FLOMEKO2019
18th International Flow Measurement Conference
Portugal | Lisbon | LNEC | 26-28 june 2019

Vertically installed Venturi tubes for wet-gas flow measurement: possible improvements to ISO/TR 11583 to extend its range of applicability

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Abstract

Venturi tubes are commonly used for wet-gas flow measurement, and the majority of commercial wet-gas flow meters generally include a Venturi tube installed vertically with embedded secondary instrumentation. The presence of the liquid causes an increase in the measured differential pressure and results in the Venturi tube over-reading the actual amount of gas passing through the meter. Most of the research in the literature is focused on the investigation of the over-reading for horizontally oriented Venturi tubes, thus limiting the development of over-reading correlations for vertical installation. An experimental campaign was recently conducted at the National Engineering Laboratory (NEL) high-pressure wet-gas loop, where three Venturi tubes of the same nominal diameter (4") but different throat to inlet diameter ratio (0.4, 0.6, 0.75) were tested, installed vertically after a blind tee. The results of this experimental campaign are presented in this paper and the effects of various parameters (line pressure, gas Froude number, diameter ratio) on the over-reading are briefly discussed. It is shown that the over-reading correlation included in the ISO/TR 11583:2012 and developed for horizontally oriented Venturis, is not applicable to vertically oriented Venturis. However, if modified, the correlation included in the ISO/TR 11583 is capable of meeting its stated uncertainty limits for the experimental data presented here for vertically installed Venturis.

1. Introduction

Venturi tubes are one of the most common types of device used worldwide 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. Major oil and gas operators acknowledge that more accurate measurement of wet-gas and multiphase flows can be used to increase production. Hence there is a drive to improve the accuracy and increase the use of this technology.

The presence of the liquid in the gas phase causes an increase in the measured differential pressure and results in the Venturi tube over-reading the actual amount of gas passing through the meter. This over-reading is usually 'corrected' using available correlations derived from the experimental data to determine the actual gas mass flowrate.

The equations used for correcting the Venturi tube over-reading included in ISO/TR 11583:2012 [1] were developed for 2-phase one-liquid-component wet-gas flows in horizontal installation. The majority of research and the development of corrections for using Venturis in wet-gas flows are for horizontal installations. Research on vertical Venturis has been conducted by [2], which developed a correlation for a non-standard Venturi tube at low pressure. Experimental and modelling work on vertically downward oriented Venturis has been conducted by [3]–[6]. Experiments and modelling for vertically upward oriented Venturis at high pressure have been conducted by [7].

The high-pressure wet-gas flow measurement facility at NEL was used to collect new data for 4-inch (DN 100) Venturi tubes with a diameter ratio from 0.4 to 0.75 installed in a vertical orientation. This data was used to assess the robustness of the correlation for horizontal installation in ISO/TR 11583 and to give insight on the development of corrections for vertical installation. The results provided further evidence that the correlation in ISO/TR 11583 is not appropriate for vertical installations and that ISO/TR 11583 correlation must be modified to reduce the measurement uncertainty. The uncorrected wet-gas data resulted in flow measurement errors of over 60%; using the ISO/TR 11853 correlation reduced this to less than 13%, which is over four times the uncertainty of 3% quoted in ISO/TR 11583. Using new correction factors for vertical installation reduced the uncertainty to less than 3%.

In section 2 some relevant definitions for wet-gas flow are briefly reported, and in section 3 the ISO/TR 11583 correlation is reported. Section 4 shows the experimental set-up and tests conditions, while in section 5 the experimental results are discussed. In section 6 conclusions are drawn and plans for future research are presented.

2. 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 is defined as

$$X = \frac{m_{liq}}{m_{gas}} \sqrt{\frac{\rho_{1,gas}}{\rho_{liq}}} \tag{1}$$

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,

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

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

$$v_{\text{gas}} = \frac{m_{\text{gas}}}{\rho_{1,\text{gas}} A} \tag{3}$$

where A is the pipe area.

