Installation effects on Venturi tubes in wet-gas flow 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. They also form the main component in the majority of commercial wet-gas and multiphase flow meters.

There are standards available for their use in wet-gas conditions; ISO/TR 11583 and ISO/TR 12748. However, these mainly cover only 2-phase flows and horizontal installation. The performance of Venturis in 3-phase conditions, including the impact from using correlations derived for 2-phase flows, has more recently been investigated.

Issues with straight upstream piping requirements for Venturis in wet-gas conditions have been highlighted by industry as there is very little information available and current recommendations are based on single-phase standards (ISO 5167-4). Long straight upstream lengths increase manufacturing costs and reduce opportunities for the use of Venturis in space-limited installations. In some cases they are installed with much shorter straight upstream lengths with no knowledge about the errors induced. NEL has conducted tests to investigate the effect of upstream installations on a Venturi tube. The results indicate that the required upstream lengths were heavily dependent on the flow conditions: in some cases the upstream lengths can be significantly reduced and in other cases the measurement errors could be up to 9%.

Most correlations and research for using Venturis in wet-gas flows are for horizontal installations; this has limited the use of Venturis in vertical installation. Many of the commercial multiphase meters are installed in a vertical installation, and, using the same hardware but different models, are used to meter wet-gas flows. NEL has collected new wet-gas data on the impact of upstream effects on the vertical installation of Venturis.

The data presented in this paper highlights and quantifies the impact of upstream installations on Venturi tubes in wet-gas flows. It is anticipated that this will lead to new research and form the basis on which the current wet-gas standards/best practice may be updated to cover a wider range of installations. This should enable Venturi tubes to be used in well defined installations with guidance available on the impact, similar to the table in ISO 5167-4 for Venturis in single-phase flows.

2 INSTALLATION EFFECTS BACKGROUND

The effect of common pipe installations upstream of Venturi tubes in wet-gas conditions is not well understood and the impact on measurement errors has not been quantified. NEL has completed a small pilot study to quantify the impact of different installation effects using the equations of ISO/TR 11583 as the baseline.

This study has allowed the recommendations given in ISO/TR 11583 to be assessed and provides information on upstream straight pipe length requirements in wet-gas conditions. Manufacturers and end-users are keen to reduce upstream lengths for cost and space considerations.

ISO/TR 11583 recommends that the reduced straight lengths outlined in ISO 5167-4 (those corresponding to 0.5% additional uncertainty) are not used and that where possible, the longer straight lengths recommended in the standard are used in order to minimise measurement uncertainty. For a β=0.6 Venturi tube, as was used in these tests, ISO 5167-4 recommends that at least a 10D length of straight pipe is used upstream of the meter for 'zero additional uncertainty'.

ISO 5167-4 recommends that for research and calibration work, the required straight lengths outlined in the standard are at least doubled, to minimise measurement uncertainty.

3 HORIZONTAL EXPERIMENTAL TEST SET-UP

A Venturi tube (β=0.6, D=0.10236 m) was installed in NEL's wet-gas facility and underwent testing with an upstream bend combination placed at various diameters upstream of the meter (6D, 10D and 17D). The number of upstream diameters was measured from the final curved portion of the downstream end of the bend to the Venturi's upstream pressure tapping.

Tests without a bend were also performed. These tests had 35D of straight pipe upstream of the Venturi. Throughout the tests, schedule 40 pipes were used to ensure no 'step' in the geometry when fluid was flowing through the various straight sections of pipe into the Venturi. The only point at which the internal diameter of the pipe varied was in the U-bend.

Gas (nitrogen) and oil (kerosene substitute Crownsol D75) flow rates were varied to correspond to gas densiometric Froude numbers (Fr_g) of 1.5 and 3.0 across a range of Lockhart-Martinelli parameters (X=0-0.3). The data were then analysed according to ISO/TR 11583, allowing comparison of the standard's predicted gas mass flow rate with the reference data.

The majority of tests were performed at 15 barg; however, selected tests were performed at 30 and 60 barg to investigate pressure (i.e. density ratio) effects. A 60 barg test with a gas Froude number of 4.5 was also performed.

Figures 1 and 2 show the test setup.

Figure 1 Photograph of the installation effects test. The bend combination is 10D upstream of the Venturi tube.

Figure 2 Photograph of the installation effects test. The bend combination is 10D upstream of the Venturi tube.

4 HORIZONTAL RESULTS AND DISCUSSION

4.1 Upstream Straight Length Requirements

The results showed that under certain conditions, an upstream bend could have a significant impact on the results obtained using the standard if there was not a sufficient length of straight pipe upstream of the Venturi. As shown in Figure 3 (Fr_g=1.5, 15 barg), as the upstream straight length between the bend and Venturi decreased, the size of the errors measured (comparing predicted gas mass flow rate from standard with reference value) increased, particularly at higher liquid loadings.

