A new over-reading correlation for vertical Venturi tubes in wet-gas flow

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1 INTRODUCTION

Venturi tubes are one of the most common types of device used for wet-gas flow measurement as they are a simple, robust, and cost-effective flow meter.

The majority of research and development for Venturi tubes in wet-gas flow are for horizontal installation and there are not many over-reading correlations developed for vertical Venturi tubes in the public domain. The ISO Technical Reports for measuring wet-gas flows (ISO/TR 11583:2012 [1] and ISO/TR 12748:2015 [2]) only cover Venturi tubes horizontally installed. Correlations developed for horizontal orientation are inappropriate for vertical installations, and their performance decrease for decreasing values of the gas Froude number with errors in gas mass flow rate exceeding 10 % [3]–[7]. Moreover, the over-reading correlation included in ISO/TR 11583:2012 is limited to density ratio greater than 0.02 and was not extensively tested at density ratio greater than 0.1.

However, most commercial multiphase meters are installed vertically, and they can be exposed to density ratio lower than 0.02 and higher than 0.1 during operation. This will be particularly true for Carbon Capture and Storage operation, where a CO_2-rich stream is transported in gaseous phase via pipeline. Wet-gas flow is to be avoided during CO_2 transportation, but if encountered the density ratio for a CO_2 wet-gas stream is expected to be higher than 0.1, and in the region of approximately 0.1 to 0.3.

Experimental data has been collected by TÜV SÜD National Engineering Laboratory (NEL) on the performance of Venturi meters installed in a vertical upward orientation. Based on these experimental results a new over-reading correlation for vertical Venturi tubes suitable for density ratio between 0.012 and 0.16 was developed.

The correlation development and its performance are presented in this paper.

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 [8] for detail, and the original definition given by Lockhart and Martinelli [9] 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

$$WLR = \frac{\frac{m_{water}}{\rho_{water}}}{\frac{m_{water}}{\rho_{water}} + \frac{m_{oil}}{\rho_{oil}}} \quad (4)$$

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

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

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

$$v_{s,gas} = \frac{m_{gas}}{\rho_{1,gas}A} \quad (6)$$

where A is the pipe area.

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

$$DR = \frac{\rho_{1,gas}}{\rho_{liq}} \quad (7)$$

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

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

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 [10] 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.

A correction is needed 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 [5]. 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 [11]. 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

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

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

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

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

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

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

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

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.

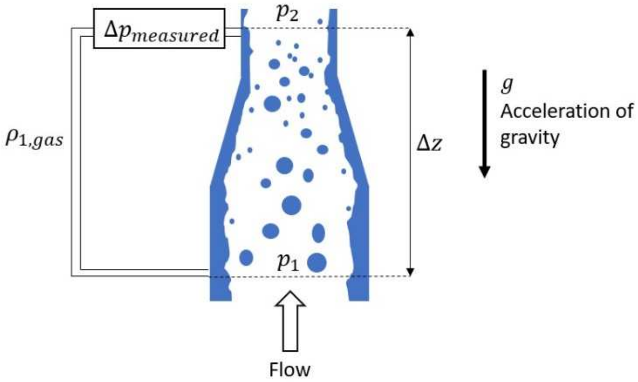

Figure 1: Schematic representation of a vertical upward oriented wet-gas Venturi tube

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 here 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 LITERATURE REVIEW

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 [12], [13] or [14] for derivation. In principle, the homogeneous model can be used with horizontally and vertically oriented Venturi tubes.

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

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

The De Leeuw correlation [15], 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 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], [16], 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

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

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

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

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

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

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 [14], [17]–[21]. Further improvement may be obtained with another simple equation for H [22].

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. [23] 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

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

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 (CEESI) in 2008 [24]. 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 installed horizontally. 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 [3] 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 3. Contrary to what was observed for horizontal Venturi tubes, 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 wet-gas 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 [24]. The correlation developed by Xu et al. [23] 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.

The same Venturi tube of the 2014 tests was tested again in 2016 at NEL [4]. 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 % (pure 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 [4].

