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Technical Paper

Performance of a Vertically Installed Venturi Tube in Wet-Gas Conditions

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1 INTRODUCTION

Venturi tubes are one of the most common types of meters used for wet-gas flow measurement as they are a simple, robust and cost-effective meter. Many commercial wet-gas and multiphase meters incorporate a Venturi tube along with other measurement technology to determine the flow rate of the individual phases.

The presence of the liquid causes an increase in the measured differential pressure and results in the Venturi tube over-reading the actual amount of gas passing through the meter. This over-reading is usually 'corrected' using available correlations derived from experimental data to determine the actual gas mass flowrate. This over-reading trend is observed in all differential-pressure meters. The flowrate of the liquid, which can be a combination of water and hydrocarbons, is normally determined by an external means such as from test separator data, tracer experiments or sampling etc. Information on the liquid flowrate and density is necessary to use the correlations.

Most Venturi meters for wet-gas applications are installed in a horizontal orientation and there are well known correlations available that will correct for the meter over-reading. However, there is increasing interest in installing Venturi-type meters in a vertical installation similar to multiphase meter installations. The well known de Leeuw correlation and the newer NEL correlation, which is included in the ISO Technical Report on wet-gas flow measurement using differential pressure devices (ISO/TR 11583:2012), were developed for horizontal installation.

There is very little published information available on the over-reading and measurement errors from installing Venturi meters in a vertical orientation. This paper presents results from a 4-inch, β = 0.6, Venturi tube installed in a vertical orientation and tested in wet-gas conditions at NEL. The errors from using different horizontal-based correlations and a vertical correlation are compared.

The pressure loss ratio, which has been used as a diagnostic tool to determine the amount of liquid in wet-gas flows, has also been measured and compared with equations available in ISO/TR 11583:2012 for horizontal installation.

2 DEFINITIONS OF WET-GAS FLOW

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

The Lockhart-Martinelli parameter,
$$X = \frac{m_{\mathrm{liq}}}{m_{\mathrm{gas}}}\sqrt{\frac{\rho_{\mathrm{gas}}}{\rho_{\mathrm{liq}}}} \tag{1}$$

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

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

Gas densiometric Froude number,
$$Fr_{\mathrm{gas}} = \frac{v_{\mathrm{gas}}}{\sqrt{gD}}\sqrt{\frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liq}} - \rho_{1,\mathrm{gas}}}} \tag{2}$$

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

The superficial gas velocity is given by
$$v_{\mathrm{gas}} = \frac{m_{\mathrm{gas}}}{\rho_{1,\mathrm{gas}} A} \tag{3}$$

where A is the pipe area.

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

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

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

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

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

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

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

3 BRIEF HISTORY OF WET-GAS CORRELATIONS FOR HORIZONTAL INSTALLATIONS

3.1 Over-reading correlations where *X* is known

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

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

3.1.1 Murdock Correlation

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

3.1.2 Chisholm Correlation

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

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

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

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

where $n = 0.25$.

3.1.3 de Leeuw Correlation

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

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

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

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

However, it is known that the extrapolation of an empirical correlation derived from a set of data with a limited range of a particular parameter has risks and that this can increase the measurement errors. This risk can be accounted for by increasing the uncertainty of the measurements derived from the correlation. It is worth noting that increased errors are more likely if using correlations at pressures lower than that covered by the correlation, rather than at higher pressures. This is due to the fact that at lower pressure the density ratio (of the gas to the liquid) is lower, and hence the fluid combination is less homogeneous.

3.1.4 Other Research

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

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

3.1.5 H-S Correlation

Lide *et al.* published a wet-gas correlation based on homogeneous and separated flow theory (H-S Correlation) in 2008 after reviewing eight available correlations.[12] The H-S correlation was developed for low and high pressure flows for horizontally installed Venturis.

The over-reading was defined as:

$$\phi = \sqrt{x \frac{1 + C_{H-S} X + X^2}{1 + \sqrt{\rho_{gas} / \rho_{liq}} X}} \tag{12}$$

where, $x = \dfrac{m_{gas}}{m_{gas} + m_{liq}}$ (13)

and m_{gas} is the gas mass flow rate and m_{liq} is the liquid gas mass flowrate

$C_{H\text{-}S}$ is defined as

$$C_{H-S} = \left(\frac{x/(1-x)}{\rho_{gas}/\rho_{liq}} \right)^n + \left(\frac{\rho_{gas}/\rho_{liq}}{x/(1-x)} \right)^n \qquad (14)$$

where $n = A + BX^k$ (15)

$$A = a_1 \beta^{a_2} Fr_{gas}^{a_3} \left(\frac{\rho_{gas}}{\rho_{liq}} \right)^{a_4} \qquad (16)$$

$$B = a_5 \beta^{a_6} Fr_{gas}^{a_7} \left(\frac{\rho_{gas}}{\rho_{liq}} \right)^{a_8} \qquad (17)$$

Coefficients for a_1 to a_8 and k were defined in the paper but appear to be incorrect when compared with available NEL data despite using the use of some NEL data for determining the correlation.

3.1.6 NEL Correlation

In 2009 NEL published a correlation based on a modification of the Chisholm model and incorporated a wet-gas discharge coefficient term [13, 14]. This correlation found that the wet-gas over-reading was dependent on the Lockhart-Martinelli parameter, the gas-to-liquid density ratio, the gas Froude number, diameter-ratio (β) and a parameter to account for the liquid type (H).

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

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

$$C = 1\text{-}0.0463\mathrm{e}^{-0.05 Fr_{\mathrm{gas,th}}} \min\left(1, \sqrt{\frac{X}{0.016}} \right) \qquad (18)$$

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

$$Fr_{\mathrm{gas,th}} = \frac{Fr_{\mathrm{gas}}}{\beta^{2.5}} \qquad (19)$$

The value of n was determined to be:

$$n = \max(0.583 - 0.18\beta^2 - 0.578 e^{-0.8 Fr_{gas}/H}, 0.392 - 0.18\beta^2) \qquad (20)$$

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

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

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

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

3.2 Correlation for a Vertically Installed Venturi in Wet-Gas Conditions

In 2012, Xu et al. published a correlation for a vertically mounted Venturi tube for low pressure [15]. This was developed from Venturi data with a diameter ratio of 0.45 over a range of pressures from 2.6 to 8.6 bar. This correlation was based on de Leeuw's correlation and modified the value of n, as shown in the following equation:

$$n = b_1 \exp\left\{(-0.5)\left[\left(\frac{(\ln(Fr_{gas}/b_2))}{b_3}\right)^2 + \left(\frac{\ln\left(\frac{\rho_{gas}/\rho_{liq}}{b_4}\right)}{b_5}\right)^2\right]\right\} \tag{21}$$

where b1 = 0.47359213
b2 = 1.9897702
b3 = 1.8384189
b4 = 0.087328207
b5 = 7.4636959

3.3 Correlation Developed For Determining the Wetness

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

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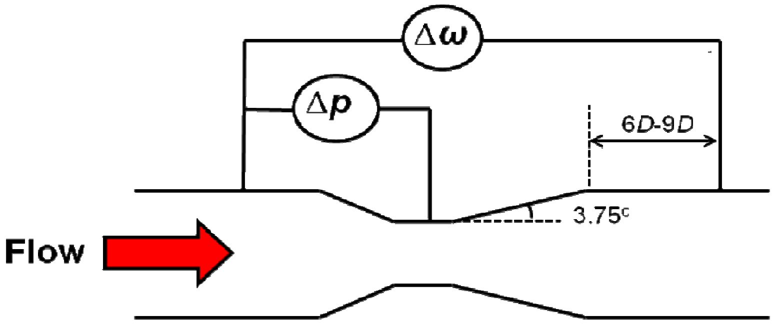


Figure 1: Schematic of Venturi tube illustrating total pressure loss ($\Delta\varpi$) and the differential pressure (Δp) to calculate the pressure loss ratio ($\Delta\varpi/\Delta p$).
(Note diagram is not drawn to correct scale or dimensions)

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

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

$$\max(5,20\beta-7)\leq\frac{L_{down}}{D}\leq 9 \qquad (22)$$

Then evaluate (this is an iterative procedure)

$$Y=\frac{\Delta\varpi}{\Delta p}-0.0896-0.48\beta^{9} \qquad (23)$$

and

$$Y_{\max}=0.61\exp\left(-11\left(\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}\right)-0.045Fr_{\text{gas}}/H\right) \qquad (24)$$

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

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

$$\frac{Y}{Y_{\max}}=1-\exp(-35X^{0.75}e^{-0.28Fr_{\text{gas}}/H}) \qquad (24)$$

Limits of use are:

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

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

and $\dfrac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}\leq 0.09$

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

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

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

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

3.4 ISO Technical Report for Wet-Gas Flow Measurement

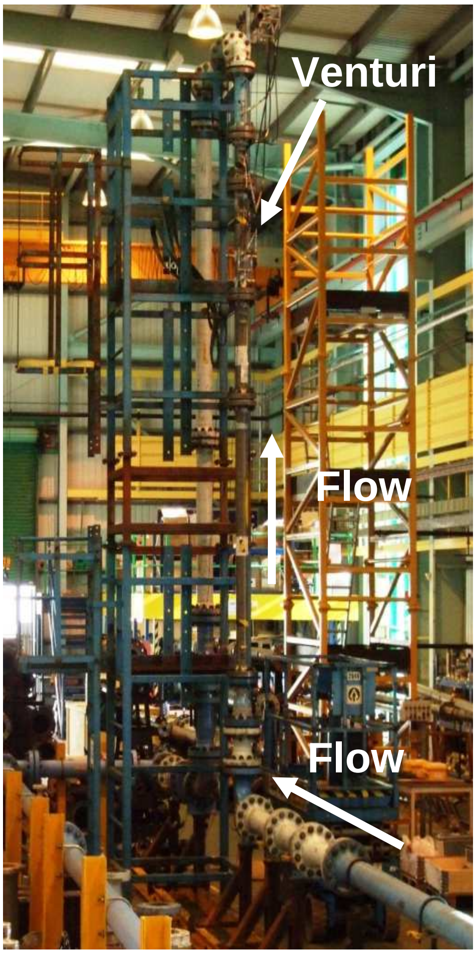
An ISO Technical Report on wet-gas flow measurement using differential pressure devices (ISO/TR 11583:2012) has been produced for horizontal meter installations and includes the NEL correlation [16]. The NEL-derived equations for the pressure-loss ratio to determine X are also included in the ISO Technical report.