For example, at Fr_g=1.5 and 15 barg, when X=0.3, the error at 17D was 2.5%, but when the straight length was reduced to 6D, the error increased to 8.6%.

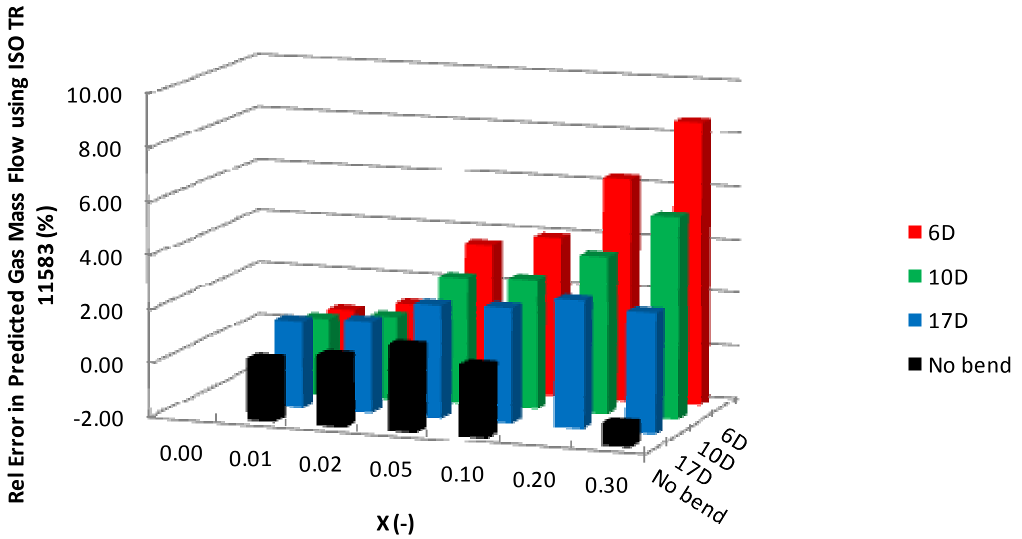

Figure 3 Effect of upstream straight lengths on gas mass flow rate error using ISO/TR 11583 for various liquid loadings (X) at 15 barg and Fr_g=1.5

4.2 Effect of Liquid Loading (X)

The liquid loading was important, and the effect of an upstream bend became more significant as X increased. As X increased, larger lengths of straight pipe were required for the data to fall within the standard uncertainty limits. This can be seen in Figure 4.

For example, at low liquid loadings (X=0.01 and X=0.02) all data lay within the standard's uncertainty, including at 6D, which is lower than the standard's 10D recommendation. For X=0.05 and X=0.1, this minimum distance increased and 10D was required for data to fall within the standard. Beyond X=0.1, this distance increased further and at least 17D of straight length pipe was required for data to fall within the standard. Therefore at Fr_g=1.5 and 15 barg, at least 17D of straight length was required upstream of the meter for the data to fall within the standard across the full range of liquid loadings (X=0-0.3) tested.

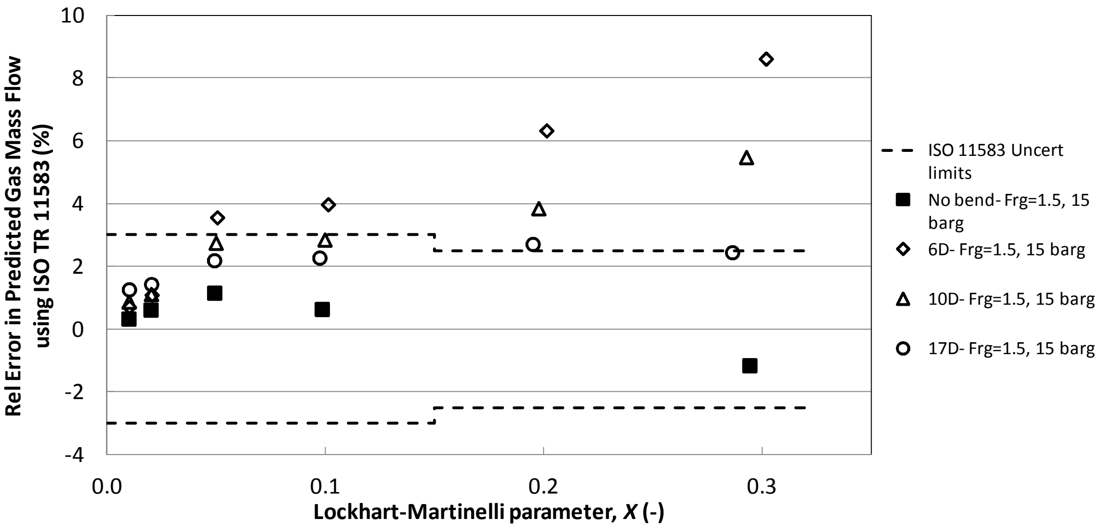

Figure 4 Effect of upstream straight lengths on gas mass flow rate error using ISO/TR 11583 for various liquid loadings (X) at 15 barg and Fr_g=1.5