In 2017 one 4-inch Venturi tube (β=0.55, D=0.078 m) installed vertically after a blind-tee was tested at NEL. 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. A summary of the test conditions is presented in Table 3. The Venturi used 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. The tappings' internal diameter was 6 mm. Using this Venturi tube design resulted in no data being rejected due to liquid collecting in the tappings and no resulting measurement bias. A correction 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 was presented and applied to the test results. The difference between the corrected and the measured differential pressure was calculated to be generally below 0.1 % and the difference increases for decreasing gas Froude numbers. It was shown that the performance of both ISO/TR 11583 and the De Leeuw correlation decrease for decreasing values of the gas Froude number. At high gas Froude numbers both the ISO/TR 11583 (approximately $Fr_{gas} > 3$) and the De Leeuw correlations (approximately $Fr_{gas} > 6.5$) performed well. The test results showed that a wet-gas discharge coefficient is probably necessary to predict the over-reading response of a vertical Venturi tube in wet-gas conditions. The over-reading response was found less sensitive to the liquid properties and the gas Froude number than for horizontal installation.

In 2018, 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 [6], [25]. 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 3.

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 Venturi tubes. 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 2. 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. The pressure tappings' length was reduced to the minimum ISO 5167-4:2003 specification 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 [3], [4].

Table 2 – Fitted values of the $\boldsymbol{n}$-exponent [6]

Venturi diameter ratio, $\boldsymbol{\beta}$ (-)	Fitted value of the $\boldsymbol{n}$-exponent (-)
0.4	0.503
0.6	0.478
0.75	0.425

In 2021, a 6-inch Venturi tube with diameter ratios, β, equal to 0.6, (convergent angle 21° and divergent angle 7°) was tested at NEL in the high-pressure multiphase flow facility installed after a blind tee. The horizontal section of the pressure tappings was complying with the ISO 5167-4:2003 minimum required length and then the pressure tappings were angled at 45° to avoid liquid accumulation in the impulse lines. The tappings' internal diameter was 5.5 mm. Fluids were nitrogen, kerosene substitute (Exxsol D140) and salt water, and the line pressure was varied between 7.5 and 115 barg. The conditions tested are shown in Table 3. It was found that also at high pressure the over-reading response is less sensitive to the liquid properties and the gas Froude number than for horizontal installation.

Extensive research was conducted at ONERA (Office National d`Etudes et de Recherches Aérospatiales) with 2-inch and 3-inch vertical downward Venturi tubes [26]–[32]. 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. [32], 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 [33] 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 [14] 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 into the physical mechanisms involved.

Chinello [14] 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 (21)) 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 [3]. 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 [3].

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

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.

Pan et al. [34] developed an over-reading correlation for vertical Venturi tubes subjected to low-pressure wet-gas flow, Equation (25). Constants in Equation (25) were obtained by fitting an experimental dataset (a=3.213, b=2.083, c=1.181, d=3.249) and assuming a constant discharge coefficient equal to 0.995.

$$\phi = \sqrt{1 + (a + b\,Fr_g)\left(c + d\,\frac{\rho_{gas}}{\rho_{liq}}\right)X + X^2} \tag{25}$$

The experiments were conducted with a 42.77 mm inlet diameter β=0.4 Venturi tube installed vertically. The operating pressure was between 8.2 and 15.2 bar, Lockhart-Martinelli parameter between 0.03 and 0.3, and the Froude gas number was between 0.5 and 2. Test fluid were oil, water, and Natural gas. The over-reading root mean square error of the developed correlation was shown as ±3 % over the fitted dataset.

It should be noted that Monni et al. [35] and Silva et al. [36] conducted relevant research at low pressure with a 3-inch and a 2-inch vertical Venturi tube, respectively.

4 DERIVATION OF THE CORRELATION

Several experimental data were collected at TÜV SÜD National Engineering Laboratory for vertical Venturi tubes and were reviewed in section 3. All the NEL test results were gathered together, a total of 667 wet-gas datapoints, to form a single dataset used to derive a new correlation, see Table 3. The dataset test points were plotted against the flow regime map by Hewitt and Roberts [37] in Figure 2, which shows that the flow regime is mainly annular flow. In fact, care must be taken to ensure that intermittent flow did not occur at any of the test points.