4 VERTICAL VENTURI TUBE WET-GAS TESTS

A 4-inch, β=0.6, Venturi tube (which had previously been installed in a horizontal installation and tested over a range of wet-gas conditions) was installed in a vertical orientation and tested at NEL. Figure 2 shows photographs of the set-up. The same upstream and downstream pipework was installed as had been used for the horizontal tests. The Venturi was installed approximately 30*D* downstream of the concentric reducer (6-inch to 4-inch) after the 6-inch pipe bend. Little information is available on upstream installation effects on the performance of Venturi tubes in wet-gas conditions. The conditions tested are shown in Table 1 over a range of Lockhart-Martinelli parameters (X) up to 0.3. The liquid used was a kerosene substitute called Exxsol D80, and at the nominal facility operating temperature of 20 ^{o}C has a density of 804 kg/m^3. The gas used for testing was nitrogen.

Table 1 Test Conditions

Gas-Liquid Density Ratio	Gas Froude Number
0.023	1.5 2.0 2.5 3.0
0.046	1.5 2.5 3.5 4.5
0.083	1.5 2.5 3.5 4.5 5.5



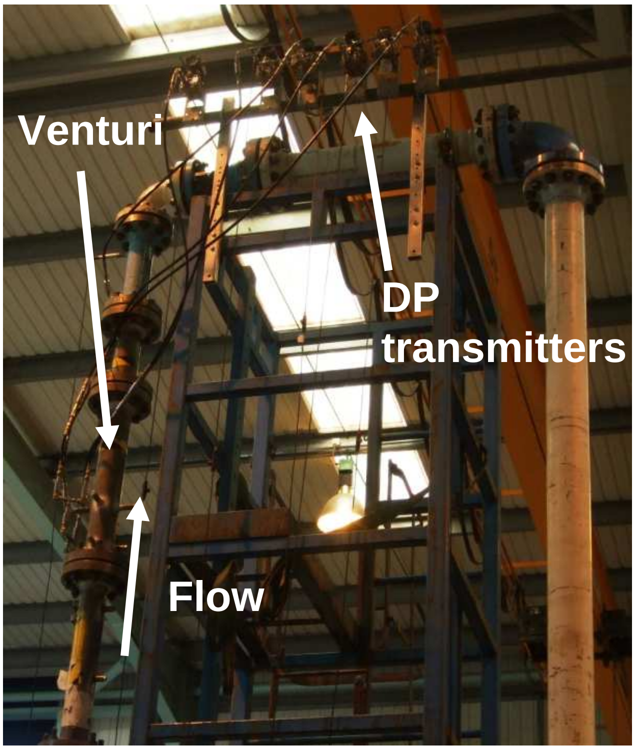


Figure 2: Photographs illustrating the Venturi and instrumentation setup

5 RESULTS AND ANALYSIS

5.1 Over-readings where *X* is known

The over-reading of the Venturi was determined and compared with that predicted using the de Leeuw correlation and the NEL correlation. Graphs are displayed in Appendix A and show the effect of different density ratio and gas Froude number. Compared with the horizontal data the over-readings show almost no dependence on the gas Froude number. Both the de Leeuw and NEL correlations incorporate the gas Froude number to predict the over-reading. At low values of X the NEL correlation seems to fit the data well but the difference from the correlation is significant at higher values of X.

The data was also compared with the homogeneous model to predict the over-reading by taking the parameter 'n' in Equation (9) as 0.5 and using the Chisholm over-reading equation (Equation (8)). Figure 3 shows all the data at different pressures (hence different density ratios) and gas Froude numbers with the predicted over-reading using the homogeneous model. This shows the insignificant effect of the gas Froude number at each density ratio and that the homogenous model using a single value of n can predict the over-reading reasonably well.

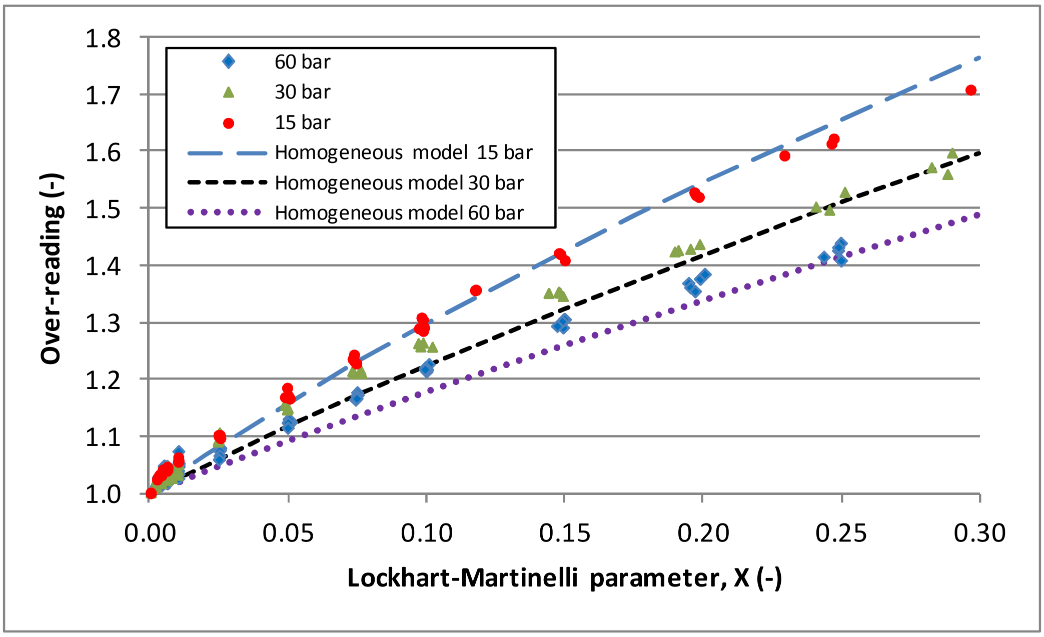


Figure 3: Predicted over-reading using the homogeneous model (*n*=0.5) compared with measured over-reading

Figure 4 compares the relative gas mass flow errors using the NEL and de Leeuw correlations and the homogeneous model. This shows that taking a single value for '*n*' of 0.5 fits the data relatively well compared with the NEL and de Leeuw correlations developed for horizontal orientation.

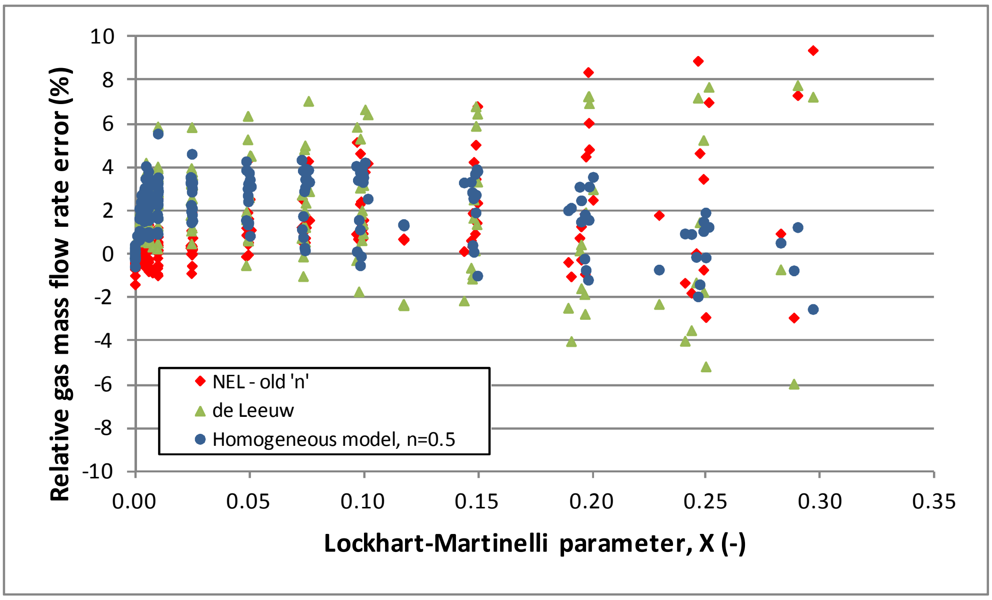


Figure 4: Relative gas mass flow rate errors when using the NEL and de Leeuw correlations and the homogeneous model to predict the over-reading and hence determine the gas mass flow rate in the vertical installation of the Venturi tube

Following from the homogenous model and use of a single value of *n*, all the vertical data was used to determine a single value of *n* for the Chisholm over-reading equation. A value of n = 0.465 was then used along with the "wet-gas discharge coefficient" (Equation (18)) to predict the over-reading for the vertical data. The results are shown in Figure 5 and show relatively good agreement. The equation to determine the "wet-gas discharge coefficient" includes a term related to the gas Froude number hence the over-reading predictions using n = 0.465 are still dependent on the gas Froude number. The over-reading predictions for the maximum and minimum gas Froude number for the test data are shown in Figure 5. At the time of publication no investigation has been made into the dependence of the "wet-gas discharge coefficient" on the gas Froude number for vertical orientation of the Venturi tube.