4.3 Effect of Pressure

The test pressure was also important; as the pressure was increased the bend appeared to have a much less significant impact on the results. For example, as shown in Figure 5, at 30 barg and Fr_g=1.5, the effects of the bend found at 15 barg and Fr_g=1.5 were not observed. At higher pressures, annular/ annular mist flow are more likely to occur.

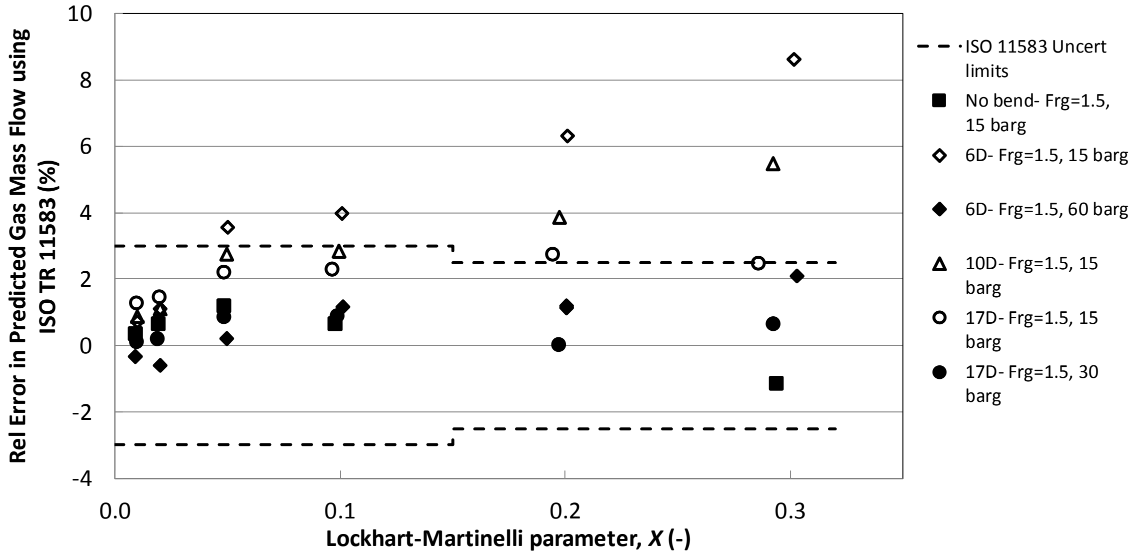

Figure 5 Effect of upstream straight lengths and pressure on gas mass flow rate error using ISO/TR 11583 for various liquid loadings (X) at 30 and 60 barg and Fr_g=1.5. 15 barg and Fr_g=1.5 data are shown for comparison.

4.4 Effect of Gas Froude Number

The gas Froude number appeared very important and the effects found for Fr_g=1.5 at 15 bar were not seen for Fr_g=3.0 at 15 bar as shown in Figure 6.