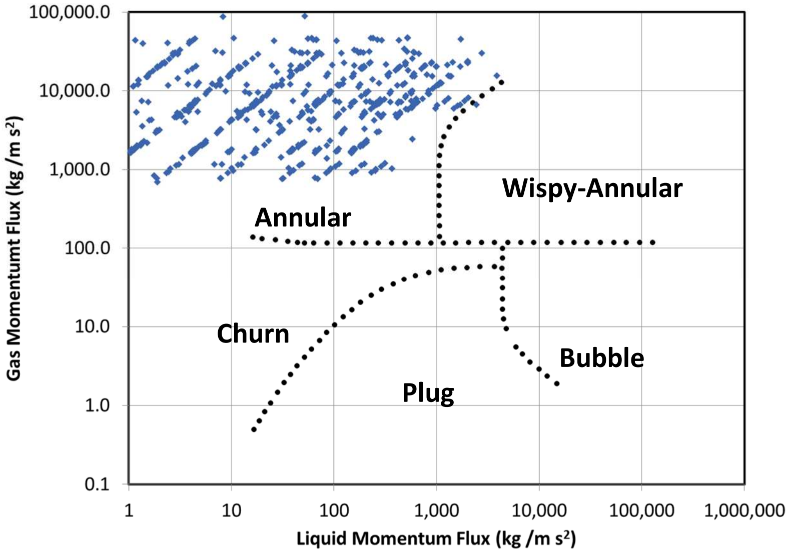

Figure 2: Dataset test points plotted on Hewitt and Roberts flow regime map [37]

From analysis of the dataset, the gradient of the over-reading was found to change rapidly between approximately X=0 to X=0.02 and X=0.02 to X=0.3 such that a "wet-gas discharge coefficient" was found needed to account for this. The data with a Lockahrt-Martinelli value below 0.02 were initially removed from the dataset and values of *C* and *n*-exponent to fit equations (26)(27)(28) were derived for each set of fluid combination, density ratios, gas Froude numbers and diameter ratios.

$$m_{gas} = \frac{\frac{C}{\sqrt{1-\beta^4}}\,\varepsilon\frac{\pi}{4}\,d^2\sqrt{2\,\Delta p_{req}\,\rho_{1,gas}}}{\phi} \tag{26}$$

$$\phi = \sqrt{1 + C_{ch}X + X^2} \tag{27}$$

$$C_{ch} = \left(\frac{\rho_{liq}}{\rho_{gas}}\right)^n + \left(\frac{\rho_{gas}}{\rho_{liq}}\right)^n \tag{28}$$

The *n*-exponent was found dependent on the diameter ratio, β, the density ratio, *DR*, and on a limited extent on the gas Froude number, Fr_{gas}. The *n*-exponent increase for increasing DR and Fr_{gas} values and decrease for increasing β.

The wet-gas discharge coefficient had a shallow dependency on the Froude gas throat number, $Fr_{gas,th}$, increasing for increasing $Fr_{gas,th}$ values. After this initial assessment of the functional relations, the following equations were fitted to the entire (including 0<X≤0.02 datapoints) database:

$$n = a - h\,\beta^{j} - w\,(DR^{k} - 1) \tag{29}$$

$$C = 1 - b\,e^{f\,Fr_{g,th}} \min\left(1, \sqrt{\frac{X}{X_{lim}}}\right) \tag{30}$$

Equation (30) was taken from ISO/TR 11583 [1]. The exponential dependency on the $Fr_{gas,th}$ could have been removed from Equation (30) with very minor effects on the overall correlation performance, but it was mainly retained to ensure that the correlation performs well in the limiting cases, see section 6. The dependancy on the density ratio in Equation (29) was found to give a small contribution for density ratio approximately greater than 0.02, and could have been disregarded for approximately DR>0.02 making Equation (29) a sole function of the Venturi tube diameter ratio. The dependancy on the density ratio in Equation (29) was retained because its contribution is relevant for density ratio less of approximately 0.02.

The constants *a, h, j, w, k, f, b* and X_{lim} were fitted to the entire database by a non-linear regression algorithm with Microsoft Excel. The constants values obtained are:

- a = 0.56
- h = 0.17
- j = 1.3
- w = 0.0007
- k = -0.9
- b = *0.033*
- f = -0.013
- X_{lim} = 0.02

The limits of the developed correlation are that of the dataset:

1. $0.4 \le \beta \le 0.75$
2. $0 < X \le 0.3$
3. $Fr_{gas} > 1$
4. $0.012 < DR < 0.16$
5. $0 \le WLR \le 100$
6. ISO 5167-2 compliant Venturi tubes

with an uncertainty in C/Φ of 3 %.