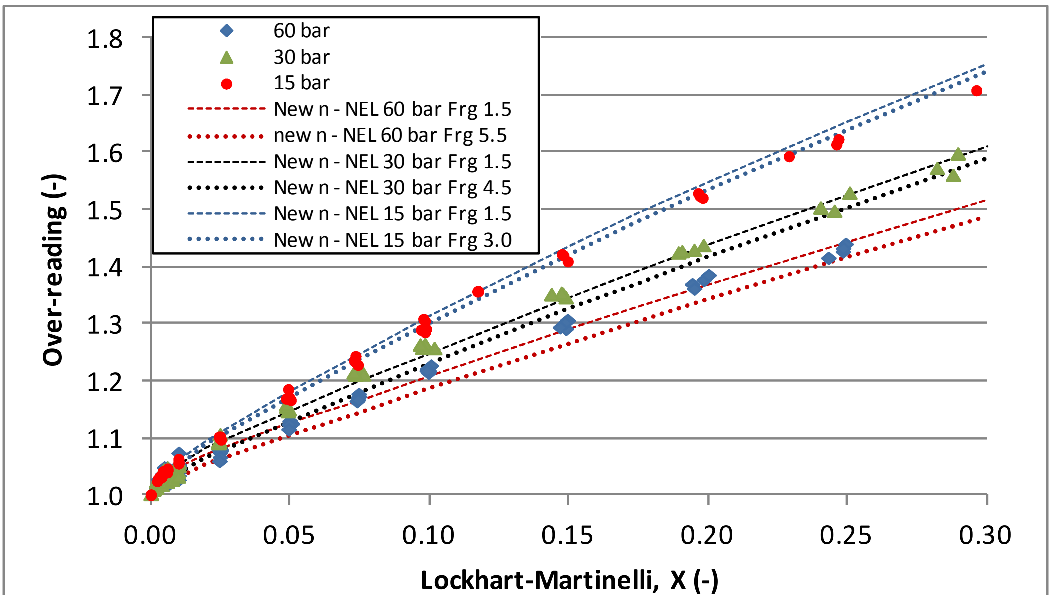


Figure 5: Predicted over-readings for different pressures and gas Froude numbers compared with the actual data for the vertical Venturi tube tests

Figure 6 shows the relative errors in the gas mass flow rate using the NEL-derived equations in ISO/TR 11583 and using a single value of n = 0.465 as a function of X. This shows a significant reduction in the errors by using n = 0.465. This shows that the gas mass flow rate can be predicted to within ±2.6% using n = 0.465. In comparison ISO/TR 11583 equations have an uncertainty of 3% for X ≤ 0.15 and 2.5% for X > 0.15 for predicting the gas mass flow rate assuming no error in X and insignificant uncertainty contributions from other measurement parameters.

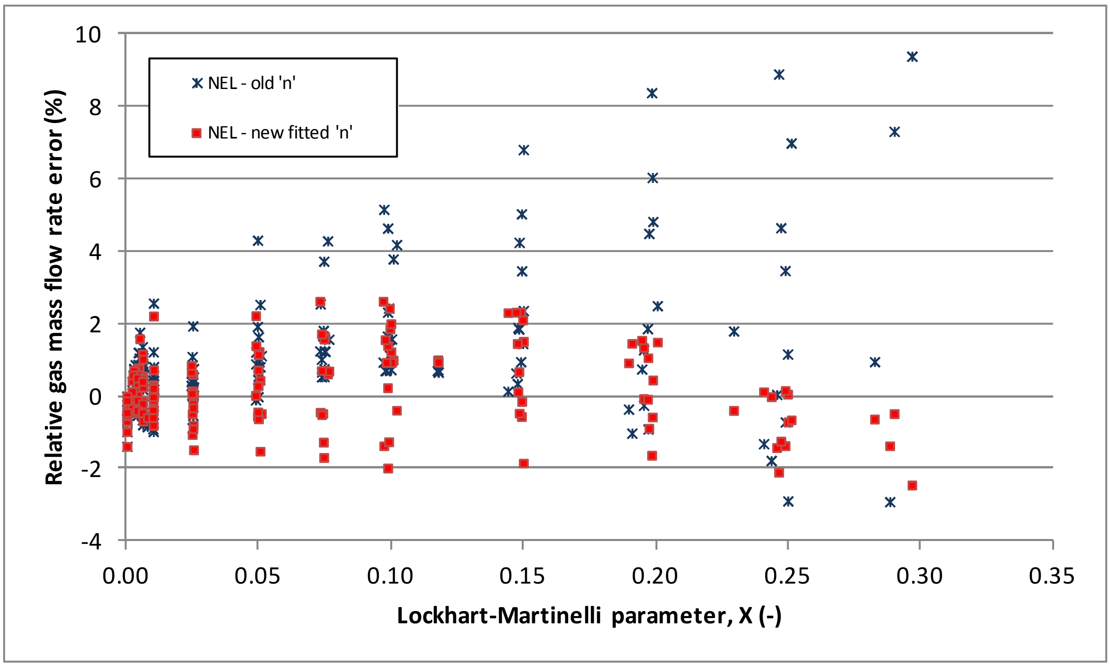


Figure 6: Relative gas mass flow rate errors when using the NEL correlation using *n* determined using Equation (20) (NEL – old 'n') and using *n* = 0.465 (NEL – new fitted 'n')

5.1.1 Dependence of *n* on Density Ratio (DR)

Further analysis of the data has shown that *n* appears to be dependent on the density ratio and specific values can be determined for the three different density ratios for the vertical test data. Table 2 shows the values of *n* for each density ratio.

Table 2 Specific values for *n* for each density ratio

Density Ratio	*n*
0.023	0.456
0.046	0.472
0.083	0.490

The use of specific values of *n* reduces the errors in the gas mass flowrate slightly as shown in Figure 7.

Based on Table 2 and homogenous conditions with *n* = 0.5 and DR=1, then the following equation can be used to determine *n:*

$$n = 0.5 - 0.00283(DR^{-0.75} - 1) \tag{26}$$

It should be noted that density ratio is already included in Equation (9) as an input to the over-reading correlation (Equation (8)).

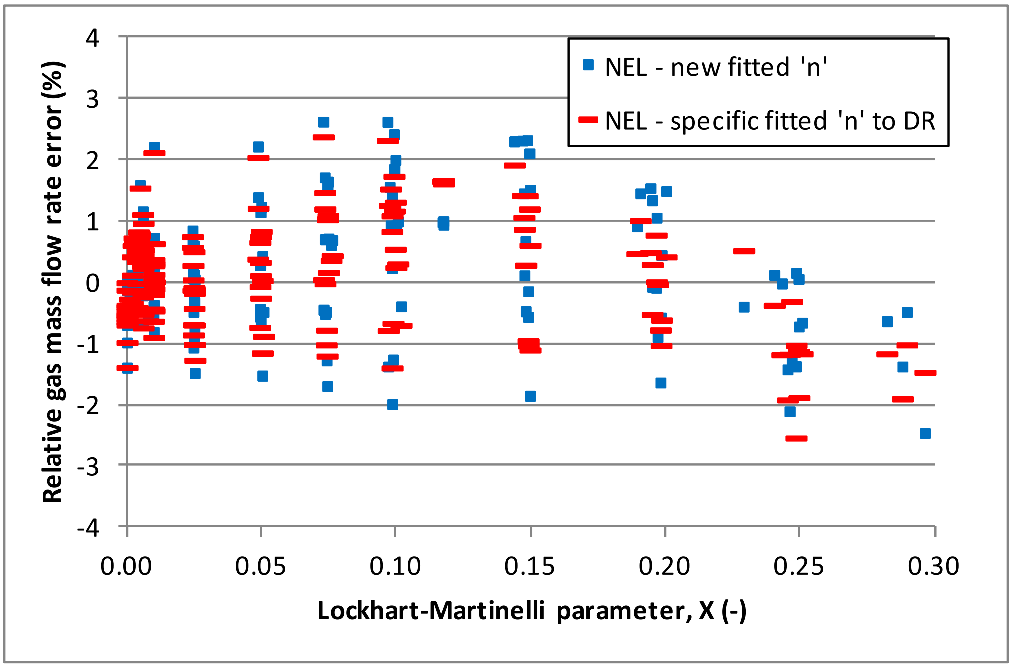


Figure 7: Relative gas mass flow rate errors when using *n* = 0.465 (NEL – new fitted 'n') and using *n* from Table 2 (NEL – specific fitted 'n' to DR)

Figure 8 shows the gas mass flow rate errors comparing using Equation (26) to determine *n* and using specific values fitted for each data set of similar density ratio (Table 2). This shows that both sets of error data lie over each other. The errors in the gas mass flow rate were less than 2.3% using Equation (26).

