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AN IMPROVED MODEL FOR VENTURI-TUBE OVER-READING IN WET GAS

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1 Introduction

Venturi tubes are commonly selected for the measurement of wet-gas flows. Reasons for this include their physical robustness to withstand erosion and the impact of liquid slugs at high velocities, familiarity with their use and the availability of standards for their use in dry-gas conditions.

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 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.

The correlations currently available for correcting the over-reading of Venturi tubes have been derived from a limited set of data and may only be suitable to cover restricted ranges of Venturi tube parameters, for example, a specific diameter ratio. Use of correlations outside the conditions used to define them can result in large errors in the calculation of the gas mass flowrate.

This paper describes a new Chisholm/de Leeuw-type model for the over-reading, which covers a broader range of Venturi parameters such as diameter ratio and pipe diameter. The model also accounts for the behaviour of the over-reading with different liquids.

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

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, $\rho_{1,\text{gas}}$.

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

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

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

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

where A is the pipe area.

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

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

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

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

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

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

$$\phi \approx \sqrt{\frac{\Delta p_{wet\text{-}gas}}{\Delta p_{gas}}} \qquad (7)$$

3 Brief History of Wet-Gas Correlations

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.

Murdock's correlation gave the over-reading as $\phi = 1 + 1.26X$ (8)

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 $\phi = \sqrt{1 + C_{\mathrm{Ch}} X + X^2}$ (9)

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

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

where n = 0.25.

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 (9) and (10) but showed that n was a function of the gas Froude number:

$$n = 0.41 \quad \text{for} \quad 0.5 \le Fr_{\mathrm{gas}} < 1.5 \tag{11}$$

$$n = 0.606\left(1 - e^{-0.746 Fr_{\mathrm{gas}}}\right) \quad \text{for} \quad Fr_{\mathrm{gas}} \ge 1.5 \tag{12}$$

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.

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].

There are no openly available correlations based on data that cover the range of fluid conditions and parameters that are encountered by industry.

4 Derivation of New Correlation

Most of the available correlations are based on Chisholm's model, which produces an almost straight-line fit though the wet-gas data. This type of model generally provides an acceptable fit for orifice-plate data. However, with Venturi data it is noticeable that as the Lockhart-Martinelli parameter, X, tends towards zero the over-reading does not tend to zero in a linear fashion. The gradient changes as the liquid fraction and hence the Lockhart-Martinelli parameter, X, tend to zero. This is in contrast to data from orifice plates (although sometimes with orifice plates the straight line fails to go exactly through the origin). Figure 1 clearly illustrates the problem for a 0.6 diameter-ratio Venturi tube using different fluid combinations with either nitrogen or argon as the gas phase and water or Exxsol D80 (a kerosene-substitute fluid) as the liquid phase.

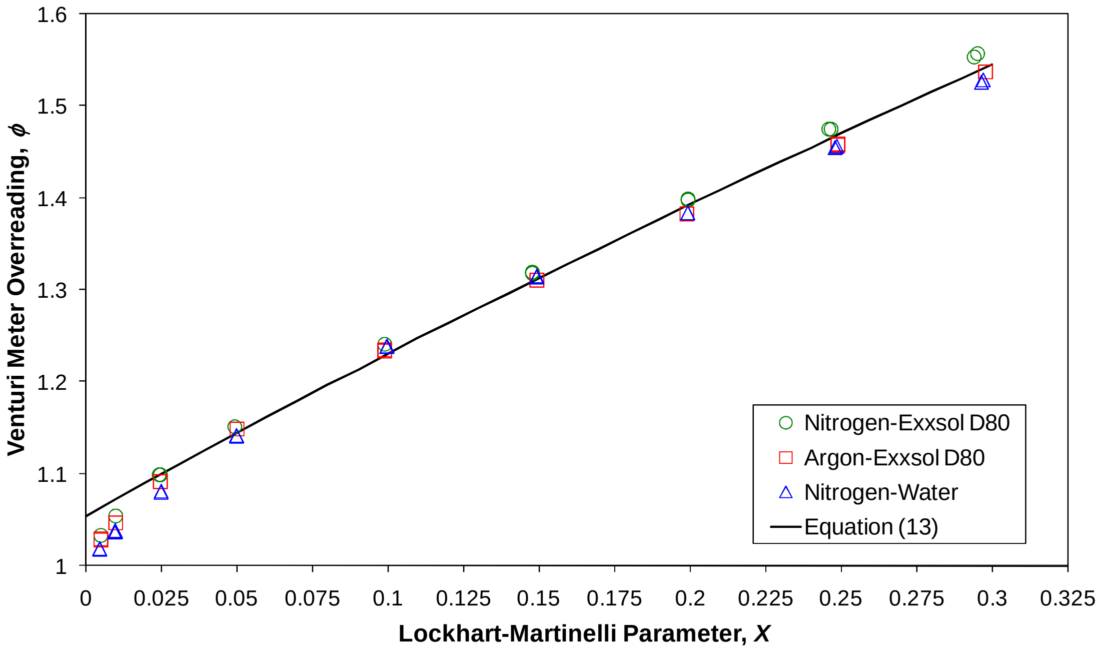

Figure 1 Over-reading data for a 4-inch Venturi tube with β = 0.6, Fr_{gas} = 1.5, $\rho_{1,gas}/\rho_{liquid}$ = 0.024

One solution to account for this effect would be to add an additional term to the model to provide a better fit to the data (e.g. as in [7]), but this has no obvious physical significance.

For the data presented in Figure 1 (excluding data with $X < 0.02$) if a multiplicative term is acceptable the best fit of a Chisholm-type model is:

$$\phi = 1.0532\sqrt{1 + C_{Ch} X + X^2}\ \text{, where } C_{Ch} = \left(\frac{\rho_{liq}}{\rho_{1,gas}}\right)^{0.3162} + \left(\frac{\rho_{1,gas}}{\rho_{liq}}\right)^{0.3162} \tag{13}$$

The over-reading is 'corrected' and provides a better fit to the data (with $X > 0.02$) by modifying the power index in the Chisholm constant (C_{ch}) to a value between those used by Chisholm and de Leeuw, and by adding a multiplicative constant to the over-reading equation.

It is proposed here that the reason for the non-linearity is that in wet-gas conditions the discharge coefficient, C, is not equal to its dry-gas value, as is often assumed. As soon as even a very small quantity of liquid is added to the gas the discharge coefficient reduces. It is interesting to note that, whereas in dry gas a Venturi tube can often emit an audible tone (it is sometimes referred to as a singing Venturi), in wet-gas conditions Venturi tubes never 'sing'; even a tiny quantity of liquid seems to change the flow in such a way as to prevent the emission of an audible tone.