As with all the empirical correlations, the effects of extrapolating the correlation outside its limits is unknown and possibly to have adverse effects. It is thus strongly suggested to assess the correlation sensitivity against experimental data before using it outside its limits. However, the over-reading response of vertical Venturi tubes appears to be less sensitive to the properties of the liquid used and the gas Froude number than for horizontal installation. It might be more reliable then to extrapolate correlations obtained in test laboratories to field conditions for vertical Venturi tubes. It should be noted that the proposed correlation could be potentially improved if more experimental data are available in the future. It is also possible to derive different correlations than what proposed here.

Table 3 – Dataset used to develop the correlation

Inlet diameter (mm)	Diameter ratio, β (-)	Line Pressure (barg)	Gas Froude number, Fr_{gas} (-)	Density Ratio, *DR* (-)	Water Liquid Ratio, *WLR* (%)	Fluids	Test Year	Ref
102.36	0.6	15	1.5, 2, 2.5, 3	0.023	0	Nitrogen Oil	2014	[3]
		30	1.5, 2.5, 3.5, 4.5	0.046				
		60	1.5, 2.5, 3.5, 4.5, 5.5	0.088				
102.36	0.6	15.9	1.5, 2.5	0.024	0	Nitrogen, Crownsol D75, Water	2016	[4]
		31.1	1.5, 4.0, 4.5	0.046				
		57	1.5, 5.5	0.084				
		20.1	1.5, 2.5	0.024	100			
		39.1	1.5, 4.5	0.046				
		57	1.5, 5.5	0.067				
		18	1.5, 2.5	0.024	50			
		35	1.5, 4.5	0.046				
		57	5.5	0.074				
78.34	0.55	58	4.6, 6.1, 7.7, 9.1	0.085	0	Nitrogen, Exxsol D80, Water	2017	[5]
		36	3.5, 6, 7.3	0.056				
		21	2.4, 4.5, 5.5	0.032				
	0.55	58	4.5, 7.2, 8.8	0.08	30			
		36	5.6, 7	0.052				
		21	2.6, 4.3	0.03				
	0.55	58	6.7, 8	0.072	80-85			
		36	5.2, 6.5	0.046				
		21	2.4, 4	0.026				
	0.55	58	7.4, 7.8	0.7	100			
		36	3.1, 3.6, 5.2	0.044				
		21	2.4, 4	0.026				
102.35	0.4	15	1, 2, 2.5	0.023	0	Nitrogen, Exxsol D80	2018	[25]
		30	1.5, 2, 3	0.046				
		60	1.5, 3, 4	0.088				
102.21	0.6	15	1.5, 2.5, 3	0.024	0			
102.27	0.75	15	2, 3, 4, 5	0.025	0			
		30	1.5, 4.5	0.044				
		60	2, 5.5	0.088				
139.76	0.6	7.5	1	0.012	0	Nitrogen, Exxsol D140, Salt Water	2021	
		60	1, 1.5, 2.5, 3.6	0.083				
		116	1, 1.5, 2.5, 3.5, 4.5, 5.5, 8	0.16				
		116	3, 8	0.148	25			
		116	3, 8	0.135	70			
		116	3, 8	0.126	100			

5 CORRELATION PERFORMANCE

The correlation performance were assessed by calulating the gas mass flow rate percentance error using Equation (31). The Lockhart-Martinelli parameter X was assumed to be known without error.

$$E = 100 \cdot \frac{m_{gas,correlation} - m_{gas,exp}}{m_{gas,exp}} \tag{31}$$

Figure 3 and Figure 4 show the relative error in gas mass flow rate obtained when using the new correlation as a function of the Lockart-Martinelli parameter and the gas Froude number respectively. The relative error lies well within ±3 %. Table 4 summarises the performance of the developed correlation and that of other correlations from literature in term of the maximum positive and negative gas mass flow rate percentage error (E) and the two times Root Mean Square Error (RMSE) calculated as follow

$$2\,RMSE = 2 \cdot 100\sqrt{\frac{\sum_{t=1}^{T}\left(\frac{m_{gas,correlation,t} - m_{gas,exp,t}}{m_{gas,exp,t}}\right)^2}{T}} \tag{32}$$

with T total number of data points. It should be noted that none of the dry-gas data points were used to calculate the RMSE, and their inclusion will lower the RMSE values shown in Table 4. The developed correlation provide the best performance with a 2 RMSE equal to 2.22 %, followed by the 2019 correlation by Chinello [14], 3.17 %, and the homogeneous model, 4.2 %.

