North Sea Flow Measurement Workshop
22-25 October 2019

Technical Paper

Using Venturi Meters Installed in Vertical Orientation for Wet-Gas Flow Measurement

G. Chinello, TÜV-SÜD NEL
E. Graham, TÜV-SÜD NEL
M. Reader-Harris, TÜV-SÜD NEL
S. Clark, Solartron ISA
A. Collins, Solartron ISA

1 INTRODUCTION

New data has been collected by TÜV-SÜD National Engineering Laboratory (NEL) on the performance of Venturi meters installed in a vertical orientation which shows errors of over four times that from using the current ISO technical reports. This paper presents possible corrections for using Venturis for vertical installations to reduce the error and provide the basis for extending the standards.

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. Major oil and gas operators acknowledge that more accurate measurement of wet-gas and multiphase flows can be used to optimise reservoir conditions and 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 experimental data to determine the actual gas mass flowrate.

The ISO Technical Reports for measuring wet-gas flows (ISO/TR 11583:2012 [1] and ISO/TR 12748:2015 [2]) only cover two-phase one-liquid-component flows and horizontal installation. The majority of research and the development of corrections for using Venturis in wet-gas flows are for horizontal installations. However, the majority of commercial multiphase meters are installed vertically, and, using the same hardware but different models, are used to meter wet-gas flows. There has been a trend to extend the capabilities of multiphase meters to accurately measure wet-gas flows, and of wet-gas meters to measure fully multiphase flows. The development of a robust and verified correlation for wet-gas vertical Venturi tubes that is available in a standard technical report would therefore be of practical interest and would add transparency to the verification process for multiphase and wet-gas meters, since most of the models/correlations used by the manufacturers are proprietary.

However, there are practical challenges when using Venturi meters in a vertical installation which are not applicable for those in a horizontal installation. This includes the major issue of liquid collecting in the pressure tappings and impulse lines which is a difficult condition to detect and correct in the field, and can easily lead to large measurement errors of over 10% and the potential of hydrate formation. Moreover, at low gas flow rates and/or low pressure the liquid film at the wall becomes unstable, and the flow regime can be highly unstable and complex (e.g. churn flow, slug flow).

The high-pressure wet-gas flow measurement facility at NEL was used to collect new data for a 4-inch Venturi tube with a diameter ratio of 0.55 (provided by Solartron ISA) installed in a vertical orientation. These data were used to assess the robustness of the horizontal-installation correlations for and to assess new possible corrections for vertical installation. The results provided further evidence that the correlations in both ISO/TRs are not appropriate for vertical installations.

In Section 2 of this paper, the non-dimensional numbers and equations commonly used in wet-gas flow measurement will be briefly described, together with a method to correct the measured inlet-throat differential pressure for hydrostatic pressure drop. Section 3 provides a brief literature review of the correlations, models and experimental tests for Venturi tubes installed in a vertical orientation. The test set-up for the Solartron ISA Venturi tube is described in Section 4. Test results are presented and discussed in Section 5. Section 6 provides the final conclusions and recommendations for future work.

2 WET-GAS DEFINITIONS

In this publication, 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 follows

$$X = \frac{m_{liq}}{m_{gas}} \sqrt{\frac{\rho_{1,gas}}{\rho_{liq}}} = \frac{(1 - GVF)}{GVF} \sqrt{\frac{\rho_{liq}}{\rho_{1,gas}}} \quad (1)$$

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, $\rho_{1,gas}$. The Gas Volume Fraction, GVF in equation (1), is defined as follows

$$GVF = \frac{\frac{m_{gas}}{\rho_{1,gas}}}{\frac{m_{gas}}{\rho_{1,gas}} + \frac{m_{liq}}{\rho_{liq}}} \quad (2)$$

It should be noted that there are different and not equivalent definitions of the Lockhart-Martinelli parameter, see [3] for detail, and the original definition given by Lockhart and Martinelli [4] differs from equation (1). However, equation (1) is commonly adopted for wet-gas metering [1], [2]. If the liquid is a mixture of hydrocarbon and water, then the liquid density is calculated as follows

$$\rho_{liq} = \rho_{water}\, WLR + (1 - WLR)\rho_{oil} \quad (3)$$

where WLR is the Water Liquid Ratio (by volume) at line conditions defined as

$$WLR = \frac{\frac{m_{water}}{\rho_{water}}}{\frac{m_{water}}{\rho_{water}} + \frac{m_{oil}}{\rho_{oil}}} \tag{4}$$

The gas densiometric Froude number, Fr_{gas}, is a dimensionless number defined as the square root of the ratio of the gas inertia (if it flowed alone) to the gravitational force on the liquid phase. The gas Froude number is directly proportional to the gas velocity, and, with similar gas-liquid density ratio and line diameter, it is used as an indication of the gas volumetric flow rate.

The gas densiometric Froude number is defined as follows

$$Fr_{gas} = \sqrt{\frac{\rho_{1,gas}\, {v_{s,gas}}^2}{(\rho_{liq} - \rho_{1,gas})gD}} = \frac{v_{s,gas}}{\sqrt{gD}} \sqrt{\frac{\rho_{1,gas}}{\rho_{liq} - \rho_{1,gas}}} \tag{5}$$

where $v_{s,gas}$ 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

$$v_{s,gas} = \frac{m_{gas}}{\rho_{1,gas} A} \tag{6}$$

where A is the pipe area.

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

$$DR = \frac{\rho_{1,gas}}{\rho_{liq}} \tag{7}$$

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

$$m_{gas} = \frac{\frac{C}{\sqrt{1-\beta^4}}\, \varepsilon \frac{\pi}{4}\, d^2 \sqrt{2\, \Delta p_{req}\, \rho_{1,gas}}}{\phi} = \frac{m_{gas,apparent}}{\phi} \tag{8}$$

where β is the diameter ratio of the Venturi tube (diameter at throat divided by diameter of pipe), d is the Venturi-tube throat area, *C* is the discharge coefficient, ε is the gas expansibility determined from ISO 5167-4 [5] using the actual value of the pressure ratio, Δp_{req} is the actual (wet-gas) differential pressure corrected for hydrostatic pressure drop and ϕ is the wet-gas over-reading or correction factor.

In this work a correction has be applied to the measured differential pressure to account for the difference in densities between the fluids in the pipe and the fluid in the impulse lines. In vertical flow there is a difference in height between inlet and throat tapping points, and thus there is a hydrostatic pressure drop between inlet and throat tap. If the fluid in both impulse lines is equal to that in the flow itself, then the measured differential pressure can be used directly in equation (8) without correction, since the hydrostatic pressure drop in the pipe is counterbalanced by the same hydrostatic pressure drop in the impulse lines, see [6]. For example, for dry gas or any single-phase flow through a vertical Venturi then no correction is necessary for the measured differential pressure. In wet-gas flow, assuming that the impulse lines contain only gas, the measured inlet-throat differential pressure is given by

$$\Delta p_{measured} = (p_1 - p_2) - \rho_{1,gas}\, g\, \Delta \mathrm{z} \tag{9}$$

where $\Delta \mathrm{z}$ is the height difference between pressure taps, see Figure 1. The requested pressure drop in equation (8) is as follows

$$\Delta p_{req} = (p_1 - p_2) - \rho_{1,mix} g\, \Delta \mathrm{z} \tag{10}$$

where $\rho_{1,mix}$ is the two-phase mixture density at the inlet pressure tap (i.e. it is assumed that the mixture density does not change between inlet and throat tap). The correction equation is obtained by combining equation (9) and (10) as follows

$$\Delta p_{req} = \Delta p_{measured} - \left(\rho_{1,mix} - \rho_{1,gas}\right) g\, \Delta \mathrm{z} \tag{11}$$

By definition the mixture density, $\rho_{1,mix}$, is defined as

$$\rho_{1,mix} = \frac{M_{gas} + M_{liq}}{V_{total}} = \rho_{1,gas}\, \alpha_{1,gas} + \rho_{liq}\, (1 - \alpha_{1,gas}) \tag{12}$$

where M_{gas} and M_{liq} are respectively the mass of the gas and the mass of the liquid, V_{total} is the total volume of a given pipe section and $\alpha_{1,gas}$ is the gas void fraction at the inlet pressure tap defined as follows

$$\alpha_{1,gas} = \frac{A_{1,gas}}{A} \tag{13}$$

with $A_{1,gas}$ cross sectional area occupied by the gas and A pipe cross sectional area.

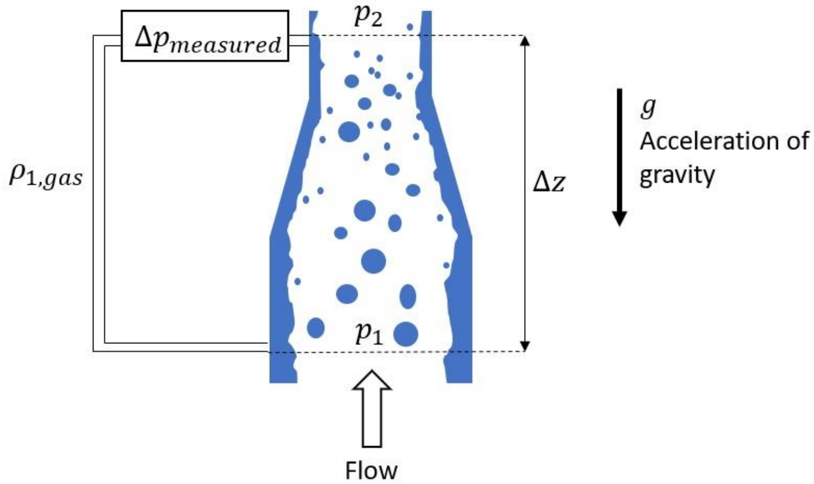

Figure 1: Schematic representation of a vertical upward oriented wet-gas Venturi tube

Secondary instrumentation (e.g. wire mesh sensor, x-ray tomography etc.) is needed to measure the gas void fraction at the inlet pressure tap. In this work the void fraction was not measured, and it is approximated by the gas volume fraction, equation (2). This approximation is without error only if the velocities of the gas and the liquid are the same (i.e. no-slip between phases), as shown by equation (14).

$$GVF = \frac{\alpha_{1,gas}}{\alpha_{1,gas} + \frac{v_{liq}}{v_{gas}}(1 - \alpha_{1,gas})} \tag{14}$$

Under no-slip assumption, the mixture density can be calculated as follows

$$\rho_{1,mix} = \rho_{1,gas}\, GVF + \rho_{liq}\,(1 - GVF) \tag{15}$$

Table 1 shows the difference in percentage between the Gas Volume Fraction and the gas void fraction obtained by solving iteratively equation (14) for different slip ratios (liquid velocity over gas velocity) and Gas Volume Fraction values. The difference between the Gas Volume Fraction and the gas void fraction decreases for increasing Gas Volume Fraction and slip ratios.