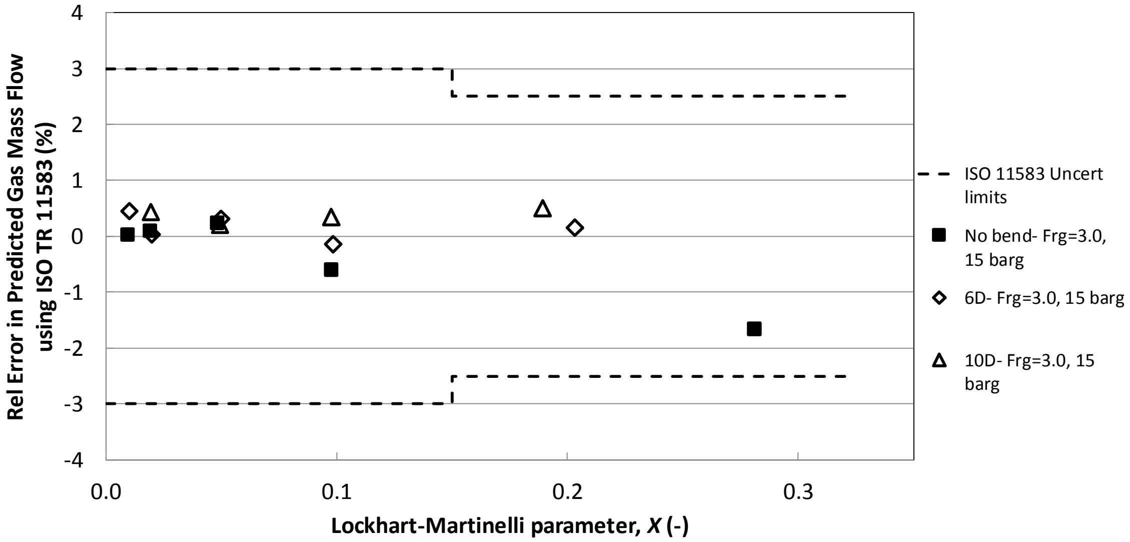

Figure 6 Effect of upstream straight lengths on gas mass flow rate error using ISO/TR 11583 for various liquid loadings (*X*) at 15 barg and *Fr*$_g$=3.0

4.5 Effect of Bend Orientation

The orientation of the bend appeared to have little impact, as shown in Figure 7. At Fr_g=3.0 and 15 barg, the data obtained with the bend (10D) installed vertically compared very well to the data obtained with the horizontal 10D installation.

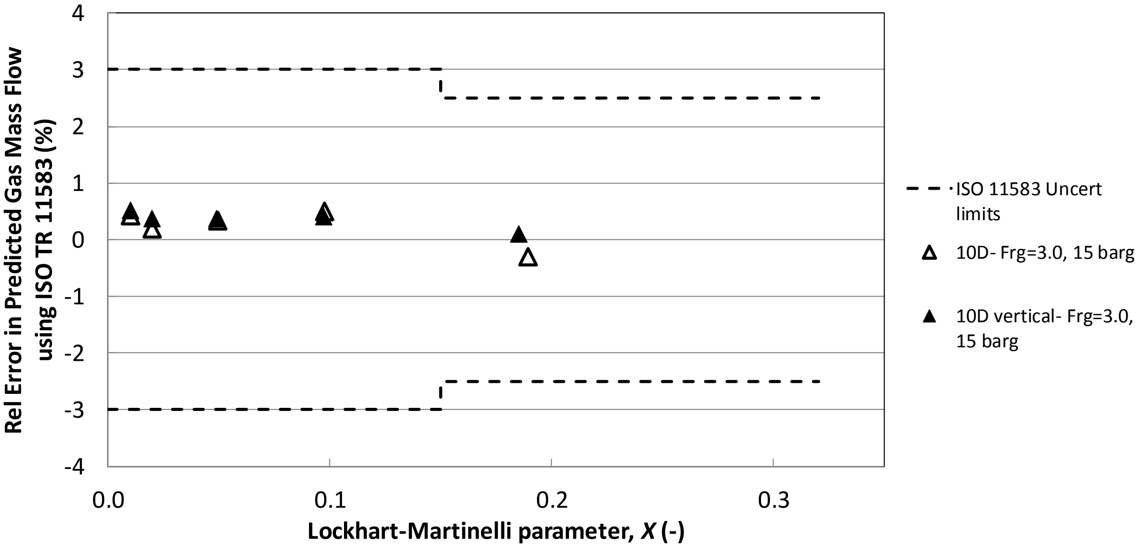

Figure 7 Effect of upstream straight lengths and bend orientation on gas mass flow rate error using ISO/TR 11583 for various liquid loadings (*X*) at 15 barg and *Fr*$_g$= 3.0.

5 CONCLUSIONS OF HORIZONTAL INSTALLATION EFFECTS

The experimental results showed that under certain conditions, an upstream bend could have a significant impact on the results obtained using the ISO/TR 11583 if there was not a sufficient length of straight pipe upstream of the Venturi. This resulted in large errors between the predicted gas mass flow rate using the standard ISO/TR 11583 and reference measurement, compared with when there was no bend present.

The effects of an upstream bend were most notable at shorter upstream straight lengths before the Venturi, lower gas Froude numbers, lower test pressures and higher liquid loadings, with larger errors being found at these conditions. The results showed that under certain conditions, larger lengths of straight pipe than those recommended by the standard were required. The bend's orientation appeared to have little impact on the results. Further investigation is necessary to clarify this.