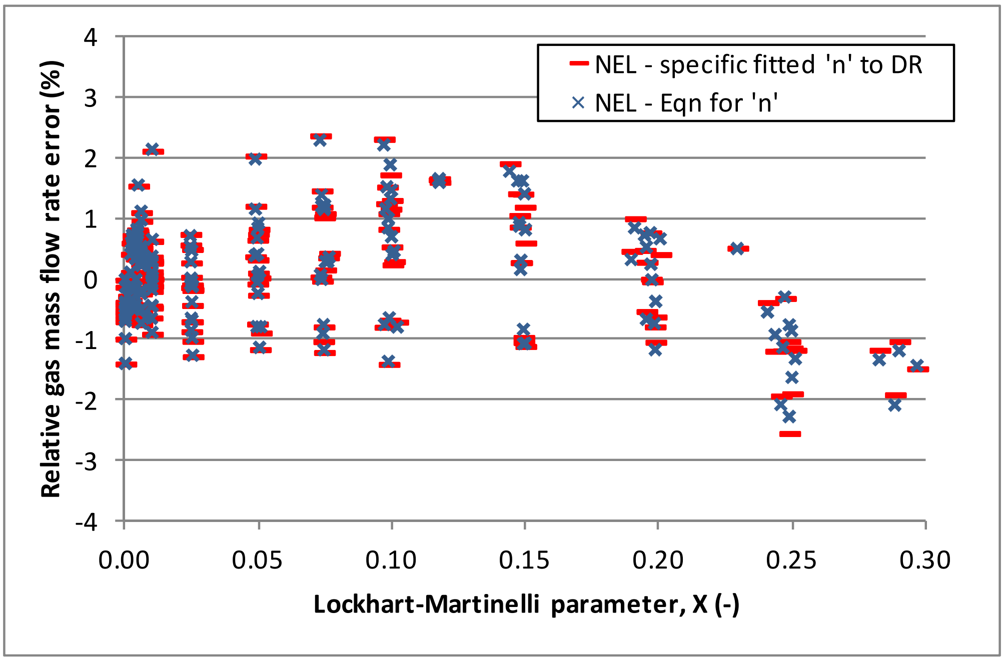


Figure 8: Relative gas mass flow errors when using *n* from Table 2 (NEL – specific fitted 'n' to DR) and using Equation (26) (NEL – Eqn for 'n')

5.1.2 Validation of Equation for *n*

CEESI have published some data on over-readings from the use of vertically installed 4-inch, β = 0.6 Venturi tube [17]. These tests were performed using either water or a hydrocarbon liquid. The relative errors in the actual gas mass flow rates from the CEESI data and the predicted gas mass flow rate using Equation (26) for n are shown in Figure 9. The errors are within ±3%. It should be noted that some of the CEESI data were taken outside the limits stated in ISO/TR 11583 as the density ratio is less than 0.02.

It has been established that the over-reading for horizontally installed Venturi tubes is dependent on the liquid fluid properties and is accounted for by the parameter '*H*' in ISO/TR 11583 in the equation for determining the value of '*n*'. The effect of liquid properties on the over-reading in vertical flow has not been considered in this paper due to the lack of data. However the CEESI water data agrees well with the equation discussed which does not include the parameter *H*.

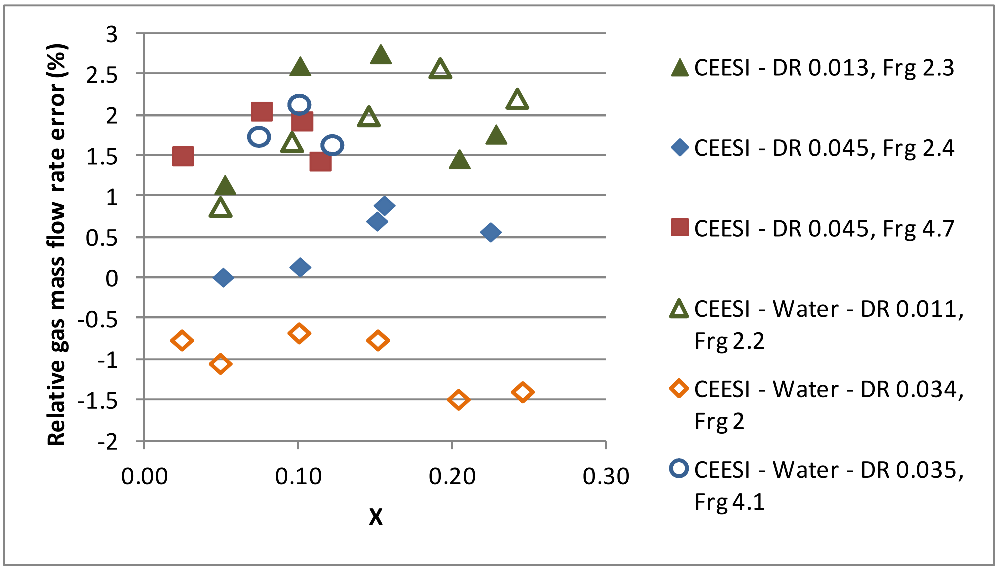


Figure 9: Relative gas mass flow rate errors using Equation (26) to determine *n* and then calculate the predicted gas mass flow rate compared with the actual values published in reference [17]

5.1.3 Comparison With Other Published Correlations

5.1.3.1 Low Pressure Vertical Venturi Correlation

The NEL vertical data was used to assess the vertical Venturi correlation developed by Xu *et al*., which is described in section 3.2. Xu *et al.* produced an equation for n based on low pressure data. Figure 10 shows the relative gas mass flow rate errors using the equation for n using the original coefficients (b_1 to b_5) and new coefficients fitted to the NEL vertical data. The gas mass flow rate errors are up to 7% using the original coefficients and up to ~4% using the new fitted coefficients (Table 3). It should be noted that the correlation was based on a Venturi with a diameter ratio of 0.45, whereas the NEL data was from a Venturi with a diameter ratio of 0.6. There is no parameter in the correlation to account for the diameter ratio effect on the over-reading; hence this will contribute to the magnitude and trend of the errors. The Xu correlation had a dependence on the gas Froude number which was found to be unrelated to the over-reading values in the NEL data. Figure 11 compares the NEL vertical correlation with the Xu correlation with new coefficients.

Table 3
New coefficients fitted for the Xu correlation based on the NEL vertical Venturi data

b_1	b_2	b_3	b_4	b_5
1.319063	2005.611	16.9713	6013637.81	14.61777

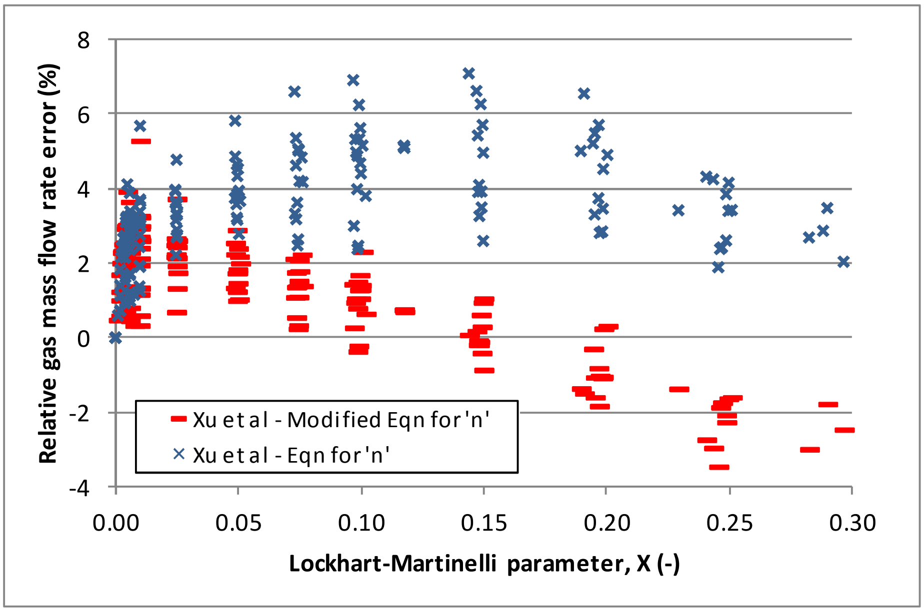


Figure 10: Relative gas mass flow rate errors using the Xu *et al.* correlation using Equation (21) to determine *n* with the original coefficients (Eqn for 'n') and new fitted coefficients from Table 3 (Modified Eqn for 'n')

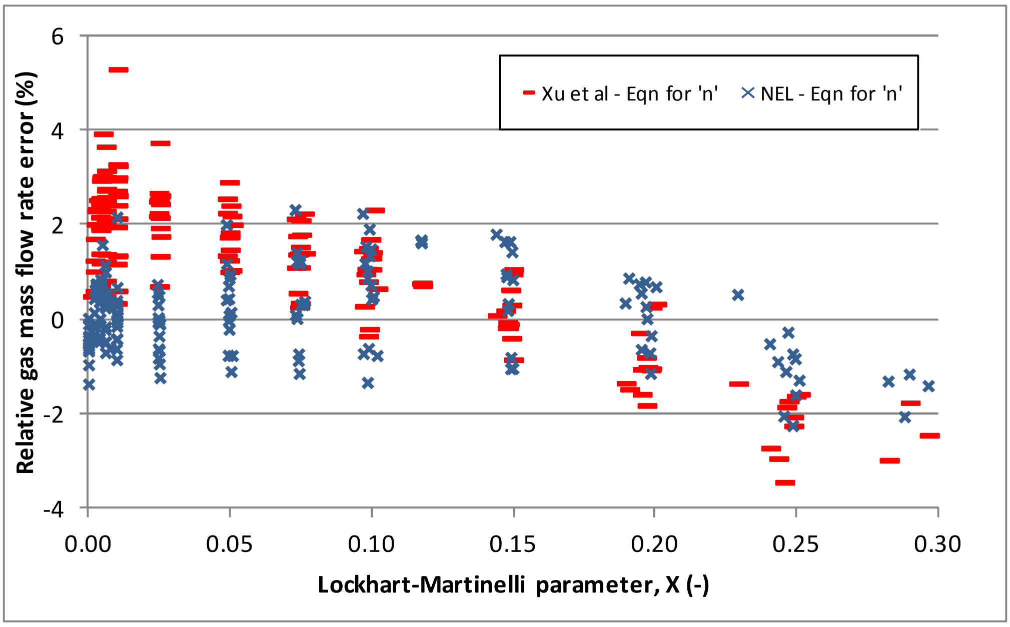


Figure 11: Relative gas mass flow rate errors using the Xu et al. correlation using Equation (21) to determine *n* with the new fitted coefficients from Table 3 (Modified Eqn for 'n') and the NEL correlation using Equation (26) to determine *n*.