Table 1 - Difference in percentage between the gas void fraction and the Gas Volume Fraction as a function of the slip ratio and the Gas Volume Fraction. The slip ratio is the ratio between liquid and gas actual velocities.

	Slip Ratio (-)									
GVF (%)	**1**	**0.9**	**0.8**	**0.70**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**
99	0.00	-0.11	-0.25	-0.43	-0.66	-0.99	-1.48	-2.28	-3.85	-8.26
95	0.00	-0.55	-1.23	-2.10	-3.23	-4.76	-6.98	-10.45	-16.67	-31.03
90	0.00	-1.10	-2.44	-4.11	-6.25	-9.09	-13.04	-18.92	-28.57	-47.37

3 BRIEF LITERATURE REVIEW

The majority of research and the development of corrections for using Venturi tubes in wet-gas flow are for horizontal installation.

In the homogeneous model, the flow is assumed to be well-mixed (i.e. mist flow with fully atomized liquid) and the over-reading is calculated using equations (16) and (17), and with n = 0.5, see [7], [8] or [9] for derivation. In principle, the homogeneous model can be used with horizontally and vertically oriented Venturis.

$$\phi = \sqrt{1 + C_{ch}X + X^2} \tag{16}$$

$$C_{ch} = \left(\frac{\rho_{liq}}{\rho_{gas}}\right)^n + \left(\frac{\rho_{gas}}{\rho_{liq}}\right)^n \tag{17}$$

The De Leeuw correlation [10], included in ISO/TR 12748:2015 [2], was obtained from tests conducted at Trondheim, Norway, with a 4-inch β=0.4 horizontally mounted Venturi tube. The De Leeuw correlation is given in equations (16), (17) and (18). It should be noted that when using the De Leeuw correlation the dry-gas discharge coefficient is used in Equation (8) to determine the correct gas flow rate.

$$\begin{aligned} n &= 0.606\,(1 - e^{-0.746\,Fr_g}) && for && Fr_{gas} > 1.5 \\ n &= 0.41 && for && 0.5 \leq Fr_{gas} < 1.5 \end{aligned} \tag{18}$$

The correlation included in the technical report ISO/TR 11583 [1], [11], was developed for horizontal installations. In the ISO/TR 11583 correlation a wet-gas discharge coefficient is derived and used in equation (8), according to the following equation

$$C = 1 - 0.0463e^{-0.05\,Fr_{gas,th}} \min\left(1, \sqrt{\frac{X}{0.016}}\right) \tag{19}$$

where the throat Froude number, $Fr_{gas,th}$, is calculated as

$$Fr_{gas,th} = \frac{Fr_{gas}}{\beta^{2.5}} \tag{20}$$

See chapter 4.3 of [9] for a discussion on the wet-gas discharge coefficient. The over-reading is calculated with equations (16) and (17), with the value of the n-exponent determined as

$$n = \max\left(0.583 - 0.18\,\beta^2 - 0.578e^{-0.8\,Fr_{gas}/H}, 0.392 - 0.18\beta^2\right) \tag{21}$$

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 temperature). The ISO/TR 11583 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 liquid ratio and linearly interpolating H between 1 and 1.35 [9], [12]–[16]. Further improvement may be obtained with another simple equation for H [17].

The ISO/TR 11583 correlation can be used to determine the gas mass flow rate under the following conditions

$$0.4 \leq \beta \leq 0.75$$

$$0 < X \leq 0.3$$

$$3 < Fr_{gas,th}$$

$$0.02 < \rho_{gas}/\rho_{liq}$$

$$D \geq 50\, mm$$

with an uncertainty of 3% for $X \leq 0.15$ and 2.5% for $0.15 \leq X \leq 0.3$, if the Lockhart-Martinelli parameter is known without error.

Xu et al. [18] developed a correlation for a 2-inch β=0.45 non-standard Venturi tube (extended throat) mounted vertically and tested over a range of pressures from 2.6 to 8.6 bara. The over-reading is derived using equations (16) and (17), and with n calculated as follow

$$n = b_1\, e^{-0.5\left[\left(\frac{\ln\left(Fr_{gas}/b_2\right)}{b_3}\right)^2 + \left(\frac{\ln\left(\frac{\rho_{gas}/\rho_{liq}}{b_4}\right)}{b_5}\right)^2\right]} \qquad (22)$$

where

$$b_1 = 0.47359213$$
$$b_2 = 1.9897702$$
$$b_3 = 1.8384189$$
$$b_4 = 0.087328207$$
$$b_5 = 7.4636959$$

A 4-inch, β=0.6, vertically installed Venturi tube was tested at Colorado Engineering Experiment Station Inc. (CEESI) in 2008 [19]. Fluids were natural gas/kerosene, and natural gas/water and the density ratio was varied between 0.011 and 0.045. The same Venturi was also tested horizontally installed. The results show that the flow tends to be more symmetrical for vertical installation; hence the Venturi response tends to agree with the homogeneous model at lower density ratio and gas Froude numbers than for horizontal installation. At high density ratio and gas Froude number the vertical and horizontal Venturi tube response was found to be almost identical. Overall, the over-reading was found to be less sensitive to the properties of the liquid used and the gas Froude number than for horizontal installation.

In 2014 [20] tests were performed at NEL with a 4-inch β=0.6 Venturi tube installed vertically, 30 diameters downstream of a concentric reducer (6-inch to 4-inch) after a 6-inch bend. Nominal test pressures were 15, 30 and 60 barg. Test fluids were nitrogen and kerosene substitute oil, and Lockhart-Martinelli parameter was up to 0.3. Test conditions are reported in Table 2. Contrary to what was observed for horizontal Venturis, see Equation (18), the over-reading was found almost independent from the gas Froude number. Considerable discrepancy with the experimental values was found when calculating the gas mass flow rate with the De Leeuw correlation and the ISO/TR 11583 correlation in its original form, and assuming the Lockhart-Martinelli parameter to be known without error. The homogeneous model was found to perform better than the De Leeuw and ISO/TR correlations and gave a relative error in gas mass flow rate approximately within ±4%. Improved results, error in gas mass flow rate approximately within ±3%, where obtained by using the ISO/TR 11583 correlation for the discharge coefficient and fitting the n-exponent as a function of the density ratio, Equation (23).

$$n = 0.5 - 0.00283\,(DR^{-0.75} - 1) \tag{23}$$

The ISO/TR 11583 correlation with Equation (23) performed within ±3% when compared with the data from the 2008 tests at CEESI [19]. The correlation developed by Xu et al. [18] was found to perform poorly even when the parameters b_1 to b_5 in equation (22), were fitted to the NEL data.

The pressure loss ratio was measured at NEL, and results show that in vertical orientation the pressure loss ratio tends to level off at a higher value of the Lockhart-Martinelli parameter than for horizontal installation; hence the pressure loss ratio method to derive the Lockhart-Martinelli could be used over a wider range of Lockhart-Martinelli for vertical installation. A maximum relative error in gas mass flow rate of 8% was obtained when using the ISO/TR 11583 equation for the wet-gas discharge coefficient, a value of n equal to 0.45 and the ISO/TR 11583 equations to determine the Lockhart-Martinelli from pressure loss ratio measurements.

Table 2 – NEL Test conditions 2014 [20]

Venturi diameter (inch)	Venturi diameter ratio, β (-)	Line Pressure (barg)	Gas Froude number, Fr_g (-)	Density Ratio, *DR* (-)	Water Liquid Ratio, *WLR* (%)
4	0.6	15	1.5, 2, 2.5, 3	0.023	0
		30	1.5, 2.5, 3.5, 4.5	0.046	
		60	1.5, 2.5, 3.5, 4.5, 5.5	0.088	

The same Venturi tube of the 2014 tests was tested again in 2016 at NEL [21]. This time the Venturi tube was installed vertically directly downstream of a blind tee; nitrogen was used as the gas and with liquid ratios of 0% (kerosene substitute Crownsol D75), 100% (fresh water) and 50%. Test nominal pressures were 16, 31, 39 and 57 barg; see Table 3 for test conditions. The 2016 test results were found to compare well with the 2014 test results. The similarity between test data suggested that the length of straight vertical pipe upstream of the meter had little impact on the meter performance, contrary to what was found for horizontal installation during the same test programme [21].

Table 3 - NEL Test conditions 2016 [21]

Venturi diameter (inch)	Venturi diameter ratio, β (-)	Line Pressure (barg)	Gas Froude number, Fr_g (-)	Density Ratio, *DR* (-)	Water Liquid Ratio, *WLR* (%)
4	0.6	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	0
		20.1 39.1 57.0	1.5, 2.5 1.5, 4.5 1.5, 5.5	0.024 0.046 0.067	100
		18.0 35.0 57.0	1.5, 2.5 1.5, 4.5 5.5	0.024 0.046 0.074	50

Extensive research was conducted at ONERA (Office National d`Etudes et de Recherches Aérospatiales) with 2-inch and 3-inch vertical downward Venturi tubes [22]–[28]. The aim was to develop a physics-based model to predict the Venturi inlet-throat pressure drop. Great effort was made in the derivation of an experimental correlation for the liquid film entrainment in the Venturi tube, as the liquid entrainment mechanism was found to play a fundamental role in the model. Couput et al. [28], assessed the model performance against tests conducted at DNV-KEMA with a 109 mm inlet diameter, β=0.7 Venturi tube installed vertically upward after a blind tee. Test pressure was between 10 and 23 bar; fluids were natural gas, kerosene substitute oil (Exxsol D120) and water with different salinities, and the water cut was varied between 0% and 100%. The relative error in the over-reading prediction between the model and the tests was found to increase for increasing Lockhart-Martinelli, reaching a maximum of approximately 12%.

Van Maanen and De Leeuw [29] developed a physics-based model to predict the pressure drop in vertically upward Venturi tubes. The model was developed using a limited proprietary dataset and was verified against a dataset acquired at K-Lab. Results show that the stability of the liquid film upstream of the Venturi is central for the applicability of the model. The model for vertical installation had progressed less than the model for horizontal installation by the same authors, see reference [9] for the latest development and results; in fact, the over-reading predictions obtained for vertical installation were less satisfactory than the predictions for horizontal installation but still gave a great insight about the physical mechanisms involved.

Chinello [9] performed experiments with a 2-inch, β=0.6, vertically upward Venturi tube at low pressure, 2.5 barg, with air and water at Glasgow Caledonian University (GCU). The ISO/TR 11583 wet-gas discharge coefficient (Equation (19)) was used and the n-exponent was obtained by fitting the data. The fitted value of the n-exponent was found to be in close agreement with Equation (23), which is based on NEL's high-pressure tests [20], see Figure 2.