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

$$DR = \frac{\rho_{1,\text{gas}}}{\rho_{\text{liq}}} \tag{4}$$

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

$$m_{gas} = \frac{E A_d C \varepsilon_{wet} \sqrt{2 \rho_{1,gas} \Delta p_{wet}}}{\phi} \tag{5}$$

where E is the velocity of approach factor defined in equation (6), 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 [8] using the actual value of the pressure ratio.

The velocity of approach factor, E, is defined as

$$E = \frac{1}{\sqrt{1-\beta^4}} \tag{6}$$

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

3. ISO/TR 11583 correlations for Venturi Tubes

The wet-gas discharge coefficient is derived using the following equation

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

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

$$\phi = \sqrt{1 + C_{\text{Ch}} X + X^2} \tag{9}$$

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

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

The value of n is determined by

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

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). The ISO/TR 11583 correlation in its original form is restricted to one-liquid-component flows only. However, later research showed that for oil/water mixtures the parameter H can be obtained by knowing the water cut and linearly interpolating H between 1 and 1.35 [9]. Further improvement may be obtained with another simple equation for H [10].

The correlation can be used to determine the gas mass flowrate under the following 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

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

if the Lockhart-Martinelli is known without error [1][11].

4. Experimental Test Set-Up

Three 4-inch Venturi meters with diameter ratios β equal to 0.4, 0.6 and 0.75 (convergent angle 21° and divergent angle 7.5°) were installed in a vertical upward orientation directly after a blind-tee in NEL's high-pressure wet-gas flow measurement facility. Figure 1 and Figure 2 show photographs of the experimental set-up. Gas (nitrogen) and oil (kerosene substitute Exxsol D80) flow rates were varied to obtain gas densiometric Froude numbers (Fr_g) between 1 and 5.5 across a range of Lockhart-Martinelli parameters (X = 0 to 0.3). The conditions tested are shown in Table 1. The line pressure was varied between 15 and 60 barg.

Table 1: Test Conditions.

Venturi diameter ratio, β (-)	**Line Pressure (barg)**	**Gas Froude number, Fr_g (-)**	**Density Ratio, *DR* (-)**
0.4	15	1, 2, 2.5	0.023
	30	1.5, 2, 3	0.046
	60	1.5, 3, 4	0.088
0.6	15	1.5, 2.5, 3	0.024
0.75	15	2, 3, 4, 5	0.025
	30	1.5, 4.5	0.044
	60	2, 5.5	0.088

Figure 1: Photograph of the Venturi setup and instrumentation.

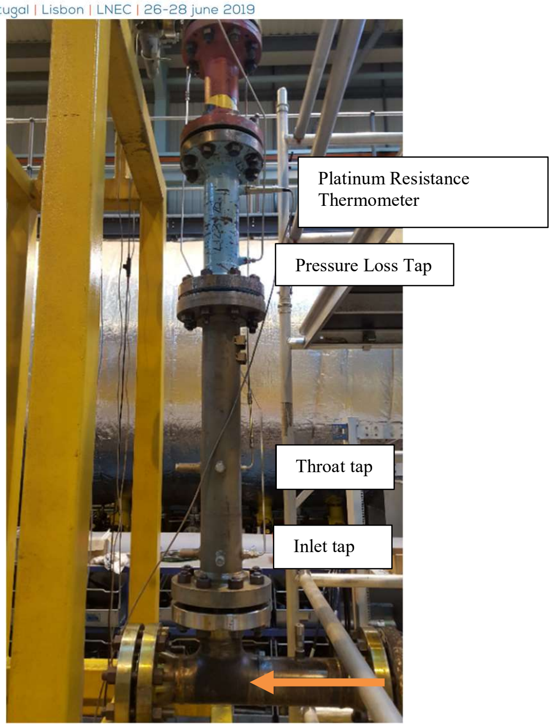

Figure 2: Photograph of the Venturi setup.

