESI and DNV GL wet gas test facilities

	CEESI	DNV GL
$U^{*}_{lab}(\dot{Q}_g)$	<0.7%	<0.7%
$U^{*}_{lab}(\dot{Q}_l)$	<0.5%	<0.5%

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.

$$\dot{m}_g = \frac{E A_t \varepsilon C_d^* \sqrt{2 \rho_g \Delta P_{tp}}}{\sqrt{1 + C X_{LM} + X_{LM}^2}} \qquad (1)$$

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

$$C_d^* = 1 - 0.0463 \exp(-0.05 \cdot Fr_{g,th}) \min\left(1, \sqrt{\frac{X_{LM}}{0.016}} \right) \qquad (3)$$

$$Fr_{g,th} = \frac{Fr_g}{\beta^{2.5}} \qquad (4)$$

$$n = \max\left[0.583 - 0.18\beta^2 - 0.578 \exp\left(\frac{-0.8 Fr_g}{H} \right), 0.392 - 0.18\beta^2 \right] \qquad (5)$$

The $Fr_{g,th}$ is the throath Froude number and the parameter H is chosen as follows

$$\begin{array}{ll} H = 1, & \text{for light hydrocarbon liquid} \\ H = 1.35, & \text{for water at ambient temperature} \\ H = 0.79, & \text{for water at elevated temperature} \end{array} . \qquad (8)$$

The correlation has the following stated limits of use:

$$\begin{array}{l} 0.4 \le \beta \le 0.75 \\ 0 \le X_{LM} \le 0.3 \\ Fr_{g,th} > 3, \\ DR > 0.02 \end{array} , \qquad (9)$$

and gas flow rate uncertainty claims of:

$$\begin{array}{ll} U_{ISO}^*(\dot{m}_g) < 3\%, & \text{for } X_{LM} \le 0.15 \\ U_{ISO}^*(\dot{m}_g) < 2.5\%, & \text{for } X_{LM} > 0.15 \end{array} . \qquad (10)$$

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 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 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 ISO TR 11583 correlation not having enough independent checks, CEESI and DNV GL agreed to both wet gas test the same ISO compliant 6”, 0.6β Venturi meter. Figure 5 shows the same meter installed at the CEESI (left) and DNV GL (right) 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.

Fig. 5 - 6”, 0.6β Venturi meter at the CEESI (left) and DNV GL(right) wet gas test facility

The CEESI data set had the range:

$$0 \le X_{LM} \le 0.16$$

$$0.015 \le DR \le 0.085$$

$$0.7 \le Fr_{g,th} \le 25.5$$

$$0 \le WLR \le 1$$

The DNV data set had the range:

$$0 \leq X_{LM} \leq 0.35$$
$$0.0125 \leq DR \leq 0.065$$
$$1.3 \leq Fr_{g,th} \leq 10.5$$
$$0 \leq WLR \leq 1$$

As observed the data set ranges have sufficient overlap between the facilities and the NEL correlation. It is important to notice that the test data was not shared between the facilities until after the execution of the tests.

The fluids used during the tests are given in Table 2. Both CEESI and DNV GL operate with natural gas, refined oil and (salt) water. A small part of the tests at DNV GL has been run with argon to attain higher DR and Fr_g. The differences between the pure oil properties at atmospheric pressure, i.e. not in equilibrium with natural gas at elevated pressure, are:

- Exxsol D80: $\rho_o = 806\ \text{kg/m}^3$, $\nu_o = 2.2\text{mm}^2\text{/s}$ and $\sigma_o = 26.3\text{mN/m}$
- Exxsol D120: $\rho_o = 831\ \text{kg/m}^3$, $\nu_o = 4.85\text{mm}^2\text{/s}$ and $\sigma_o = 28.1\text{mN/m}$

where the density is evaluated at 15°C and the kinematic viscosity and surface tension at 25°C. The effect of the oil density is taken into account in the ISO 11583 correlation. Although the factor H in the correlation is often associated with a surface tension effect, the effect of liquid viscosity and surface tension is still not fully understood.

