Wet-Gas Measurement: ISO/TR 11583

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1 INTRODUCTION

ISO/TR 11583 [1] was published in April 2012. This paper gives some information on the history of the document. It gives a brief summary of the work on which it was based. It gives, partly in an appendix, a detailed reply to criticisms of the document made at the North Sea Workshop in October 2011, and it shows how work done since October 2011 has provided support for ISO/TR 11583.

2 A BRIEF HISTORY OF ISO/TR 11583

This project started with a New Work Item Proposal sent out to the members of ISO/TC 30/SC 2 in September 2007. It stated that the proposed 'Technical Report will cover the measurement of wet gas flow with Venturi tubes or orifice plates. It will cover two-phase flows of gas and liquid in which the flowing fluid mixture is approximately 95% gas by volume or more. Gases covered include air, nitrogen, natural gas and steam. Liquids covered include water, kerosene and condensate. It will be an extension to ISO 5167.' Item 6 in its outline of the proposed TR was 'Correlations for the over-reading'. This New Work Item Proposal was accepted in early 2008. To the statement 'We agree that a globally relevant International Standard on this subject is feasible and therefore agree to the addition of the proposed new work item to the program of work of the committee' there were 11 positive votes (including those of Norway and the USA) and 2 abstentions and no negative votes. One US expert was nominated in 2007 and two more in October 2008.

ISO/TR 11583 is based on guidelines prepared by technical experts for the UK Dept. of Trade and Industry [2], and was developed with the input of different experts on different sections.

ISO/TC 193 (natural gas) also wished to work on wet gas. ISO/TC 30 agreed that TC 30's wet-gas TR could be part of a wider ranging document, with TC 30's part addressing generic aspects (covering wet natural gas and wet steam among other wet gases), and aspects specific to natural gas being addressed by ISO/TC 193/SC 3 in a subsequent part. This structure was accepted in principle in 2008: in an e-mail to the TC 193/SC 3 members dated 11 September 2008 the TC 193/SC 3 Secretary wrote, 'This document [the then draft of ISO/TR 11583-1] serves as an initial effort to call for experts from both committees. Please circulate this draft document among your experts, and if possible, please nominate experts who could participate on the JWG on behalf of ISO/TC 193/SC 3. The intent of this draft document is to serve as a generic Part 1 to a multi-part document on wet gas.' ISO/TC 30 worked in accordance with this arrangement and awaited the development of Part 2, but eventually had to complete the TR as a stand-alone document.

The correlations for Venturi tubes that appear in TR 11583 were first circulated to ISO/TC 30/SC 2/WG 15 in February 2009. They were published at the North Sea Workshop in 2009 [3]. A draft TR containing these correlations was circulated to SC 2 in August 2009. The correlation for orifice plates was taken from [4].

ISO/TC 193 expressed concern about the Venturi-tube correlation. Accordingly a meeting between key members of ISO/TC 30 and ISO/TC 193 was held at TC 193's request in November 2009 in London. One particular concern of TC 193 was that the NEL data used as the largest part of the data set to develop the correlations were not available for Working Group members to check the correlation. In June 2010 NEL agreed to make available such NEL data as might be necessary to carry out validation of the Venturi correlations in TR 11583, subject to any party who wished access to these data first signing a confidentiality agreement which would clearly define the reason for disclosure and limit the use of the data solely to the validation process. The Venturi-tube correlation in TR 11583 was in much better agreement with the database that that of de Leeuw [5]. The ballot on TR 11583 was started in September 2010. This passed by 6 votes to 4.

ISO/TR 11583 was at the proof stage in July 2011. ISO/TC 193 appealed to ISO Central Secretariat and publication was stopped. Several inconclusive meetings were held: TC 30 regards the document as generic and so within its scope and wished to publish it. TC 193 maintained the document is flawed. A paper (referred to in this paper as de Leeuw et al [6]) was published at the North Sea Workshop in 2011 giving arguments against its publication. A reply to all the points (similar to that in 3 and Appendix A) was sent to the authors of [6] in January 2012; no response has been received. Ultimately ISO/TC 28 and ISO/TC 193 went to the ISO Technical Management Board (TMB) requesting that oil and gas be excluded from the scope of ISO/TC 30. The TMB's resolution was that 'It reminds ISO/TC 30 that they should develop generic standards on flow measurement, and decides that further sectorial needs of the oil and gas industry should be addressed by ISO/TC 28 and ISO/TC 193 taking account of the generic standards from ISO/TC 30.' TC 30 is happy with this resolution. However, the TMB also insisted that the following words were added to ISO/TR 11583: 'This Technical Report is not intended for the oil and gas industry.' ISO/TC 30 had no real choice but to accept, although it believes that its standards are generic and for use by all industries. The UK National Committee, unhappy with the TMB's extra words, put the following text into PD ISO/TR 11583 [7]: 'The UK national committee, CPI/30/2, consider the content of this technical report to be suitable for general application in wet gas measurement using differential pressure meters.'

2 EQUATIONS FOR WET GAS FLOW THROUGH VENTURI TUBES

2.1 General

Most currently used equations have similar form; they have been developed one from another. All those considered here have the gas mass flowrate, $q_{m,\text{gas}}$, given by

$$q_{m,\text{gas}} = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \frac{\sqrt{2\Delta p \rho_{1,\text{gas}}}}{\phi} \tag{1}$$

C is a discharge coefficient, ε is determined from ISO 5167-4:2003, $\rho_{1,\text{gas}}$ is the upstream gas density and ϕ is the over-reading correction factor. C and ϕ are described below. In evaluating ε the actual values of p_1 and p_2 measured in wet gas are used.

ϕ depends on the gas-liquid density ratio, $\rho_{1,\text{gas}}/\rho_{\text{liquid}}$, where ρ_{liquid} is the density of the liquid, on the Lockhart-Martinelli parameter, X, as defined in equation (2), and on the gas densiometric Froude number, Fr_{gas} (equation (3)):

Lockhart-Martinelli Parameter, $$X = \left(\frac{q_{m,\text{liquid}}}{q_{m,\text{gas}}}\right)\sqrt{\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}} \tag{2}$$

Gas Densiometric Froude Number, $$Fr_{\text{gas}} = \frac{4q_{m,\text{gas}}}{\rho_{1,\text{gas}}\pi D^2\sqrt{gD}}\sqrt{\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}-\rho_{1,\text{gas}}}} \tag{3}$$

where g is the acceleration due to gravity and $q_{m,\text{liquid}}$ is the liquid mass flowrate.

2.2 Test work

In test work C/ϕ is determined from Equation (1).

In dry-gas flow $\phi = 1$, and C is determined.

The mean of the values of C in dry-gas flow (for that Venturi tube at that pressure) was used to calculate ϕ for the wet-gas points.

2.3 Models for field use

2.3.1 General

In both models for field use ϕ is given by Equation (4)

$$\phi = \sqrt{1 + C_{\mathrm{Ch}} X + X^2} \tag{4}$$

where C_{Ch} is given by the following equation:

$$C_{\mathrm{Ch}} = \left(\frac{\rho_{\mathrm{liquid}}}{\rho_{1,\mathrm{gas}}}\right)^n + \left(\frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liquid}}}\right)^n \tag{5}$$

n depends on the particular model.

2.3.2 ISO/TR 11583

$C = C_{\mathrm{wet}}$ as given by Equation (6):

$$C_{\mathrm{wet}} = 1\text{-}0.0463\mathrm{e}^{-0.05 Fr_{\mathrm{gas,th}}} \min\left(1, \sqrt{\frac{X}{0.016}}\right) \tag{6}$$

where

$$Fr_{\mathrm{gas,th}} = \frac{Fr_{\mathrm{gas}}}{\beta^{2.5}}. \tag{7}$$

$$n = \max(0.583\text{-}\ 0.18\beta^2 \text{-}0.578\mathrm{e}^{-0.8 Fr_{\mathrm{gas}}/H}, 0.392\text{-}0.18\beta^2) \tag{8}$$

H depends on the liquid and is equal to 1 for hydrocarbon liquid, 1.35 for water at ambient temperature, and 0.79 for liquid water in a wet-steam flow. It is a function of the surface tension of the liquid.

2.3.3 de Leeuw Equation

C is obtained from a dry-gas calibration of the Venturi tube.

n is as follows:

$$n = \begin{cases} 0.41 & 0.5 \le Fr_{\mathrm{gas}} < 1.5 \\ 0.606\left(1 - e^{-0.746 Fr_{\mathrm{gas}}}\right) & Fr_{\mathrm{gas}} \ge 1.5 \end{cases}. \tag{9}$$

de Leeuw [5] produced his wet-gas Venturi-tube correlation based on a Venturi tube of β = 0.4.

2.4 Value of *X*

To perform the flowrate computation X is required. In most of the experimental work and the field tests calculations this is taken from experimental measurements of liquid flowrate.

For a limited range of X it is possible to use the pressure loss to calculate the Lockhart-Martinelli parameter. Formulae are given in ISO/TR 11583 for a Venturi tube with divergent total angle in the range 7° to 8° with the pressure loss, $\Delta\varpi$, measured from the upstream pressure tapping to a tapping a distance L_{down} downstream of the downstream end of the Venturi tube divergent section, where L_{down} is such that

$$\max(5, 20\beta - 7) \le \frac{L_{down}}{D} \le 9 .$$

In this case the following calculations are performed:

$$Y = \frac{\Delta\varpi}{\Delta p} - 0.0896 - 0.48\beta^9 \qquad (10)$$

and

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

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

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

$$\frac{Y}{Y_{\max}} = 1 - \exp(-35X^{0.75} e^{-0.28 Fr_{\text{gas}} / H}) \qquad (12)$$

Since in this case Fr_{gas} is itself an unknown the procedure is iterative.

The reasons for the forms in Equations (6) – (8) and (10) – (12) are given in [3] and [8].

2.5 Data used to derive and to validate the ISO/TR 11583 Venturi-tube Correlation

The derivation data are given in Table 1 and the validation data in Table 2.

Table 1 Wet-gas derivation data for Venturi-tube correlation

Diameter ratio	Pipe size	Gas phase	Liquid phase	Reference
0.6	2-inch	natural gas	Stoddard solvent	9
0.6	2-inch	natural gas	water	9
0.4	4-inch	nitrogen	Exxsol D80	10
0.4	4-inch	natural gas	decane	11
0.6	4-inch	nitrogen	water	12, 13
0.6	4-inch	nitrogen	Exxsol D80	12, 13
0.6	4-inch	argon	Exxsol D80	12, 13
0.6	4-inch	nitrogen	Exxsol D80	-
0.6	4-inch	natural gas	Exxsol D80	-*
0.7	4-inch	steam	very hot water	14
0.75	4-inch	nitrogen	water	12, 13
0.75	4-inch	nitrogen	Exxsol D80	12, 13
0.75	4-inch	argon	Exxsol D80	12, 13
0.55	6-inch	nitrogen	Exxsol D80	15

* 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.

Table 2 Wet-gas validation data (from Krohne) for Venturi-tube correlation

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 errors in gas mass flowrate using the ISO/TR 11583 equations ((6) – (8)) are given in Figure 1 and those using de Leeuw's equation in Figure 2. The data in Figure 2 are divided by β because the performance of the correlation depends on β.

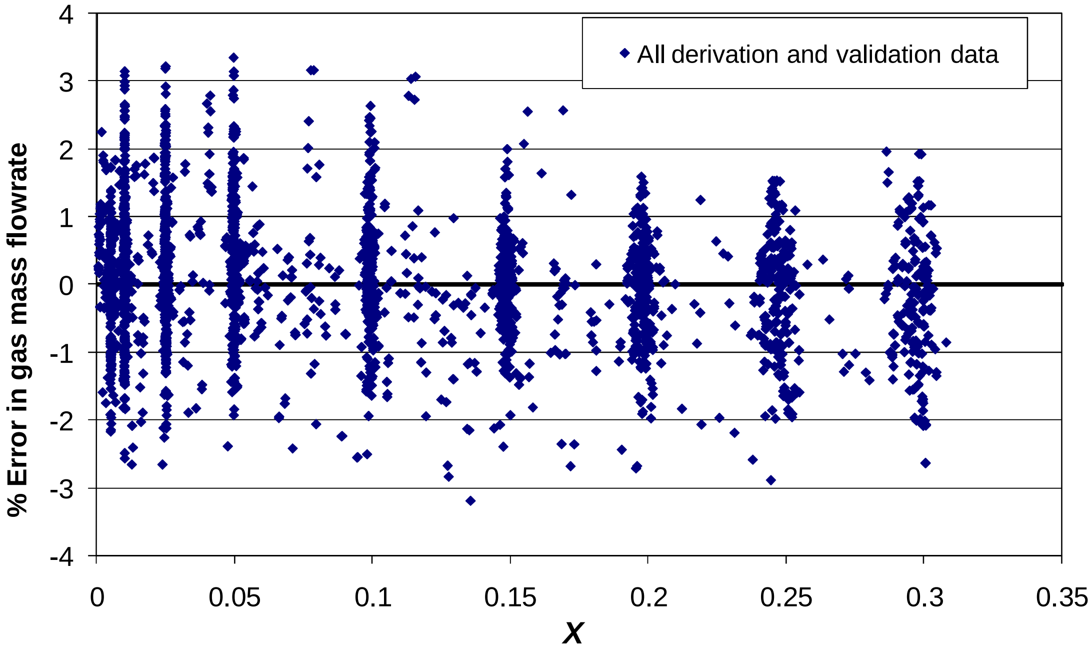

Figure 1 Errors obtained using the ISO/TR 11583 correlation for the derivation data (Table 1) and validation data (Table 2)

