33nd International North Sea Flow Measurement Workshop
20-23 October 2015

Impact of Using ISO/TR 11583 for a Venturi Tube in 3-Phase Wet-Gas Conditions

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1 INTRODUCTION

Venturi tubes are one of the most common types of device used for wet-gas flow measurement as they are a simple, robust and cost-effective flow meter. The presence of the liquid in the gas phase causes an increase in the measured differential pressure and results in the Venturi tube over-predicting the actual amount of gas passing through the meter. This over-reading is usually ‘corrected’ using available correlations derived from experimental data to determine the actual gas mass flowrate. This over-reading trend is observed in all differential-pressure meters. The flowrate of the liquid, which can be a combination of water and hydrocarbons, is normally determined by an external means such as from test separator data, tracer experiments or sampling etc. Information on the liquid flowrate and density is necessary to use the correlations.

The majority of commercial wet-gas and multiphase meters incorporate a Venturi tube along with other measurement technology to determine the flow rate of the individual phases.

The equations used for correcting the Venturi tube over-reading included in the ISO Technical Report on wet-gas flow measurement using differential pressure devices (ISO/TR 11583:2012) were developed for 2-phase flows of gas and water or gas and hydrocarbon liquid. There is a parameter, H, in the equations which accounts for the effect of the liquid properties on the over-reading. Values for H have been determined for water and liquid hydrocarbon but not for a mixture with varying water cut.

There has been some criticism voiced from industry over the robustness of the equations for real field applications partly due to not including the effect of different water cuts which are common in the field. Until recently there has been limited openly available 3-phase wet-gas flow data which can be used for deriving equations. ISO/TR 11583 is a step forward in the standardisation of using Venturi tubes for measuring wet-gas flows but another stride is necessary to align with industry’s metrology needs for 3-phase wet-gas measurement using Venturi tubes.

The upgraded high-pressure 3-phase wet-gas facility at NEL was used to collect 3-phase wet-gas flow data over a range of water cuts from a 4-inch, β=0.6, Venturi tube installed in a horizontal orientation. The data was used to assess the errors from applying the equations to determine the gas flowrate from ISO/TR 11583:2012. The equations within the ISO Technical Report using the pressure-loss measurement across a Venturi tube to determine an estimate of the amount of liquid in wet-gas flows have been assessed to determine their robustness for 3-phase wet-gas flow.

This paper summarises this research and supports the need to revise the ISO technical report to cover Venturi tubes for 3-phase wet-gas flow measurement.

It is anticipated that a revision to ISO/TR 11583 for Venturi tubes will follow a more extensive research programme to develop and validate more robust equations to correct the over-reading in 3-phase wet-gas conditions.

2 DEFINITIONS OF WET-GAS FLOW

For the research presented in this paper wet-gas flow is defined as the flow of gas and liquids with a Lockhart-Martinelli parameter, X, in the range $0 < X \leq 0.3$.

The Lockhart-Martinelli parameter,

$$X = \frac{m_{\mathrm{liq}}}{m_{\mathrm{gas}}}\sqrt{\frac{\rho_{\mathrm{gas}}}{\rho_{\mathrm{liq}}}} \qquad (1)$$

where m_{liq} and m_{gas} are the mass flowrates of the liquid and gas phase respectively and ρ_{liq} and ρ_{gas} are the densities of the liquid and gas phase respectively. In this work the density of the gas phase is that at the upstream pressure tapping, $\rho_{1,\mathrm{gas}}$.

The gas densiometric Froude number, Fr_{gas}, is a dimensionless number directly proportional to the gas velocity. It is defined as the square root of the ratio of the gas inertia if it flowed alone to the gravitational force on the liquid phase.

Gas densiometric Froude number,

$$Fr_{\mathrm{gas}} = \frac{v_{\mathrm{gas}}}{\sqrt{gD}}\sqrt{\frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liq}} - \rho_{1,\mathrm{gas}}}} \qquad (2)$$

where v_{gas} is the superficial gas velocity, g is the acceleration due to gravity and D is the pipe internal diameter.

The superficial gas velocity is given by

$$v_{\mathrm{gas}} = \frac{m_{\mathrm{gas}}}{\rho_{1,\mathrm{gas}} A} \qquad (3)$$

where A is the pipe area.

The gas-to-liquid density ratio, DR, is defined as

$$DR = \frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liq}}} \qquad (4)$$

The corrected gas mass flowrate, m_{gas}, is given by

$$m_{gas} = \frac{EA_d C\varepsilon_{wet}\sqrt{2\rho_{1,gas}\Delta p_{wet}}}{\phi} \quad (5)$$

where E is the velocity of approach factor defined below, A_d is the Venturi-tube throat area, C is the discharge coefficient in the actual (wet-gas) conditions, ε_{wet} is the gas expansibility in wet-gas conditions, Δp_{wet} is the actual (wet-gas) differential pressure and ϕ is the wet-gas over-reading or correction. ε_{wet} was determined from ISO 5167-4 [1] using the actual value of pressure ratio.

The velocity of approach factor, E, is defined as $E = \frac{1}{\sqrt{1-\beta^4}}$ (6)

where β is the diameter ratio of the Venturi tube (diameter at throat / diameter of pipe).

3 BRIEF HISTORY OF WET-GAS CORRELATIONS FOR HORIZONTAL INSTALLATIONS

3.1 Over-reading correlations where *X* is known

Correlations for the use of orifice plates in wet-gas conditions have existed since the 1960s; the most commonly used correlations are those of Murdock and Chisholm. These correlations are still used and commonly referred to. These equations have been applied to other types of differential-pressure meter including Venturi tubes.