6 INTRODUCTION TO VERTICAL TESTING

The behaviour of Venturi tubes installed vertically in wet-gas conditions is not well understood. There is little published work on the area, and the impact of a vertical installation on measurement errors and uncertainty has not been quantified. NEL has completed a small pilot study to quantify the impact of a vertical installation using ISO/TR 11583 (which was developed for horizontal flow) to see if it can be adequately applied to a vertical installation. There is increasing interest in installing Venturi meters in vertical installations, similar to multiphase meter installations.

There is no mention of the impact of vertical installations in ISO/TR 11583, and it is hoped that testing on vertical configurations can allow recommendations for vertical installation and its impact on uncertainty to be established.

7 VERTICAL EXPERIMENTAL TEST SET-UP

A Venturi tube (β=0.6, D=0.10236 m) was installed vertically after a blind-tee in NEL's wet-gas facility and underwent testing. There was no straight length of vertical pipe before the meter (Figure 8).

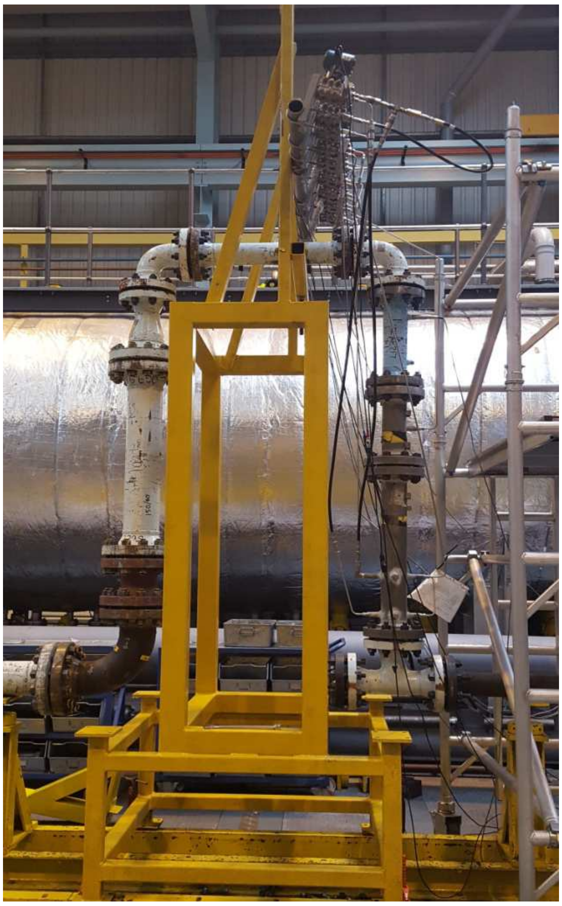

Figure 8 Vertical Venturi tube installation

Three-phase testing took place with gas (nitrogen) and oil (kerosene substitute Crownsol D75) flows, gas and water flows or gas + water + oil flows (with 50% water cut). Flow rates were varied to correspond to a range of gas densiometric Froude numbers (Fr_g) between 1.5 and 5.5 being tested across a range of Lockhart-Martinelli parameters (X=0.05 to 0.3).

Testing was performed at pressures ranging from 15.9 to 57.0 barg, and various Froude numbers (usually two) were tested at each pressure. The data were then analysed according to ISO/TR 11583, allowing comparison of the standard's predicted gas mass flow rate with the reference data.

In 2014, the meter was installed vertically with 30D of straight vertical pipe before the meter. The vertical data collected in these current tests were for similar conditions to these previous studies, allowing comparisons to be made.

The test criteria that were covered are summarised in Table 1.

TABLE 1
TESTS PERFORMED

Liquid	Pressure (barg)	Fr_g	Density Ratio
Oil (0% WC)	15.9 31.1 57.0	1.5, 2.5 1.5, 4.0, 4.5 1.5, 5.5	0.024 0.046 0.084
Water (100% WC)	20.1 39.1 57.0	1.5, 2.5 1.5, 4.5 1.5, 5.5	0.024 0.046 0.067
Oil + Water (50% WC)	18.0 35.0 57.0	1.5, 2.5 1.5, 4.5 5.5	0.024 0.046 0.074

8 RESULTS AND ANALYSIS

8.1 Effect of Liquid Loading (*X*) and Gas Froude Number

The liquid loading was important and as *X* increased, the magnitude of the error in predicted gas mass flow rate using ISO/TR 11583 increased (Figure 9). For all Fr_g=1.5 tests, as *X* increased the relative error increased in a positive direction. For Fr_g=4.0 to 5.5, however, as *X* increased the relative error became larger in the negative direction.