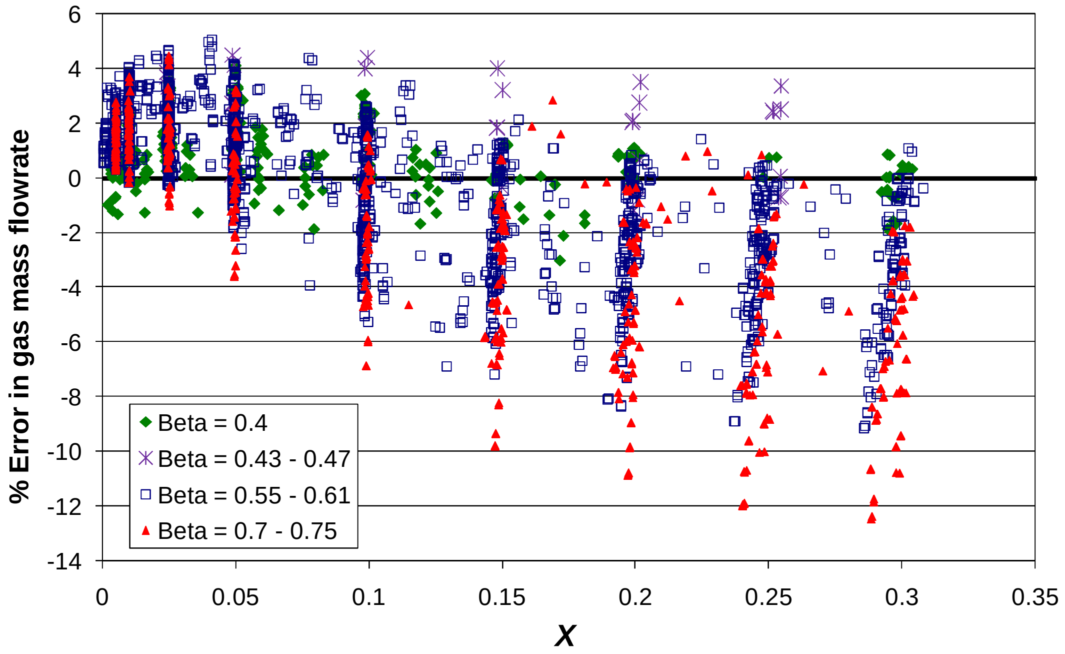

Figure 2 Errors obtained using the de Leeuw correlation for the derivation data (Table 1) and validation data (Table 2)

The errors in gas mass flowrate using pressure loss ratio to give X (equations (6) – (8) and (10) – (12)) are given in Figure 3 (ISO/TR 11583 only applies for $Y/Y_{max} < 0.65$).

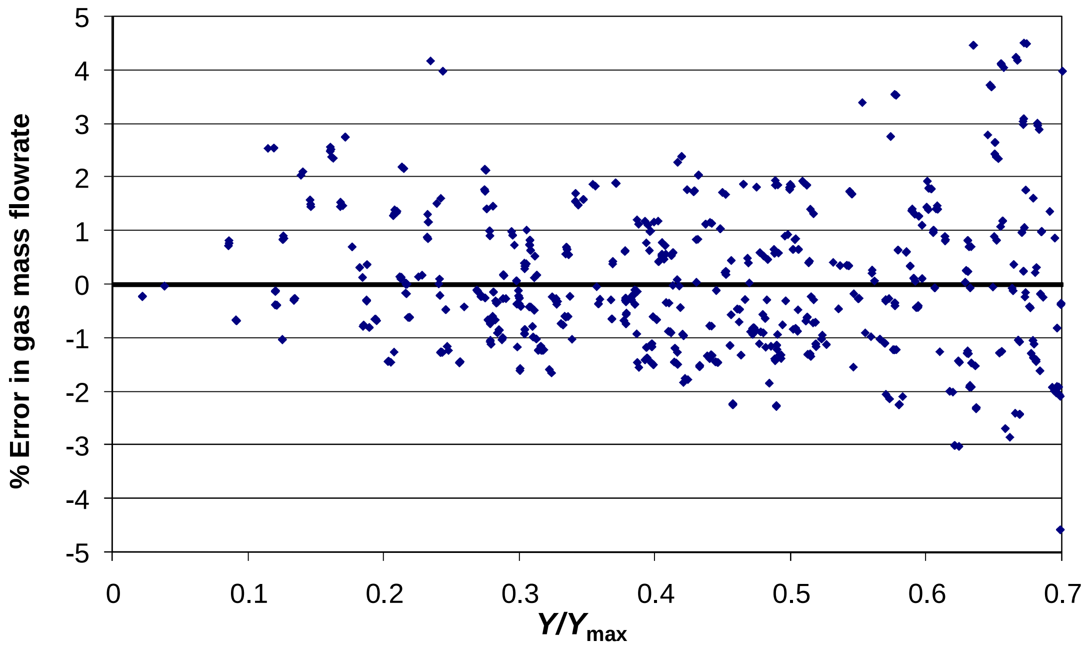

Figure 3 Errors in gas mass flowrate for the derivation data for $Fr_{gas,th} > 4$ using pressure loss and Equations (6) – (8) and (10) – (12)

3 RESPONSE TO de LEEUW et al

3.1 General

A response is given in Appendix A, but the main points are given here. The main criticisms of the Venturi correlations and a brief response are as follows:

- It is claimed that the understanding of the effects of physical properties is inadequate; however, ISO/TR 11583 is careful to state what fluids were used for the test work and not to imply that any fluids can be used with the correlations.
- It is claimed that the correlations have an incorrect behaviour in limiting cases; however, several limits have been tested as described in Appendix A and all give good results.
- The correlation is only applicable to two-component flows; however, there are insufficient data for three-component flows in the public domain to determine whether the correlation (with additional text as to how it should be used) is adequate; so TR 11583 makes no claim that it is adequate for three-component flows (see also 6 below).
- The term ‘discharge coefficient’ should not be used for anything other than the dry-gas discharge coefficient; however, it is found that the substantial change that occurs in C/ϕ as X changes from 0 to 0.025 is most easily described as a change in C. If there is a lack of clarity it is desirable to distinguish clearly between dry-gas and wet-gas discharge coefficients.
- The most important criticism is that there are data sets which the correlation does not fit; however, they would have been considered if they had been given to ISO/TC 30/SC 2/WG 15; to those sets in de Leeuw et al an answer is given below.

3.2 Data sets outside the derivation and regression data sets

3.2.1 The NAM Venturi tube

The errors using the NAM Venturi tube are shown in Figure 3 of de Leeuw et al. However, the same Venturi tube was tested by CEESI [11], and NEL analysis of those data give the results in Figure 4.

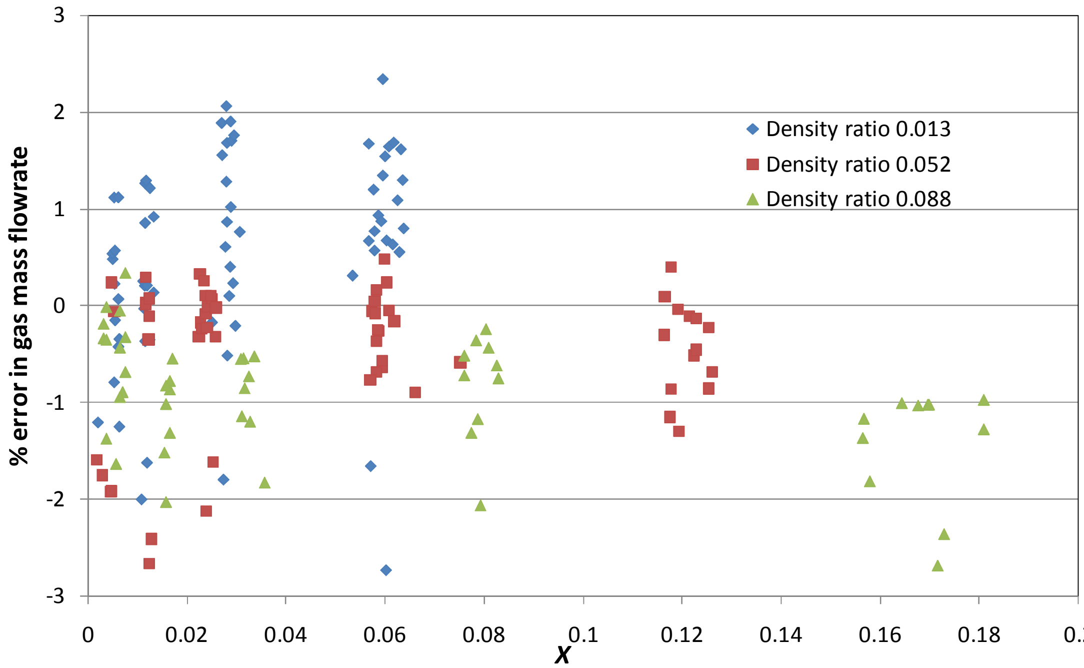

Figure 4 Errors on the NAM Venturi tube when tested at CEESI: correction according to ISO/TR 11583

All points except one are within ISO/TR 11583. The striking feature is that the results at SINTEF are shifted from those at CEESI by perhaps 2%. The results are sufficiently similar in terms of wet-gas effects that it might be that SINTEF’s data are in error by 2% and should be disregarded. It looks as if the measured dry-gas discharge coefficient at SINTEF was about 0.98, whereas at CEESI it was about 0.997. Moreover, when CEESI presented results on this Venturi tube they stated that its throat is 1.16d long, outside ISO 5167-4.

3.2.2 K-Lab data

Figure 4 of de Leeuw et al shows that the vast majority of the data lie within the ISO/TR 11583 limits. The behaviour as X tends to 0 is interesting: as X tends to 0 all the sets except two (violet circles and golden triangles) are reasonably close to +2.5%, as would be expected with a dry-gas discharge coefficient of 0.975; why the two are so different it is impossible to tell unless the data are revealed in detail. NEL agreed to reveal its data to those checking ISO/TR 11583; the same requirement should apply to those who wish to criticize it. It appears likely that for small X the two different sets (violet circles and golden triangles) have a negative over-reading, which is surprising. The blue star-like data (the furthest from 0) move towards 0 as X increases.

Figure 5 of de Leeuw et al attempts to improve ISO/TR 11583 by assuming that if the discharge coefficient is known the results can be improved by multiplying the calculated mass flowrate by the dry-gas discharge coefficient (or similarly but not identically) replacing the first ‘1’ in Equation (6) by the dry-gas discharge coefficient. This, however, is wrong: ISO/TR 11583 has to be followed in its entirety not corrected in this way. A possible way to improve the fit is described in 4.

3.2.3 Calibration at NEL

Data from a 12” Venturi tube calibrated at NEL are shown in Figure 6 of de Leeuw et al. The dry-gas discharge coefficient was 0.936. To use the data from such a Venturi tube to judge ISO/TR 11583 is surprising. If uncalibrated Venturi tubes are to be used, manufacturing quality is of the essence. This is why NEL now requires spark erosion for the tappings for Venturi tubes manufactured for NEL: there is still a scatter in results, but poor results are avoided.

NOTE: It may be asked whether it is reasonable to have an uncertainty in wet gas approximately equal to that in dry gas.

Figure 7 of de Leeuw et al shows Venturi tubes in dry gas: all of their discharge coefficients are well within 1.00 ± 3%, which is a necessary condition for ISO/TR 11583 to be true as X tends to 0. Then there is a tendency for those Venturi tubes with a dry-gas discharge coefficient far from 1 to have their measurement errors move towards 0 as X increases (see 4); so the uncertainty reduces slightly for X > 0.15. As stated earlier the standard deviation of the gas mass flow errors in the derivation and validation data is 0.98%; so the quoted uncertainty aimed to be sufficiently conservative.

3.2.4 Wet-gas flows with mixtures of liquids

Figure 8 of de Leeuw et al shows the errors using the correlation in ISO/TR 11583 on CEESI data when the liquid consists of a mixture of water and hydrocarbon liquid. ISO/TR 11583 does not cover flows with a mixture of liquids because it is careful to avoid using formulae outside the range of data. An amendment to cover mixtures would be possible if there were sufficient data to analyse. If it were desired to experiment with using the formulae in ISO/TR 11583 for wet-gas flows with mixtures of liquid then to take H as linear with water cut would be a reasonable choice. The data in de Leeuw et al always take H as equal to either 1 or 1.35: the results therefore do not give the best results that can be obtained using ISO/TR 11583.

The only data for wet-gas flows with a mixture of liquids that are available for the author of this paper to analyse are 2” data from CEESI [9] (but see also 6). On looking at them the results in Figure 5 are obtained, once the data that are outside the range of density ratio in ISO/TR 11583 are excluded. All the points are within ISO/TR 11583. More detail is given in Reference 8.