Research by Murdock [2] in 1962 on orifice plates in wet-gas conditions stated that the wet-gas over-reading was dependent on the Lockhart-Martinelli parameter.

3.1.1 Murdock Correlation

Murdock's correlation gave the over-reading as $\phi = 1 + 1.26X$ (7)

3.1.2 Chisholm Correlation

Chisholm's research on orifice plates found that the wet-gas over-reading was dependent on the Lockhart-Martinelli parameter and the gas-to-liquid density ratio [3, 4]. Many of the available correlations for correcting the wet-gas over-reading are based on the Chisholm model.

Chisholm's correlation gave the over-reading as $\phi = \sqrt{1 + C_{\text{Ch}}X + X^2}$ (8)

where C_{Ch} accounts for the density ratio and is given by the following equation:

$$C_{\mathrm{Ch}} = \left(\frac{\rho_{\mathrm{liq}}}{\rho_{1,\mathrm{gas}}}\right)^{n} + \left(\frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liq}}}\right)^{n} \tag{9}$$

where $n = 0.25$.

3.1.3 de Leeuw Correlation

The most commonly used correlation for Venturi tubes is that of de Leeuw published in 1997 [5]. He used data collected from a 4-inch, 0.4 diameter-ratio Venturi tube and fitted the data using a modification of the Chisholm model. This research found that the wet-gas over-reading was dependent on the Lockhart-Martinelli parameter, the gas-to-liquid density ratio and the gas Froude number. De Leeuw used Equations (8) and (9) but showed that n was a function of the gas Froude number:

$$n = 0.41 \quad \text{for} \quad 0.5 \le Fr_{\mathrm{gas}} < 1.5 \tag{10}$$

$$n = 0.606\left(1 - e^{-0.746 Fr_{\mathrm{gas}}}\right) \quad \text{for} \quad Fr_{\mathrm{gas}} \ge 1.5 \tag{11}$$

The de Leeuw correlation or modifications of the Murdock and Chisholm correlations are used extensively throughout industry to correct for the differential-pressure over-reading from Venturi tubes and to determine the actual gas flowrate.

However, it is known that the extrapolation of an empirical correlation derived from a set of data with a limited range of a particular parameter has risks and that this can increase the measurement errors. This risk can be accounted for by increasing the uncertainty of the measurements derived from the correlation

3.1.4 Other Research

Since the publication of de Leeuw's correlation it has been shown by Stewart *et al.* [6] that there is a diameter-ratio effect on the wet-gas over-reading. Reader-Harris *et al.* [7, 8] and Steven *et al.* [9, 10] have shown that the liquid properties can have an effect on the response of differential-pressure meters in wet-gas conditions.

Other correlations have been published and an in-depth review is provided by ASME [11].

3.1.5 NEL Correlation

In 2009 NEL published a correlation based on a modification of the Chisholm model and incorporated a wet-gas discharge coefficient term [12, 13]. This correlation found that the wet-gas over-reading was dependent on the Lockhart-Martinelli parameter, the gas-to-liquid density ratio, the gas Froude number, diameter-ratio (β) and a parameter to account for the liquid type (H).

This new correlation can be used to determine a value for *n* in the wet-gas over-reading based on the Chisholm model. In addition, the discharge coefficient in wet-gas conditions, which has been found to differ from the value in dry-gas conditions, can be used with the over-reading to determine the gas mass flowrate in wet-gas conditions.

The wet-gas discharge coefficient can be derived using this equation:

$$C = 1\text{-}0.0463\mathrm{e}^{-0.05Fr_{\mathrm{gas,th}}}\ \min\left(1, \sqrt{\frac{X}{0.016}}\right) \tag{12}$$

where the throat Froude number ($Fr_{\mathrm{gas,th}}$) is calculated as:

$$Fr_{\mathrm{gas,th}} = \frac{Fr_{\mathrm{gas}}}{\beta^{2.5}} \tag{13}$$

The value of *n* was determined to be:

$$n = \max(0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_{gas}/H}, 0.392 - 0.18\beta^2) \tag{14}$$

where H is a parameter to account for the effect of the liquid properties on the over-reading. H = 1 for liquid hydrocarbon, H = 1.35 for water at ambient temperature and H = 0.79 for liquid water in wet-steam flow (hence at elevated temperatures).

The correlation can be used to determine the gas mass flowrate for the following Venturi tube parameters and wet-gas conditions:

$0.4 \leq \beta \leq 0.75$
$0 < X \leq 0.3$
$3 < Fr_{\mathrm{gas,th}}$
$0.02 < \rho_{1,\mathrm{gas}}/\rho_{\mathrm{liq}}$
$D \geq 50$ mm

with an uncertainty of $\begin{cases} 3\% \text{ for } X \leq 0.15 \\ 2.5\% \text{ for } 0.15 < X \leq 0.3 \end{cases}$

3.2 Correlation Developed For Determining the Wetness

The pressure loss across a Venturi tube is a function of the wetness of the gas. In dry gas the pressure loss is generally in the range of 5 to 30% of the differential pressure for a divergent angle of 15° and in the range of 5 to 15% for a divergent angle of 7°. In wet-gas conditions the pressure loss can be much greater, and under certain circumstances the ratio of the pressure loss to the differential pressure can be used to determine X and hence determine the gas mass flowrate without a separate measurement of the liquid flowrate. Figure 1 shows a schematic of the different pressure measurements across a Venturi.