The gas Froude number appeared very important. At lower gas Froude numbers (Fr_g=1.5), the error in the predicted gas mass flow rate was larger (particularly at higher liquid loadings) than at the higher Froude numbers tested (Fr_g=4.0 to 5.5) (Figure 9). At lower gas Froude numbers, as *X* increased the relative error increased in a positive direction. This differed from the results at higher Froude numbers where the errors generally increased in a negative direction (Figure 9).

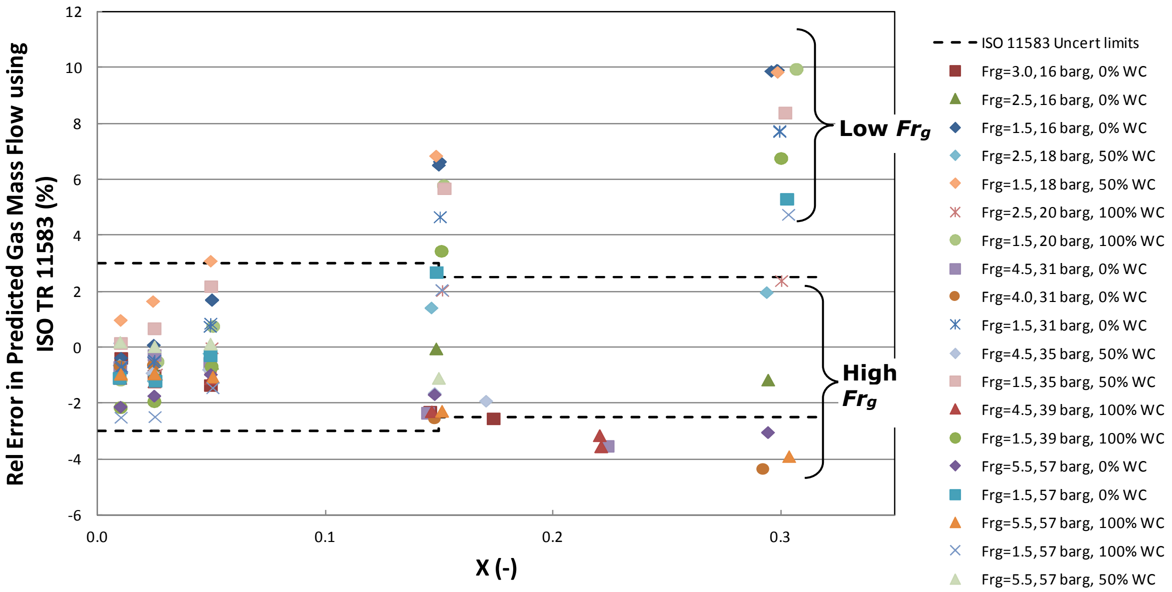

Figure 9 Gas mass flow rate error using ISO/TR 11583 for various liquid loadings (*X*)

The effects seen are probably due to the meter being installed vertically, rather than the Venturi being installed vertically directly after the blind-tee and change in flow direction. This is discussed in more detail in Section 9.3, where the results are shown to compare closely to previous tests where 30D of straight vertical pipe was installed between the change in flow direction and the Venturi.

8.2 Effect of Test Pressure and Density Ratio

The test pressure and density ratio were also important and as the pressure/ density ratio was increased, the gas mass flow error generally decreased, particularly at larger liquid loadings. This brought data closer to falling within the standard's uncertainty limits. For example, as shown in Figure 10, at 57 barg, X=0.15 and Fr_g=1.5, the data fell within the standard but in the equivalent tests at lower pressures (and density ratios) the data fell outwith the standard.