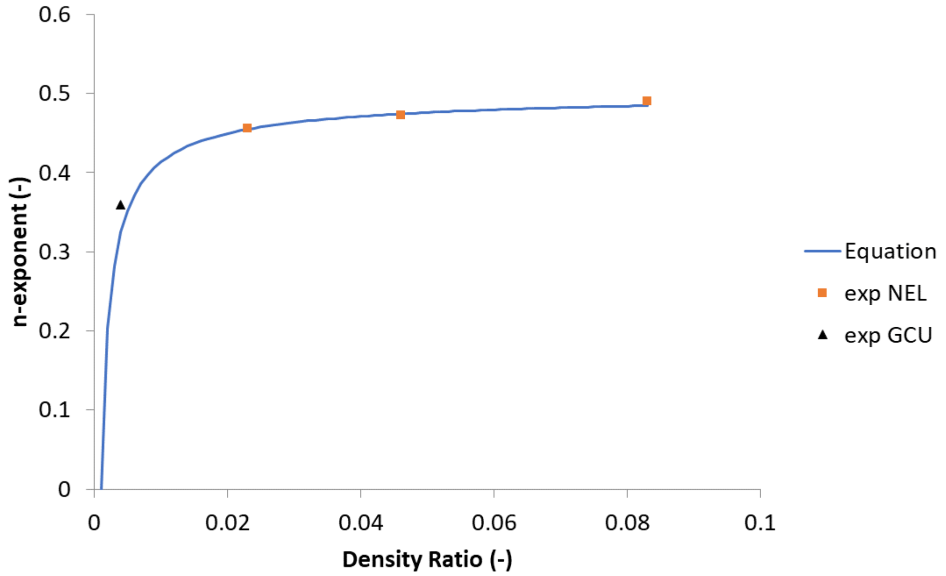

Figure 2: Experimental values of the n-exponent obtained at low pressure by [9] (exp GCU), at high pressure by [20] (exp NEL), compared with the prediction given by Equation (23) (equation)

Assuming a constant value of the wet-gas discharge coefficient of 0.985, a correlation, Equation (24), was obtained by Chinello for the n-exponent by fitting the low pressure data and NEL's high pressure data [20].

$$n = 0.65 \left(\frac{\rho_{1,gas}}{\rho_{liq}} \right)^{0.097} \tag{24}$$

When using Equation (24), and a constant value of the wet-gas discharge coefficient of 0.985, the predicted over-reading was found to be within approximately ±3 % of the experimental values for both the low pressure and the NEL high-pressure data set.

Recently, three 4-inch Venturi tubes with diameter ratios, $\boldsymbol{\beta}$, 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 facility [30]. Fluids were nitrogen and kerosene substitute (Exxsol D80), and the line pressure was varied between 15 and 60 barg. The conditions tested are shown in Table 4.

Table 4 – NEL Tests Conditions 2018 [30]

Venturi diameter (inch)	Venturi diameter ratio, β (-)	Line Pressure (barg)	Gas Froude number, Fr_g (-)	Density Ratio, *DR* (-)	Water Cut, *WC* (%)
4	0.4	15 30 60	1, 2, 2.5 1.5, 2, 3 1.5, 3, 4	0.023 0.046 0.088	0
	0.6	15	1.5, 2.5, 3	0.024	
	0.75	15 30 60	2, 3, 4, 5 1.5, 4.5 2, 5.5	0.025 0.044 0.088	

The results confirmed that the over-reading is not much affected by the gas Froude number when the Venturi is installed vertically. The over-reading was found to be significantly affected by the density ratio between the gas and liquid phases. 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 still found to have a significant effect on the over-reading. It was confirmed that the ISO/TR 11583 over-reading correlation cannot be employed directly for Venturi tubes installed vertically. 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 was predicted within ±3% error. The fitted values of the n-exponent as a function of the diameter ratio β are reported in Table 5. The pressure tappings of the three Venturi tubes, which were designed for horizontal installation, were modified to reduce the likelihood of liquid flooding the impulse lines and the impulse lines were made of vertical hard pipes. However, only minor improvements were found with respect to the long straight pressure tappings previously tested at NEL [20], [21].

Table 5 – Fitted values of the n-exponent [30]

Venturi diameter ratio, β (-)	Fitted value of the n-exponent (-)
0.4	0.503
0.6	0.478
0.75	0.425

It should be noted that Monni et al. [31] and Silva et al. [32] conducted relevant research at low pressure with a 3-inch and a 2-inch vertical Venturi tube, respectively.

4 EXPERIMENTAL TEST SET-UP

A nominal 4-inch Venturi tube (β=0.55, D=0.078 m) specifically designed for vertical installation was kindly provided by Solartron ISA for wet-gas testing at NEL. The Venturi was installed vertically after a blind-tee, see Figure 3. The connecting blind-tee to the Venturi tube was internally machined to match the bore of the Venturi, to ensure no steps or mis-alignment. Two-phase two-liquid-components testing was carried out using nitrogen, oil (kerosene substitute Exxsol D80) and fresh water with different water cuts. Nominal line pressure was 21, 36, 58 barg, the Lockhart-Martinelli parameter was from 0 to 0.3 and the gas Froude number was adjusted to match previous tests conducted at CEESI. A summary of the test conditions is presented in Table 6. Experimental results are presented and discussed in Section 5.

Figure 3 – Installation set-up of the Solartron Venturi tube

Table 6 – Test conditions for Solartron vertical Venturi

Venturi diameter (mm)	Venturi diameter ratio, β (-)	Line Pressure (barg)	Gas Froude number, Fr_g (-)	Density Ratio, *DR* (-)	Water Liquid Ratio, *WLR* (%)
78	0.55	58 36 21	4.6, 6.1, 7.7, 9.1 3.5, 6, 7.3 2.4, 4.5, 5.5	0.085 0.056 0.032	0
	0.55	58 36 21	4.5, 7.2, 8.8 5.6, 7 2.6, 4.3	0.080 0.052 0.030	30
	0.55	58 36 21	6.7, 8 5.2, 6.5 2.4, 4	0.072 0.046 0.026	80-85
	0.55	58 36 21	7.4, 7.8 3.1, 3.6, 5.2 2.4, 4	0.700 0.044 0.026	100

5 RESULTS AND DISCUSSION

In this section the test results are presented and discussed.

5.1 Pressure tappings and impulse lines

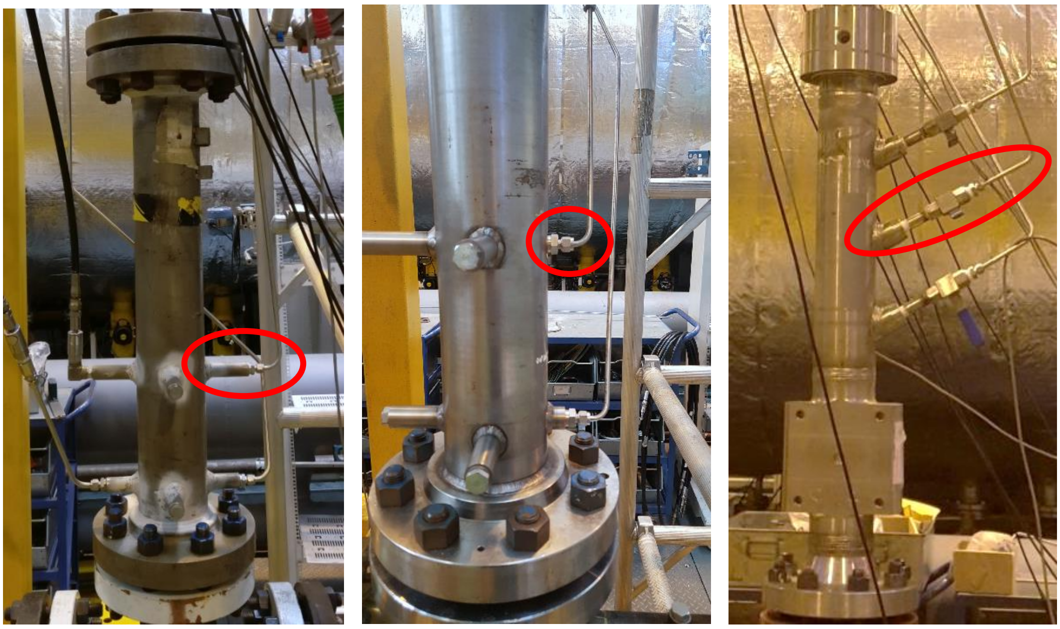

Figure 4 – From left to right: NEL Venturi tube with long pressure tappings [21], NEL Venturi tube with shortened pressure tappings [30], Solartron Venturi tube with angled pressure tappings

When Venturi tubes are used installed vertically in wet-gas flow, the pressure tappings and impulse lines tend to fill with liquid. This can result in a bias in the measured differential pressure, and hence in the calculated gas mass flow rate. Based on data collected at NEL in clean laboratory conditions, the increase in the baseline differential pressure can easily result in a measurement bias of greater than 10% in the gas flow rate. This is a serious concern, since during past tests conducted at NEL [20], [21], approximately one third to half of the data sets were rejected because the measurements were affected by pressure tappings filled with liquid.

Generally the length of the pressure tappings (~100 mm) are significantly longer than the minimum specified in ISO 5167-4:2003 [5] (minimum length of 2.5 times the pressure tapping internal diameter). It was believed that connecting vertical impulse lines to shorter pressure tappings would decrease the likelihood of liquid filling the impulse lines. Tests were carried at NEL [30], with shortened pressure tappings (4 mm internal diameter) of length 2.5 times the tapping internal diameter, see Figure 4. No major improvements were found with respect to the tests carried out with longer pressure tappings.

The Solartron Venturi used in the tests presented in this paper was designed specifically for vertical flows, with the horizontal section of the pressure tapping complying with ISO 5167-4:2003 and then the pressure tapping angled as shown Figure 4. The tappings' internal diameter was 6 mm.

Using the Solartron Venturi design resulted in no data being rejected due to liquid collecting in the tappings and no resulting measurement bias. To check for bias in differential pressure measurement caused by flooded impulse lines, the differential pressure transmitter's zero was checked after collecting a series of test points (approximately after 5 to 20 test points). A bad zero would indicate that some liquid is trapped in the impulse lines, and the associated collected data were rejected. However, a good differential pressure transmitter zero is a condition necessary but not sufficient to ensure impulse lines free from liquid during tests. To check the differential pressure zero, the flow needs to be interrupted such that any accumulated liquid can possibly drain from the impulse lines. A proposed additional check would be to repeat the first data point of the series before the zero check, and to check the repeatability as it would be unlikely that exactly the same amount of liquid is present in the impulse lines for the duration of a series of test points. However, both the zero check and the repeatability check would be possible only in test laboratories, and alternative methods to detect flooded impulses lines are necessary for field applications.