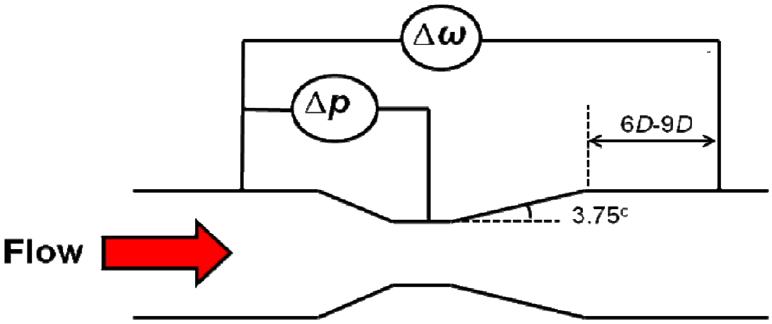

Figure 1: Schematic of Venturi tube illustrating total pressure loss ($\Delta\varpi$) and the differential pressure (Δp) to calculate the pressure loss ratio ($\Delta\varpi/\Delta p$).
(Note diagram is not drawn to correct scale or dimensions)

For a limited range of X it is possible to use the pressure loss ratio to determine the Lockhart-Martinelli parameter. The formulae in this paper are valid for a Venturi tube with divergent total angle in the range 7° to 8°.

The pressure loss, $\Delta\varpi$, from the upstream pressure tapping to a tapping a distance L_{down} downstream of the downstream end of the Venturi tube divergent section is measured. L_{down} should be such that

$$\max(5,20\beta-7) \le \frac{L_{down}}{D} \le 9 \qquad (15)$$

Then evaluate (this is an iterative procedure)

$$Y = \frac{\Delta\varpi}{\Delta p} - 0.0896 - 0.48\beta^9 \qquad (16)$$

and

$$Y_{\max} = 0.61\exp\left(-11\left(\frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liquid}}}\right) - 0.045 Fr_{\mathrm{gas}}/H\right) \qquad (17)$$

If $Y/Y_{\max} \ge 0.65$ it is not possible to use the pressure loss ratio to determine X.

If $Y/Y_{\max} < 0.65$ X is evaluated from

$$\frac{Y}{Y_{\max}} = 1 - \exp(-35X^{0.75}e^{-0.28Fr_{\text{gas}}/H}) \tag{18}$$

Limits of use are:

$$Fr_{\text{gas,th}} > 4$$

$$\frac{Fr_{\text{gas}}}{H} \le 5.5$$

and $\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}} \le 0.09$

The uncertainty in C/ϕ using the additional equations to determine the liquid content is

$$\begin{cases} 4\% \text{ for } \frac{Y}{Y_{\max}} < 0.6 \\ 6\% \text{ for } 0.6 \le \frac{Y}{Y_{\max}} < 0.65 \end{cases}$$

where Y is the increase in the pressure loss ratio due to wetness and $Y_{\max}$ is the maximum value of Y.

These equations are included in ISO/TR 11583:2012; their derivation is explained in much more detail in references [13, 14].

3.3 ISO Technical Report for Wet-Gas Flow Measurement

An ISO Technical Report on wet-gas flow measurement using differential pressure devices (ISO/TR 11583:2012) has been produced for horizontal meter installations and includes the NEL correlation [14]. The NEL-derived equations for the pressure-loss ratio to determine *X* are also included in the ISO Technical report.

4 3-PHASE HORIZONTAL VENTURI TUBE WET-GAS TESTS AT NEL

A 4-inch, β=0.6, Venturi tube with convergent angle 21° and divergent angle 7.5° (which had previously been tested in 2-phase wet-gas conditions at NEL) was installed in a horizontal orientation and tested in NEL's new 3-phase wet-gas flow measurement facility. Figure 2 shows a photograph of the set-up. The Venturi was installed approximately 40*D* downstream of two concentric reducers (8-inch to 6-inch and 6-inch to 4-inch). The conditions tested are shown in Table 1 over a range of Lockhart-Martinelli parameters (*X*) up to 0.3. The hydrocarbon liquid used was a kerosene substitute called Crownsol D75, which at the nominal facility operating temperature of 20 °C has a density of 801 kg/m^3 and dynamic viscosity of 1.93 cP. Pure water was used as the third phase, and the gas used was nitrogen.

During the commissioning of the 3-phase facility it was noticed that the density output of the reference liquid Coriolis flow meters was affected by pressure. This is discussed separately in the Appendix and was corrected in this data set.