Table 4 – Performance of the derived correlation and other correlations from literature over the entire database. Dry *C* means that the calibrated dry-gas discharge coefficient was used instead of 1 with the Homogeneous model.

	+Max Error (%)	-Max Error (%)	2 RMSE (%)
New Correlation	3.19	-3.49	2.22
Chinello 2019	4.90	-4.78	3.17
Homogeneous Model *C*=1	5.50	-5.90	4.20
Homogeneous Model Dry *C*	5.59	-5.93	4.71
ISO/TR 11583	12.65	-5.22	4.95
De Leeuw	10.79	-12.08	7.28
Pan et al. 2019	5.85	-48.40	37.75

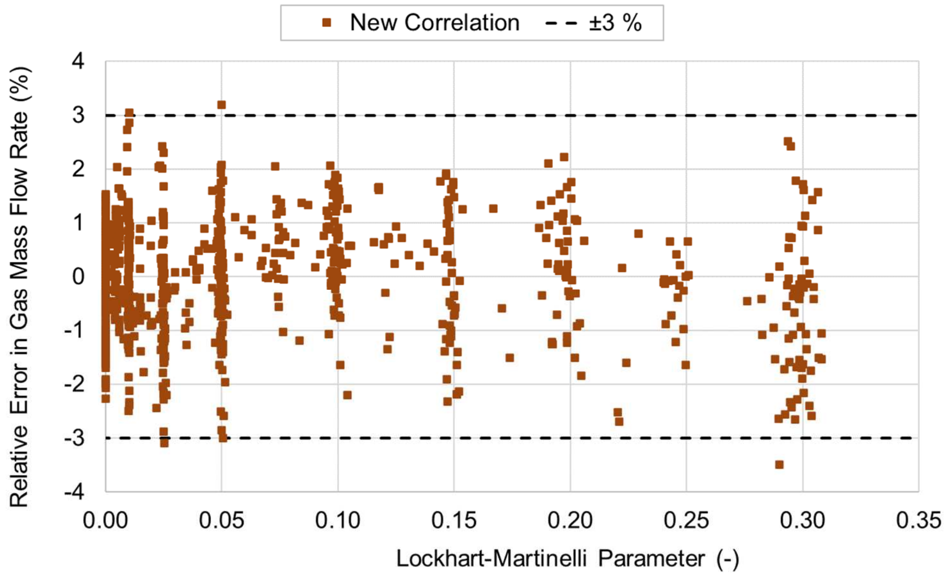

Figure 3: Relative error in gas mass flow rate using the new correlation as a function of the Lockhart-Martinelli parameter for the fitted dataset

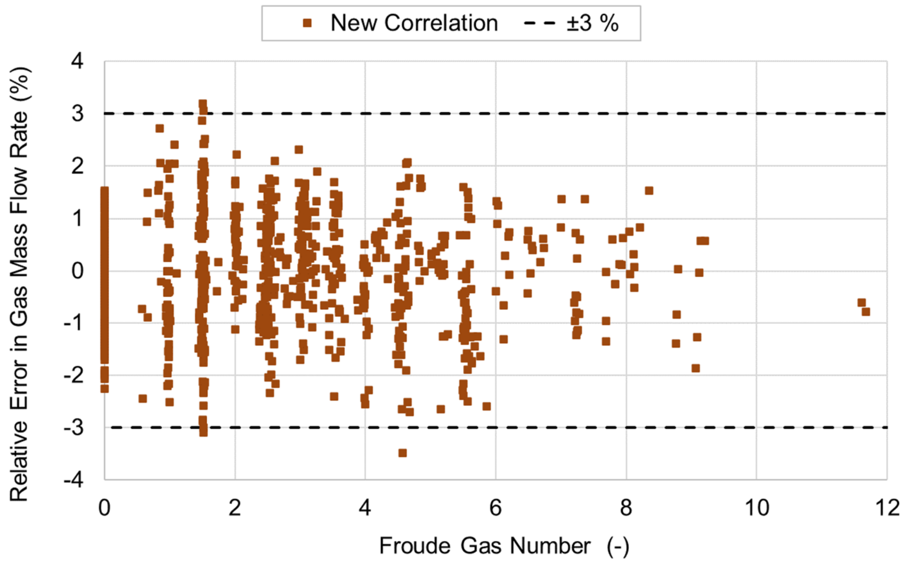

Figure 4: Relative error in gas mass flow rate using the new correlation as a function of the Froude gas number for the fitted dataset