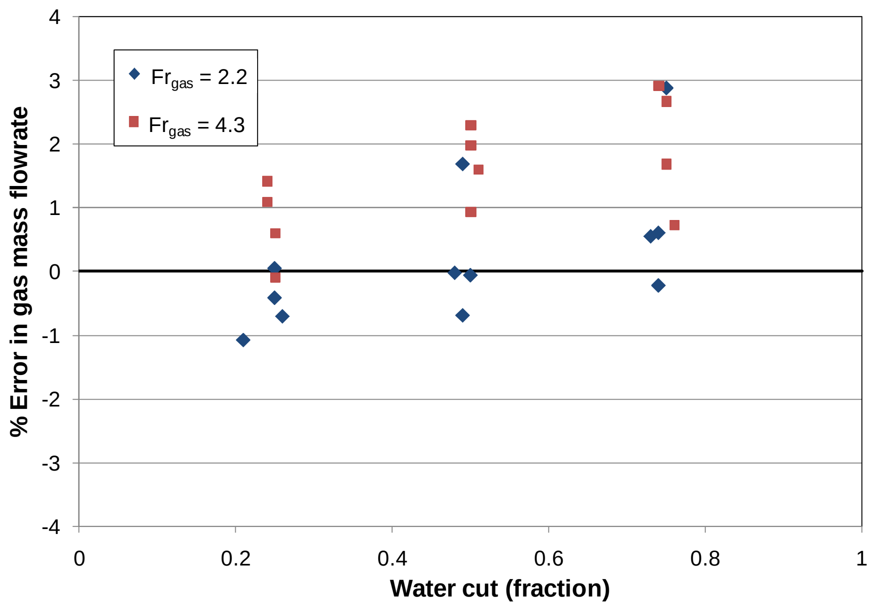

Figure 5 CEESI 2" data β = 0.6 (0.02 < X < 0.11) H: linear with water cut

Figure 9 of de Leeuw et al shows the errors using the correlation in ISO/TR 11583 on K-Lab data when the liquid consists of a mixture of water and hydrocarbon liquid. It is not clear how the correction was done, i.e. what value of H was used. Figure 10 of de Leeuw et al aims to improve upon ISO/TR 11583, but, as seen in 3.2.2, this is wrong: ISO/TR 11583 has to be followed in its entirety, not corrected in the way that de Leeuw et al corrects it.

3.3 The correlation for the pressure loss ratio

De Leeuw et al point out that according to ISO/TR 11583 the pressure loss ratio increases with β, but according to ISO 5167-4 [16] it decreases with increasing β. However, ISO 5167-4 includes the effect of subtracting the pressure loss that there would have been in a straight pipe. ISO/TR 11583 for reasons of ease of use does not do that (the definition is in its Table 1). If the formula in ISO/TR 11583 is used with the pipe loss removed it is in accordance with Figure C.1 of ISO 5167-4, towards the bottom of the band. See also Figure 6.

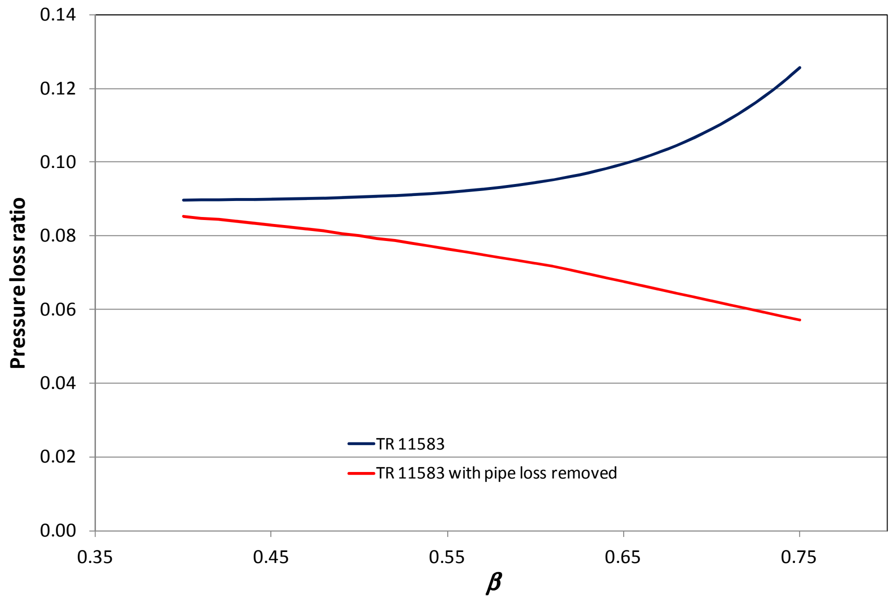

Figure 6 Pressure loss ratio: the equation as in ISO/TR 11583 and the same equation with the pipe pressure loss removed (friction factor λ = 0.012; loss to the mid-point of the permitted range in 6.4.5 of ISO/TR 11583)

In Figure 11 of de Leeuw et al the pressure loss at SINTEF appears surprisingly high, another reason to accept the CEESI data rather than the SINTEF data for the NAM Venturi tube; for the 12" Venturi tube tested at NEL the pressure loss ratio is very low (6 to 7% for β = 0.476): the Venturi tube has much too low a discharge coefficient.

The very poor results in Figure 12 of de Leeuw et al are caused by the problem with the Venturi tube (see 3.2.3).

The new data in [18] (see 6) include data with an additional downstream pressure tapping. The diffuser angle is 12° (outside the range in ISO/TR 11583), but when the data are analysed in accordance with Equations (6) – (8) and (10) – (12) the data nevertheless are within the uncertainty band given in ISO/TR 11583.

4 USING THE DRY-GAS DISCHARGE COEFFICIENT TO IMPROVE THE CORRELATION

It is striking that where the discharge coefficient in single-phase flow differs significantly from 1 the errors often move towards 0 as *X* increases. By way of illustration the errors for two Venturi tubes are given in Figure 7. These are rather extreme examples (outside de Leeuw et al's Figure 7) and yet the wet-gas errors are surprisingly satisfactory. It is possible that the big variation in dry-gas discharge coefficients (not seen in water) is suppressed by wet gas.

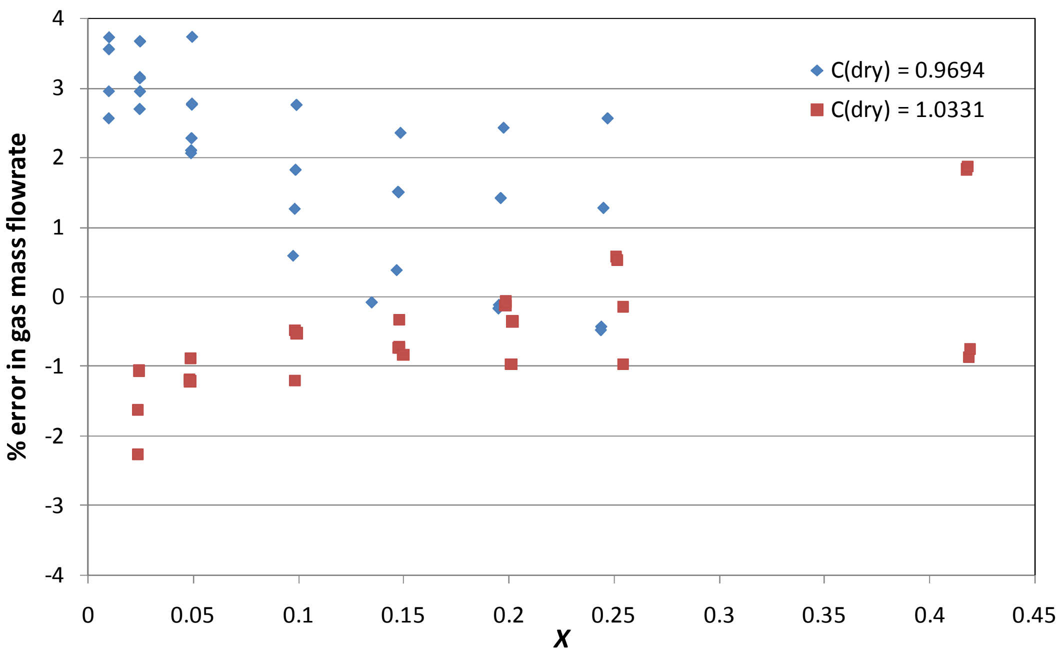

Figure 7 Errors on two Venturi tubes with dry-gas discharge coefficients about 3% away from 1.00: correction according to ISO/TR 11583

It is also possible to consider in a more systematic way how the dry-gas discharge coefficient affects the wet-gas results. It is clear how it affects them as *X* tends to 0. To consider the issue more broadly, suppose the measured gas mass flowrate in ISO/TR 11583 is multiplied by

$$1+(C_{dry}-1)\exp(-aX) \tag{13}$$

Then if *a* = 0 the correction method in de Leeuw et al is (at least to a very good approximation) obtained. Then over the derivation and validation database the standard deviation is 1.068% instead of 0.980% using ISO/TR 11583 without any extra term. So the fact that the errors in Figure 5 of de Leeuw et al are greater than those in Figure 4 of de Leeuw et al is not surprising (they have been increased by de Leeuw et al's correction). The minimum standard deviation using equation (13) is obtained with *a* = 11.25 and is 0.88693%. It is also possible to consider if it would be better to have

$$1+(C_{dry}-1)\left((1-b)\exp(-aX)+b\right) \quad (14)$$

The best fit is obtained with *a* = 12.8 and *b* = 0.05 and is 0.88682%: the inclusion of *b* is not a significant improvement; the inclusion of *a* is an improvement, but not consistent with the desire in ISO/TR 11583 to have an equation for uncalibrated Venturi tubes. Errors for the data in Figure 7 with TR 11583 equations with an additional term as in equation (13) with *a* = 11.25 are shown in Figure 8.

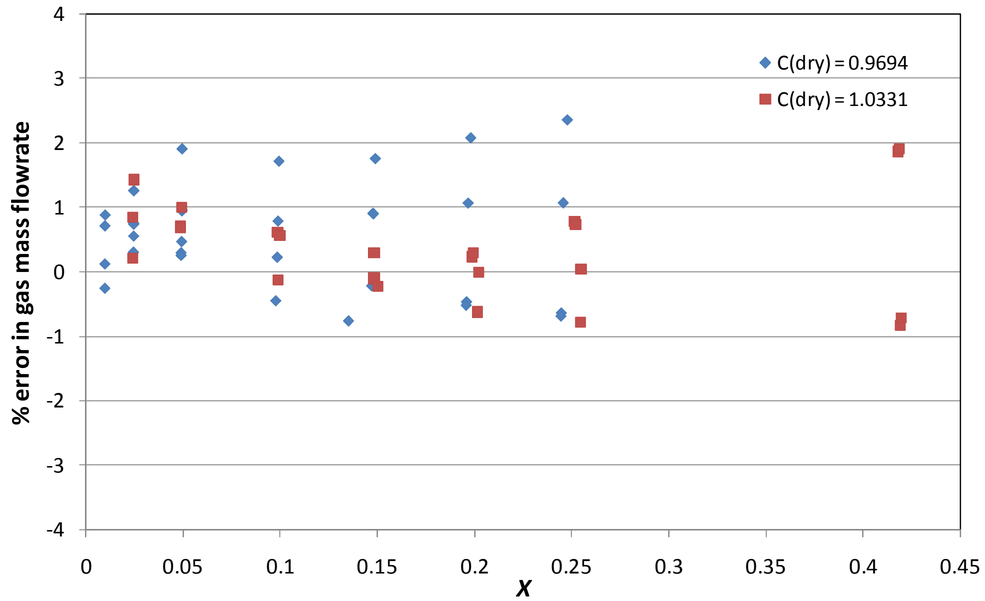

Figure 8 Data as in Figure 7 using TR 11583 equations with an additional term as in Equation (13) with *a* = 11.25

Errors for derivation and validation data with TR 11583 equations with an additional term as in equation (13) with *a* = 11.25 are shown in Figure 9.

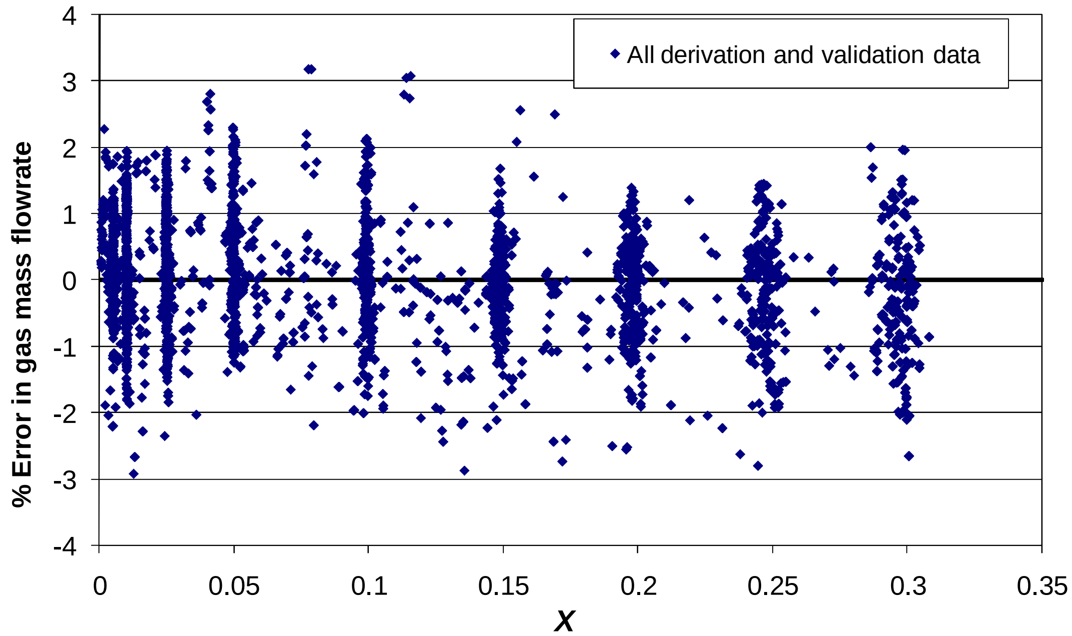

Figure 9 Derivation and validation data using TR 11583 equations with an additional term as in Equation (13) with *a* = 11.25

So the correction method used by de Leeuw et al does not improve the fit; an improved correlation for Venturi tubes calibrated in dry gas is possible; the equation in ISO/TR 11583 is for uncalibrated Venturi tubes.