Table 2 – Used fluids at CEESI and DNV GL wet gas test facility during inter-comparison tests

	CEESI	DNV GL
Gas	Natural gas	Natural gas, Argon
Oil	Exxsol D80	Exxsol D120
Water	Water	Salt water (38 g/kg)

4 WET GAS INTER-COMPARISON RESULTS

Figure 8 shows the combined data from CEESI and DNV GL 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 GL data agree with each other and the combined data corrected by the NEL / ISO TR 11583 correction falls within the stated uncertainty bands.

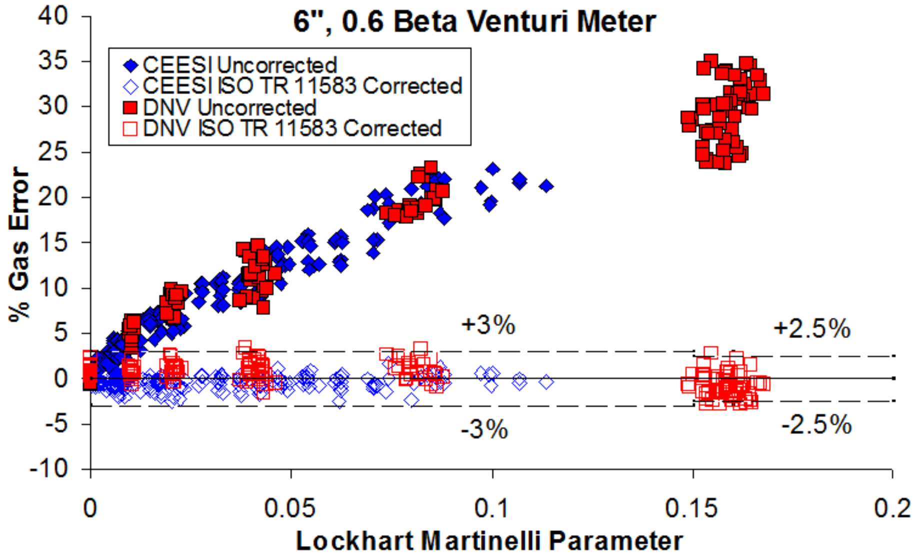

Fig.6 - CEESI & DNV GL 6”, 0.6β Venturi meter wet gas data within ISO TR range

Figures 7 & 8 show the CEESI & DNV GL individual data sets, respectively, split into gas with oil and gas with water. (The DNV GL data shows a token multiphase wet gas data set, i.e. gas with water & oil.)