For the Venturi tube whose data are in Figure 1 the dry-gas discharge coefficient is a function of Reynolds number with a mean value of 1.009 over all its calibrations. However, the effective discharge coefficient in wet gas when calculated for $X > 0.02$ is more than 5% lower than the value in dry gas. The effective discharge coefficient was calculated by determining best-fit values of C and n in Equations (5), (9) and (10) for the data with $X > 0.02$.

Following this observation the discharge-coefficient values in wet-gas conditions were calculated for more data sets to establish if the discharge coefficients in dry and wet gas were generally different. The discharge coefficients were calculated from Equations (5), (9) and (10) (allowing n to vary) for the data sets in Table 1.

Table 1 Wet Gas Data

Beta ratio	Pipe size	Gas phase	Liquid phase	Reference
0.4	4-inch	nitrogen	Exxsol D80	5
0.6	4-inch	nitrogen	water	6, 7
0.6	4-inch	nitrogen	Exxsol D80	6, 7
0.6	4-inch	argon	Exxsol D80	6, 7
0.75	4-inch	nitrogen	water	6, 7
0.75	4-inch	nitrogen	Exxsol D80	6, 7
0.75	4-inch	argon	Exxsol D80	6, 7
0.55	6-inch	nitrogen	Exxsol D80	11

The discharge coefficient in dry-gas conditions varies between the different Venturi tubes. So it is not surprising that there is a significant variation in the value of the discharge coefficient in wet-gas conditions. This variation makes it harder to see what parameters affect the value. Flow calibrations usually relate the discharge coefficient to the Reynolds number; however, from analysis of the data it seemed more reasonable to use the throat Reynolds number or throat Froude number. Of these the throat Froude number seems more reasonable to use on physical grounds.

The throat Froude number is calculated as:

$$Fr_{\text{gas,th}} = \frac{Fr_{\text{gas}}}{\beta^{2.5}} \tag{14}$$

Figure 2 shows the discharge-coefficient data plotted as a function of the throat Froude number.

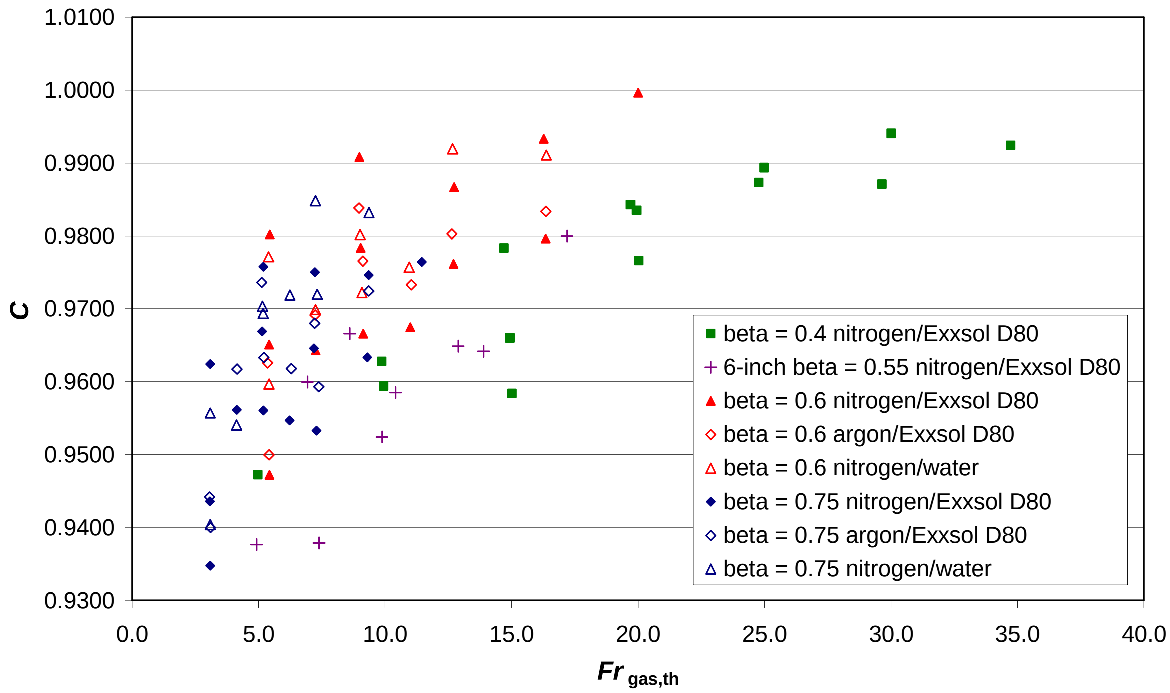

Figure 2 Values of the discharge coefficient as a function of $Fr_{gas,\ th}$. Data from Table 1

The power index, n, from the Chisholm correlation (in Equation (10)) has been calculated and plotted in Figure 3 against a suitable function of Fr_{gas}. The function $\exp(-0.8Fr_{gas}/H)$ was used to linearise the data. The choice of the liquid has a significant effect and this has been accounted for in the use of an additional term, H. H depends on the liquid type and was defined as equal to 1 for Exxsol D80. H = 1 is found to be a satisfactory value for other hydrocarbon liquids, and H = 1.35 was determined for water from fitting the data. Analysis of the available data shows that the choice of gas has a negligible effect on the relationship between n and Fr_{gas}, provided that the density ratio between the gas and the liquid is kept constant.