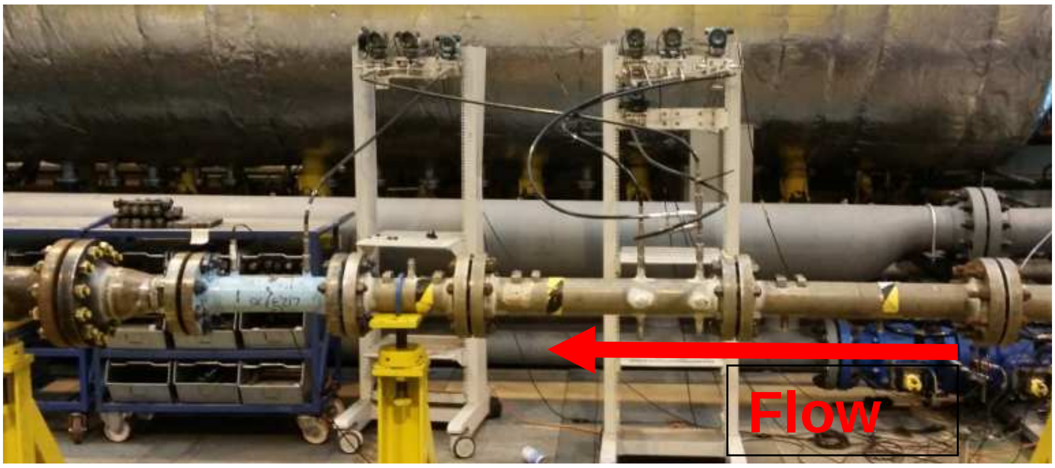

Figure 2: Photograph illustrating the Venturi and instrumentation setup

Table 1 Test Conditions

WC /%	Density Ratio (*DR*)	Pressure /barg	Gas Froude No. (Fr_{gas})
0	0.025	16	1.5, 3
25	0.024	17	1.5, 3
50	0.025	18	2, 3
70	0.025	20	1.5, 3.5
100	0.025	21	1.5, 3
0	0.046	31	1.5, 3.5
25	0.047	33	2.5, 3.5
50	0.047	35	1.5, 2.5, 3.5
70	0.047	37	1.5, 2.5, 3.5
100	0.046	38	1.5, 3.5
0	0.089	61	2.5, 5.5
25	0.084	61	2.5, 4, 5.5
50	0.080	61	2.5, 5.5
70	0.075	61	2.5, 5.5
100	0.072	61	2.5, 5.5

A total of 63 two-phase data points (0% WC and 100% WC) and 119 three-phase data points (25% WC, 50% WC and 70% WC) were collected.

5 RESULTS AND ANALYSIS

5.1 Over-readings where *X* is known

The parameter *H*, which accounts for the effect of the liquid properties on the over-reading when using equations (12) and (14) has been determined as $H = 1$ for liquid hydrocarbon (0% WC) and $H = 1.35$ for water (100% WC) at ambient temperature. Values have not previously been determined for liquid flows with water cuts between 0% and 100%. Linear interpolation of values for *H* between 1 and 1.35 has been used in this study to determine values for water cuts between 0% and 100%, see Table 2.

Table 2 Values of *H* for Different Liquid Flow Water Cuts (WC)

WC (%)	*H* (-)
0	1
25	1.09
50	1.18
70	1.25
100	1.35

Figure 3 shows the errors in gas mass flow rate uncorrected for the presence of liquid and corrected using equations (12) and (14), which are included in ISO/TR 11583. For the 3-phase data "variable H" refers to a linearly interpolated value based on the water cut.

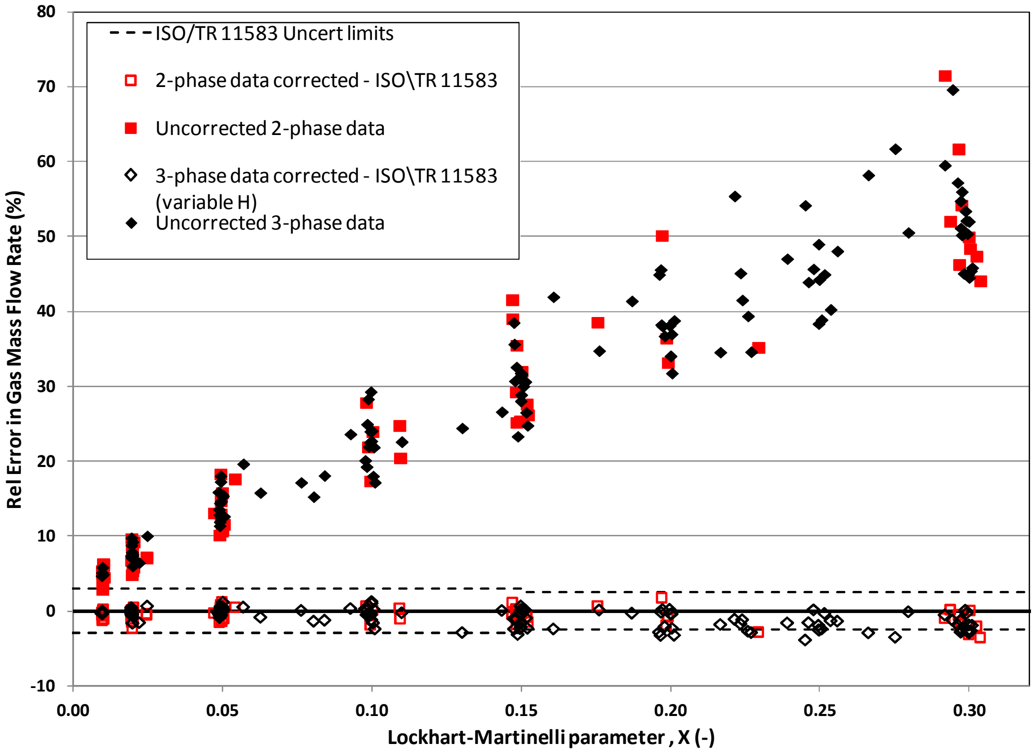

Figure 3 Errors in gas mass flow rate uncorrected for the presence of liquid and corrected using ISO/TR 11583. "variable H" refers to a linearly interpolated value based on the water cut.

Figure 3 shows the interpolating the value of *H* based on the water cut is a generally robust approach to use in applying ISO/TR 11583 to 3-phase flows of water, oil and gas. For the 2-phase data (0% WC and 100% WC) 95.2% of the data points were within the uncertainty limits of ISO/TR 11583 and for the 3-phase data 84% of the data points were within the uncertainty limits of ISO/TR 11583.