When some liquid enters the impulse lines, the measured differential pressure is as follows

$$\begin{aligned}\Delta p_{measured} = (p_1 - p_2) - \rho_{liq}\, g\, (\Delta z_{1,liq} - \Delta z_{2,liq}) \\ - \rho_{1,gas}\, g\, (\Delta z_{1,gas} - \Delta z_{2,gas})\end{aligned} \qquad (25)$$

where $\Delta z_{1,liq}$ and $\Delta z_{2,liq}$ are the liquid height in the inlet impulse line and the throat impulse line, respectively, $\Delta z_{1,gas}$ and $\Delta z_{2,gas}$ are the gas height in the inlet impulse line and the throat impulse line, respectively, see Figure 5. The requested differential pressure to substitute in Equation (8) is as follows

$$\Delta p_{req} = (p_1 - p_2) - \rho_{1,mix} g\, \Delta z \qquad (26)$$

By combining equation (25) and (26) the following equation is obtained

$$\begin{aligned}\Delta p_{req} = \Delta p_{measured} + (\rho_{liq} - \rho_{1,mix})\, g\, (\Delta z_{1,liq} - \Delta z_{2,liq}) \\ - (\rho_{1,mix} - \rho_{1,gas})\, g\, (\Delta z_{1,gas} - \Delta z_{2,gas})\end{aligned} \qquad (27)$$

It should be noted that Equation (27) reduces to Equation (11) if the impulse lines are free from any liquid (i.e. $\Delta z_{1,liq} = \Delta z_{2,liq} = 0$). Equation (27) shows that the bias in measurement is more relevant for low measured values of the differential pressure and that it increases for increasing values of the difference between the height of the liquid collected in the inlet impulse line and the height of the liquid collected in the throat impulse line. The worst-case scenario would be to have a low differential pressure and long impulse lines with the inlet impulse line completely flooded with liquid and the throat impulse line free from liquid. It is then suggested to have the impulse lines as short as possible and to measure high differential pressures, in order to decrease the impact of any accumulated liquids. Pressure transmitters with capillary tubes and diaphragm seals may be an option to avoid flooded impulse lines. However, careful design would be necessary to ensure that no liquid is trapped between the diaphragm seal and the pressure tapping, which may leads to hydrates formation and/or bias in differential pressure measurements. It should also be noted that transmitters fitted with diaphragm seals have a greater measurement uncertainty than those that are not fitted with diaphragm seals.

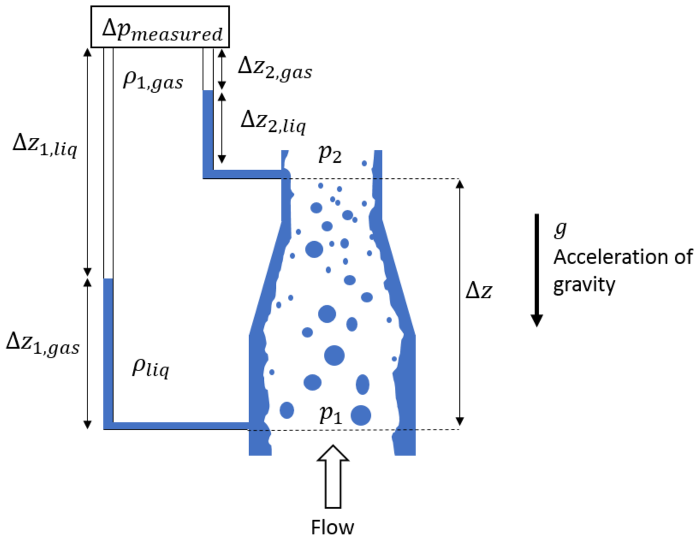

Figure 5 – Schematic representation of a wet-gas Venturi tube vertically installed

Generally, for the testing of Venturi tubes in flow laboratories for wet-gas applications, the pressure tappings are connected to the differential pressure cells using flexible tubing. Based on field and testing experience from Solartron it was advised that for vertical wet-gas testing in a laboratory hard piping should be used instead of flexible hoses to ensure no liquid is trapped in the impulse line causing measurement bias, and all the impulse lines should be at an upward angle. Moreover, the internal diameter of the pressure tappings and impulse lines is believed to play a crucial role in liquid accumulation, but further investigation is needed to draw any conclusions.

5.2 Performance of Wet-Gas Correlations

Previous NEL publications have shown that the correlations developed for horizontal orientation are inappropriate for vertical installations and will result in errors in gas mass flow rate exceeding 10% [20], [21], [30].

Figure 6 shows the errors in the gas mass flow rate when using ISO/TR 11583 to correct the meter over-reading. Some of the data points are outside the uncertainty limits specified in the ISO technical report and confirm the previous NEL's findings. It should be noted that the parameter H in Equation (21) was linearly interpolated between 1 and 1.35 as a function of the water liquid ratio. Comparable results to those with the ISO/TR 11583 correlation were obtained when using the De Leeuw correlation with a calibrated average dry-gas discharge coefficient of 1.01045 (pipe Reynolds number is between 2.02×10^6 and 1.05×10^7), see Figure 8.

Figure 7 and Figure 9 show that both ISO/TR 11583 and the De Leeuw correlation performance decrease for decreasing values of the gas Froude number. At high gas Froude numbers both the ISO/TR 11583 and the De Leeuw correlations perform well. This can be explained by the fact that at high gas Froude numbers the response of a vertically and that of a horizontally installed Venturi tube tends to be the same since the flow regime tends to be the same. It is expected that at very high gas Froude numbers the same correlation would apply for both vertical and horizontal installation.

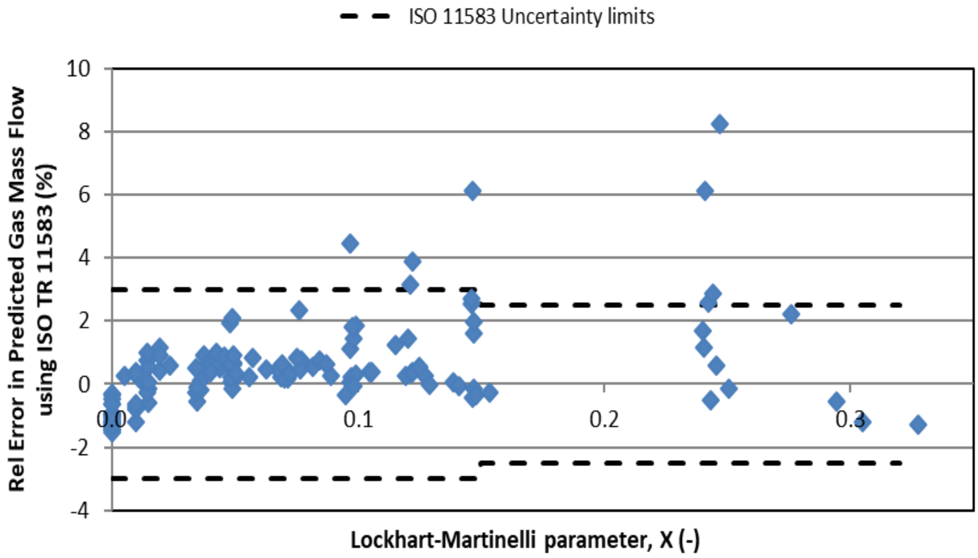

Figure 6 – Relative gas mass flow rate error using ISO/TR 11583 correlation as a function of the Lockhart-Martinelli parameter

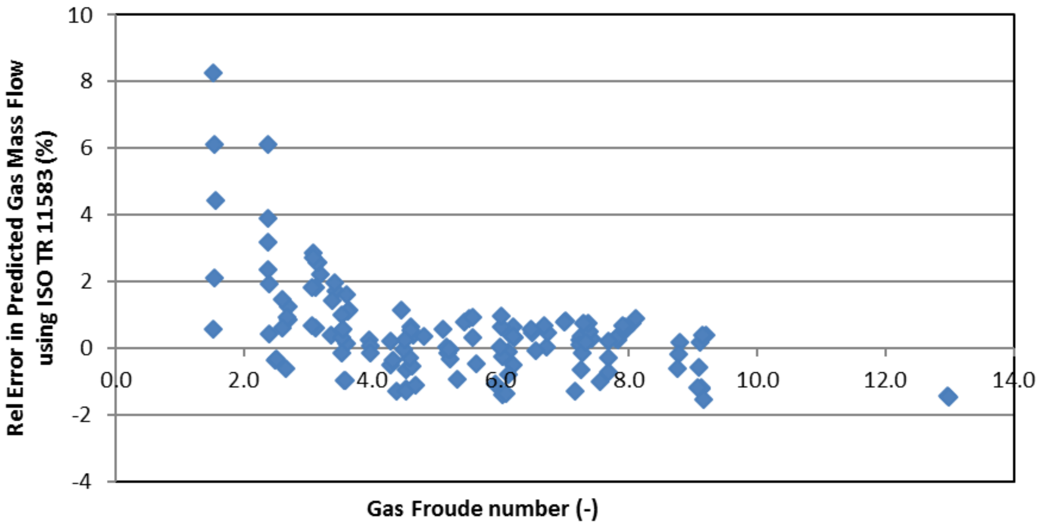

Figure 7 - Relative gas mass flow rate error using ISO/TR 11583 correlation as a function of the gas Froude number

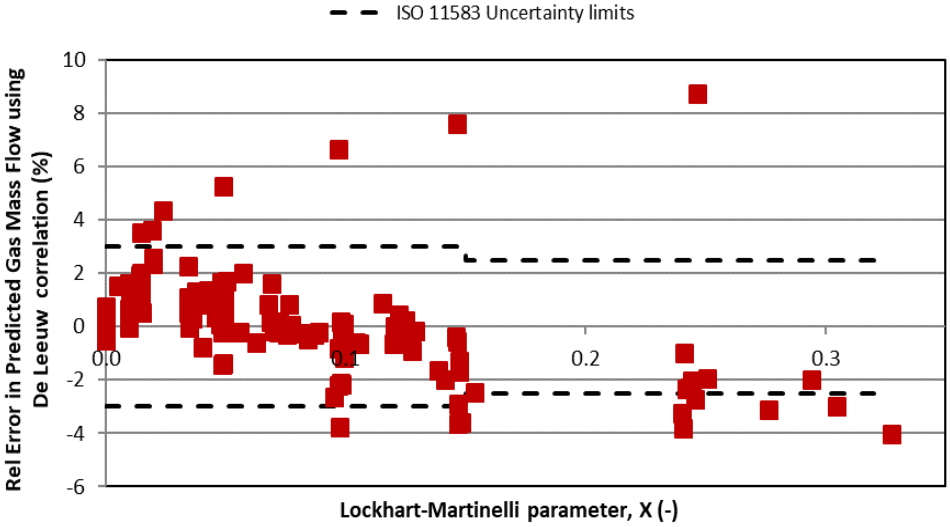

Figure 8 - Relative gas mass flow rate error using the De Leeuw correlation as a function of the Lockhart-Martinelli parameter