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

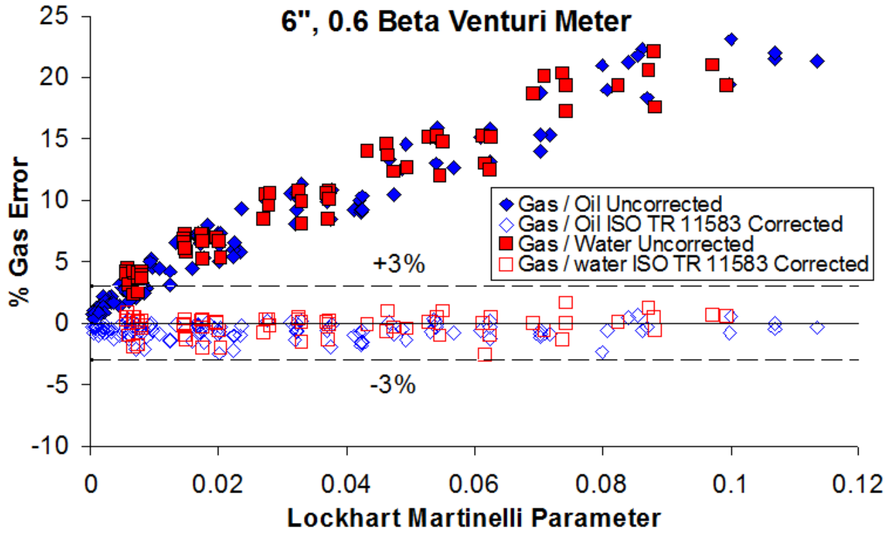

Fig. 7 - CEESI wet gas data within range of ISO TR 11583

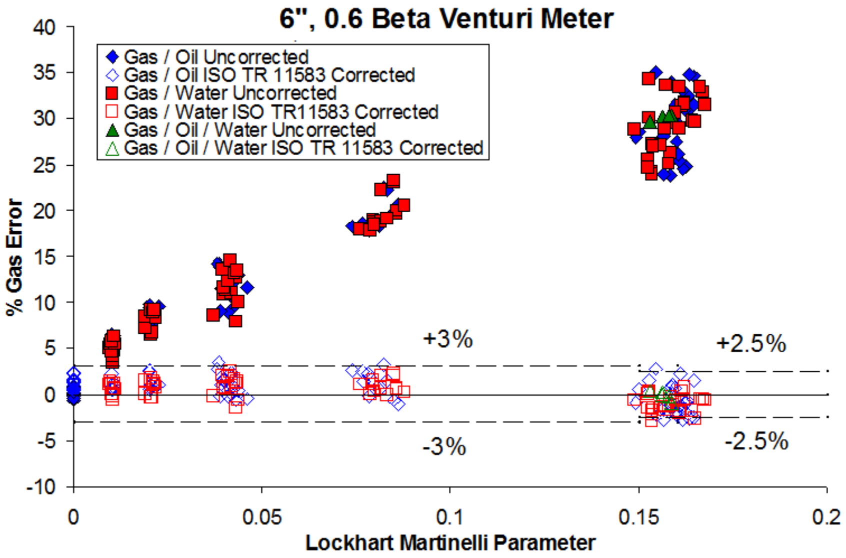

Fig. 8 - DNV GL wet gas data within range of ISO TR 11583 (plus a small multiphase wet gas data set)

A parameter to evaluate the success of the inter-comparison is given by the ISO 17043 [8] in terms of the E_n -numbers when using the Venturi combined with the ISO 11583 correlation as the travel standard

$$E_n = \frac{\varepsilon_{OR\%}}{\sqrt{\left(U^*_{ISO}\right)^2 + \left(U^*_{lab}\right)^2}} \quad . \tag{11}$$

where $\varepsilon_{OR\%}$ is the remaining error in the over-reading after correction with the ISO 11583 correlation. In the case $E_n \leq 1$ the inter-comparison can be qualified as satisfactory, which is the case for all test points in the range specified in equation (9).

5 EXTRAPOLATION OF ISO TR 11583's CORRELATION

It is useful to know the effects of extrapolating a correlation. Figure 9 shows the effect of using the ISO TR 11583 with the multiphase wet gas (i.e. gas with oil and water) CEESI data 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 $X_{LM} < 0.12$. For the value of H a linear interpolation is used.