5. Results

The equations in ISO/TR 11583 were developed to correct the gas reading of horizontally installed Venturi tubes subjected to wet gas flows. Figure 3 shows the errors when using the ISO/TR 11583 correlation with the new data collected for vertical Venturi tubes. The error increases for increasing Lockhart-Martinelli values and a maximum error of approx. 13% is found at X≈0.3, which is over four times higher than the 3% uncertainty quoted in ISO/TR 11583.

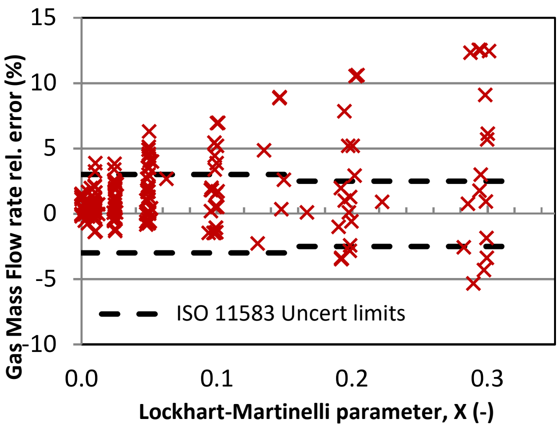

Figure 3: Relative error in gas mass flow rate obtained when applying the ISO/TR 11583 correlation to the present experimental data for vertically oriented Venturi tubes.

For Venturi tubes installed horizontally the gas Froude number has a substantial impact on the meter over-reading; above a gas Froude number of approx. 1.5, as the gas Froude number increases the over-reading increases reaching a constant maximum value at high gas Froude number. This effect is accounted for in both Equations (7) and (11) used respectively to determine the value of the wet gas discharge coefficient and the value of the *n*-exponent. Instead, for Venturi tubes installed in a vertical orientation, the gas Froude number seems to have much less impact on the meter over-reading, see also [12]. For example, Figure 4 shows the over-reading for the β=0.4 Venturi tube at a single line pressure of 30 barg (DR=0.046) but varying the gas Froude number. It can be seen that the over-reading values are approximately the same. This effect was noted in all the data sets presented here.

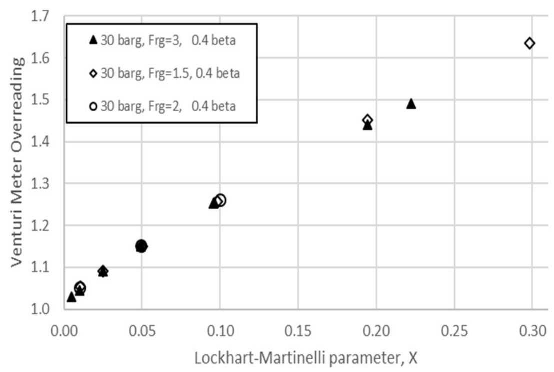

Figure 4: Over-reading for β=0.4 Venturi at 30 barg (density ratio 0.046) tested at three gas Froude numbers (Frg = 1.5, 2, 3).

For comparison Figure 5 shows some of the data from Figure 4 plotted together with some data previously collected with the same β=0.4 Venturi tube at the same line pressure of 30 barg (DR=0.046) but installed in a horizontal orientation. This show that the effect of the gas Froude number on the meter over-reading is almost negligible when the Venturi is installed vertically in comparison with when it is installed horizontally.

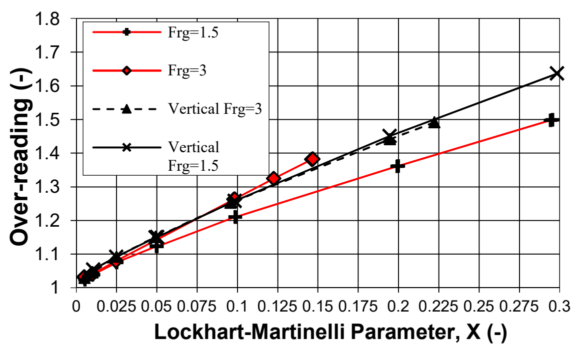

Figure 5: Over-reading for β=0.4 Venturi at 30 barg (density ratio 0.046) in a horizontal orientation (red curves) and vertical orientation (black curves) as a function of the gas Froude number.