5 TEST WORK

5.1 General

One of the needs has been to check that the effect of liquid viscosity is small over the range of liquids found in common wet-gas applications. A liquid with similar surface tension to kerosene but smaller viscosity was not available for test. So three 4" Venturi tubes with β = 0.4, 0.6 and 0.75 were tested in the NEL National Standard wet gas facility with nitrogen and velocite. The Venturi tube with β = 0.6 was also tested with nitrogen and gasoil. The three Venturi tubes had previously been tested with nitrogen and kerosene (and indeed in the case of β = 0.6 and β = 0.75 with argon and kerosene and with nitrogen and water). Kerosene, gasoil and velocite have kinematic viscosities of approximately 2.5 cSt, 6.3 cSt and 23.5 cSt, respectively, at 20 °C.

Data were collected at three nominal static pressures, 15 bar, 30 bar and 60 bar. No data are presented for 60 bar and β = 0.4.

The over-readings are given in Appendix B.

5.2 Deviations from ISO/TR 11583 equation

The errors in gas mass flowrate using the ISO/TR 11583 equation are given in Figures 10 - 13. The data for β = 0.6 for each liquid are given first, then the data for the other values of β.

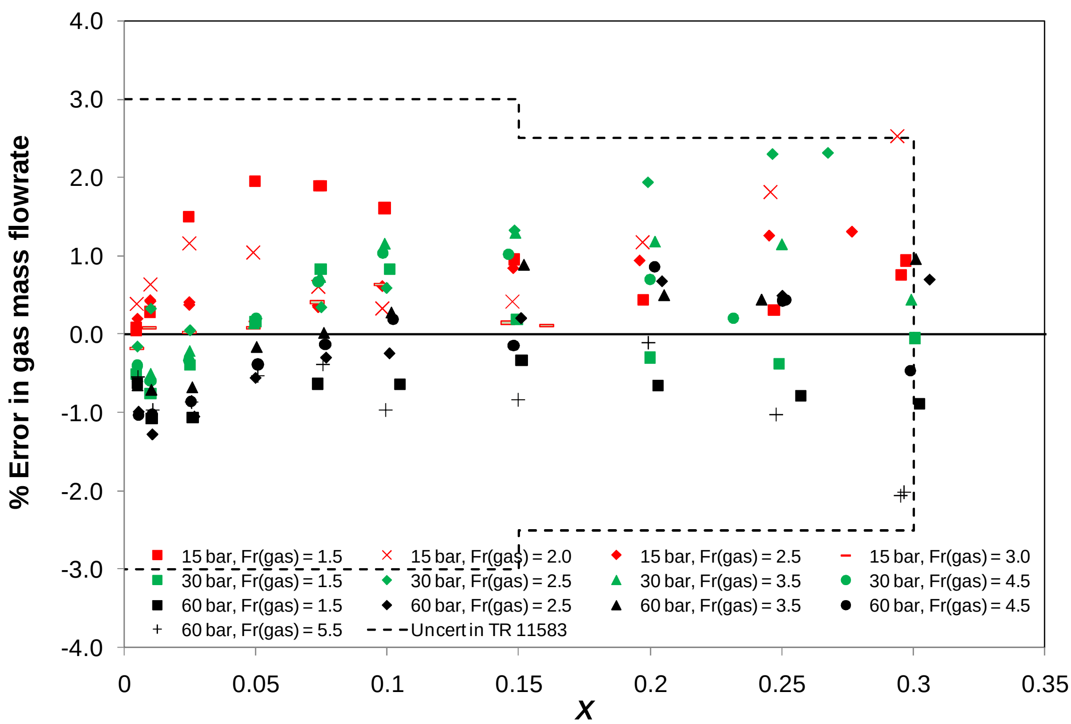

Figure 10 Error in gas mass flowrate using the ISO/TR 11583 Equation: nitrogen and gasoil: β = 0.6

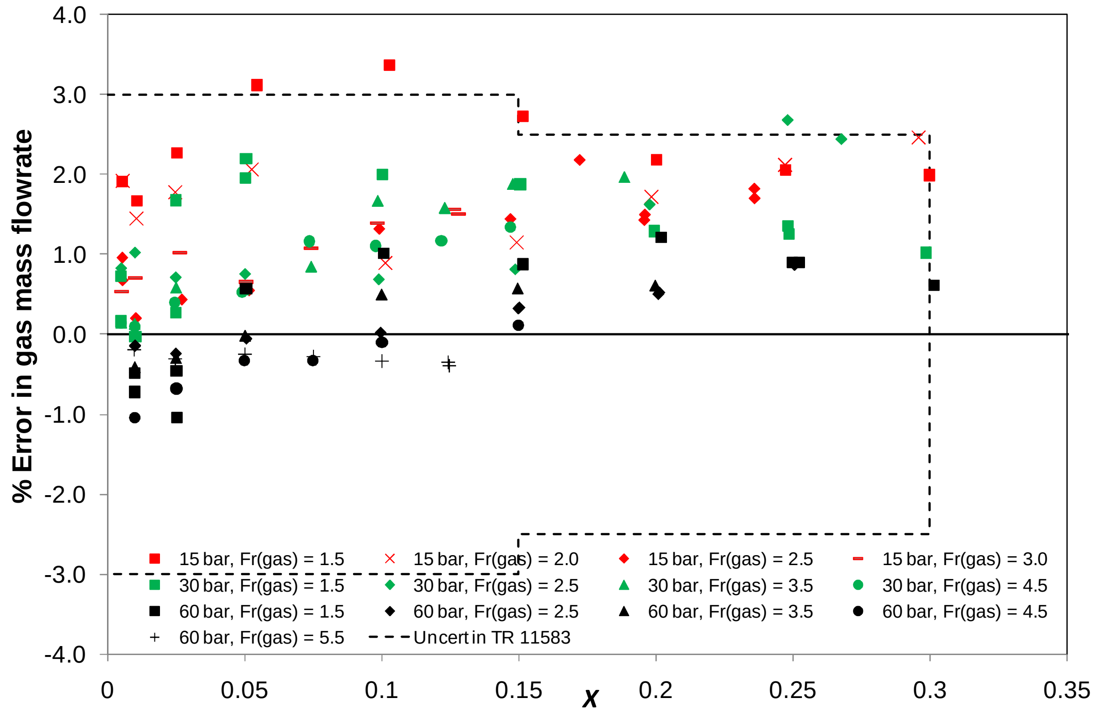

Figure 11 Error in gas mass flowrate using the ISO/TR 11583 Equation: nitrogen and velocite: $\beta = 0.6$

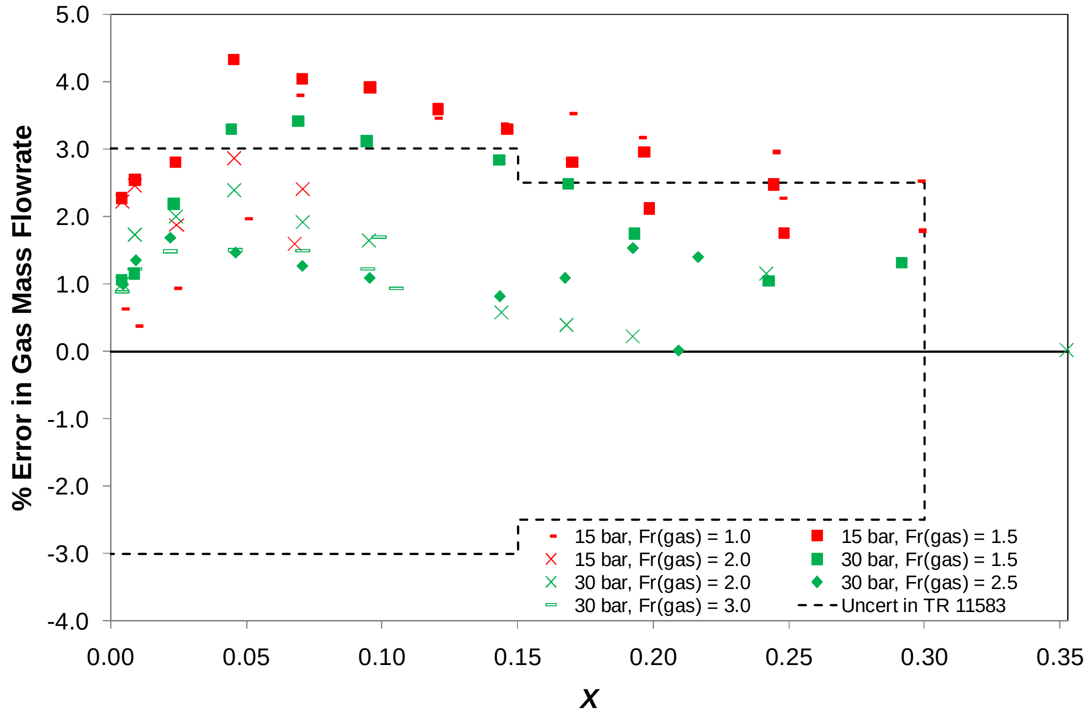

Figure 12 Errors in gas mass flowrate using the ISO/TR 11583 Equation: nitrogen and velocite: $\beta = 0.4$

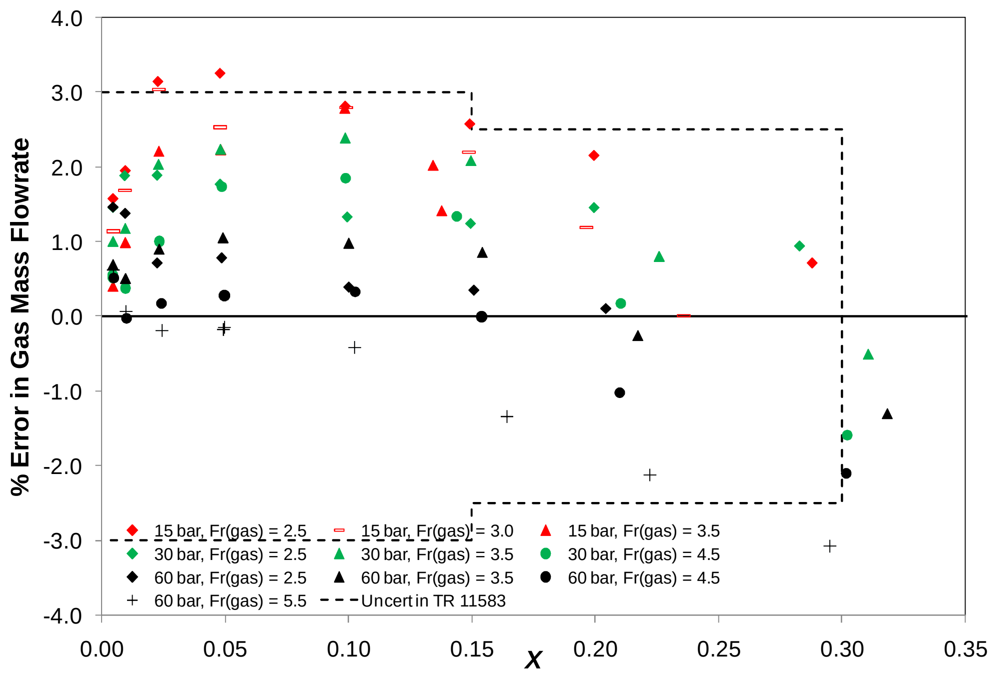

Figure 13 Errors in gas mass flowrate using the ISO/TR 11583 Equation: nitrogen and velocite: $\beta = 0.75$

ISO/TR 11583 lists the fluids used to create the correlation and then adds 'It is possible that the equations do not apply to liquids significantly different from those tested, particularly to highly viscous liquids'. However, the errors using the ISO/TR 11583 correlation outside its range are remarkably satisfactory. For the gasoil set 99% of the points lie within the error bands that would have been expected for less viscous liquids. Of the velocite data excluding only the data for Fr_{gas} of 1.5 or below at 15 bar 96% of the errors lie within the error bands. Presumably for Fr_{gas} of 1.5 or below at 15 bar too much of the velocite adheres to the walls.

5.3 Deviations from the de Leeuw equation

The errors in gas mass flowrate using the de Leeuw equation are given in Figures 14 - 17.