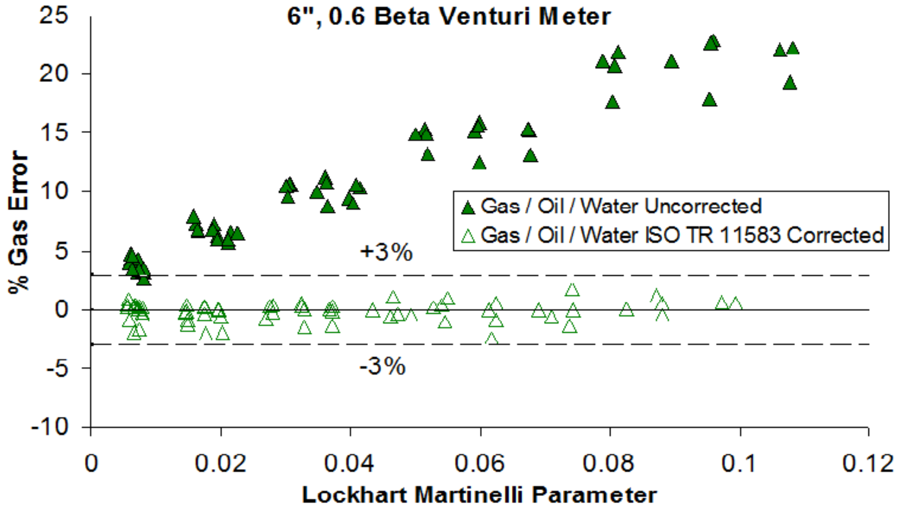

Fig. 9 - CEESI multiphase wet gas data

Figure 10 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 10 has the ranges $0.7 < Fr_{g,th} < 3$ and $0.016 < DR < 0.02$. The ISO TR 11583 correlation performs well.

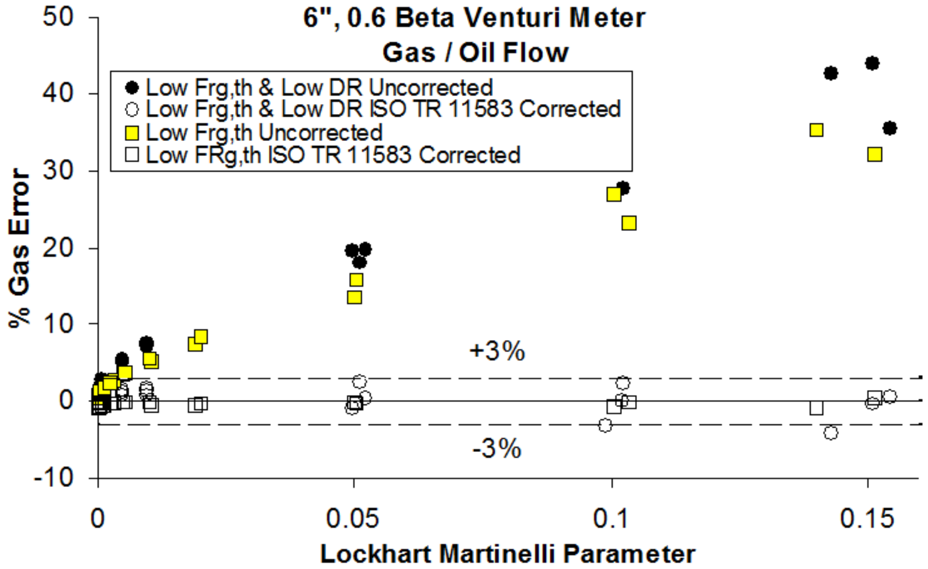

Fig. 10 - CEESI gas with oil wet gas data with DR and / or $Fr_{g,th}$ outside ISO TR 11583 range