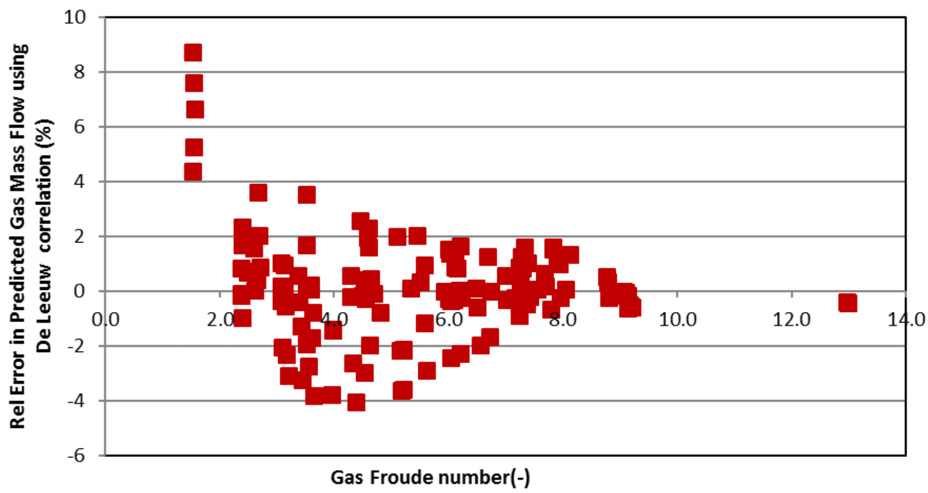

Figure 9 - Relative gas mass flow rate error using the De Leeuw correlation as a function of the gas Froude number

Figure 10 shows the error in the gas mass flow rate using an *n*-exponent equal to 0.5 (i.e. the homogeneous model). The results were analysed using the average calibrated dry-gas discharge coefficient and the ISO/TR 11583 wet-gas discharge coefficient. The results show an improved fit using the wet-gas discharge coefficient. A value for the *n*-exponent was determined from fitting the data set, resulting in a value of 0.487 when using the wet-gas discharge coefficient and a value of 0.552 when using the dry-gas discharge coefficient; these results are shown in Figure 11.

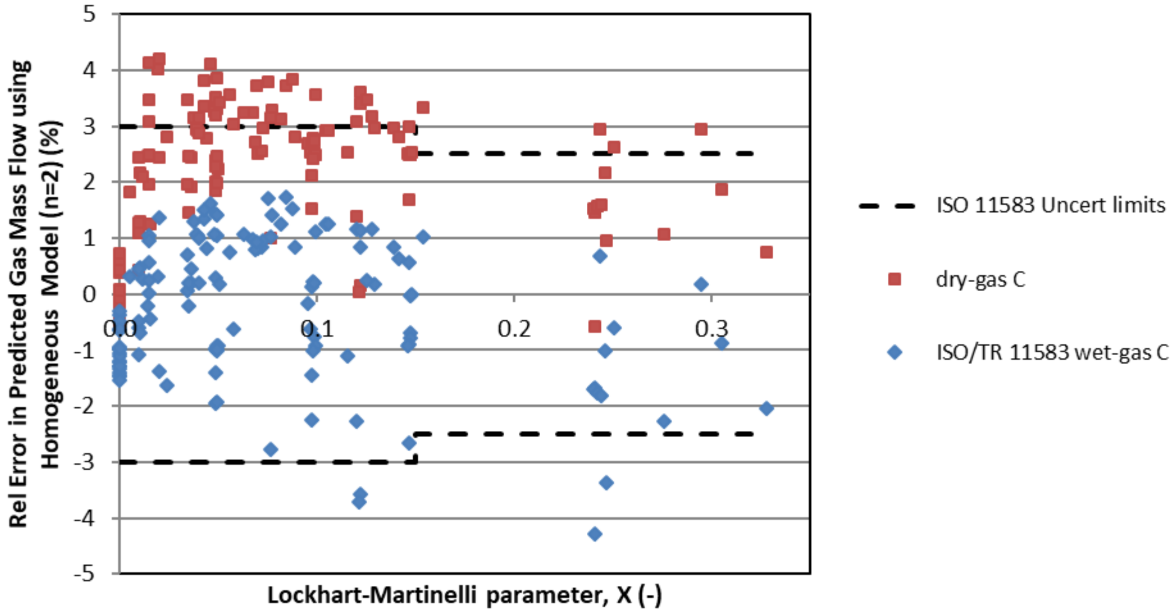

Figure 10 – Relative gas mass flow rate error using an *n*-exponent equal to 0.5 and either the dry-gas discharge coefficient (red square) or the ISO/TR 11583 wet-gas discharge coefficient (blue diamond) and assuming the Lockhart-Martinelli parameter to be known without error

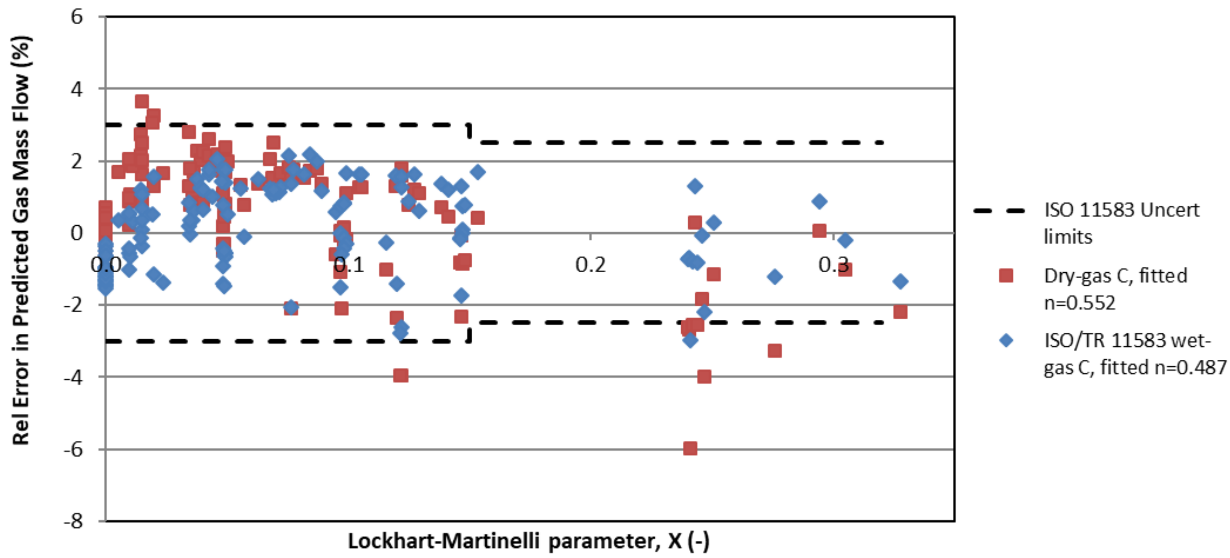

Figure 11 - Relative gas mass flow rate error using either the dry-gas discharge coefficient and an *n*-exponent equal to 0.552 (red square) or the ISO/TR 11583 wet-gas discharge coefficient (blue diamond) and an *n*-exponent equal to 0.487 and assuming the Lockhart-Martinelli parameter to be known without error

Although these results suggest that using the ISO/TR 11583 wet-gas discharge coefficient can reduce the error, this was not the case for an earlier data set collected at NEL for a 4-inch, β=0.6 Venturi tube. A quick assessment of the wet-gas discharge coefficient using the single data set for the Solartron Venturi tube revealed a different relationship from that for horizontal flows based on the gas Froude number at the Venturi throat, see equation (19). It should be noted that using only a small data set is insufficient to determine the relationship between the discharge coefficient and the value of n for vertical flows.

It is recommended that additional data sets are collected to assess the wet-gas discharge coefficient as it must be assessed whether the empirical equation derived for horizontal flows (ISO/TR 11583) is appropriate for vertical flows.

Figure 12 shows that the data for horizontal installation cannot be easily fitted to account for low and high values of the Lockhart-Martinelli parameter X; the gradient of the data changes rapidly between X=0 to X=0.025 and X=0.025 to X=0.3. The "wet-gas discharge coefficient" accounts for this effect. This effect is also noticed in the vertical installation tests, as shown in Figure 13 and Figure 14. This suggests that a wet-gas discharge coefficient is necessary also for vertical installation.

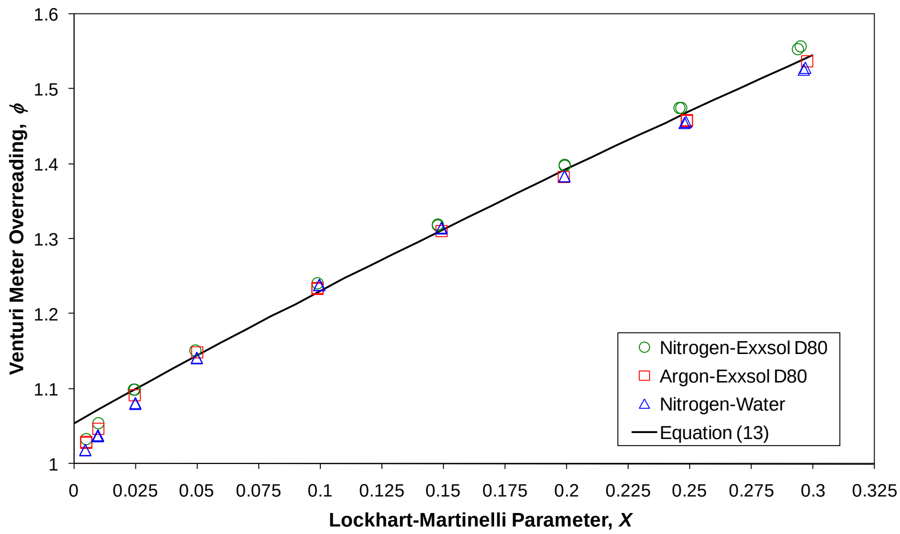

Figure 12 - Over-reading data for a 4-inch, β=0.6 Venturi tube horizontally installed for Fr_{gas}=1.5, and DR=0.024 [11]