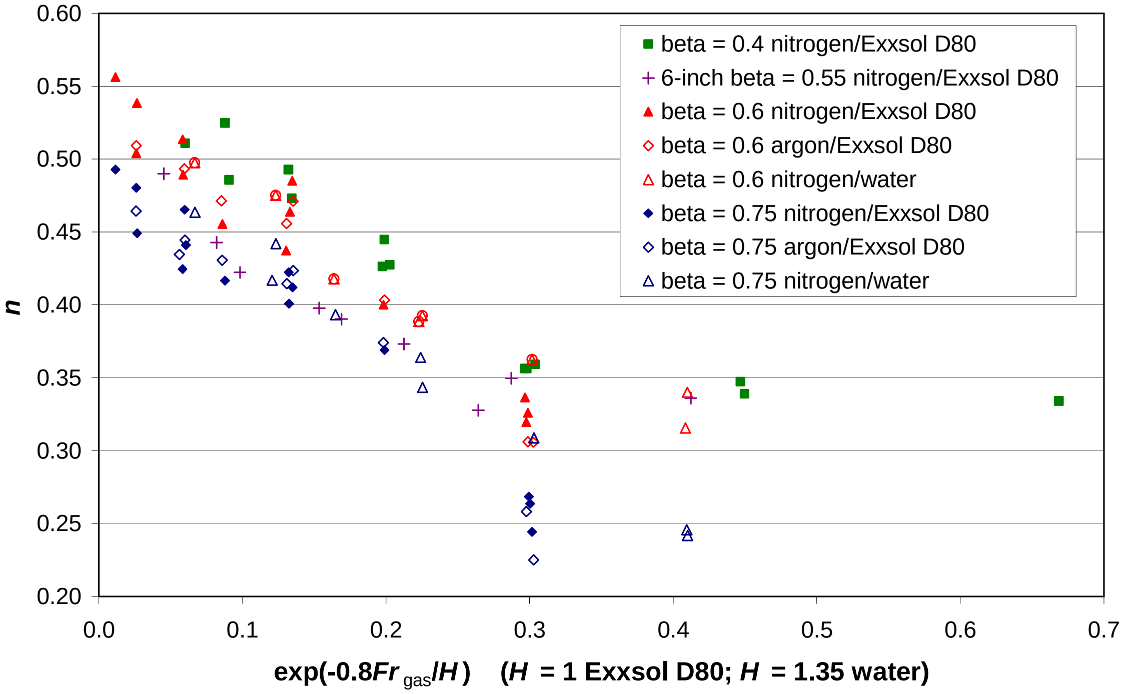

Figure 3 Values of the power index, *n*, from the Chisholm constant, as a function of the gas Froude number.

The strong effect of the liquid could suggest that the phase boundaries for a wet-gas flow in which the liquid is water are actually different from those in which the liquid is Exxsol D80 (or a general hydrocarbon liquid). Figure 4 shows the two-phase flow pattern map produced by Shell, which is commonly referred to in many wet-gas documents. This shows the flow conditions where certain flow patterns, for example stratified flow, are likely to exist. The phase boundaries, illustrated in this figure, between the flow regimes may depend on the liquid properties. This work and previous CFD [7] suggest that the effect of the liquid on the over-reading of Venturi tubes is strongly related to the surface tension of the liquid.

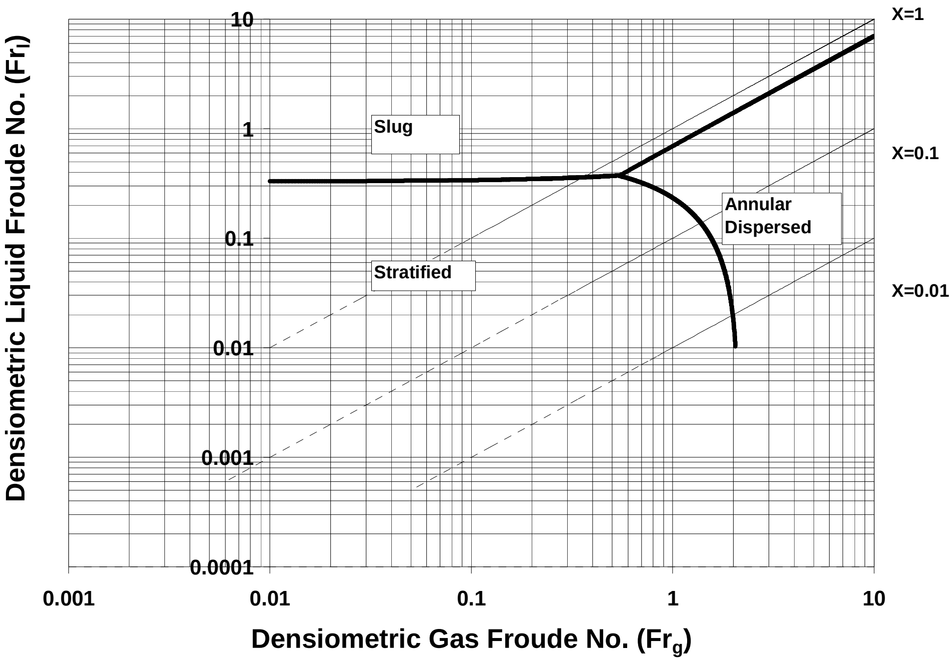

Figure 4 Horizontal two-phase flow pattern map (courtesy of Shell)

The analysis presented so far established appropriate dependencies for the values of *n* and *C* to develop a new correlation based on the Chisholm correlation. The range of data used for development of the correlation was extended and is summarised in Table 2.

Table 2 Wet gas data

Diameter ratio	Pipe size	Gas phase	Liquid phase	Reference
0.4	4-inch	nitrogen	Exxsol D80	5
0.6	4-inch	nitrogen	water	6, 7
0.6	4-inch	nitrogen	Exxsol D80	6, 7
0.6	4-inch	argon	Exxsol D80	6, 7
0.75	4-inch	nitrogen	water	6, 7
0.75	4-inch	nitrogen	Exxsol D80	6, 7
0.75	4-inch	argon	Exxsol D80	6, 7
0.55	6-inch	nitrogen	Exxsol D80	11
0.6	4-inch	nitrogen	Exxsol D80	-
0.6	4-inch	natural gas	Exxsol D80	-*
0.6	2-inch	natural gas	Stoddard solvent	12
0.6	2-inch	natural gas	water	12
0.4	4-inch	natural gas	decane	13
0.7	4-inch	steam	very hot water	14

* data points with the r.m.s of the fluctuating component of the differential pressure greater than 0.98% of the mean differential pressure were excluded.

The values for n determined from the data from Table 2 were plotted in a similar manner to those shown in Figure 3 and fitted to determine a formula for n. The value of n was determined as the maximum value from one of two equations. These equations describe the two patterns in the data that can be seen in Figure 3 with the initial negative gradient changing to a horizontal line. n is the larger of the values returned by

$$n = 0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_{gas}/H} \qquad (15)$$

and

$$n = 0.392 - 0.18\beta^2 . \qquad (16)$$

This is summarised in one equation as

$$n = \max(0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_{gas}/H}, 0.392 - 0.18\beta^2) \qquad (17)$$

As can be seen from Figure 1 the over-reading value changes its slope as X tends to zero. This is due to a change in discharge coefficient. Therefore an appropriate equation was fitted to the data from Table 2 to account for this change in the discharge coefficient, C. The discharge coefficient was fitted based on a threshold value of X, called X_{lim}. X_{lim} was defined as the value where the over-reading data showed a distinct change in gradient. Then C is given by

$$C = \begin{cases} C_{\text{fully wet}} & X \ge X_{\mathrm{lim}} \\ C_{\mathrm{dry}} - (C_{\mathrm{dry}} - C_{\text{fully wet}})\sqrt{\dfrac{X}{X_{\mathrm{lim}}}} & X < X_{\mathrm{lim}} \end{cases} \qquad (18)$$

where, from the overall fit of the data, $X_{\mathrm{lim}} = 0.016$

An effective discharge coefficient for wet gas, $C_{\text{fully wet}}$, was determined by fitting the data from Table 2. This was based on an exponential fit as a function of throat Froude number, $Fr_{\text{gas, th}}$

$$C_{\text{fully wet}} = 1 - 0.0463e^{-0.05Fr_{\text{gas,th}}} \qquad (19)$$

where the value of 1 is a remarkably close approximation to the fitted value for the single-phase discharge coefficient, C_{dry}, which should apply both to dry-gas flow and to homogeneous flow as $Fr_{\text{gas,th}}$ tends to ∞.