Figure 6 shows all the data for the vertically installed Venturi tube with diameter ratio 0.4. This shows that the density ratio (i.e. gas pressure) does still have a significant effect on the meter over-reading for vertically installed Venturi tubes.

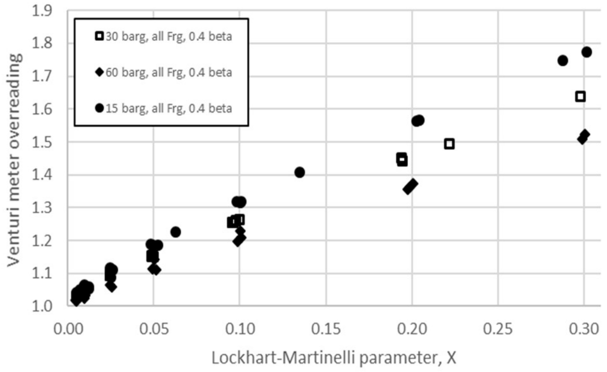

Figure 6: Over-reading for vertically installed β=0.4 Venturi at all pressures and gas Froude numbers.

The diameter ratio β of the Venturi does still have a significant impact on the over-reading. Figure 7 shows the over-reading data for horizontal and vertical Venturi tubes with diameter ratios from 0.4 to 0.75 at 30 barg and similar gas Froude numbers, $Fr_{gas}\approx1.5$. This shows that the over-reading is more sensitive to the diameter ratio β when installed horizontally than vertically, but that the diameter ratio still has an effect for vertically installed Venturis.

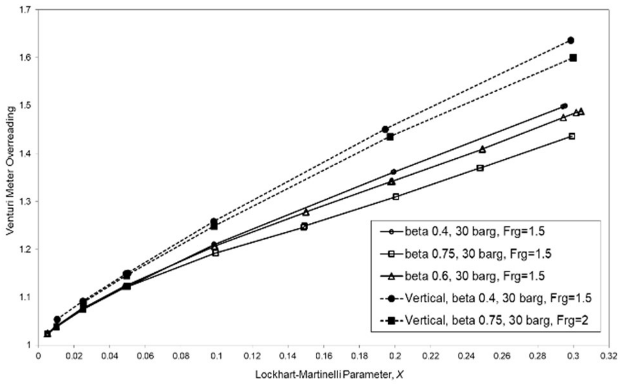

Figure 7: Over-reading for vertically installed β=0.4 and β=0.75 Venturi tubes, and for β=0.4, 0.6, 0.75 horizontally installed Venturi tubes at 30 barg line pressure and gas Froude numbers approx. equal to 1.5.

Because the gas Froude number has a negligible effect on the over-reading of vertically installed Venturi tubes, then a single value of the n-exponent can be fitted for each diameter ratio. The effect of the gas pressure (i.e. density ratio) is considered accounted for by the density ratio in Equation 7. Table 2 shows the derived values of the n-exponent for each Venturi tube.

Table 2: Fitted values of the n-exponent for each Venturi.

Venturi diameter ratio	Fitted value of n
Beta 0.4	0.503
Beta 0.6	0.478
Beta 0.75	0.425

The n-exponent values were obtained by minimizing the root-mean-square error of the gas mass flow rate for each diameter ratio, over all the tested conditions for the Venturi diameter ratio β. Figure 8 shows the relative error in the gas mass flow rate using the values of n from Table 2 and using the wet-gas discharge coefficient given by Equation 7. This shows that the gas mass flow rate can be corrected to within 3% (99.4% coverage factor) by fitting the n-exponent as a function of the diameter ratio.