5.1.3.2 Homogeneous and Separated Flow Correlation (H-S Correlation)

The H-S correlation is described in section 3.1.5. As the original coefficients for *n* in the publication appear incorrect, new coefficients were derived for the Venturi meter using horizontal data. Figure 12 compares the NEL correlation and the H-S correlation (with new horizontal coefficients) for the Venturi in a horizontal position. The gas mass flow rate errors increase using the H-S correlation as the Lockhart Martinelli parameter increases. Figure 13 compares the NEL correlation with new *n* and the H-S correlation with new coefficients for *n* based on the vertical data. This shows that at very low Lockhart Martinelli parameters the NEL correlation has lower errors but at higher Lockhart Martinelli values the H-S model gives lower errors in the gas mass flow rate and a more even distribution of the errors about the x-axis. This would indicate a better fit of the data to the correlation. It was noted that removing the gas Froude number parameter from the equations to determine *n* in the H-S correlation had an insignificant effect on the gas mass flow rate errors.

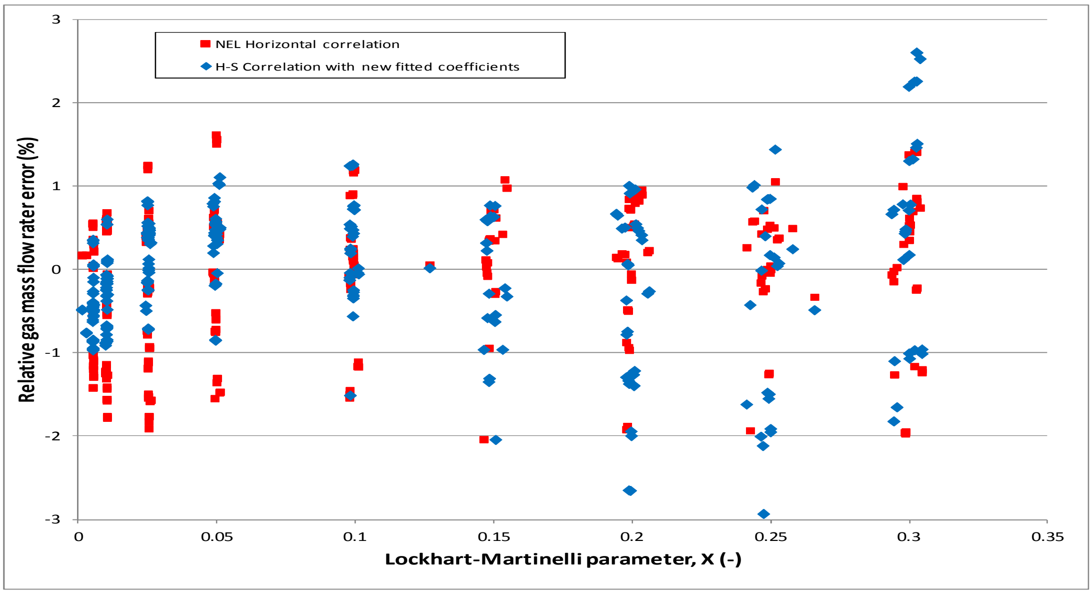


Figure 12: Relative gas mass flow rate errors using the H-S correlation using new fitted coefficients to determine *n* from horizontal Venturi data and the NEL correlation.

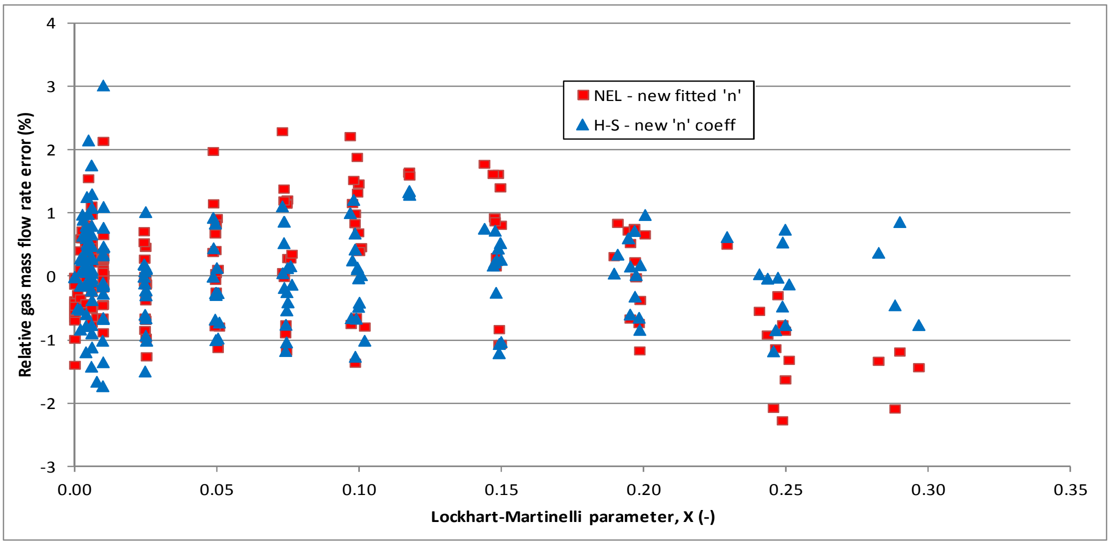


Figure 13: Relative gas mass flow rate errors using the H-S correlation using new fittedcoefficients to determine *n* from vertical Venturi data and the NEL correlation using Equation (26) to determine *n*.

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

Appendix B shows results comparing the measured PLR values for the Venturi tube when installed in a horizontal and in a vertical orientation. At 60 bar the gradient of the slope on initially increasing *X* is slightly less steep for the vertical orientation than for the horizontal before levelling off at higher *X*. The less steep gradient is more noticeable for the 30 bar and 15 bar tests; so at lower values of *X* the increase in the PLR is less sensitive to changes in *X*.

For the 15 bar and 30 bar pressure tests it is noticeable that the PLR curves for different gas Froude numbers for the horizontal orientations tend to merge at higher X, but in the vertical orientation there are significant differences in the PLR curves for different gas Froude numbers even at higher X. For all pressures the difference between PLR values for vertical and horizontal orientation at higher X is more significant for lower gas Froude numbers; the maximum value of Y tends to be larger in a vertical orientation than horizontal. In the NEL-derived equations for predicting X by using the PLR in a horizontally orientated Venturi tube, Y_{max} is the value of Y at maximum gas wetness ($X \approx 0.3$); Y is the difference between the wet-gas PLR and the predicted dry-gas PLR.

For horizontal orientation the PLR tends to level off by approximately $X = 0.06$ and hence is only useful for determining the wetness of the gas (or X) at very low values of X. However, in vertical orientation the PLR ratio tends to level off at a higher value of X; hence there is a wider range of X over which X can be determined.

Using

- the NEL-derived equations in ISO/TR 11583 and the PLR measurements to determine X
- the value of $n = 0.465$
- NEL-derived equation for the "wet-gas discharge coefficient" from ISO/TR 11583,

then the gas mass flowrate can be determined in an iterative process. The relative errors from determining the gas mass flowrate using this method compared with the actual gas mass flow rate are shown in Figures 14 and 15 as a function of Y/Y_{max} and X, respectively.

Within ISO/TR 11583 the limit for using the equations to determine X is $Y/Y_{max} < 0.65$. However, for vertical orientation the equations can be used for $Y/Y_{max} < 1$, where Y_{max} is the value obtained for horizontal flow and given in Equation (24); hence the use of the equations is extended. Table 4 shows the uncertainty in the gas mass flow rate using the equations ($n = 0.465$), assuming insignificant uncertainty contributions from other measurement parameters such as the fluid densities, differential pressure measurements and diameter ratio. For $Y/Y_{max} < 0.4$ then the results meet ISO/TR 11583 uncertainty limits in predicting the value of the gas mass flow rate to within ±4%. For $Y/Y_{max} < 1$ the equations can be used to predict the value of the gas mass flow rate to within approximately ±8%. In terms of X, provided $Y/Y_{max} < 1$, if $X < 0.025$ then the equations can be used to predict the gas mass flow rate to within ±4% and if $X < 0.1$ to predict gas mass flow rate to within approximately ±8%.

Table 4
Uncertainty in the gas mass flow rate from using the ISO/TR 11583 equation to determine X and the corrected gas mass flow rate using $n = 0.465$

Range of Y/Y_{max}	Relative uncertainty in gas mass flow rate (%)
< 0.4	4%
< 0.6	6%
<1.0	8%

For comparison ISO/TR 11583 states that the equations for Y/Y_{max} < 0.6 will predict the gas mass flow rate to within 4% and for 0.06 ≤ Y/Y_{max} < 0.65 will predict the gas mass flow rate to within 6% for horizontal orientation of the Venturi tube.

With the availability of more data the equations using the PLR measurements to determine X and hence the corrected gas mass flow rate could be significantly improved, and potentially the uncertainty limits reduced. No modification of the PLR equations in ISO/TR 11583 was attempted.