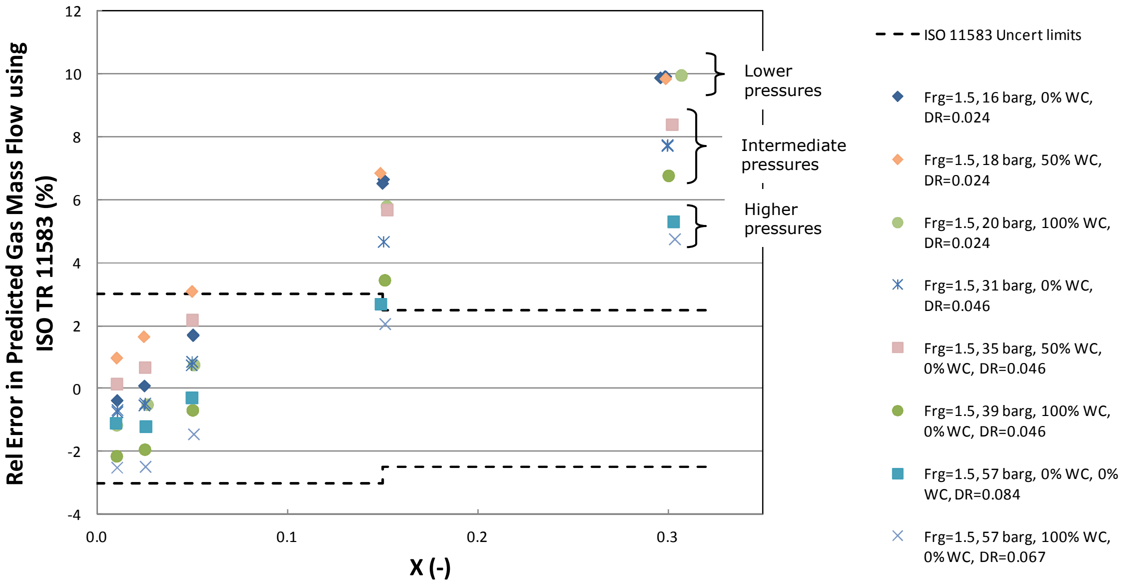

Figure 10 Effect of pressure on gas mass flow rate error using ISO/TR 11583 for various liquid loadings (X) and pressures at Fr_g=1.5

8.3 Comparisons of Upstream Effects on Vertical Installations

The same Venturi tube was installed in a vertical orientation with 30D straight pipe upstream and tested under 2-phase conditions using nitrogen and oil in 2014 [1]. Refer to Figure 11 for comparison photographs of the different installations.

Figures 12 and 13 compare the Venturi tube over-readings for 31 barg and 16 barg, respectively, for the two different vertical installations. The results indicate that upstream installation effects for the vertical orientation of the Venturi tube are minimal.

Figure 11 Photographs showing the installation of the Venturi directly after a blind-T and with 30D straight upstream pipe (tested in 2014).

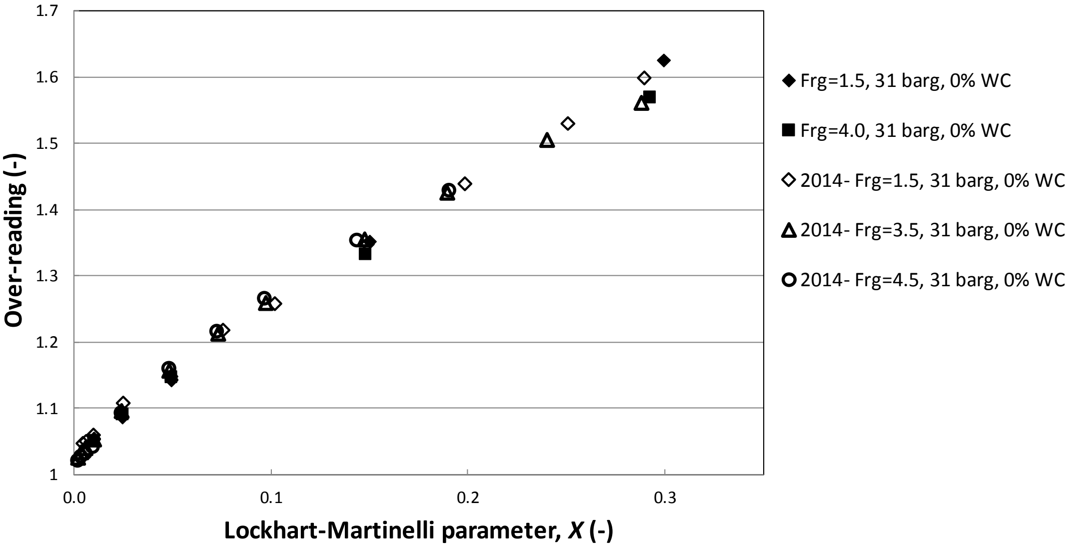

Figure 12 Comparing over-readings between the vertical Venturi tube installed downstream of a blind-T and with 30D upstream straight pipework (2014 data). Pressure 31 barg.