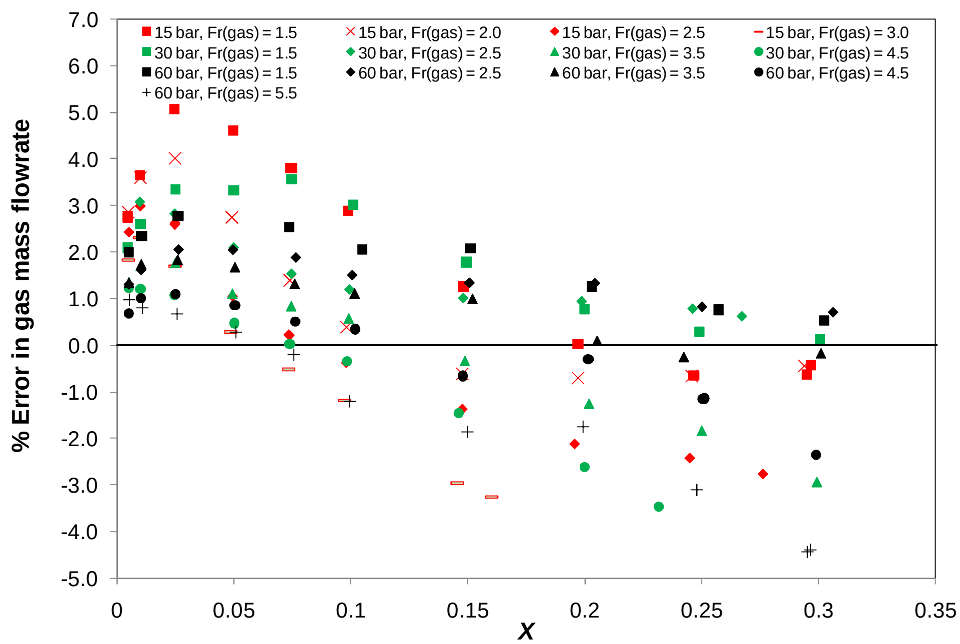

Figure 14 Errors in gas mass flowrate using the de Leeuw Equation: nitrogen and gasoil: $\beta = 0.6$

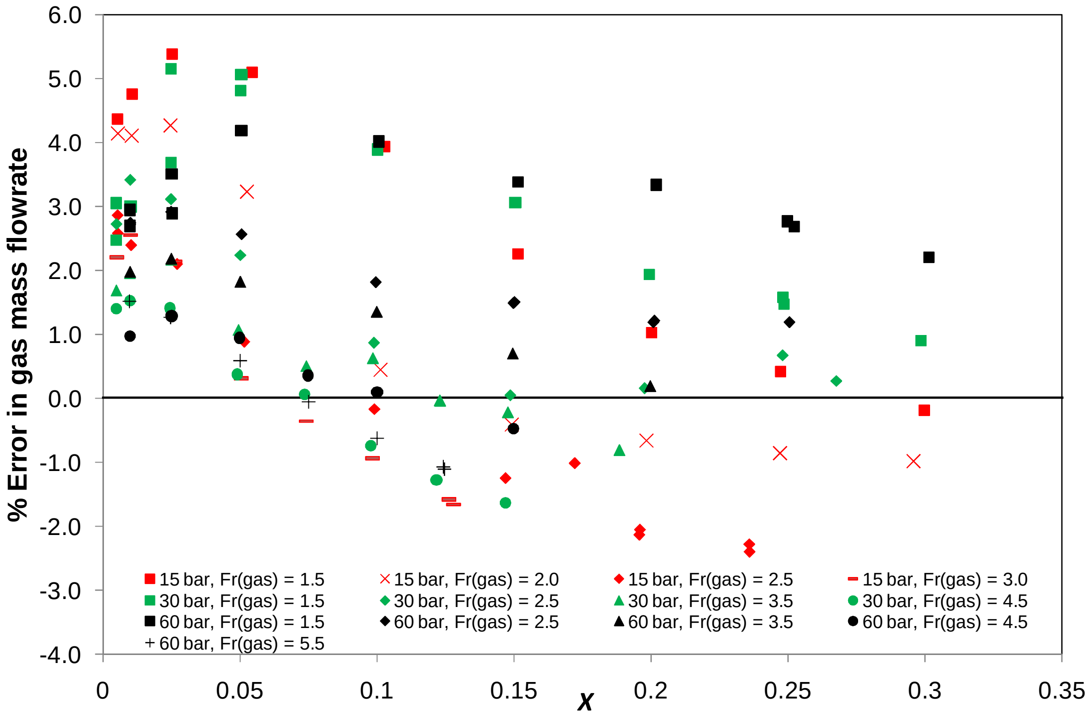

Figure 15 Errors in gas mass flowrate using the de Leeuw Equation: nitrogen and velocite: $\beta = 0.6$

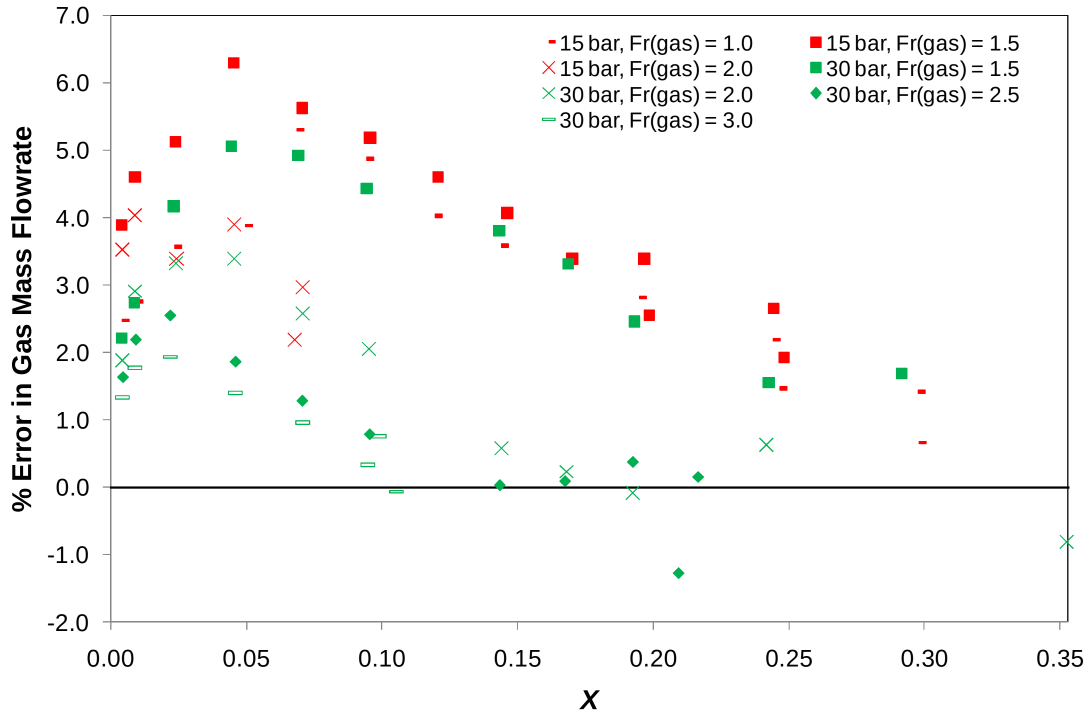

Figure 16 Errors in gas mass flowrate using the de Leeuw Equation: nitrogen and velocite: $\beta = 0.4$

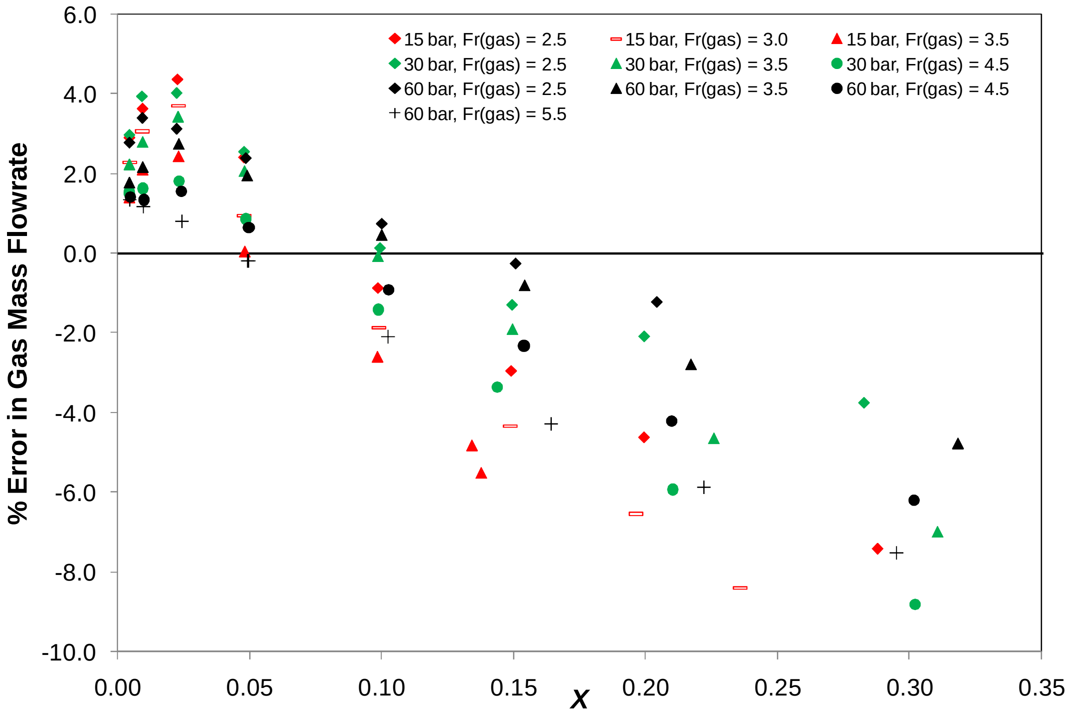

Figure 17 Errors in gas mass flowrate using the de Leeuw Equation: nitrogen and velocite: $\beta = 0.75$

The standard deviation of the errors using the de Leeuw equation is on average around twice that of the standard deviation using the ISO/TR 11583 equation.

5.4 Errors using ISO/TR 11583 with *X* determined from the pressure loss ratio

Using the downstream pressure tapping and equations (6) – (8) and (10) – (12) the errors in gas mass flowrate in Figures 18-21 were obtained. All the points lie within the error bands in ISO/TR 11583.

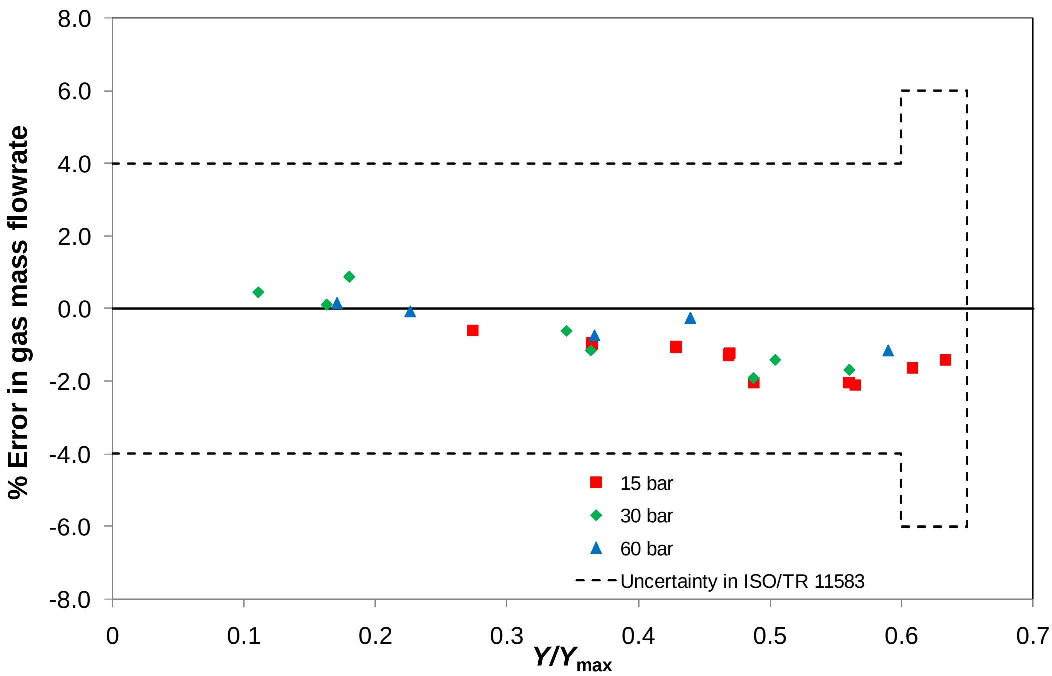

Figure 18 Errors in gas mass flowrate using the ISO/TR 11583 Equation with downstream tapping to measure pressure loss ratio: nitrogen and gasoil: $\beta = 0.6$