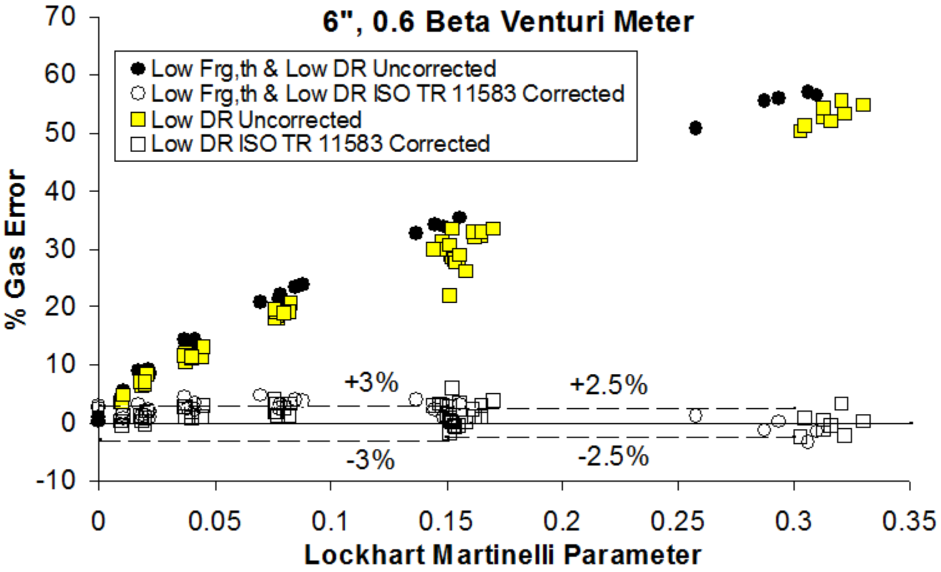

Fig. 11 - DNV GL gas with oil or water wet gas data with DR and / or $Fr_{g,th}$ outside ISO TR 11583 range

Figure 11 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 11 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.

6 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 12 and 13 show these meters under test at CEESI. Table 3 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 14 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, all four Venturi meter gas flow rate predictions predicted the gas flow 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.

Fig. 12 - 2” (left) and 4”(right), 0.6β Venturi meter at CEESI

Fig. 13 - 6” (left) and 8”(right), 0.6β Venturi Meter at CEESI

Table 3 – CEESI 2” to 8” Venturi meter wet gas test data shown in Figure 14 & the ISO TR 11583 Venturi meter wet gas flow correlation ranges.

Parameter	CEESI test range	ISO TR 11583 stated limits
Pressure	$14.8 \leq p < 77$ bara	N/A
Gas to Liquid DR	$0.016 < DR < 0.085$	$DR > 0.02$
Fr_g range	$0.25 < Fr_g < 7.13$	$Fr_g > 3\beta^{2.5}$
X_{LM}	$0 \leq X_{LM} \leq 0.28$	$X_{LM} < 0.3$
Inlet Diameter	$1.939" \leq D \leq 7.981"$	$D \geq 2"$
Beta	$\beta = 0.6$	$0.4 \leq \beta < 0.75$
Gas / Liquid phase	Gas /Oil/ Water	Gas / Oil or Gas / Water