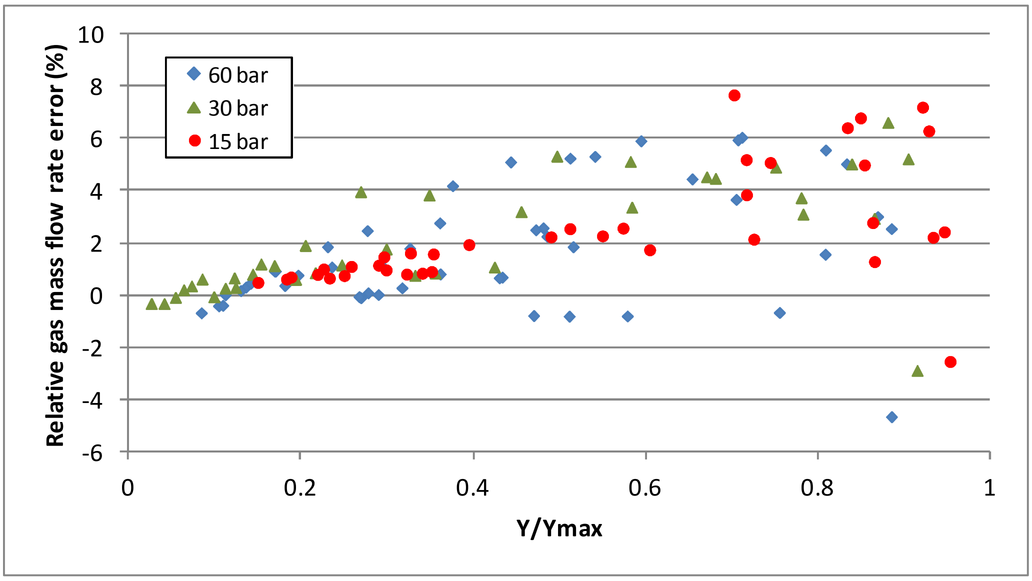


Figure 14: Relative gas mass flow rate error as a function of Y/Y_{max} (predicted gas mass flow rate determined using PLR equations from ISO/TR 11583 and *n* = 0.465)

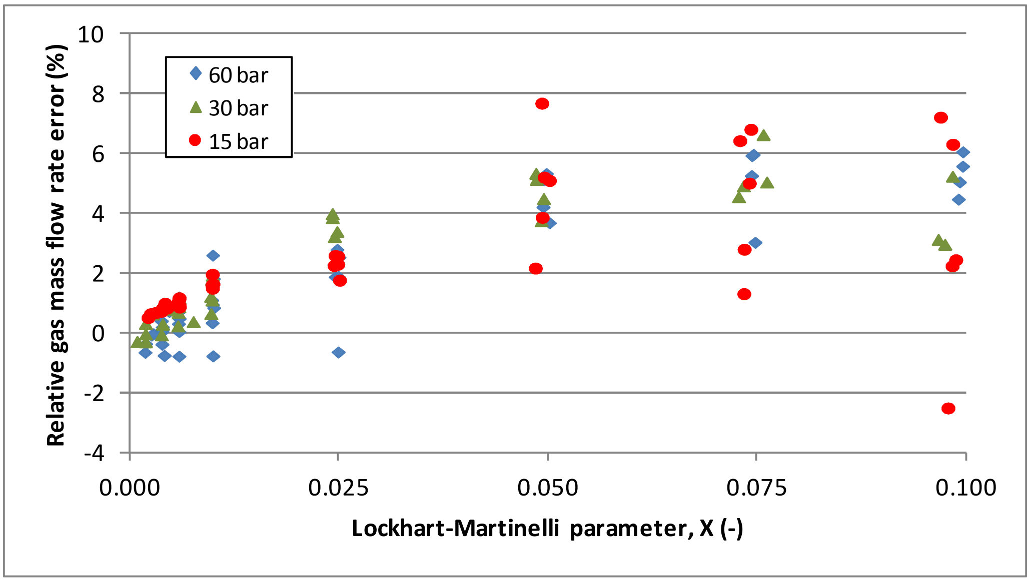


Figure 15: Relative gas mass flow rate error as a function of *X* (provided Y/Y_{max} < 1) (predicted gas mass flow rate determined using PLR equations from ISO/TR 11583 and *n* = 0.465)

It should be noted that using Equation (26) to determine n and then using the pressure loss ratio equations to determine X has an insignificant effect on the gas mass flow rate errors shown in Figures 14 and 15.

6 CONCLUSIONS

It has been shown from a very limited data set that the current wet-gas over-reading correlations in ISO/TR 11583 derived for the horizontal orientation of Venturi meters are not suitable for the installation of Venturi tubes in a vertical orientation. The current correlations have a dependence on the gas Froude number which appears to be irrelevant for vertical installations. A single value for parameter n (which accounts for gas-to-liquid density ratio effect on the over-reading) in the over-reading equations can be used quite accurately to predict the over-reading. More research is required to determine if there is an effect of the Venturi diameter ratio (β) and liquid properties on the over-reading.

A single value for n in the over-reading equations can be used to determine the gas mass flow rate within ±2.6% for $X \leq 0.3$ for the data set presented in this paper. In comparison ISO/TR 11583 equations have an uncertainty of ±3% for $X \leq 0.15$ and ±2.5% for $X > 0.15$ for predicting the gas mass flow rate in horizontal flow assuming no error in X and insignificant uncertainty contributions from other measurement parameters.

From the limited vertical data set an equation for n was determined based on the density ratio (gas density / liquid density). Using this equation produced a similar magnitude of errors as using a single value of n. The gas mass flow rate errors were less than 2.3%. The equation for n was used to determine the gas mass flow rate errors for a different published data set.

The pressure loss ratio equations in ISO/TR 11583 can be used to determine X in a vertically installed Venturi over a greater range of X than in a horizontal installation. ISO/TR 11583 states that the equations for $Y/Y_{max} < 0.6$ will predict the gas mass flow rate to within 4% and for $0.6 \leq Y/Y_{max} < 0.65$ will predict the gas mass flow rate to within 6% for horizontal orientation of the Venturi tube. In comparison, for the vertical orientation data presented in this paper, the same equations can be used to predict the gas mass flowrate to ±4% for $Y/Y_{max} < 0.4$ and to within approximately ±8% for $Y/Y_{max} < 1$, where Y_{max} is the value that is calculated for horizontal orientation. In terms of X, provided $Y/Y_{max} < 1$, if $X < 0.025$ then the equations can be used to predict the gas mass flow rate to within ±4% and if $X < 0.1$ to predict gas mass flow rate to within approximately ±8%.

Significantly more data and research are required to modify the existing equations in ISO/TR 11583 to enable new correlations to be established for using Venturi meters in a vertical installation in wet-gas conditions. Vertical installation may simplify the over-reading correlations due to the apparent reduced dependence on the gas Froude number, and the pressure loss ratio could be used to determine X over a greater range of X (increased wetness).

7 ACKNOWLEDGMENTS

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APPENDIX A

OVER-READING VALUES PREDICTED BY THE DE LEEUW AND NEL CORRELATIONS COMPARED WITH MEASURED VALUES

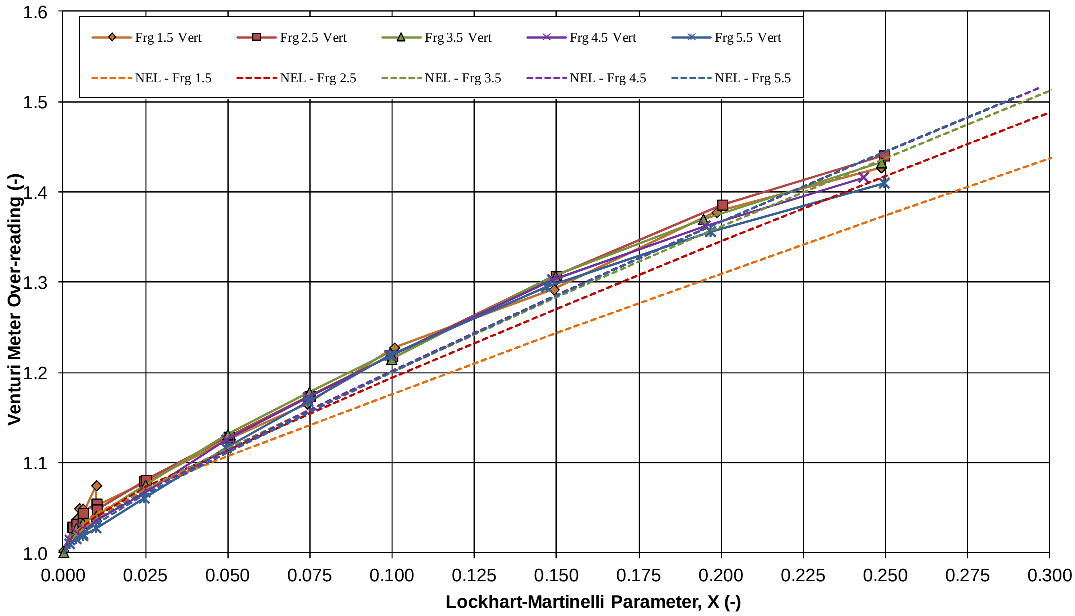

Figure A1: Measured over-reading compared with that predicted by the NEL correlation at 57 bar(g), density ratio 0.083.