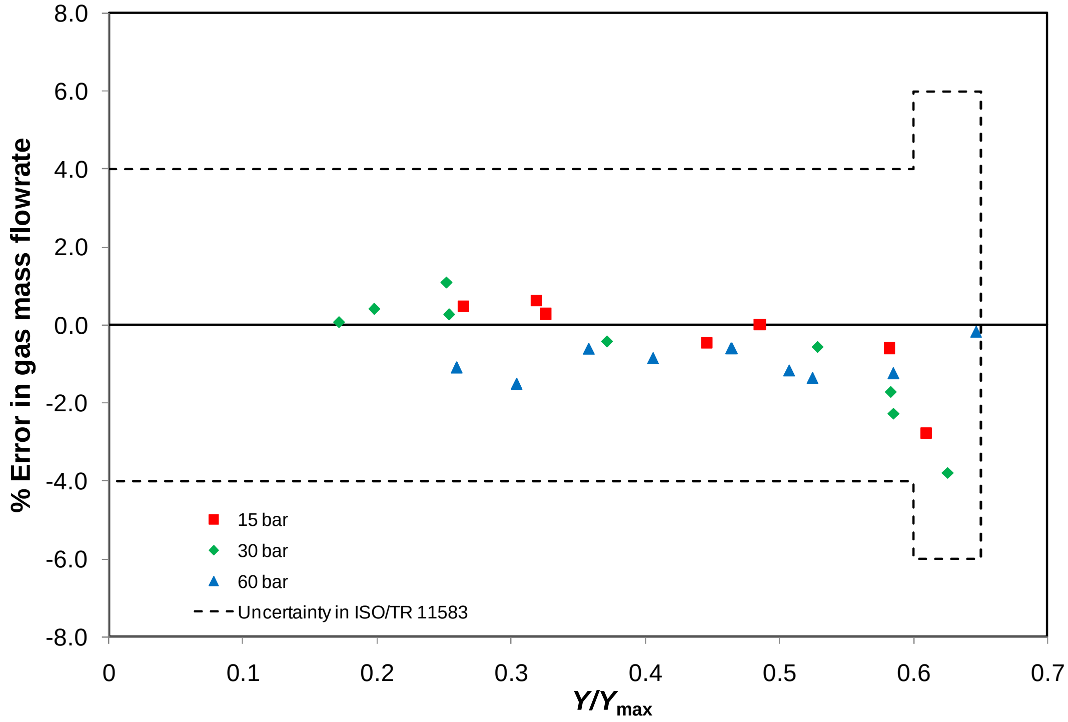

Figure 19 Errors in gas mass flowrate using the ISO/TR 11583 Equation with downstream tapping to measure pressure loss ratio: nitrogen and velocite: $\beta = 0.6$

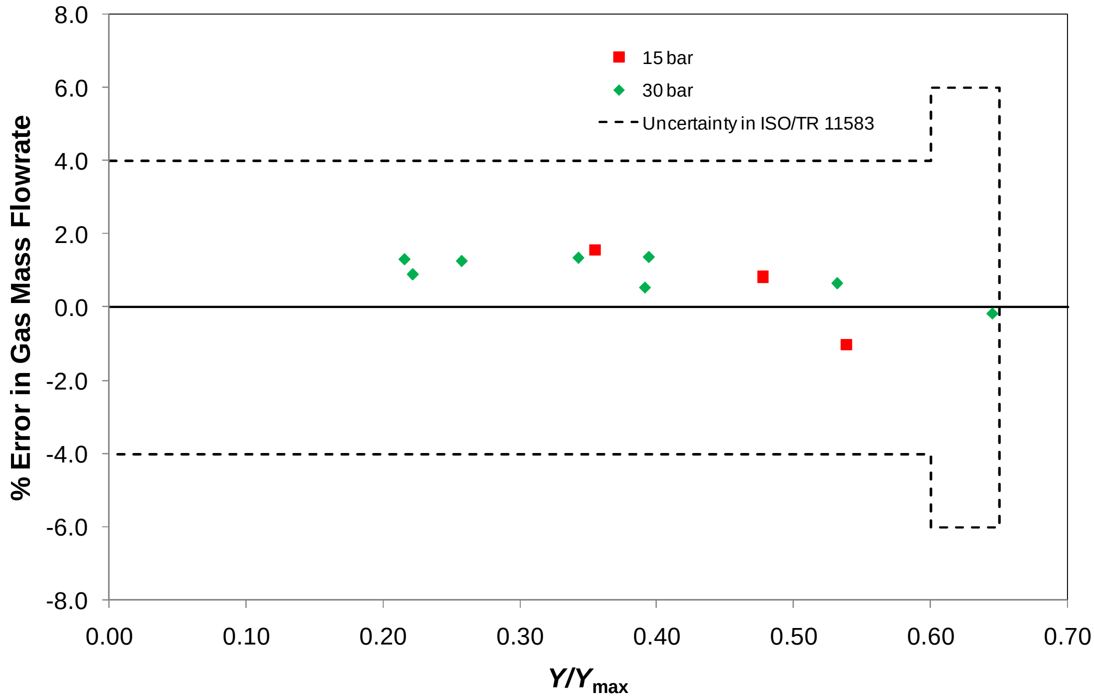

Figure 20 Errors in gas mass flowrate using the ISO/TR 11583 Equation with downstream tapping to measure pressure loss ratio: nitrogen and velocite: $\beta = 0.4$

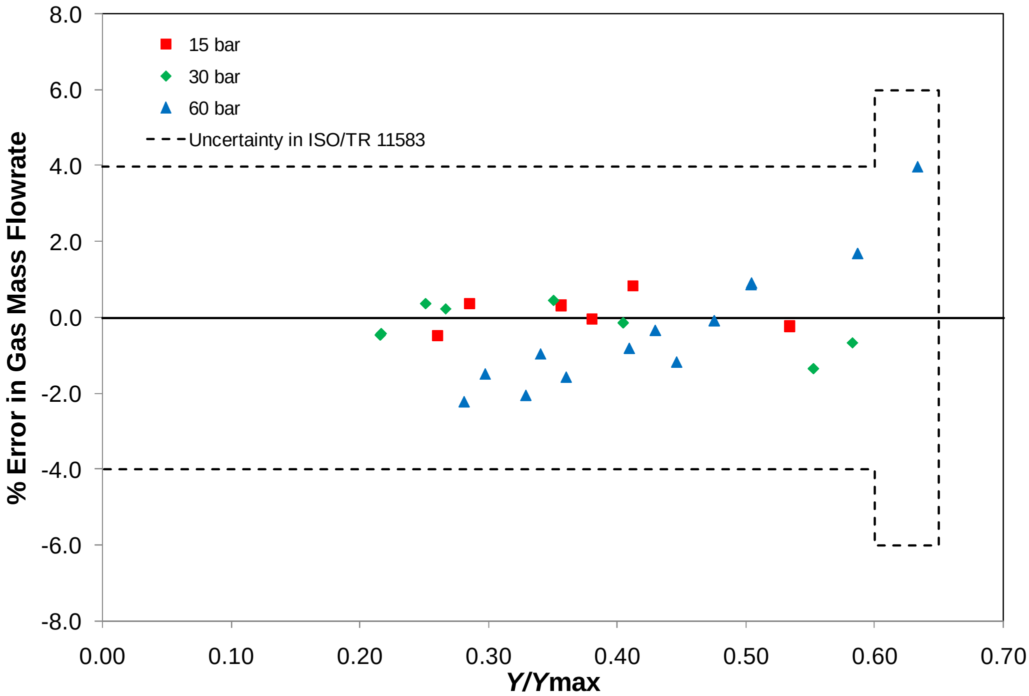

Figure 21 Errors in gas mass flowrate using the ISO/TR 11583 Equation with downstream tapping to measure pressure loss ratio: nitrogen and velocite: β = 0.75

5.5 Analysis

To evaluate the difference between the errors in gas mass flowrate using nitrogen and velocite and that using nitrogen and kerosene the nitrogen/kerosene data were fitted as a function of X for each value of pressure and Fr_{gas} and calculated values subtracted from the nitrogen/velocite data. The same exercise was carried out for nitrogen/gasoil data: in this case at 60 bar the difference between the values of Fr_{gas} in nitrogen/gasoil and nitrogen/kerosene at the same nominal value of Fr_{gas} was such that corrections for the effect of this difference were applied. The differences in error are given in Figures 22 – 25.

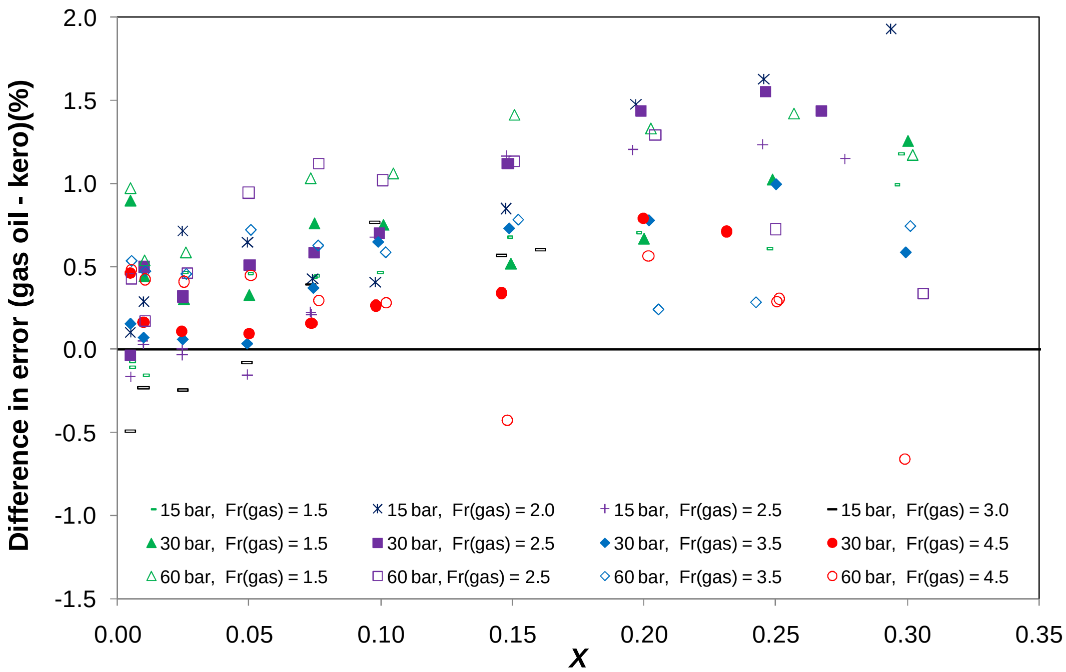

Figure 22 Difference in the error using the ISO/TR 11583 equation when gasoil replaced kerosene: β = 0.6

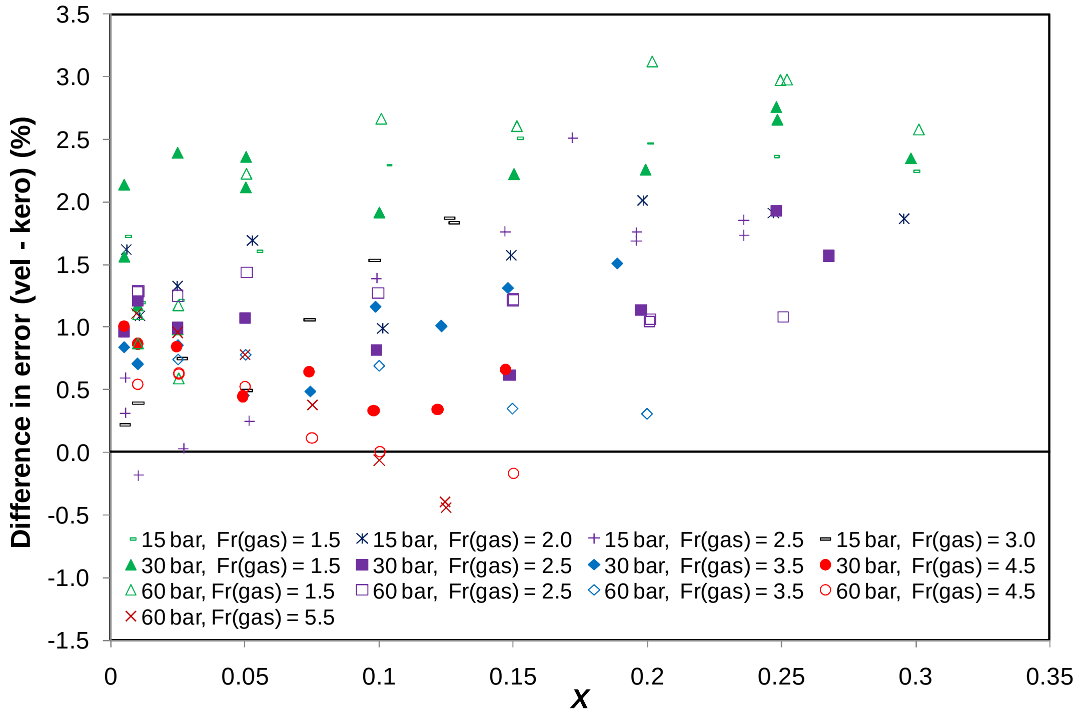

Figure 23 Difference in the error using the ISO/TR 11583 equation when velocite replaced kerosene: $\beta = 0.6$