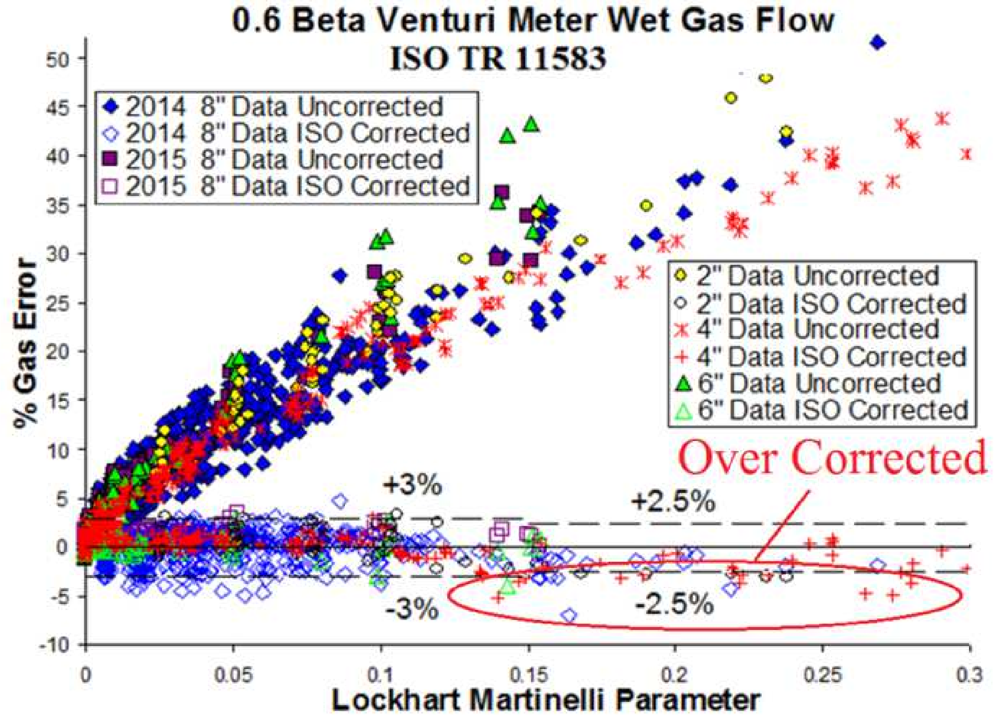

Fig. 14 - 2”, 4”, 6”, & 8” ISO compliant Venturi meter wet gas data from CEESI, corrected by ISO TR 11583.

In a separate project CEESI multiphase wet gas tested seven nominally identical 6”, 0.6β Venturi meters. Figure 15 shows four of these meters under test at the CEESI wet gas flow facility. Figure 16 shows the combined data set from these seven meters. Figure 17 shows the corrected data only. Again, as with the data shown in Figure 14, at higher Lockhart-Martinelli parameter values ($X_{LM} > 0.15$) the ISO TR 11583 correlation slightly over-corrects the multiphase wet gas flow data.

Fig. 15 - Four Out of Seven 6”, 0.6β Venturi Meters at CEESI

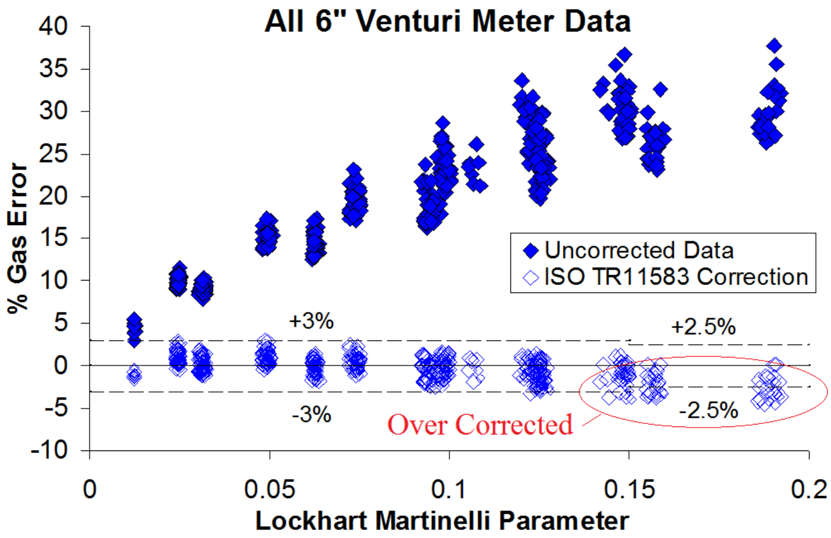

Fig. 16 - CEESI massed 6” Venturi meter multiphase wet gas uncorrected & TR 11583 corrected data