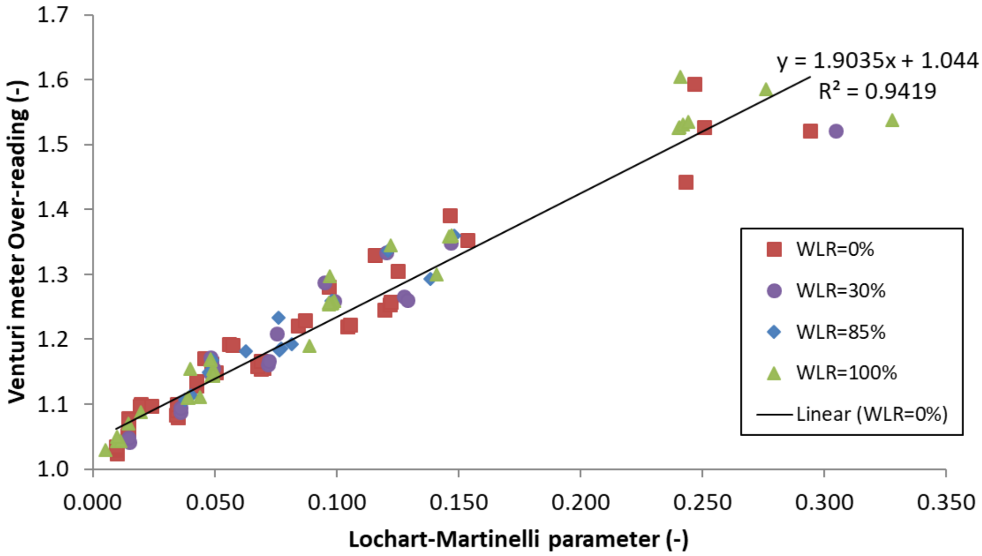

Figure 13 - Over-reading data for Solartron vertical Venturi tube. Note: the linear fit is only for the data with 0% water liquid ratio

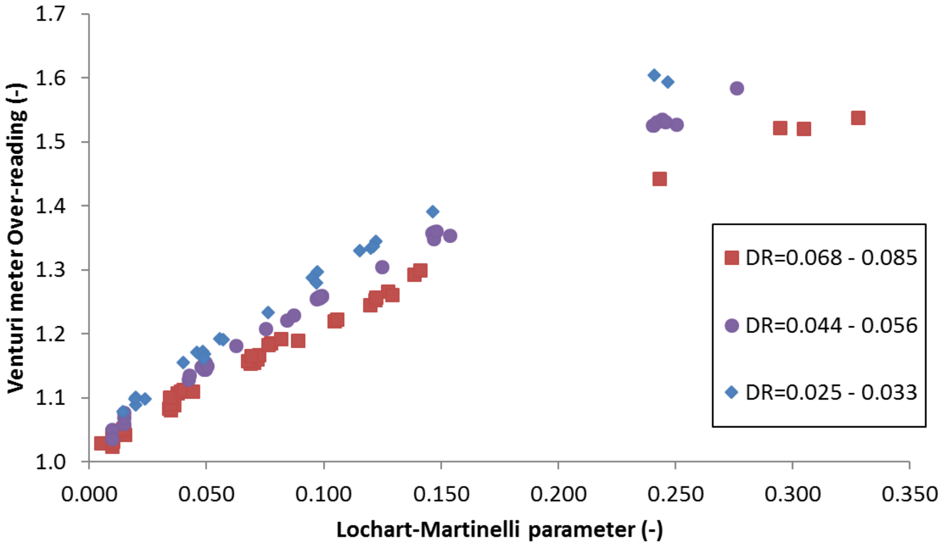

Figure 14 - Over-reading data for Solartron vertical Venturi tube

Figure 15 shows the relative errors in the gas mass flow rate when the correlation for low and high pressure conditions by [9] (Equation (24) and a constant wet-gas discharge coefficient of 0.985) is used to correct the meter over-reading. The Lockhart-Martinelli parameter was assumed to be known without error. Most of the data points are within the uncertainty limits specified in ISO/TR 11583:2012. However, this correlation is rather simple and based on a very limited data-set. For example, the over-reading dependence on the Venturi diameter ratio, as found by tests at NEL [30], is not included in this correlation. It is recommended that additional data sets are collected to develop a more accurate over-reading correlation for Venturi tubes installed vertically.

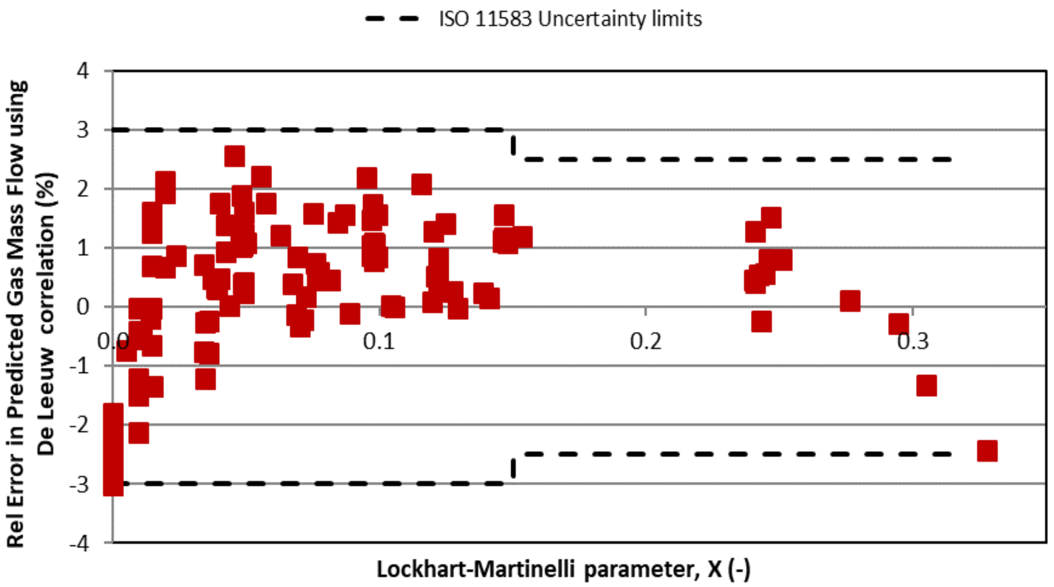

Figure 15 - Relative gas mass flow rate error using a constant wet-gas discharge coefficient of 0.985 and an *n*-exponent given by Equation (24), and assuming the Lockhart-Martinelli parameter to be known without error

As described in Section 2 the measured differential pressure has been corrected to account for the hydrostatic pressure drop with Equation (11). The measured differential pressure is shown in Figure 16, and the difference between the measured differential pressure, $\Delta p_{measured}$, and the corrected differential pressure, Δp_{req}, is shown in Figure 17. Figure 18 shows the difference in percentage between the corrected and the measured differential pressure.

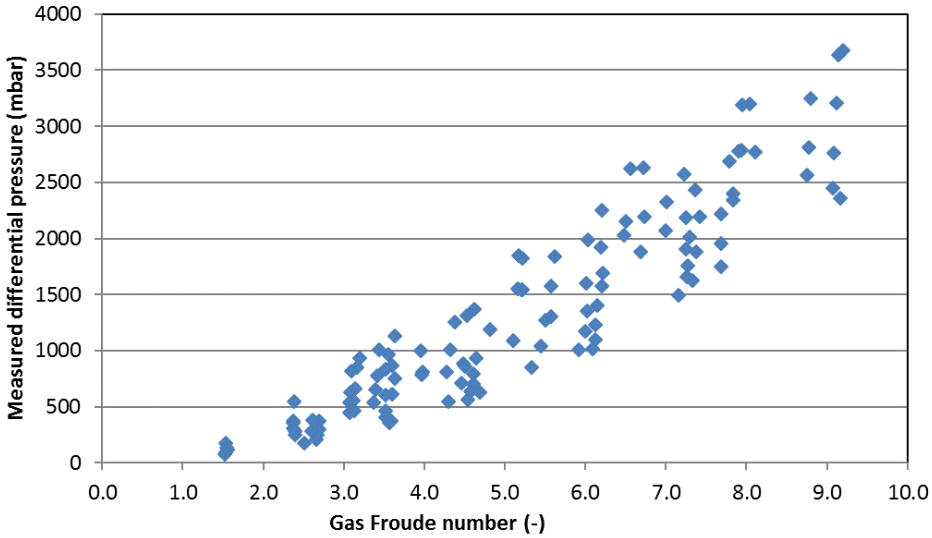

Figure 16 – Measured differential pressure against gas Froude number

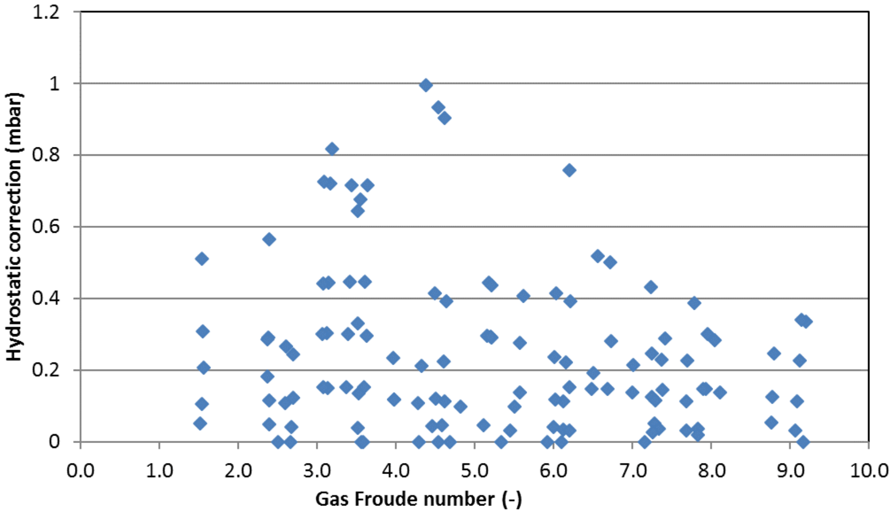

Figure 17 – Difference between the measured differential pressure, $\Delta p_{measured}$, and the differential pressure corrected with Equation (11), Δp_{req}, against gas Froude number