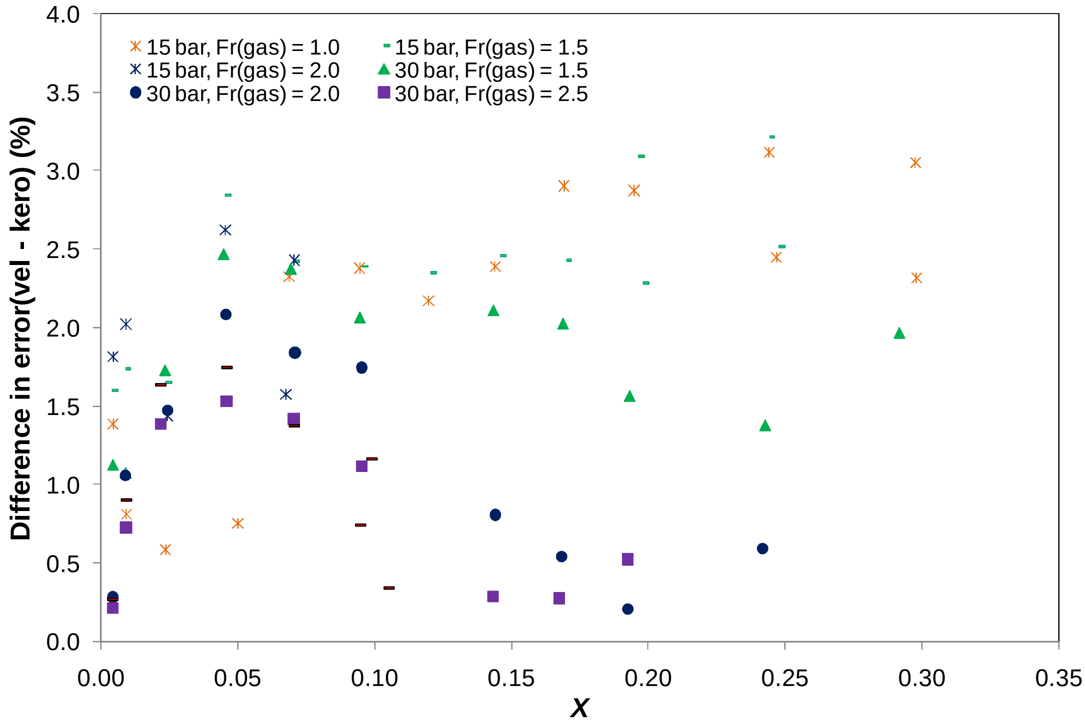

Figure 24 Difference in the error using the ISO/TR 11583 equation when velocite replaced kerosene: $\beta = 0.4$

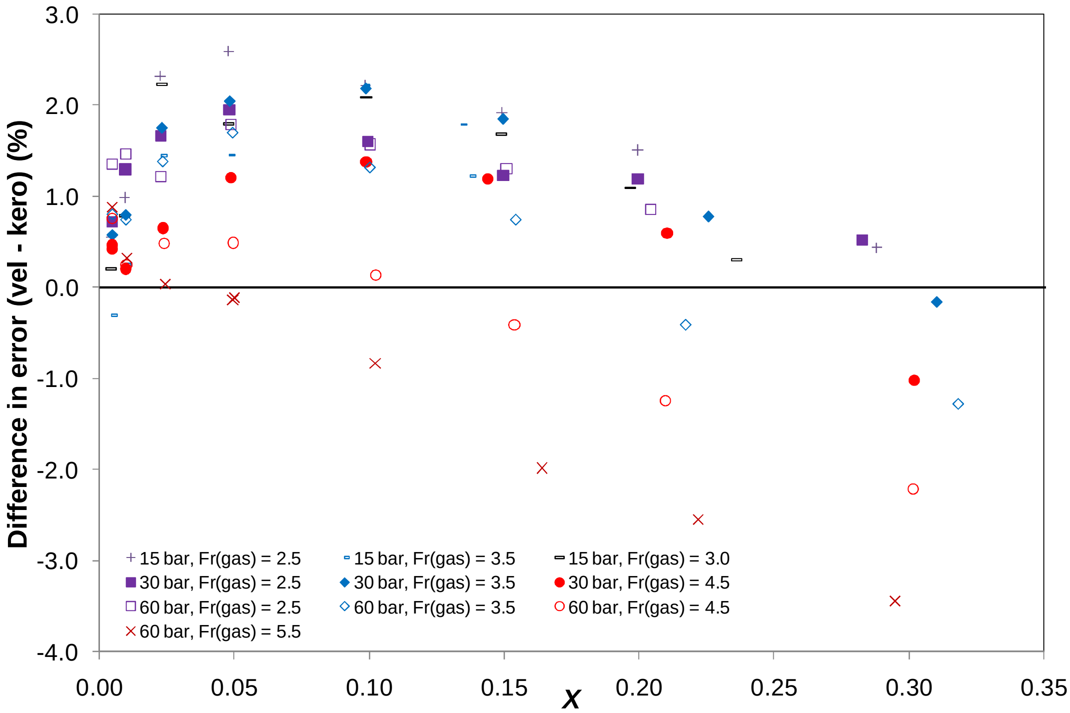

Figure 25 Difference in the error using the ISO/TR 11583 equation when velocite replaced kerosene: $\beta = 0.75$

Although there is a substantial scatter in Figures 22 - 25 at least for lower X the error increases as Fr_{gas} reduces and is fairly constant for X from 0.025 to 0.1. It appears that at least for X up to 0.1 the main change to the flow is that there is a layer of oil on the wall and so C takes a lower value than that in equation (6). This is consistent with the model in ISO/TR 11583, in which there is a wet-gas discharge coefficient. To provide an approximate correction for the equation the average of the following was determined for X up to a nominal value of 0.1:

$$d_{\text{vel/kero}} = \frac{e_{\text{vel}} - e_{\text{kero}}}{\min\left(1, \sqrt{\dfrac{X}{0.016}}\right)}$$

where e_{vel} is the percentage error using velocite and nitrogen and e_{kero} that using kerosene and nitrogen. The averages are in Figure 26. The fitted equation is

$$d_{\text{vel/kero}} = 3.21\exp(-0.33 Fr_{\text{gas}})$$

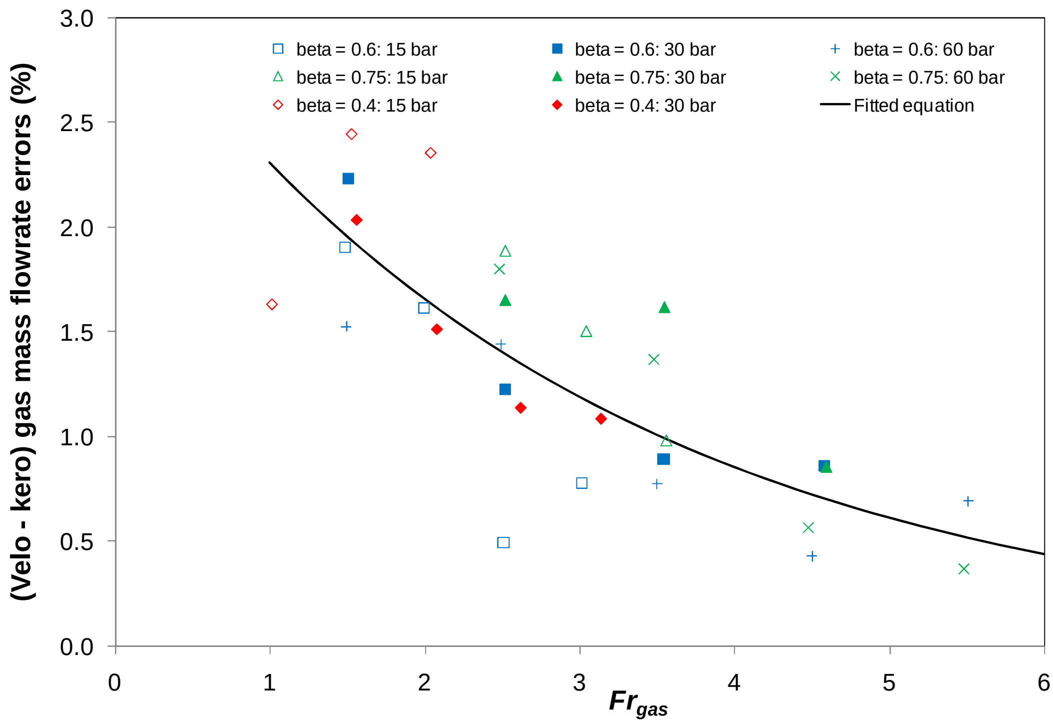

Figure 26 Average shifts in gas mass flowrate for *X* up to a nominal value of 0.1 when kerosene is replaced by velocite

A similar calculation was carried out for the gasoil data. The data are shown in Figure 27. The fit is

$$d_{\text{gasoil/kero}} = 1.03\exp(-0.33 Fr_{\text{gas}})$$

There is a dependence on β in this case, but the effect is quite small. The effect of changing from kerosene to gasoil is 31% of the effect of changing from kerosene to velocite.

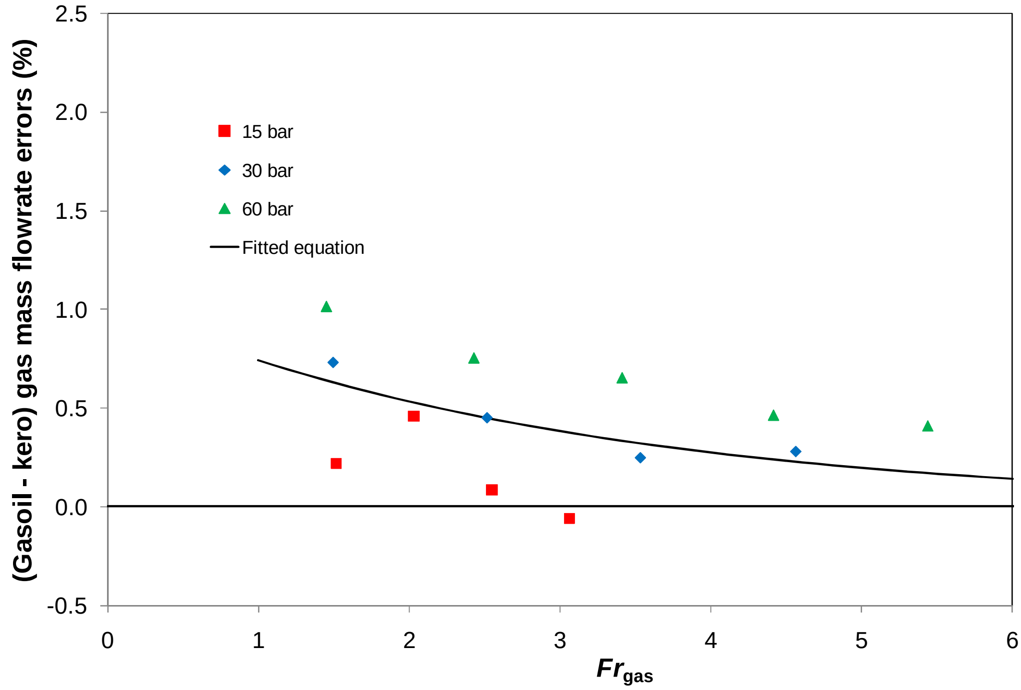

Figure 27 Average shifts in gas mass flowrate for X up to a nominal value of 0.1 when kerosene is replaced by gasoil

If the ISO/TR 11583 equation is used with

$$C_{\text{wet}} = \frac{1 - 0.0463 e^{-0.05 Fr_{\text{gas,th}}} \min\left(1, \sqrt{\frac{X}{0.016}}\right)}{1 + a \exp(-0.33 Fr_{\text{gas}}) \min\left(1, \sqrt{\frac{X}{0.016}}\right)} \tag{15}$$

where a = 0.0321 for velocite and 0.0103 for gasoil, then the errors in Figures 28 - 31 are obtained.

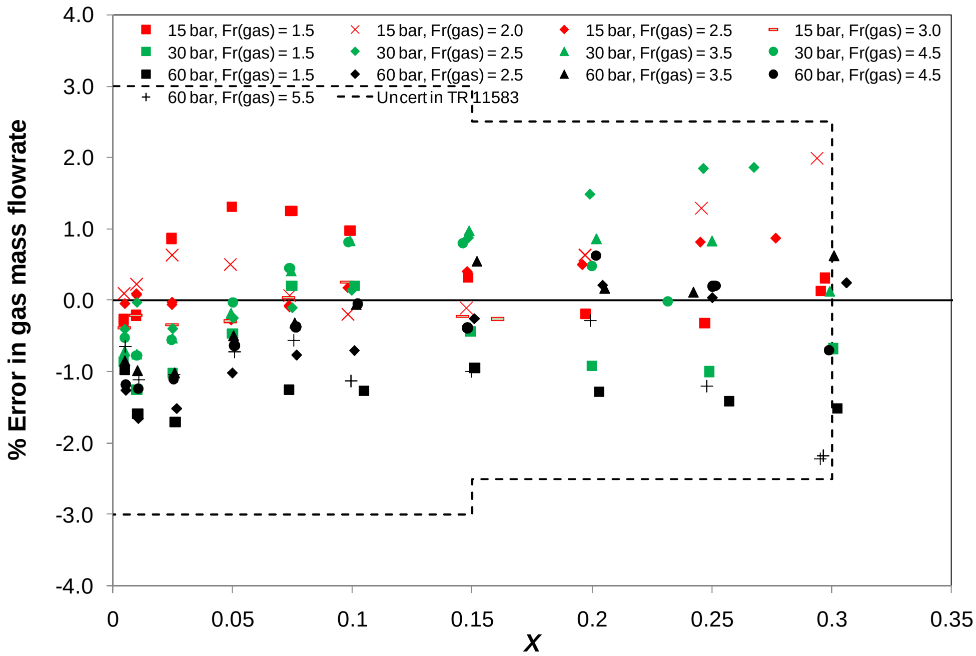

Figure 28 Errors in gas mass flowrate using the ISO/TR 11583 Equation with *C* given by C_{wet} as in equation (15): nitrogen and gasoil: β = 0.6