Figure 4 compares the data corrected using the well known de Leeuw correlation and ISO/TR 11583. It should be noted that the de Leeuw correlation was developed using a Venturi tube with diameter ratio 0.4, whereas these data were collected using a Venturi tube with diameter ratio 0.6. The magnitude of the over-reading is dependent on the diameter ratio.[6] For comparison, 66.7% of the 2-phase data points (0% WC and 100% WC) and 54.6% of the 3-phase data points were within the ISO/TR 11583 uncertainty limits when applying the de Leeuw correlation.

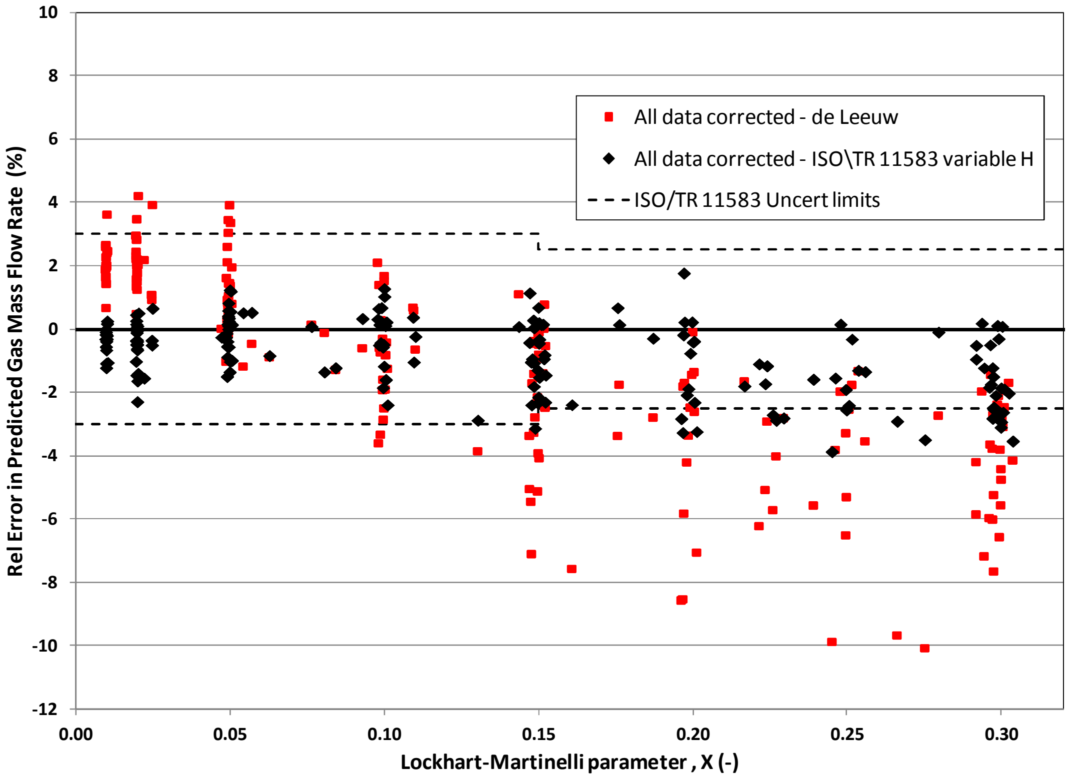

Figure 4 Gas mass flow rate errors using the de Leeuw and ISO\TR 11583 correlations for the 2-phase and 3-phase data.

Figure 5 compares all the data (2-phase and 3-phase) corrected using ISO/TR 11583 with *H*=1.35 and those corrected using ISO/TR 11583 with a linearly interpolated value for *H*. For this data set using *H*=1.35 produces a better overall fit and a higher percentage of points within the uncertainty limits quoted in ISO/TR 11583 with 97.3% of data using *H*=1.35 within the uncertainty limits compared with 87.9% when using a linearly interpolated value for *H*. Using a value of *H*=1 rather than *H*=1.35 for data with 0% WC, as recommended in ISO/TR 11583, did ensure all the data were within the ISO/TR 11583 uncertainty limits as shown in Figure 6.