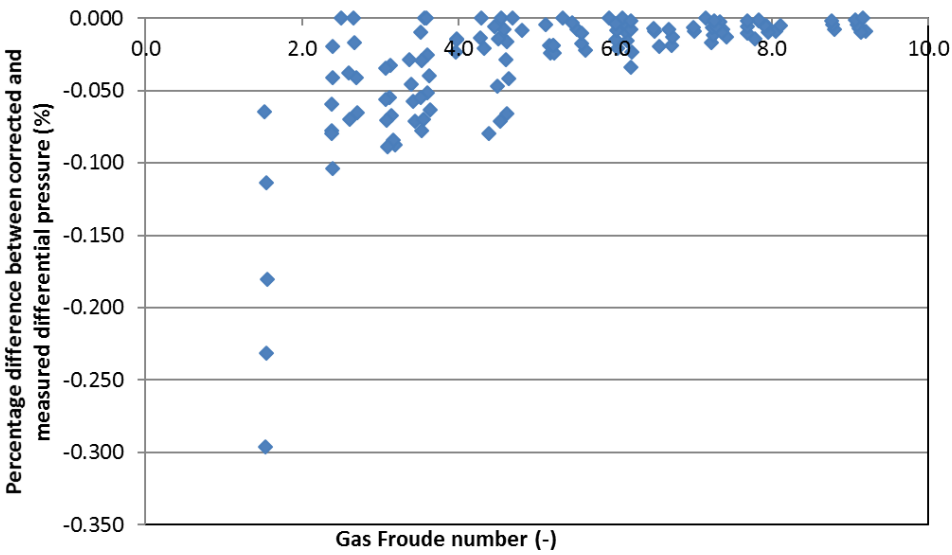

Figure 18 - Difference in percentage between the differential pressure corrected with Equation (11), Δp_{req}, and the measured differential pressure, $\Delta p_{measured}$, against gas Froude number

For these tests the difference between the corrected and the measured differential pressure is generally below 0.1%. The difference increases for decreasing gas Froude numbers, since the measured differential pressure substantially decreases, while the hydrostatic correction remains fairly constant, see Figure 16 and Figure 17. In general, the results show that the hydrostatic correction can be neglected at high gas Froude number. It should be noted that due to the square root relation, see Equation (8), half of the error in differential pressure measurement is propagated to the gas mass flow rate. It should be noted that the values shown in

Figure 17 and Figure 18 have been obtained under the assumption of no-slip between the phases. A sensitivity analysis to apply this assumption is required.

5.3 Pressure loss ratio method

The Solartron Venturi has a downstream tapping, located where the conical divergent section joins the downstream full-bore pipe section, to measure the pressure loss across the Venturi. All previous research conducted at NEL on the pressure loss ratio have used a pressure tapping approximately 6*D* to 9*D* downstream of where the conical divergent section joins the downstream full-bore pipe section. The pressure loss was measured using both the Solartron downstream tapping on the Venturi body (pressure loss A) and using an additional downstream pressure tapping ~7.5*D* (pressure loss B) downstream from the Solartron downstream tapping, see Figure 19.

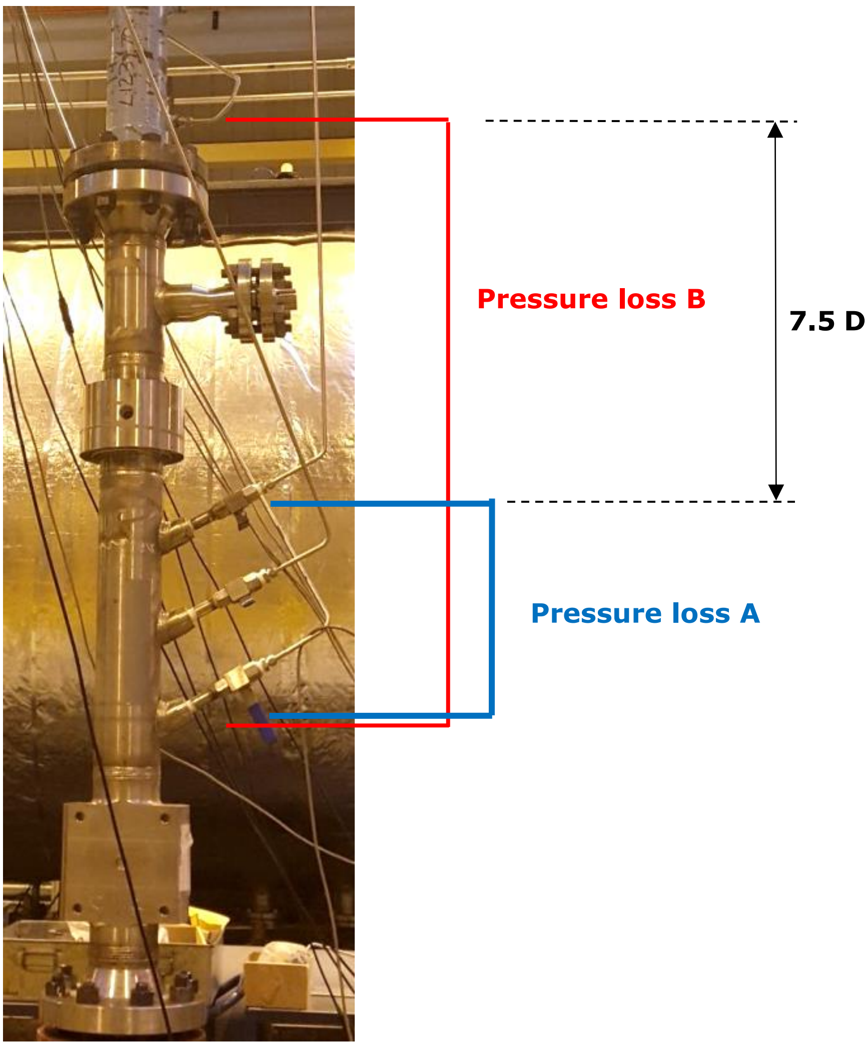

Figure 19 – Pressure loss measurement set-up

Some examples of the Pressure Loss Ratios (PLR) measured for A and B downstream tappings are shown in Figure 20 to Figure 22. These also show the values for a similar Venturi tube (4-inch, β=0.6) installed in a horizontal orientation. It can be seen than the PLR values for tapping A (PLR A) are significantly higher than for tapping B (PLR B). Present results confirm that the pressure loss ratio in vertical orientation generally tends to level off at a higher value of the Lockhart-Martinelli parameter than for horizontal installation. However, it is recommended that the method is further investigated for vertical installations and equations determined that could be used similarly to those for horizontally installed Venturi tubes.

Using the PLR A value has advantages due to the greater resolution in PLR to determine the wetness of the gas but also in terms of practical implementation in the field as significantly smaller lengths of impulse lines are required and the DP sensors could be packaged closer to the Venturi. Moreover, it results in a shorter meter.

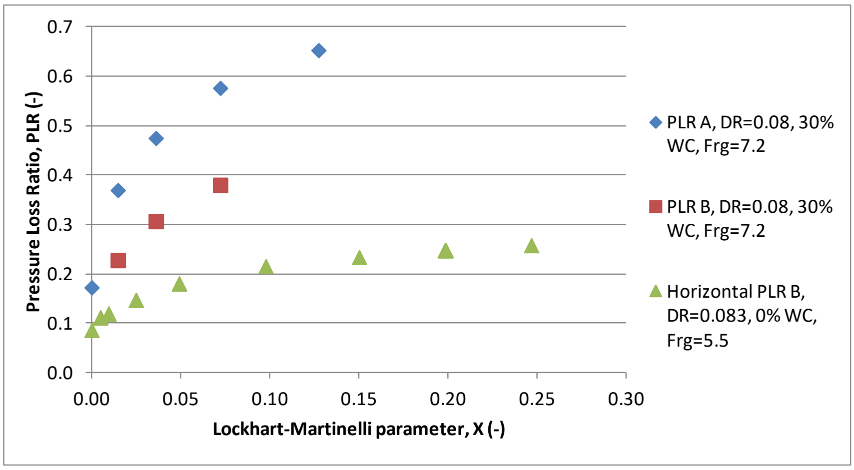

Figure 20 - Pressure Loss Ratio (PLR) values for the Solartron vertical Venturi with tappings A and B and a similar horizontal Venturi with B tappings. Pressure 58 barg

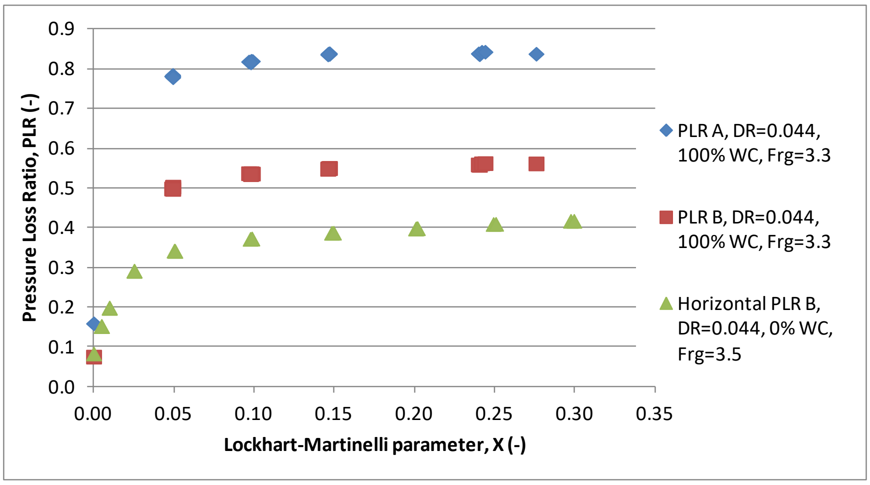

Figure 21 - Pressure Loss Ratio (PLR) values for the Solartron vertical Venturi with tappings A and B and a similar horizontal Venturi with B tappings. Gas Froude numbers from 3.3 to 3.5 and gas pressure 36 barg

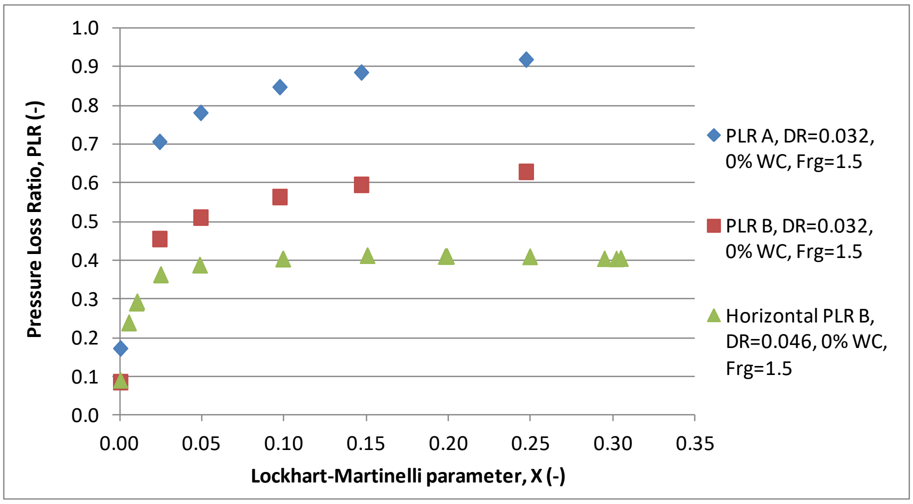

Figure 22 - Pressure Loss Ratio (PLR) values for the Solartron vertical Venturi with tappings A and B and a similar horizontal Venturi with B tappings. Gas Froude number of 1.5 and gas pressure 36 barg

6 CONCLUSION AND RECOMMENDATIONS

In this article wet-gas flow measurement with vertical Venturi tubes has been discussed and the results of new tests conducted at TÜV-SÜD National Engineering Laboratory (NEL) with a Venturi tube specifically designed for vertical installation by Solatron ISA have been presented.