A summary equation to determine the discharge coefficient, C, accounting for the full range of X is

$$C = 1\text{-}0.0463\mathrm{e}^{-0.05Fr_{\mathrm{gas,th}}} \min\left(1, \sqrt{\frac{X}{0.016}}\right) \tag{20}$$

Figure 5 shows the errors in the gas mass flowrate determined when using these new equations as a function of the Froude number. The data from Table 2 are used. The percentage errors were calculated as

$$\sigma = 100 \frac{m_{\mathrm{correlation}} - m_{\mathrm{actual}}}{m_{\mathrm{actual}}} \tag{21}$$

where σ is the percentage error in the gas mass flowrate, $m_{\mathrm{correlation}}$ is the gas mass flowrate determined from using the correlation and m_{actual} is the actual measured gas mass flowrate.

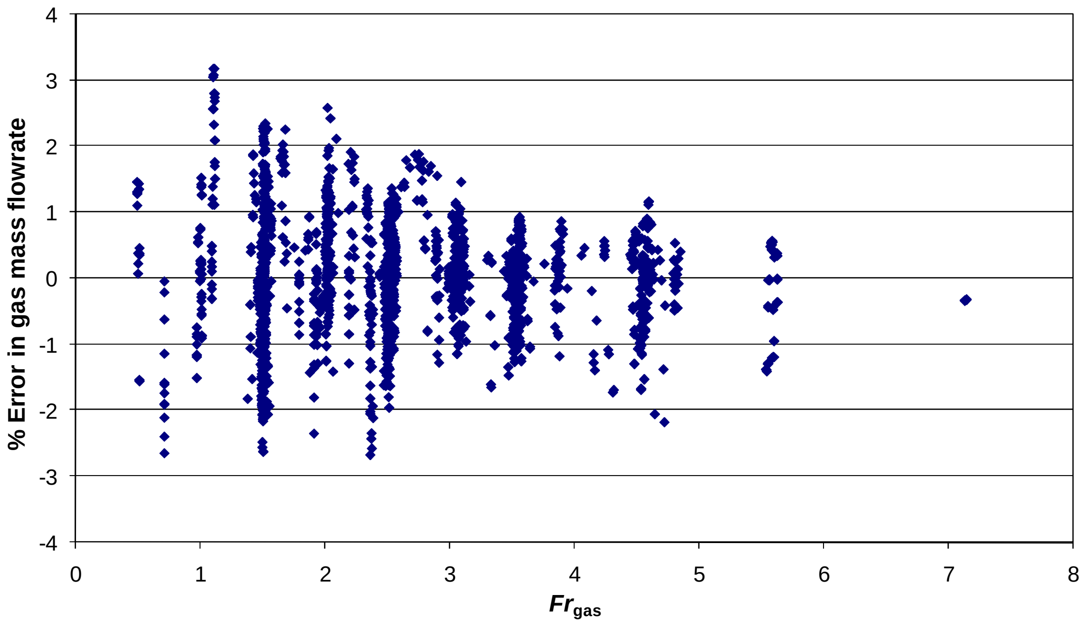

Figure 5 Errors in gas mass flowrate using Equations (17) and (20) as a function of Fr_{gas}

As stated earlier the liquid type affects the over-reading value. Using the data for water, hydrocarbons and very hot water (in a steam/water flow) in Table 2 the value of H was determined. This value is shown in relation to the liquid properties of surface tension and viscosity in Table 3. This shows that there is no obvious correlation of H with the liquid viscosity and that it is more likely that the surface tension is the dominant factor in the value of H.

Table 3 Liquid properties

Liquid	H (-)	Surface tension (N/m)	Viscosity (mPa s)
Water	1.35	0.060	1
Hydrocarbon	1	0.027	2.4
Very hot water	0.79	0.022	0.1

5 Testing the correlation

The correlation was mostly fitted to data recorded for research purposes in which accurate dimensions were measured to check compliance with ISO 5167-4.

However it is important to test the correlation using data that were not used to derive the correlation. This illustrates the applicability of the correlation to other Venturi tubes and can provide confidence in the use of the correlation.

Krohne very kindly agreed to allow their data on a large number of Venturi tubes calibrated at TUV NEL in nitrogen/Exxsol D80 to be used. The data for $0.4 \leq \beta \leq 0.75$, where β is the diameter ratio, are summarised in Table 4.

Table 4 Wet gas data from Krohne

Diameter ratio	Pipe size	Gas phase	Liquid phase	Number of Venturi tubes
0.6	4-inch	nitrogen	Exxsol D80	6 off
0.47	4-inch	nitrogen	Exxsol D80	1 off
0.43	4-inch	nitrogen	Exxsol D80	1 off
0.4	4-inch	nitrogen	Exxsol D80	1 off
0.57	6-inch	nitrogen	Exxsol D80	6 off
0.61	6-inch	nitrogen	Exxsol D80	5 off
0.61	10-inch	nitrogen	Exxsol D80	2 off

The data for one of the 4-inch and for one of the 6-inch Venturi tubes were not used as each had a mean discharge coefficient in dry gas below 0.97. On the basis of Table B.2 of ISO 5167-4 it is expected that the discharge coefficient will be equal to 1.010 ± 3% for $10^8 > Re_d > 2 \times 10^6$, where Re_d is the throat Reynolds number. Overall the data from 20 Venturi tubes were used to test the correlation.

Figure 6 shows the percentage error in the gas mass flowrate of the data used to derive the correlation (Table 2) and of the validation data from Krohne (Table 4) as a function of the gas Froude number.