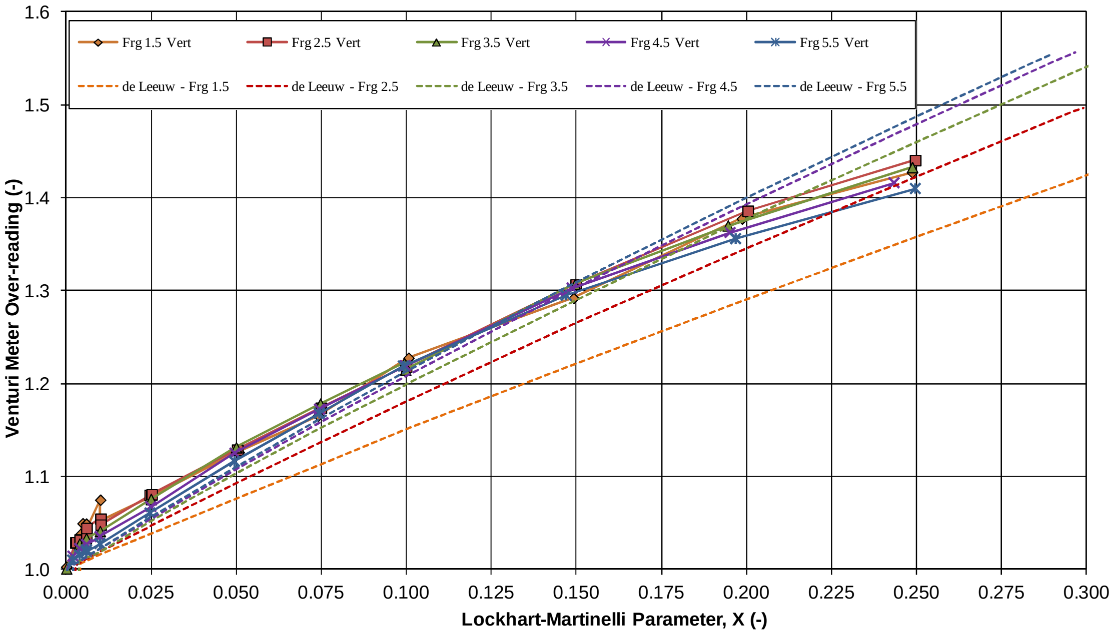

Figure A2: Measured over-reading compared with that predicted by the de Leeuw correlation at 57 bar(g), density ratio 0.083.

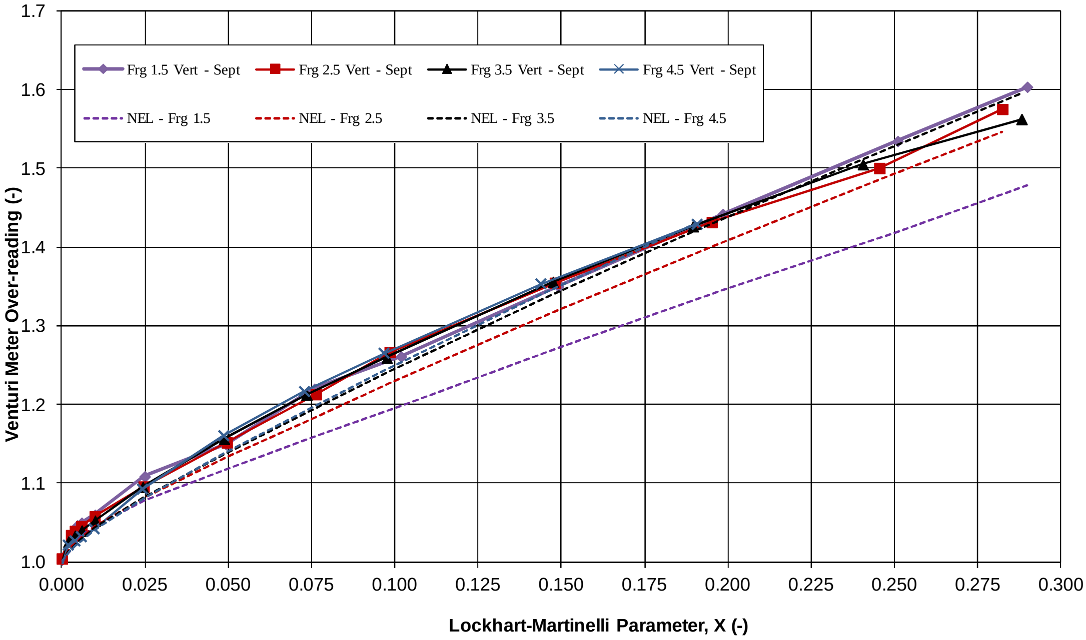

Figure A3: Measured over-reading compared with that predicted by the NEL correlation at 30 bar(g), density ratio 0.046.

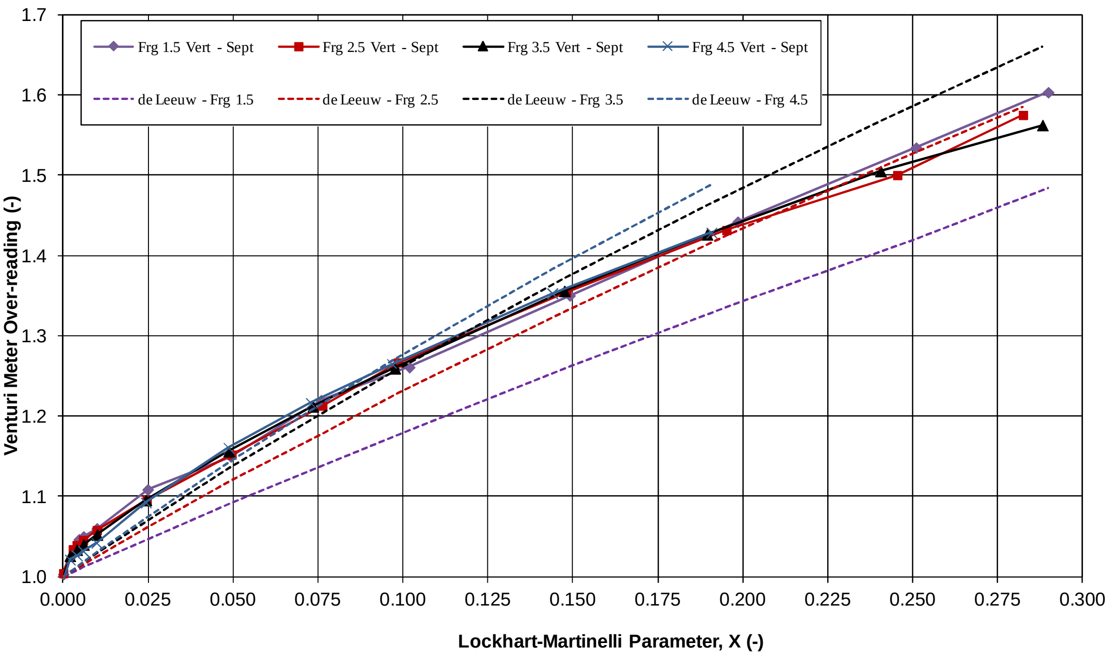

Figure A4: Measured over-reading compared with that predicted by the de Leeuw correlation at 30 bar(g), density ratio 0.046.

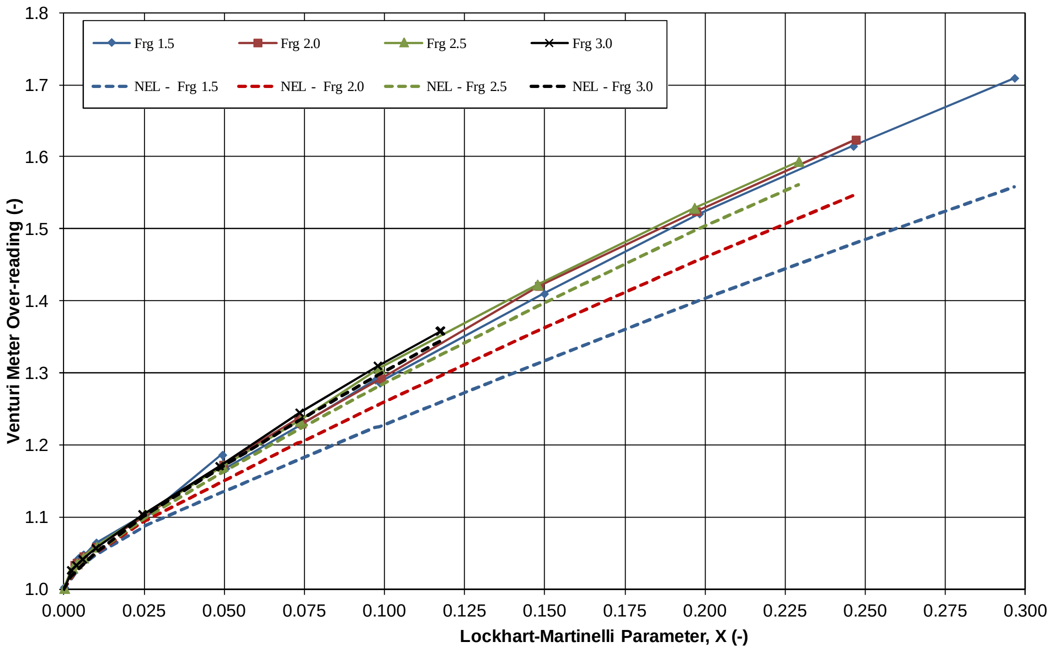

Figure A5: Measured over-reading compared with that predicted by the NEL correlation at 15 bar(g), density ratio 0.023.