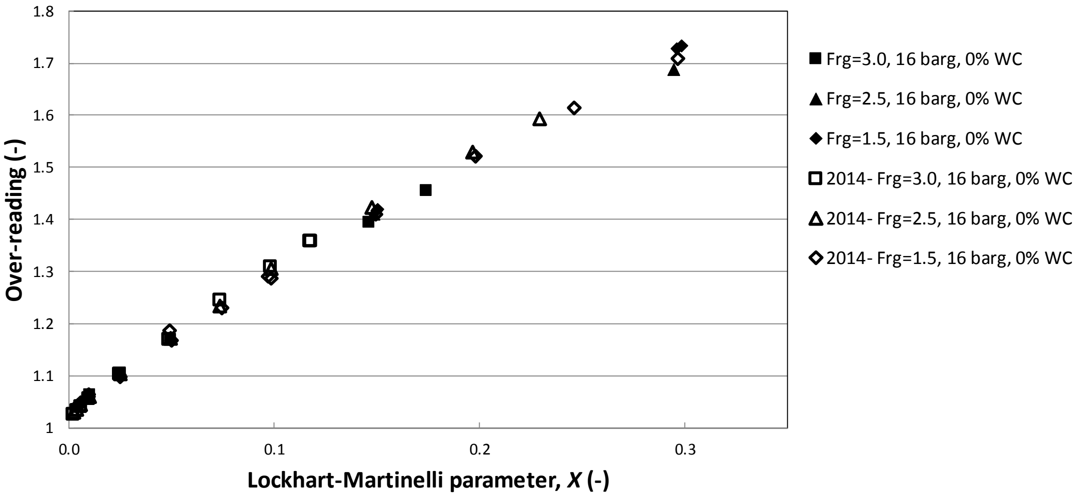

Figure 13 Comparing over-readings between the vertical Venturi tube installed downstream of a blind-T and with 30D upstream straight pipework (2014 data). Pressure 16 barg.

9 CONCLUSIONS OF VERTICAL INSTALLATION EFFECTS

The experimental results showed that under certain conditions, a vertical installation will have a significant impact on the results obtained using the standard ISO/TR 11583. This resulted in large errors between the predicted gas mass flow rate using ISO/TR 11583 and the reference measurement. This caused the data to fall outwith the standard's uncertainty limits under certain conditions. This implies that the standard is not applicable to vertical installations without modification of the equations.

The effects of the vertical installation were most notable at lower gas Froude numbers, lower test pressures and higher liquid loadings, with larger errors being found at these conditions.

The data were compared with previous vertical tests done in 2014 using the same meter. For the 2014 installation, there was 30D of straight pipe between the change in flow direction to vertical and the Venturi. This differed from the work outlined in this report where the Venturi was placed directly after the change in flow direction.

The 2016 data compared well to the 2014 tests, particularly for the lower gas Froude numbers and higher liquid loadings. This was where the data fell outwith the standard's uncertainty limits and gas mass flow rate errors were high. The similarity between the 2014 data and 2016 data suggests that the length of straight vertical pipe before the meter has little impact on the results but that the meter's vertical orientation has a significant impact: 30D of straight pipe appeared to make little difference compared with when there was no straight length. This differed from the study in horizontal conditions where the straight length before the meter was important and 17D of straight pipe before the Venturi was needed to bring data within ISO/TR 11583 for some upstream conditions to those studied in the vertical tests.

Based on the findings of this pilot study, additional work is required to allow ISO/TR 11583 to be modified for vertical installations. Further work on the requirements for straight vertical pipe before the vertical Venturi are also required.

10 REFERENCES

[1] Graham, E. et al., "Performance of a vertically installed Venturi tube in wet-gas conditions", North Sea Flow Measurement Workshop, St. Andrews, Scotland, Oct 2014

APPENDIX

Definitions of Wet-Gas Flow

For this research, 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, $$X = \frac{m_{liq}}{m_{gas}} \sqrt{\frac{\rho_{1,gas}}{\rho_{liq}}} \qquad (1)$$

where m_{liq} and m_{gas} are the mass flow rates 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, $\rho_{1,\text{gas}}$.

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

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

where A is the pipe area.

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

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

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

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

where E is the velocity of approach factor defined below, A_d is the Venturi-tube throat area, C is the discharge coefficient, 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 $E = \dfrac{1}{\sqrt{1-\beta^4}}$ (6)

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

ISO/TR 11583 Corrections for Venturi Tubes

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

$$C = 1\text{-}0.0463\mathrm{e}^{-0.05Fr_{\text{gas,th}}} \min\left(1, \sqrt{\frac{X}{0.016}}\right) \tag{7}$$

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

$$Fr_{\text{gas,th}} = \frac{Fr_{\text{gas}}}{\beta^{2.5}} \tag{8}$$

The over-reading is $\phi = \sqrt{1 + C_{\text{Ch}} X + X^2}$ (9)

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

$$C_{\text{Ch}} = \left(\frac{\rho_{\text{liq}}}{\rho_{1,\text{gas}}}\right)^n + \left(\frac{\rho_{1,\text{gas}}}{\rho_{\text{liq}}}\right)^n \tag{10}$$

The value of n was determined to be:

$$n = \max(0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_{gas}/H}, 0.392 - 0.18\beta^2) \tag{11}$$

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). For oil/water mixtures, interpolation is used to obtain an appropriate H value.

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

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

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