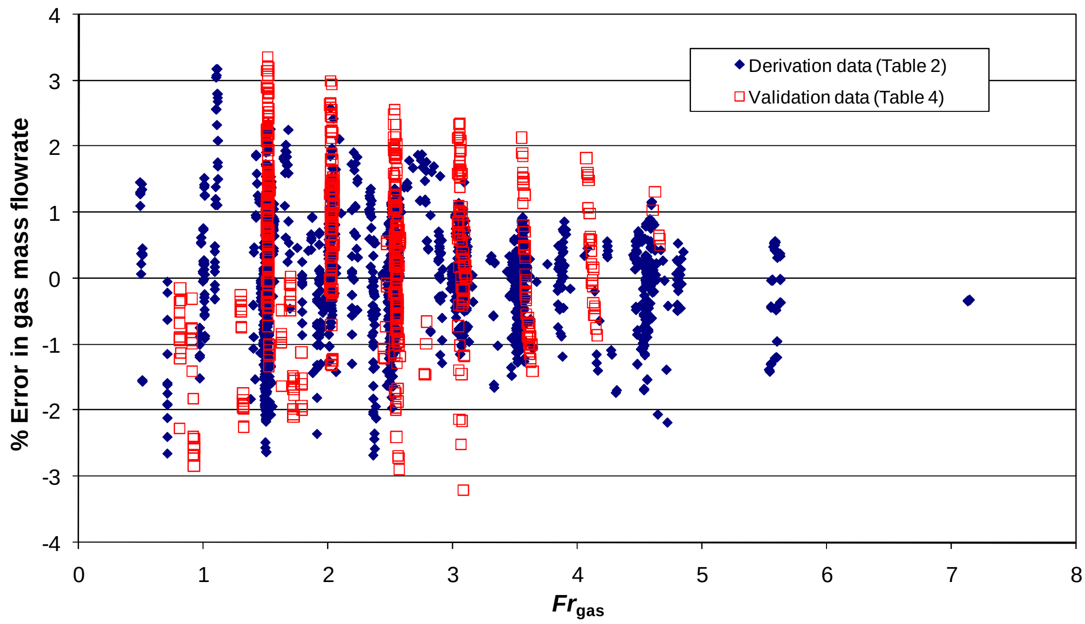

Figure 6 Errors in gas mass flowrate using Equations (17) and (20) as a function of Fr_{gas}

It can be seen that the Krohne validation data show only very slightly increased errors in the gas mass flowrate compared with the derivation data. This provides confidence that the correlation is robust enough to be used for Venturi tubes that are within the tolerances of the standard ISO 5167. The standard deviation of the errors in gas mass flowrate is given in Table 5.

Table 5 Standard deviation of errors in gas mass flowrate

Data fitted to give best-fit equations	Data tested to give errors	Standard deviation of errors in gas mass flowrate
Table 2[a]	Table 2	0.86%
Table 2[a]	Tables 2 and 4	0.980%
Tables 2 and 4[b]	Tables 2 and 4	0.969%
Table 2[a]	Table 4	1.34%

[a] Equations (17) and (20) [b] Equations (17) and (20) with revised constants

On the basis of Table 5 there is no benefit in using the Krohne data as derivation data as the standard deviation of the errors only reduces from 0.980% to 0.969%. Moreover, it is better to use the Krohne data only for validation purposes since no metrological information on the Venturi tubes was available and since it was good to have test data to which the constants in Equations (17) and (20) had not been fitted.

The error in the gas mass flowrate as a function of the Lockhart-Martinelli parameter, X, is presented in Figure 7 as this may be more informative. It is interesting to note that when the errors for the Venturi tube with mean C_{dry} = 0.9694 (omitted because it was less than 0.97) are added to Figure 7 they are approximately 3% for small X but are less for larger X. This supports the view that Equations (17) and (20) can be used to determine the gas mass flowrate with an uncertainty of 3% for $X \leq 0.15$ and 2.5% for $0.15 < X \leq 0.3$.

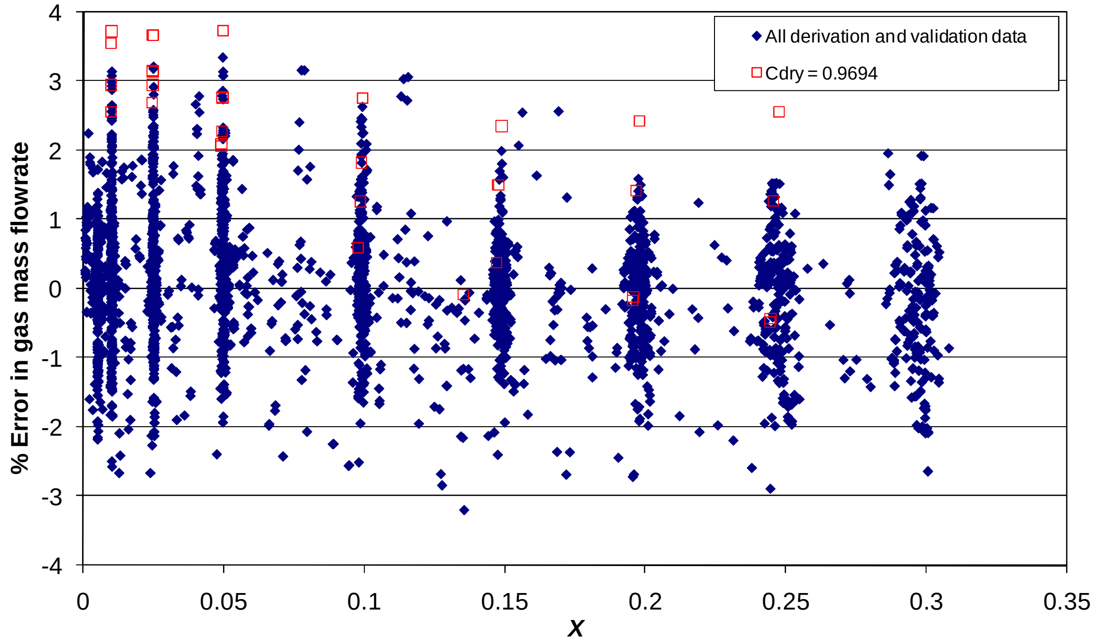

Figure 7 Errors in gas mass flowrate using Equations (17) and (20) as a function of *X*

In summary the new correlation can be used to determine the discharge coefficient in wet-gas conditions and a value for n to use in determining the wet-gas over-reading based on the Chisholm model. This can be used to determine the gas mass flowrate. From this research the over-reading was found to be dependent on the Lockhart-Martinelli parameter, the gas-to-liquid density ratio, the gas densiometric Froude number, the diameter ratio and the liquid properties.

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

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

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

It has been assumed here that there is no need for a maximum limit on $Fr_{\mathrm{gas,th}}$ as at higher values of $Fr_{\mathrm{gas,th}}$ the flow becomes more homogeneous and less likely to deviate from the behaviour accounted for in the correlation.

6 Using pressure-loss measurements to determine the liquid content

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^o 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 this can be exploited to determine the wetness. 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 measure of the liquid flowrate. All the information presented in this paper is based on Venturi tubes with a divergent angle of 7.5°. The downstream tapping is placed around 6D downstream of the downstream end of the divergent of the Venturi tube.