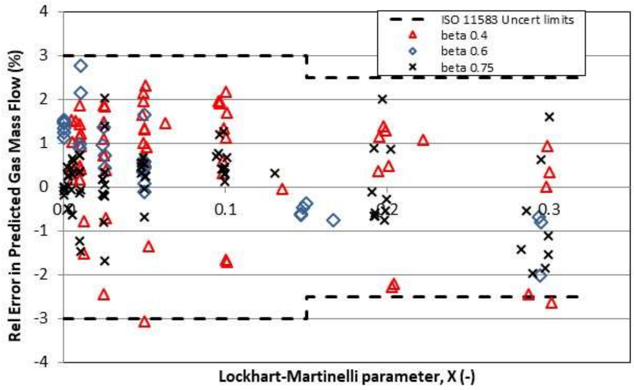

Figure 8: Errors when using new fitted values of the n-exponent for each Venturi and using wet-gas discharge coefficient from ISO/TR 11583:2012.

Figure 9 compares the errors when using the dry-gas discharge coefficient and re-fitted values of the n-exponent, against using the wet-gas discharge coefficient and the fitted values for n in table 2. This shows that the wet-gas discharge coefficient derived for horizontal Venturi tubes provides a robust fit also to the vertical Venturi data and significantly reduces the errors compared with using the dry-gas discharge coefficient.

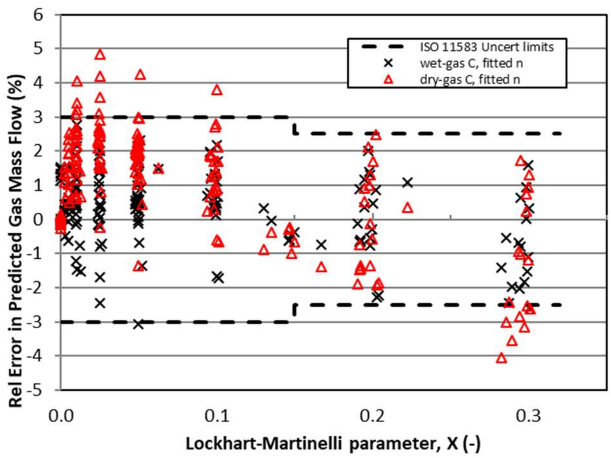

Figure 9: Comparison of errors when using values of *n* for each Venturi and using wet-gas discharge coefficient from ISO 11583 and the dry-gas discharge coefficient.

6. Conclusion

New experimental results were obtained at the National Engineering Laboratory for three different Venturi tubes of 4” nominal diameter but different diameter ratio (0.4, 0.6, 0.75) installed vertically and subject to wet-gas flow. The results confirm that the over-reading is not significantly affected by the gas Froude number when the Venturi is installed vertically, as previously found by [5]. The over-reading was found still largely affected by the line pressure. The results show that the Venturi’s diameter ratio has a smaller impact on the over-reading than for horizontally installed Venturis. However, the diameter ratio was found still to have a significant effect on the over-reading. Present results confirm that the ISO/TR 11583 over-reading correlation cannot be employed directly for Venturi tubes installed vertically. However, if the *n*-exponent is fitted as a function of the diameter ratio and the wet-gas discharge coefficient included in ISO/TR 11583 is used, then the gas mass flow rate can be predicted within ±3% error.

A larger and extended experimental dataset is needed to draw further conclusions and to develop a suitable over-reading correlation for vertically installed Venturi tubes. It is thus planned to conduct further research with the aim of forming the basis on which the current wet-gas standards/best practice will be updated to cover a wider range of installations for Venturi tubes.

Acknowledgements

The work described in the paper was carried out as part of the National Measurement System’s Engineering and Flow Programme, under the sponsorship of the United Kingdom Department for Business, Energy and Industrial Strategy.

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