It should be noted that the measured experimental differential pressure was corrected with Equation (11) and Equation (15) and assumed no-slip condition to account for the difference in densities between the fluids in the pipe and the fluid in the impulse lines [5]. The two times RMSE for the developed correlation increases from 2.22 % to 2.23 % if the experimental differential pressure is not corrected with Equations (11) and (15), i.e. the correction has a negligible effect for this dataset. This is also valid for the other correlations presented in Table 4.

The correlation performance was further assessed against two additional datasets not fitted to the correlation. Figure 5 show the over-reading percentage error for the new correlation against test data from CEESI [24] for a 4-inch, β=0.6, vertically installed Venturi tube. Fluids at CEESI were natural gas/kerosene, and natural gas/water, the density ratio was varied between 0.011 and 0.045 and the gas Froude number between 2 and 4.1. The correlation is found to perform well within ± 3%.

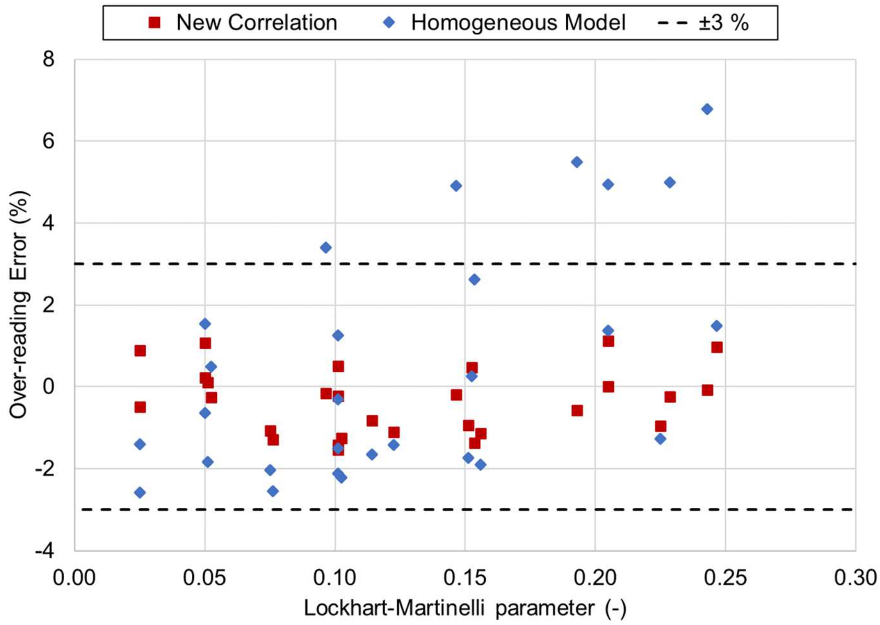

Figure 5: Over-reading percentage error of the new correlation using wet-gas data from CEESI and the homogeneous model with *C*=1 [24]

Figure 6 show the gas mass percentage error for the new correlation against test from Glasgow Caledonian University (GCU) [14] performed with a 2-inch, β=0.6, vertically upward Venturi tube at 2.5 barg, *DR*=0.0035, with air and water. The error is within ±3 % for most of the points, suggesting that the developed correlation could be suitable for low pressure applications too. However, it is necessary that more extensive datasets at low pressure are collected before reaching any conclusion, and it is strongly recommended to use particular care when applying the correlation outside its limits, especially at low density ratios and low Froude gas numbers where intermittent flow regime can occur.