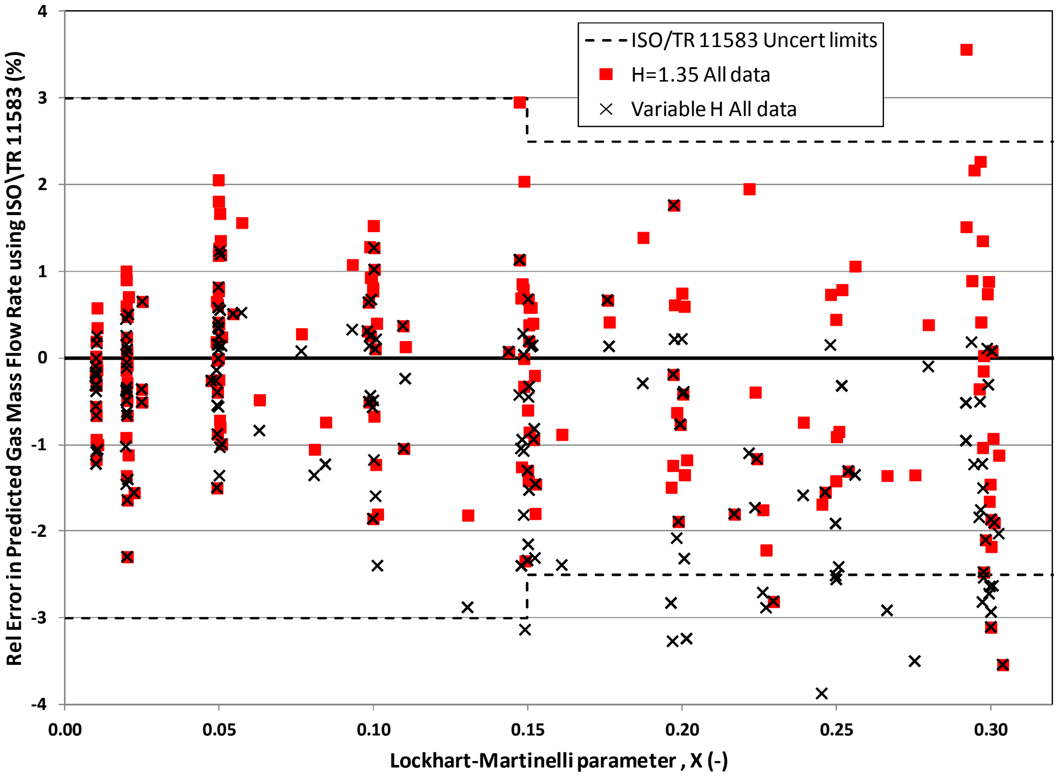

Figure 5 Gas mass flow rate errors using ISO/TR 11583 correlations with *H* = 1.35 and *H* determined by linear interpolation for all the data.

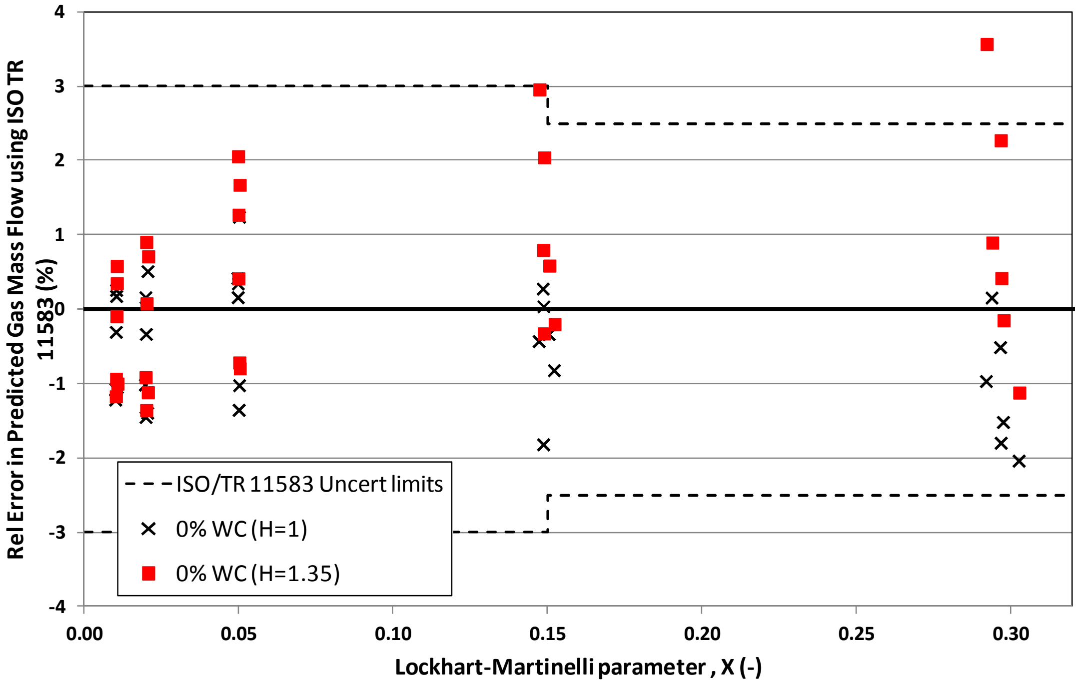

Figure 6 Gas mass flow rate errors using ISO/TR 11583 correlations with *H* = 1.35 and *H* = 1 for data with 0% water cut, i.e. oil and gas flows.

5.2 Using the Pressure Loss Ratio (PLR) to Determine *X*

Figures 7 and 8 show the relative errors in the gas mass flow rate using the pressure loss ratio (PLR) method as outlined in ISO/TR 11583 and Section 3.3. The PLR method can be used in limited conditions (very small values of *X*) to determine the wetness defined as *X* and hence use the equations to correct for the Venturi over-reading.