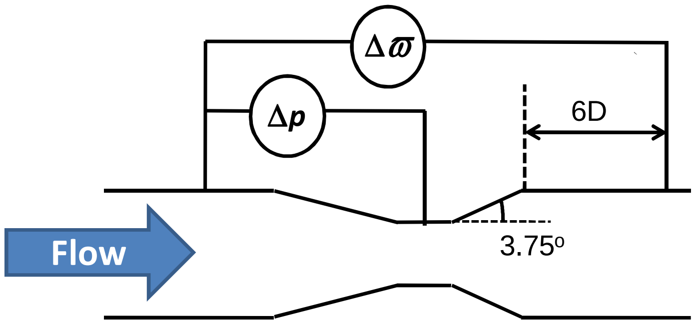

Figure 8 Schematic of Venturi tube illustrating total pressure loss (Δϖ) and the differential pressure (Δ*p*) to calculate the pressure loss ratio (Δϖ/Δ*p*). (Note diagram is not drawn to correct scale or dimensions)

Table 6 shows the sets of data that were used to derive a correlation between the pressure loss ratio and X.

Table 6 Wet gas data

Diameter ratio	Pipe size	Gas phase	Liquid phase
0.4	4-inch	nitrogen	Exxsol D80
0.6	4-inch	nitrogen	water
0.6	4-inch	nitrogen	Exxsol D80
0.6	4-inch	argon	Exxsol D80
0.75	4-inch	nitrogen	water
0.75	4-inch	nitrogen	Exxsol D80
0.75	4-inch	argon	Exxsol D80
0.6	4-inch	nitrogen	Exxsol D80
0.6	4-inch	natural gas	Exxsol D80

From these data the ratio of the pressure loss, $\Delta\varpi$, to the differential pressure, Δp, was determined in dry gas as

$$\left.\frac{\Delta\varpi}{\Delta p}\right|_{\mathrm{dry}} = 0.0896 + 0.48\beta^{9} \tag{22}$$

The increase in pressure loss due to wetness was defined as

$$Y = \frac{\Delta\varpi}{\Delta p} - \left.\frac{\Delta\varpi}{\Delta p}\right|_{\mathrm{dry}} \tag{23}$$

The maximum value of the increase in pressure loss due to wetness cannot be exactly determined from the database, but a good approximation is obtained by defining Y_{max}, as

$$Y_{\max} = \left.\left(\frac{\Delta\varpi}{\Delta p} - \left.\frac{\Delta\varpi}{\Delta p}\right|_{\mathrm{dry}}\right)\right|_{X\approx 0.3} \tag{24}$$

$Y_{\max}$ was first plotted as a function of $\rho_{1,\mathrm{gas}}/\rho_{\mathrm{liq}}$. This is shown in Figure 9.

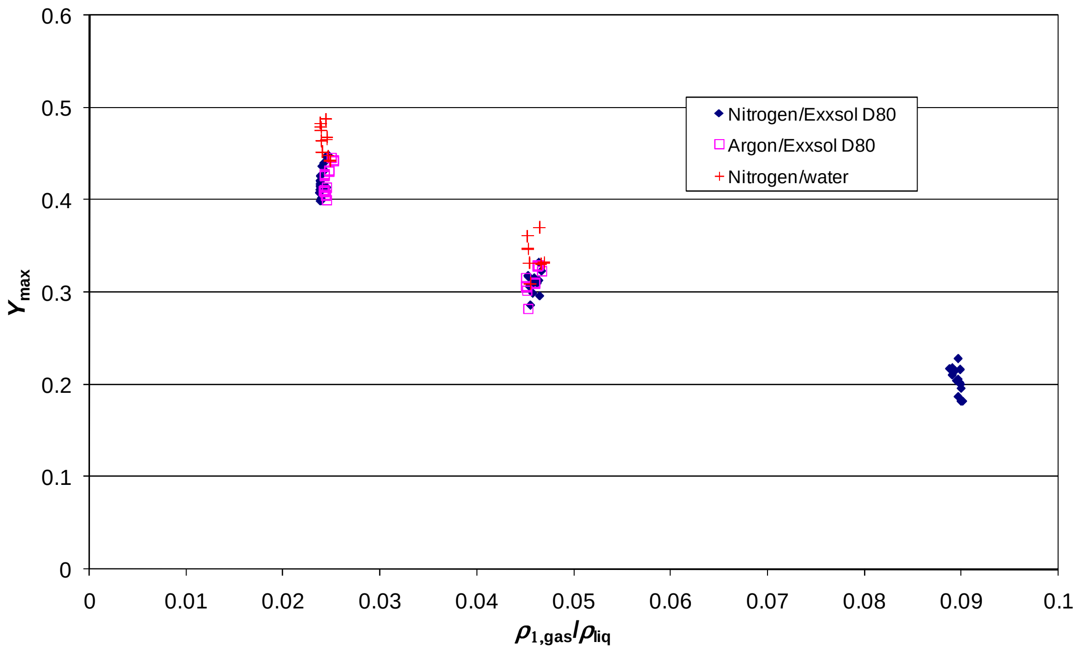

Figure 9 $Y_{\max}$ as a function of $\rho_{1,\mathrm{gas}}/\rho_{\mathrm{liq}}$ for nominal values of Fr_{gas} in the range 1.5 to 4.5

Figure 9 shows that that $Y_{\max}$ is dependent on the density ratio as well as on the liquid type but appears to show no effect of the gas type. The argon/Exxsol D80 and nitrogen/Exxsol D80 fluid combinations have overlapping data points, whereas when the liquid is water (as in the Nitrogen/water combination) $Y_{\max}$ has a higher value.

From examination of the data it appears that the same dependence on liquid as was found when determining the value of n (Equation (17)), is appropriate to use here. Therefore the data for Y_{max} were plotted against a function of Fr_{gas}/H in order to account for the liquid type (Figure 10).