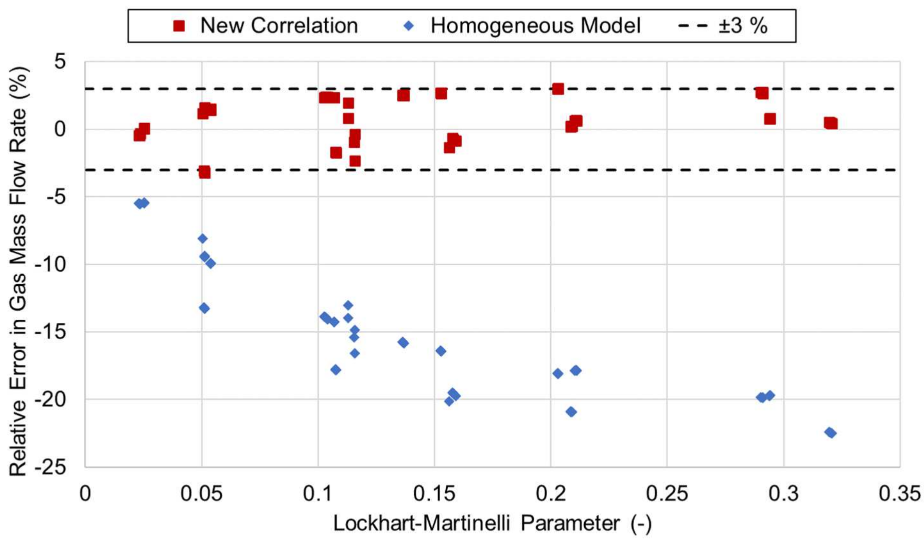

Figure 6: Gas mass flow rate percentage error of the new correlation using low pressure wet-gas data from GCU and the homogeneous model with *C*=1 [14]

6 CORRELATION LIMITING BEHAVIOUR

It is good practice for a wet-gas correlation to respect the following three physical conditions in the limiting cases [13], [14], [21], [33], [39]:

1. Dense phase condition: for gas to liquid density ratio tending to 1 the over-reading should approach $\phi=1+X$. As $DR \rightarrow 1$, $Fr_{gas,th} \rightarrow \infty$ and $C \rightarrow 1$ according to Equation (30). Moreover, the n-exponent tend to a positive value, $C_{ch} \rightarrow 2$ and $\phi \rightarrow 1+X$ according to Equations (27),(28) and (29)

2. Dry-Gas condition: for Lockhart-Martinelli tending to zero (dry-gas) the over-reading should tend to 1. This is ensured by Equation (27) and (30)

3. Minimum energy condition: the minimum value of the over-reading is given by $\phi=1+X$, which is verified both when the gas and liquid have the same density (dense phase condition) or for ideal perfectly stratified flow. This means that $C \leq 1$ and $C_{ch} \geq 2$. As per Equation (30) $C \leq 1$. Equations (28) and (29) and $DR \leq 1$ ensure that $C_{ch} \geq 2$.

It should be noted that Equation (28) converge to infinity for DR tending to 0. This is further exacerbated by the term $w\,(DR^k - 1)$ in Equation (29), given that k is a negative number. As such, it is necessary to impose a lower limit for the density ratio.

It is worth noting that for increasing values of the Froude gas number the ISO/TR 11583 correlation for horizontal Venturi tubes and the new correlation for vertical Venturi tubes give similar results, see Figure 7. This should be the case since both horizontal and vertical Venturi tubes will be exposed to a similar flow pattern for increasing Froude gas number and their response is expected to be similar in the limiting case.