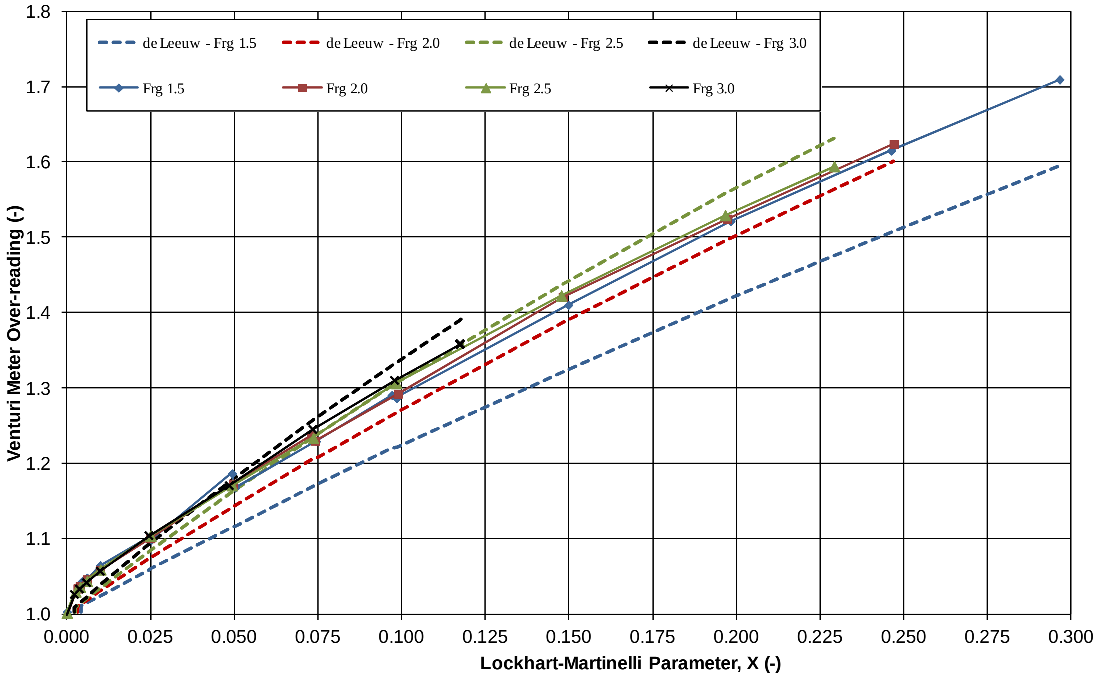

Figure A6: Measured over-reading compared with that predicted by the de Leeuw correlation at 15 bar(g), density ratio 0.023.

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APPENDIX B

PRESSURE LOSS RATIOS FOR THE 4-INCH, β = 0.6, VENTURI TUBE INSTALLED IN A HORIZONTAL AND VERTICAL ORIENTATION

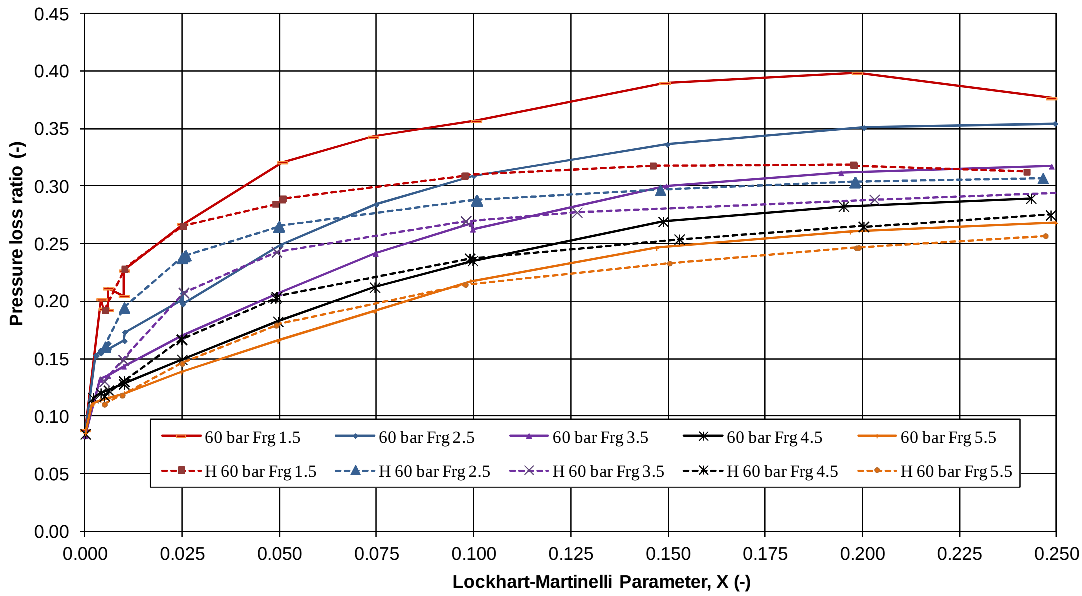

Figure B1: Pressure loss ratio measured in a vertical and horizontal orientation at approximately 60 bar(g). 'H' in the legend identifies the horizontal data at different gas Froude numbers.

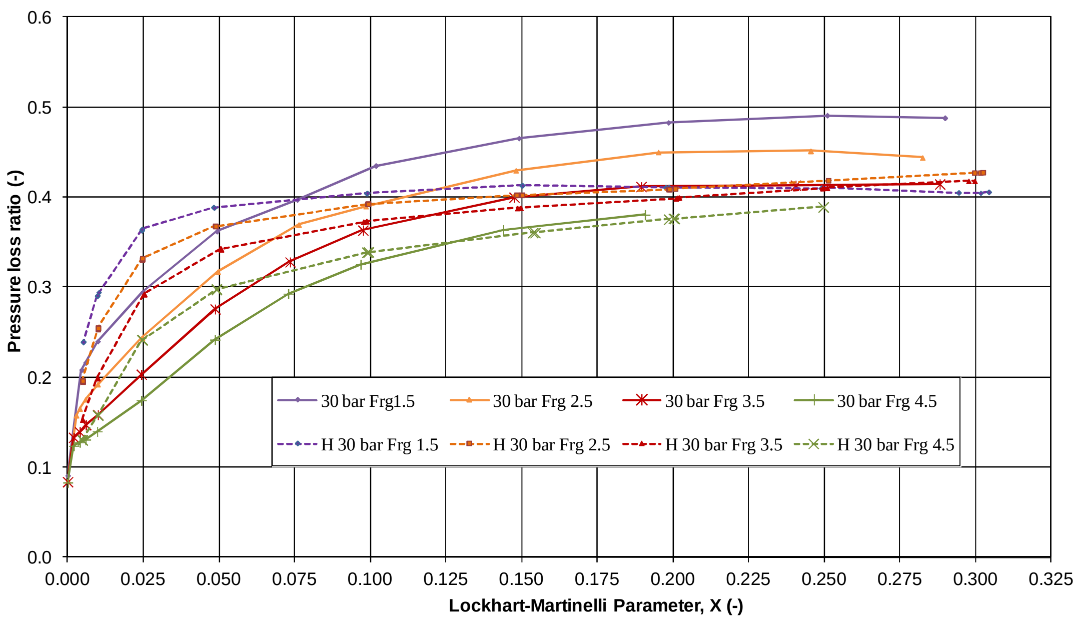

Figure B2: Pressure loss ratio measured in a vertical and horizontal orientation at approximately 30 bar(g). 'H' in the legend identifies the horizontal data at different gas Froude numbers.

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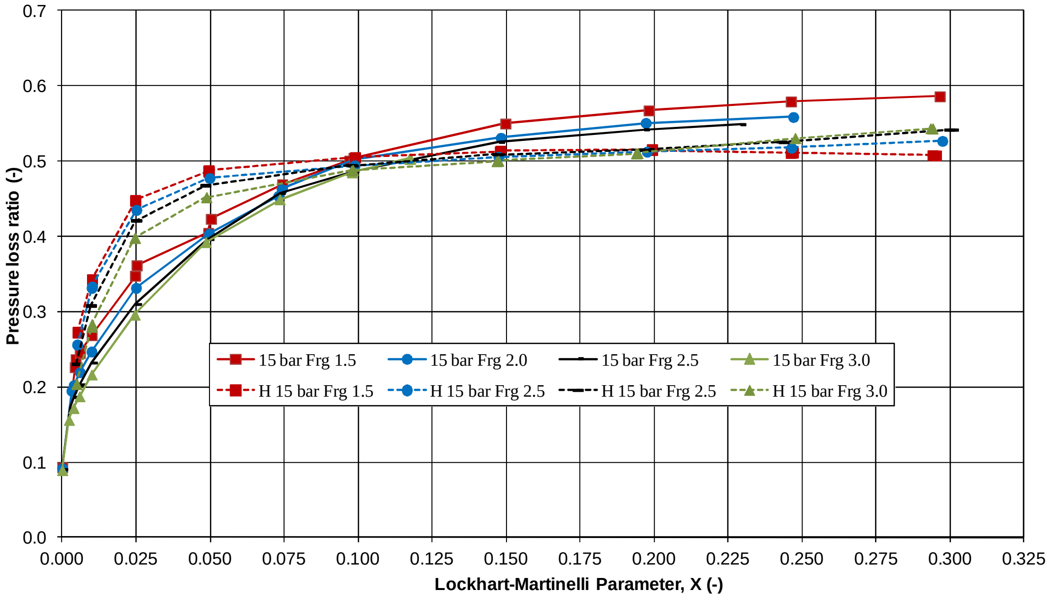

Figure B3: Pressure loss ratio measured in a vertical and horizontal orientation at approximately 15 bar(g). 'H' in the legend identifies the horizontal data at different gas Froude numbers.