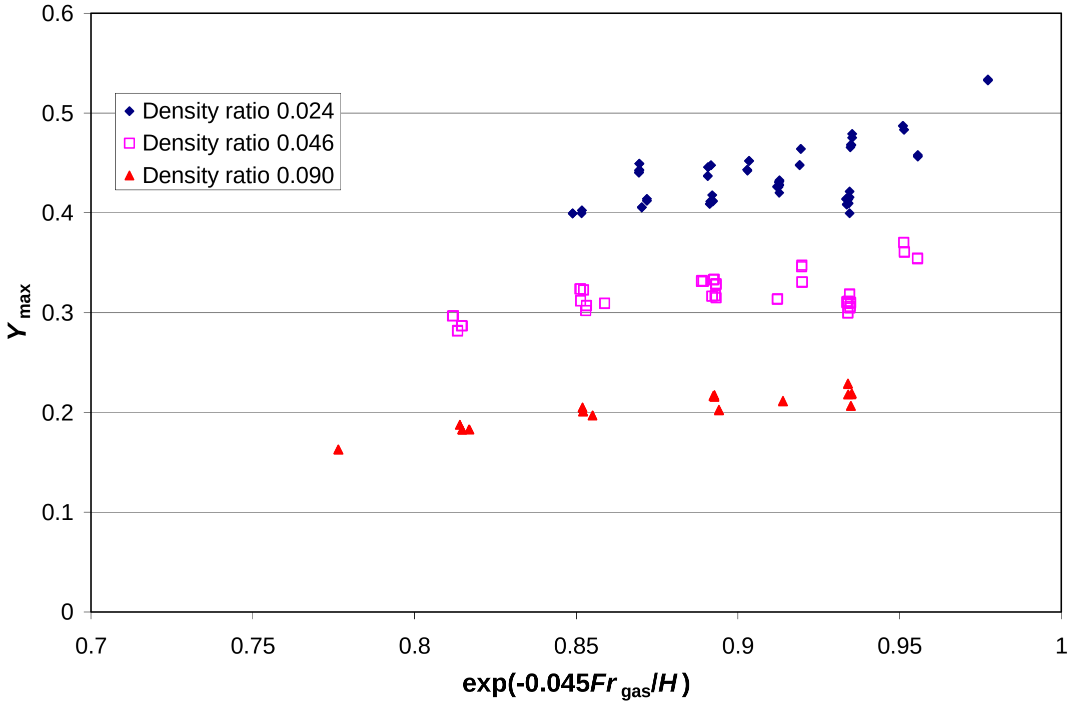

Figure 10 Y_{max} as a function of Fr_{gas}/H

Figure 10 clearly shows a dependence on the density ratio, $\rho_{1,gas}/\rho_{liq}$, and this dependence can be represented by a simple function that becomes extremely small as $\rho_{1,gas}/\rho_{liquid}$ tends to 1.

The following form for Y_{max} was then assumed:

$$Y_{max} = a\exp\left(-b\left(\frac{\rho_{1,gas}}{\rho_{liq}}\right) - cFr_{gas}/H\right) \tag{25}$$

On fitting the available data from Table 6 Y_{max} was determined as

$$Y_{max} = 0.61\exp\left(-11\left(\frac{\rho_{1,gas}}{\rho_{liquid}}\right) - 0.045Fr_{gas}/H\right) \tag{26}$$

Y/Y_{max} was then evaluated for each point and plotted in Figure 11.

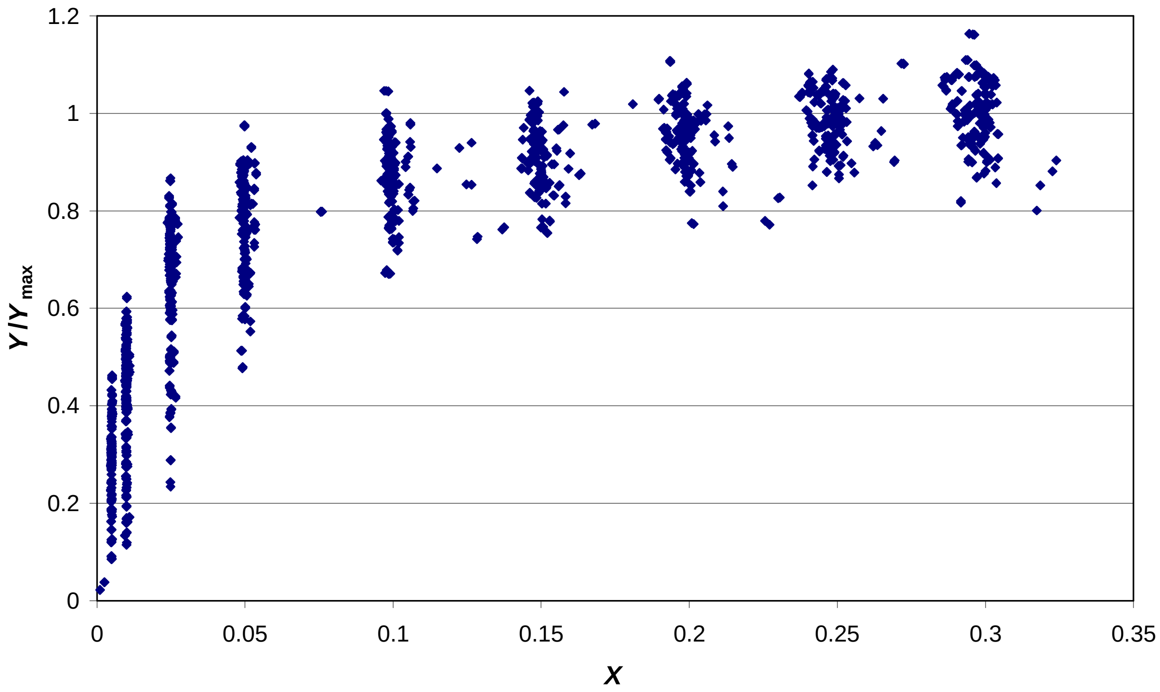

Figure 11 Y/Y_{max} as a function of X

In Figure 11 the levelling off (tending to a zero gradient) of the graph at higher values of X confirms that Y reaches its maximum value around X = 0.3. Even if X = 0.3 did not give the true maximum of Y this would not invalidate the final formula as it is based on Equation (24), not the true maximum.

However, Figure 11 is inadequate for practical use. For example, a value of Y/Y_{max} = 0.6 could give a value of X anywhere between 0.015 and 0.07. Therefore the data were replotted for small Y/Y_{max} divided by ranges of Fr_{gas}/H (Figure 12). Data obtained with $Fr_{gas,th} < 4$ increased the uncertainty and were excluded.