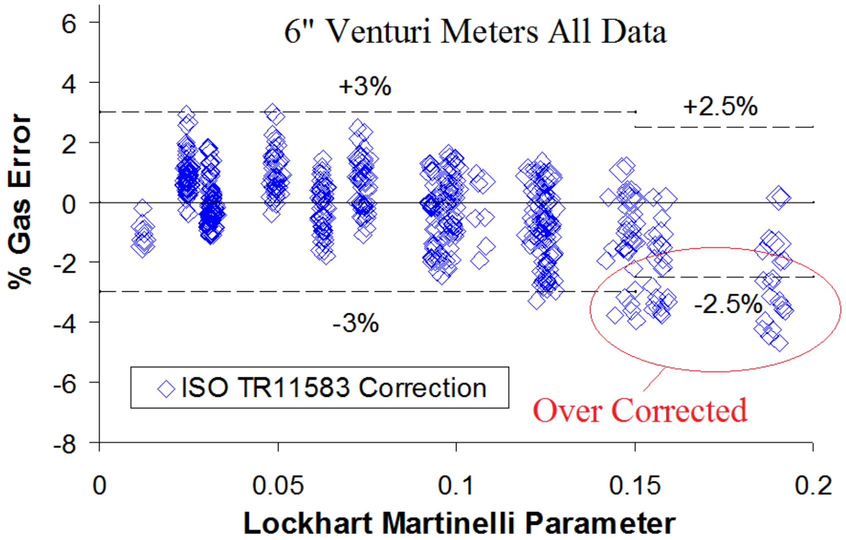

Fig. 17 - CEESI massed 6” Venturi meter multiphase wet gas TR 11583 corrected data

TUV NEL, 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 [9]) 4” Venturi meter data that shows for gas with oil or water the ISO TR 11583 correlation worked within its stated uncertainty, but for gas with oil and water at $X_{LM} > 0.15$ the TR 11583 correlation slightly over-corrects the data. Figure 18 shows this. This is essentially the same result as independently found by CEESI on two different projects.

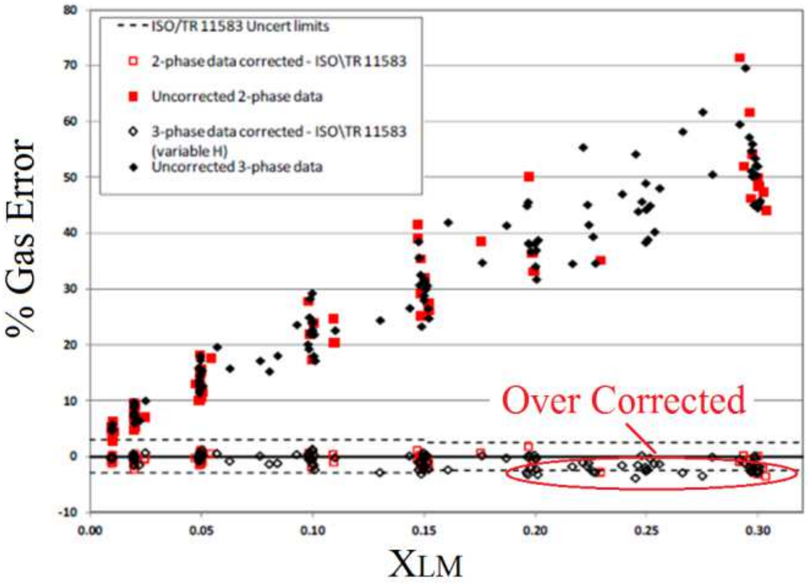

Fig. 18 - NEL 4” Venturi meter wet gas uncorrected & TR 11583 corrected data.

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.

7 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 with similar fluid properties, and far more importantly by extension, for the case of similar fluid properties a known performance in the field. The precise effects of extrapolating fluid properties are as yet uncertain. 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.

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.

8 NOTATION

A_t	Throath area of Venturi
C_d	Discharge coefficient
DR	Density ratio (gas/liquid)
E	Velocity of approach
E_n	Performance number
Fr_g	Gas densiometric Froude number
$Fr_{g,th}$	Gas densiometric Froude number evaluated at throath conditions
H	Parameter ISO 11583 correlation
$\dot{m}_g$	Mass flow rate of the gas
OR	Over-reading
ΔP_g	Venturi differential pressure at single phase gas flow
ΔP_{tp}	Venturi differential pressure at two-phase gas-liquid flow
$\dot{Q}_k$	Volume flow rate of phase *k*
u_{sk}	Superficial velocity of phase *k*
U^*	Relative expanded uncertainty
WLR	Water Liquid Ratio at line conditions
X_{LM}	Lockhart-Martinelli parameter
β	Venturi beta ratio
ε	Gas expansibility factor
ρ_k	Mass density of phase *k*

9 REFERENCES

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