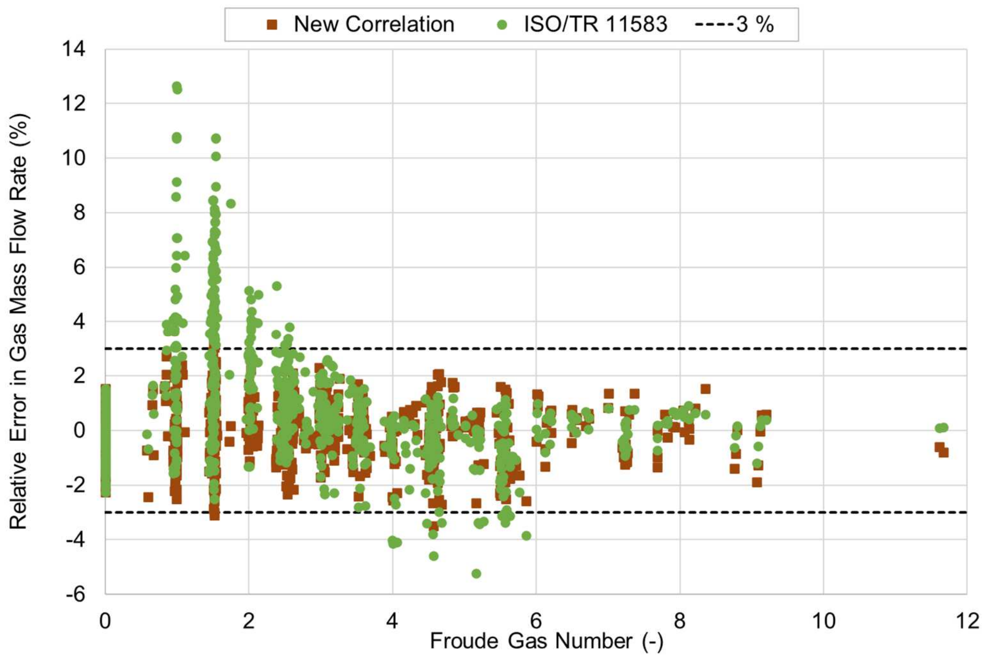

Figure 7: Relative error in gas mass flow rate with the new correlation and the ISO/TR 11583 correlation as a function of the Froude gas number for the fitted dataset

7 CONCLUSION AND RECOMMENDATIONS

In this paper a new over-reading correlation for wet-gas flow measurement with vertical Venturi tubes was presented. The correlation was obtained by fitting of experimental data collected in the past years by TÜV SÜD National Engineering Laboratory (NEL), a total of 667 wet-gas datapoints.

The results presented in this paper show that the gas mass flow rate can be predicted within approximately ±3 % by the new correlation assuming the Lockhart-Martinelli parameter to be known without error. The developed correlation provide the best performance by far when compared with other over-reading correlations available in the literature using this dataset. To the best of the author's knowledge this is the first time a correlation is developed based on test data from 7.5 barg, *DR*=0.012, up to 116 barg, *DR*=0.16.

The limits of the correlation were presented. As with all the empirical correlations, the effects of extrapolating the correlation outside its limits is unknown and could possibly have adverse effects. It is thus strongly suggested to assess the correlation sensitivity against experimental data before using it outside its limits. However, it should be noted that the over-reading response of vertical Venturi tubes appears to be less sensitive to the properties of the liquid used and the gas Froude number than for horizontal installation. It might be more reliable then to extrapolate correlations obtained in test laboratories to field conditions for vertical Venturi tubes.

The correlation performance was further assessed against two additional datasets not fitted to the correlation. Both show results within ±3 % down to 2.5 barg, *DR*=0.0035 suggesting that the developed correlation could be suitable for low pressure applications too. However, it is necessary that more extensive datasets at low pressures are collected before reaching any conclusion, and it is strongly recommended to use particular care when applying the correlation outside its limits, especially at low density ratios and low Froude gas numbers.

It is recommended that additional datasets are acquired, and new equations are developed for the pressure loss ratio method for vertical installation; this will increase the applicability and usefulness of the over-reading correlation presented here.

As a final note it should be recognised that there are practical challenges when using Venturi meters in a vertical installation which are not applicable for those in a horizontal installation. These include liquid collecting in the pressure tappings and impulse lines, and the flow regime be highly unstable and complex (e.g. churn flow, slug flow) at low gas flow rates and low pressure due to the liquid film at the wall becoming unstable (the transition to intermittent flow is dependent on Lockhart-Martinelli and water to liquid ratio values too). Care must be taken to ensure that the pressure tappings and impulse lines are properly designed to reduce the likelihood of liquid accumulation. Employing pressure tappings with the horizontal section of the pressure tapping complying with ISO 5167-4 and then the pressure tapping angled 45° was found a suitable solution to reduce the likelihood of liquid accumulation. It is also necessary to ensure that the tappings' internal diameter is large enough to allow any liquid to drain back to the line, but still within ISO 5167-4. Care must be taken to avoid intermittent flow, and it is recommended to do not use vertical Venturi tubes with intermittent flow at this stage. It is recommended to develop diagnostic tools which make use of the differential pressure signal response to identify intermittent flow occurrence as well as liquid accumulation in the impulse lines.

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