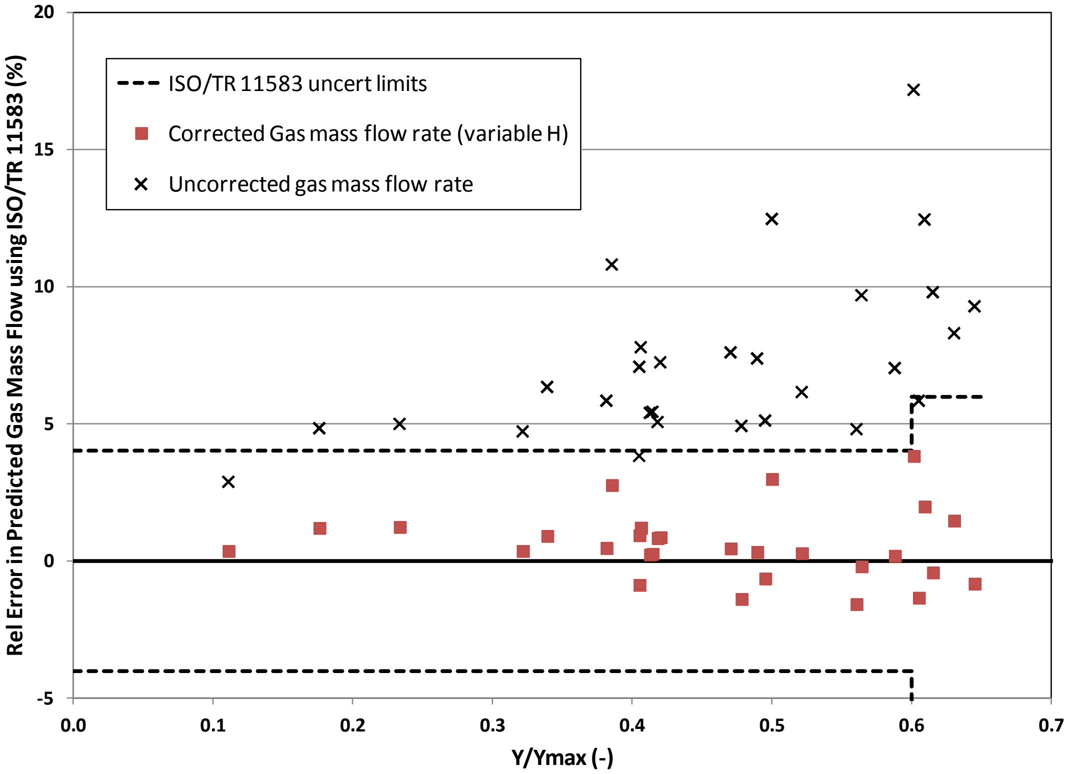

Figure 7 Relative gas mass flow rate error as a function of Y/Y_{max} (predicted gas mass flow rate determined using PLR equations from ISO/TR 11583 and linearly interpolated value for *H* based on water cut).

The graphs provide evidence that when the criteria for using the PLR method are met as defined in ISO/TR 11583, then the method is robust enough to use over a range of water cuts using a value of *H* based on the water cut. Using the method can significantly reduce the errors in the gas mass flow rate.

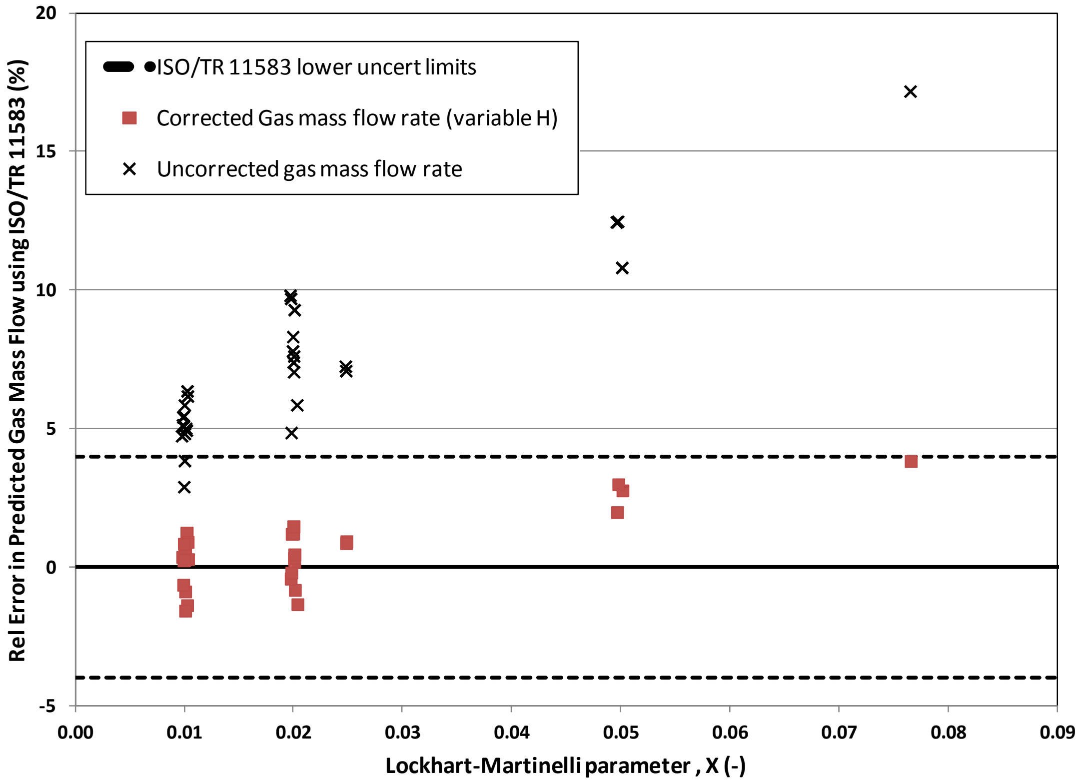

Figure 8 Relative gas mass flow rate error as a function of *X* (provided Y/Y_{max} < 0.65) (predicted gas mass flow rate determined using PLR equations from ISO/TR 11583 and linearly interpolated value for *H* based on water cut).

6 CONCLUSIONS

It has been shown from a limited data set that the current wet-gas over-reading correlations in ISO/TR 11583 derived for Venturi meters can be used with reasonable accuracy for 3-phase wet-gas flows with water cuts from 0% to 100% provided the parameter *H* is determined by linear interpolation based on the water cut. Using this method over 85% of the 3-phase data were corrected so that the predicted gas mass flow rate errors using ISO/TR1183 were within the quoted uncertainty limits of either 2.5% or 3%.