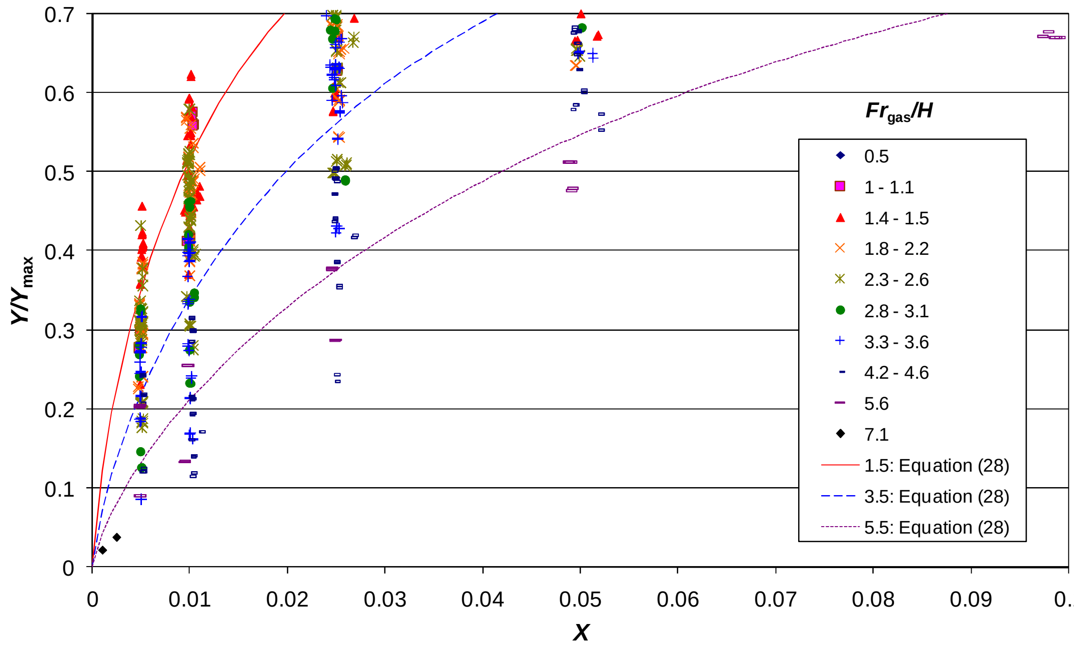

Figure 12 Y/Y_{max} as a function of X, for $Y/Y_{max} < 0.7$ and $Fr_{gas,th} > 4$

The data in Figure 12 are fitted using the following form:

$$\frac{Y}{Y_{max}} = 1 - \exp\left(-bX^{d} e^{-cFr_{gas}/H}\right) \tag{27}$$

This gives the following equation:

$$\frac{Y}{Y_{max}} = 1 - \exp\left(-35X^{0.75} e^{-0.28Fr_{gas}/H}\right) \tag{28}$$

Provided a value of the pressure loss is known from measurements it is then possible to use Equations (22), (23) and (26) to determine values for Y and Y_{max}. A value of X can then be determined from Equation (28), which can be used to determine the wet-gas over-reading using Equations (17), (9) and (10). The gas mass flowrate can be determined from Equation (5) using the over-reading and the value for the wet-gas discharge coefficient, C, determined from Equation (20).

The percentage error in the gas mass flowrate as a function of Y/Y_{max} is shown in Figure 13. The results are remarkably good, but as soon as Y/Y_{max} exceeds 0.7 the method becomes very inaccurate.

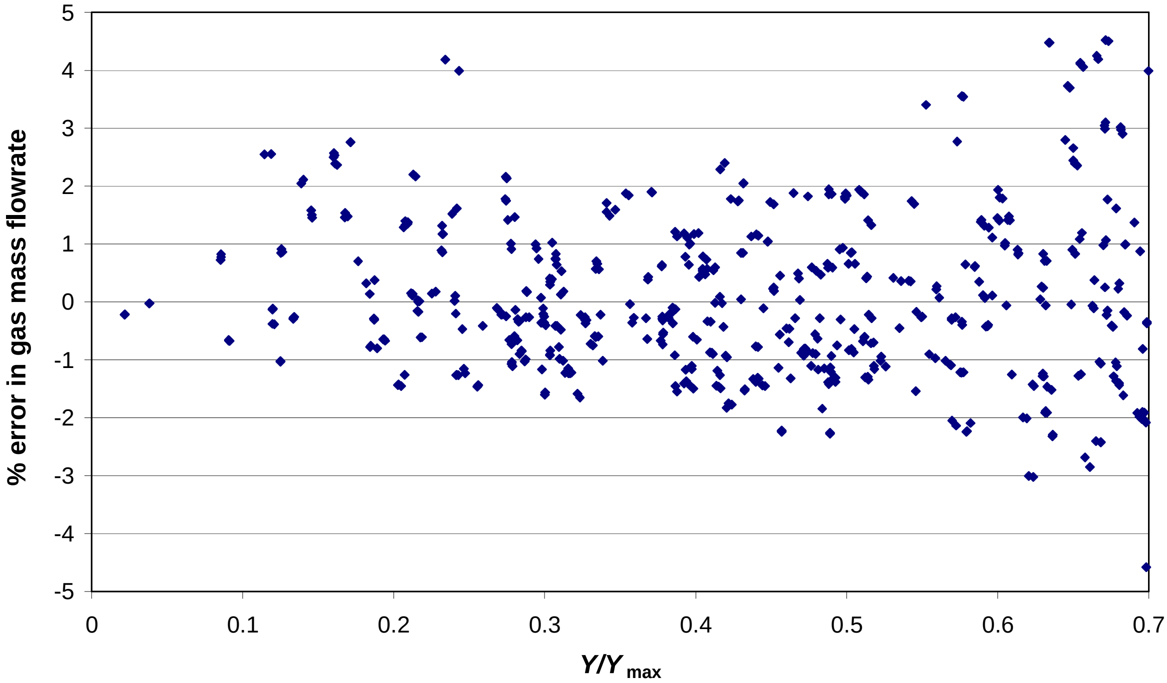

Figure 13 Errors in gas mass flowrate for $Fr_{gas,th} > 4$ using pressure loss and Equations (22), (26), (28), (17) and (20)

To use these equations with Venturi tubes other than those from which the equation was derived it is desirable to be cautious as the equation has not been validated against additional data, as was done for the equations for *n* and *C*. A reasonable estimate for the uncertainty in gas mass flowrate using pressure loss ratio measurements and Equations (22), (26), (28), (17) and (20) is

$$\begin{cases} 4\% \text{ for } \dfrac{Y}{Y_{max}} \leq 0.6 \\ 5\% \text{ for } 0.6 < \dfrac{Y}{Y_{max}} < 0.7 \end{cases}$$

Additional limits to those for the use of Equations (17) and (20) are that the divergent angle shall be between 7° and 8°

$$\frac{Y}{Y_{max}} < 0.7$$

$Fr_{gas}/H \leq 5.5$

$\rho_{1,gas}/\rho_{liq} \leq 0.09$

and $Fr_{gas,th} > 4$.

7 Conclusion

The 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. This research found that the over-reading was dependent on the Lockhart-Martinelli parameter, the gas-to-liquid density ratio, the gas densiometric Froude number, the diameter ratio and the liquid properties.

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

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

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

The ratio of pressure loss to the differential pressure can be used to determine the liquid content in the wet-gas stream using the equations derived in this paper. Under certain circumstances this can eliminate the need for a separate technique to determine the liquid content. The uncertainty in gas mass flowrate using the additional equations to determine the liquid content is

$$\begin{cases} 4\% \text{ for } \dfrac{Y}{Y_{max}} \leq 0.6 \\ 5\% \text{ for } 0.6 < \dfrac{Y}{Y_{max}} < 0.7 \end{cases}$$

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

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