Using the Solartron Venturi pressure tapping design for vertical installation resulted in no data being rejected due to issues with the tappings filling with liquid. This is in contrast with previous tests at NEL using a standard Venturi installed in a vertical orientation, which resulted in one third to half of the data being rejected due to the issue of the pressure impulse lines filling with liquid. If there is liquid in the impulse lines this can result in a measurement bias of over 10% over-reading in the gas mass flow rate.

The results presented in this article show that a wet-gas discharge coefficient is probably necessary to improve the accuracy of the predicted over-reading response of a vertical Venturi in wet-gas conditions. The equation for the wet-gas discharge coefficient for horizontal installation was investigated to assess its application and use for vertical installations. It is recommended to determine an equation for the wet-gas discharge coefficient for vertical installations.

A simplified equation to predict the over-reading response of vertical Venturis could be used instead of applying the recommendations from ISO/TR 11583. Using the equations in ISO/TR 11583 is not recommended for vertical installations. It is recommended that more extensive data sets are collected, or data sets are shared within the wet-gas community to determine a simplified equation for vertical installations. It should be noted that the response of vertical Venturis in wet-gas flow appears to be less sensitive to the properties of the liquid used, the gas Froude number (when a minimum value of the gas Froude number is exceeded – i.e. the liquid film is stable) and the beta ratio than for horizontal installation. A reduced sensitivity to the process parameters is desirable when extrapolating correlations obtained in test laboratories to field conditions.

Using the Pressure Loss Ratio (PLR) method to determine the wetness of the gas, and hence correct the over-reading, can potentially be used over a more extensive range when the Venturi is installed in a vertical orientation than in a horizontal orientation. There are advantages to moving the downstream pressure tapping closer to the Venturi similar to that in Solartron ISA design, as this can improve the range and resolution over which the PLR method can be used and make the meter more compact. It is recommended that additional data sets are acquired, and new equations are developed for vertical installation; this will increase their application and usefulness for wet-gas flow measurement and reduce the need for costly periodic external measurements of the wetness or additional embedded instrumentation.

The development and publication of robust and verified equations to correct the Venturi over-reading and use the PLR method would enable the development of cost-effective wet-gas measurement with vertical Venturis. The publication of equations and models increases the understanding of the performance of Venturi meters in a vertical orientation to measure wet-gas flows, especially as these form the main component in the majority of commercial multiphase and wet-gas meters with proprietary models applied. 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.

The uncertainty in using generic equations which cover a wide range of wet-gas conditions and different diameters ratios, can be substantially reduced by manufacturers if they determine bespoke coefficient values, for example, for a specific diameter ratio or limited wet-gas conditions.

7 ACKNOWLEDGEMENTS

The work described in this 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.

Solartron ISA for the provision of a Venturi meter for testing and guidance on vertical wet-gas testing.

8 REFERENCES

[1] ISO, *Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits*. Geneva: ISO/TR 11583:2012, International Organization for Standardization, 2012.

[2] ISO, *Natural Gas — Wet gas flow measurement in natural gas operations*. Geneva: ISO/TR 12748:2015, International Organization for Standardization, 2015.

[3] A. Hall, D. Griffin, and R. Steven, "A Discussion on Wet Gas Flow Parameter Definitions," in *25th International North Sea Flow Measurement Workshop*, 2007.

[4] R. Lockhart and R. Martinelli, "Proposed correlation of data for isothermal two-phase, two-component flow in pipes," *Chem. Eng. Prog.*, vol. 45, no. 1, pp. 39–48, 1949.

[5] ISO, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 4: Venturi tubes*. Geneva: ISO 5167-4:2003, International Organization for Standardization, 2003.
[6] M. Reader-Harris, *Orifice Plates and Venturi Tubes*. Springer International Publishing, 2015.
[7] R. Steven, "Wet gas metering," PhD Thesis, University of Strathclyde, UK, 2001.
[8] R. de Leeuw, R. Steven, and H. van Maanen, "Venturi Meters and Wet Gas Flow," in *29th North Sea Flow Measurement Workshop*, 2011.
[9] G. Chinello, "Wet gas metering with Venturi tubes," PhD Thesis, Glasgow Caledonian University, UK, 2019.
[10] R. de Leeuw, "Liquid correction of Venturi meter readings in wet gas flow," in *15th North Sea Flow Measurement Workshop*, 1997.
[11] M. Reader-Harris and E. Graham, "Venturi Tubes in Wet Gas – Improved Models for the Over- Reading and the Pressure-Loss Ratio Method," in *9th South East Asia Hydrocarbon Flow Measurement Workshop*, 2010.
[12] E. Graham *et al.*, "Impact of Using ISO / TR 11583 for a Venturi Tube in 3-Phase Wet-Gas Conditions," in *33rd International North Sea Flow Measurement Workshop*, 2015.
[13] A. Collins and S. Clark, "Evolution of Wet Gas Venturi Metering and Wet Gas Correction Algorithms," *Meas. Control*, vol. 46, no. 1, pp. 15–20, 2013.
[14] R. Steven, J. Kinney, and C. Britton, "Comparisons of Ultrasonic and Differential Pressure Meter Responses to Wet Natural Gas Flow," in *33rd International North Sea Flow Measurement Workshop*, 2015.
[15] D. He and B. Bai, "A new correlation for wet gas flow rate measurement with Venturi meter based on two-phase mass flow coefficient," *Meas. J. Int. Meas. Confed.*, vol. 58, pp. 61–67, Dec. 2014.
[16] M. Bjørner, P. Fosbøl, M. Lisberg, and H. Lisberg, "Generalized Wet Gas Venturi Meter Correlations: Assessment and Improvement," in *35th North Sea Flow Measurement Workshop*, 2017, no. October, pp. 24–26.
[17] M. Reader-Harris, E. Graham, and C. Forsyth, "Testing ISO/TR 11583 outside its range of applicability: areas of possible improvements," in *European Flow Measurement Workshop (Powerpoint only)*, 2017.
[18] L. Xu, W. Zhou, and X. Li, "Wet gas flow modeling for a vertically mounted Venturi meter," *Meas. Sci. Technol.*, vol. 23, no. 4, pp. 1–9, 2012.
[19] C. Britton, J. Kinney, and R. Steven, "Liquid Property and Diameter Effects on DP Meter Wet Gas Over-Readings," in *26th International North Sea Flow Measurement Workshop*, 2008, pp. 349–382.
[20] E. Graham, M. Reader-Harris, D. Hodges, R. Hone, A. Barrie, and N. Ramsay, "Performance of a Vertically Installed Venturi tube in Wet - Gas Conditions," in *32nd International North Sea Flow Measurement Workshop*, 2014.
[21] E. Graham, M. Reader-Harris, and C. Forsyth, "Installation effects on Venturi tubes in wet-gas flow conditions," in *35th North Sea Flow Measurement Workshop*, 2017, no. October.
[22] J. Cazin *et al.*, "Lessons from Wet Gas Flow Metering System Using Differential Measurement Devices: Testing and Flow Modelling Results," in 23rd *North Sea Flow Measurement Workshop*, 2005.
[23] A. Lupeau, "Etude et modelisation du comportement d'un ecoulement annulaire disperse. Application a la mesure de debit de gaz humide a l'aide d'un debitmetre a venturi," PhD Thesis, Ecole Nationale Superieure de l'Aeronautique et de l'Espace, FR, 2005.
[24] A. Lupeau, B. Platet, P. Gajan, A. Strzelecki, J. Escande, and J. P. Couput, "Influence of the presence of an upstream annular liquid film on the wet gas

flow measured by a Venturi in a downward vertical configuration," *Flow Meas. Instrum.*, vol. 18, no. 1, pp. 1–11, 2007.

[25] G. Salque, J. P. Couput, P. Gajan, A. Strzelecki, and J. Fabre, "New correction method for wet gas flow metering based on two phase flow modelling: Validation on industrial Air/Oil/Water tests at low and high pressure," in *26th International North Sea Flow Measurement Workshop*, 2008, pp. 331–348.

[26] G. Salque, P. Gajan, A. Strzelecki, J. P. Couput, and L. El-Hima, "Atomisation rate and gas/liquid interactions in a pipe and a venturi: Influence of the physical properties of the liquid film," *Int. J. Multiph. Flow*, vol. 51, pp. 87–100, 2013.

[27] P. Gajan, G. Salque, J. P. Couput, and J. Berthiaud, "Experimental analysis of the behaviour of a Venturi meter submitted to an upstream air/oil annular liquid film," *Flow Meas. Instrum.*, vol. 33, pp. 160–167, 2013.

[28] J. P. Couput, B. Tanguy, and P. Gajan, "Venturi flow meters behaviour in high pressure 3 phases wet gas conditions," in *32nd International North Sea Flow Measurement Workshop*, 2014, pp. 71–79.

[29] H. R. E. van Maanen and H. de Leeuw, "Modelling of Wet Gas flow in Venturi Meters to Predict the Differential Pressure," in *34th International North Sea Flow Measurement Workshop*, 2016, no. October.

[30] E. Graham, M. Reader-Harris, G. Chinello, K. Harkins, N. Bowman, and L. Wales, "Vertically installed Venturi tubes for wet-gas flow measurement: possible improvements to ISO/TR 11583 to extend its range of applicability," in *18th International Flow Measurement Conference FLOMEKO*, 2019.

[31] G. Monni, M. De Salve, and B. Panella, "Two-phase flow measurements at high void fraction by a Venturi meter," *Prog. Nucl. Energy*, vol. 77, pp. 167–175, 2014.

[32] F. S. Silva, P. Andreussi, and P. Di Marco, "Total Mass Flowrate Measurement in Multiphase Flow By Means of a Venturi Meter," *Multiph. Prod.*, pp. 145–155, 1991.