The ISO/TR 11583 equations using the pressure loss ratio to determine *X* work well when using a linearly interpolated value for *H* based on the water cut. Using this method on this data set reduced the errors in the gas mass flow rate to within the limits of ISO/TR 11583. This method can reduce the errors in the gas mass flow rate by a factor of four.

This small data set provides evidence of the robustness of the equations for correcting Venturi over-readings in ISO/TR 11385 when they are used for 3-phase wet-gas flows with water cuts from 0% to 100%. Significantly more data will be required before there can be a revision of ISO/TR 11583 to extend its application to wet-gas flows with water cuts from 0% to 100% with equations more suitable for more realistic field conditions.

7 ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the National Measurement and Regulation Office's Flow Programme, under the sponsorship of the United Kingdom Department for Business Innovation and Skills.

We would like to thank Chris Mills, Bob Belshaw and Muir Potter for support with using Coriolis liquid reference meters, Brendan Robson for data acquisition software modifications, Derek MacLeod for financial management, and Norman Glen and Phil Mark for assistance with density measurements from Coriolis flow meters.

This paper is published by permission of the Managing Director, NEL.

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APPENDIX

ERRORS IN THE DENSITY OUTPUT OF A CORIOLIS FLOW METER AT DIFFERENT PRESSURES

During commissioning of the new 3-phase wet-gas flow measurement facility at NEL it was discovered that the density output of the reference liquid Coriolis flow meters was providing erroneous reading at higher pressures (facility operates from 10 barg to 63 barg). The Coriolis meters were calibrated at atmospheric pressure by the manufacturer with an uncertainty in the output density of 0.1%. One of the Coriolis flow meters was custom calibrated for the density output in NEL’s Industrial Densitometer Calibration Facility (reference fluid density uncertainty of 0.02%, k=2) over a range of temperature from 10^{o}C to 40^{o}C and pressures from 1 bara to 71 bara. Figure A1 shows the relative errors in the uncorrected and corrected density output from the Coriolis flow meter as a function of pressure. There is a noticeable temperature effect but this is much smaller than the pressure effect on the density output. The density output was corrected by fitting coefficients to an equation form that is commonly used in industrial offshore densitometers. More work on the pressure and temperature effects on Coriolis flow meter will be conducted at NEL to reduce the uncertainty in the reference measurements used in NEL’s facility.

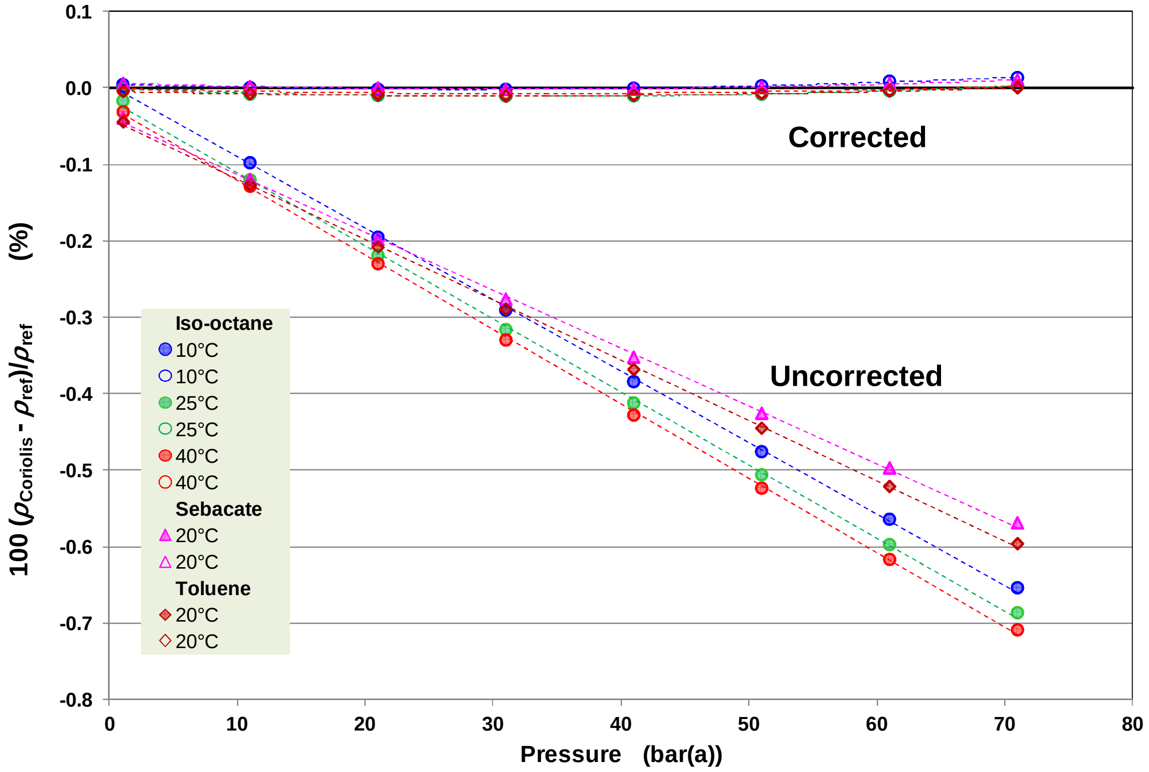

Figure A1: The relative errors in the uncorrected and corrected density output from a 1.5-inch Coriolis flow meter as a function of pressure.