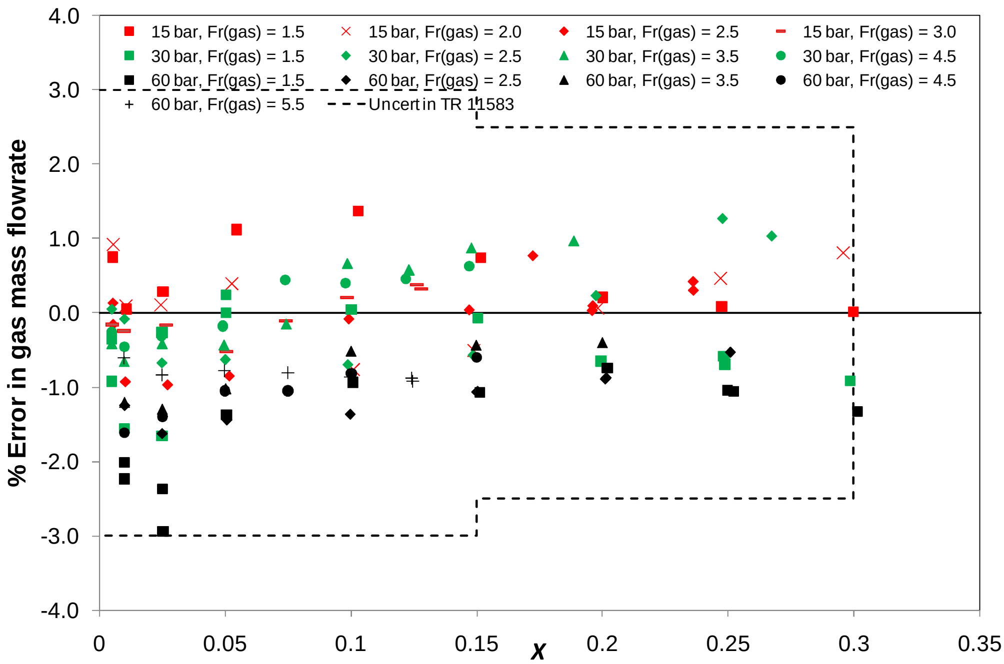

Figure 29 Errors in gas mass flowrate using the ISO/TR 11583 Equation with *C* given by C_{wet} as in equation (15): nitrogen and velocite: β = 0.6

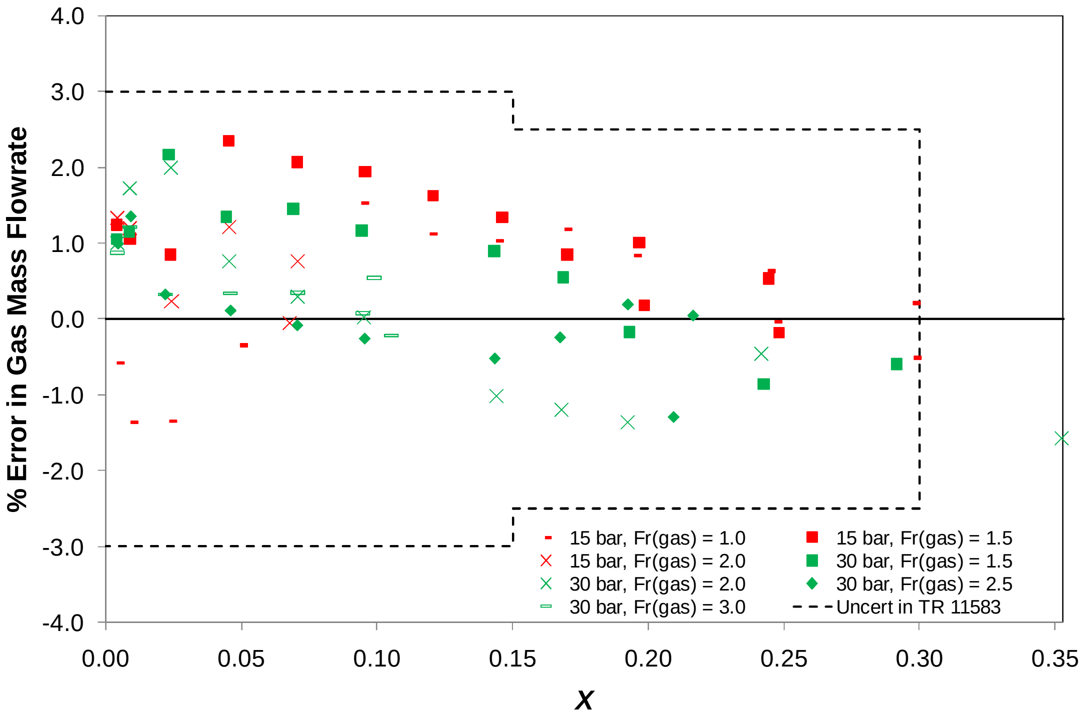

Figure 30 Errors in gas mass flowrate using the ISO/TR 11583 Equation with *C* given by C_{wet} as in equation (15): nitrogen and velocite: $\beta = 0.4$

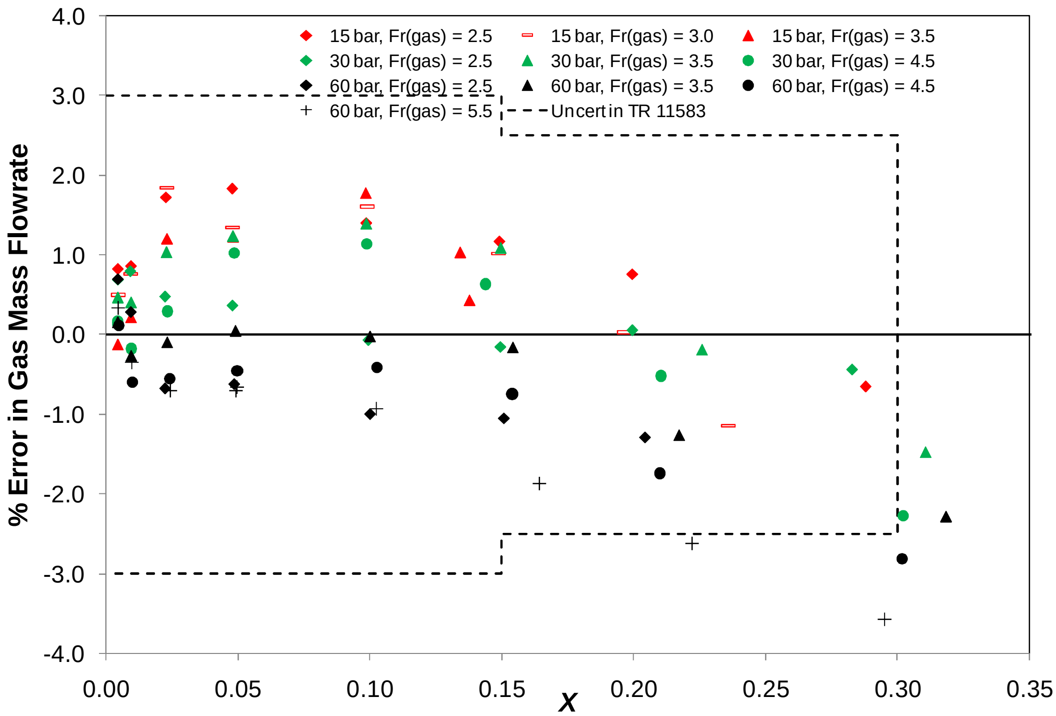

Figure 31 Errors in gas mass flowrate using the ISO/TR 11583 Equation with *C* given by C_{wet} as in equation (15): nitrogen and velocite: $\beta = 0.75$

It is not intended to introduce Equation (15) to ISO/TR 11583. It has been determined in order to quantify the effect of liquid viscosity. It has also shown that the main effect of liquid viscosity is to change the wet-gas discharge coefficient. If an equation for wet-gas flow with more viscous oils were required then further analysis would be required since Equation (15) alone appears insufficient for Fr_{gas} = 4.5 or 5.5 at high *X*.

5.6 Horizontal tappings

Given the interest in measuring wet steam (see final sentence of Appendix A) it was important to check that if horizontal tappings instead of vertical tappings were used ISO/TR 11583 would still prove satisfactory. Figures 32 and 33 (using horizontal tappings) are not very different from Figures 30 and 31 (using vertical tappings).

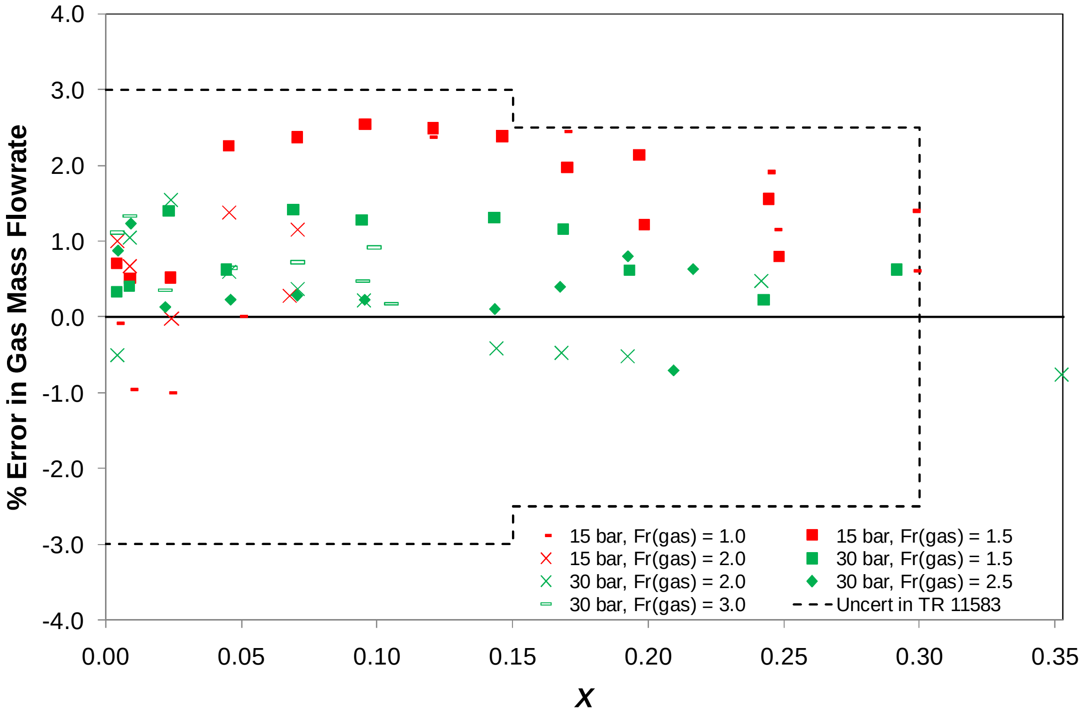

Figure 32 Errors in gas mass flowrate using the ISO/TR 11583 Equation with *C* given by C_{wet} as in equation (15): nitrogen and velocite: $\beta = 0.4$: horizontal tappings

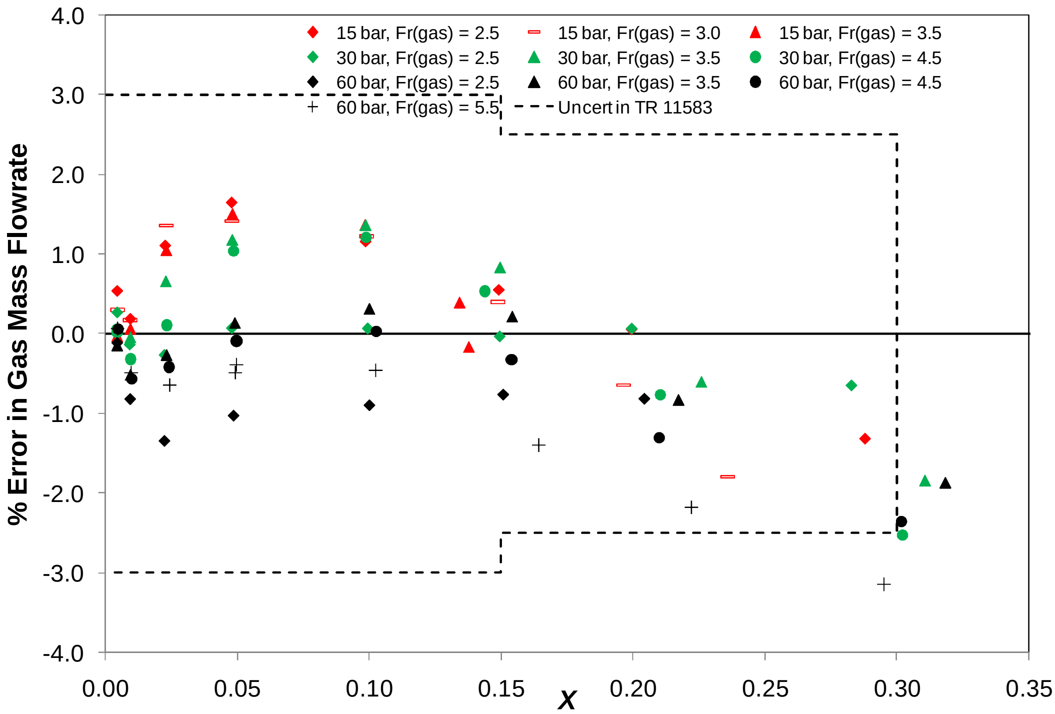

Figure 33 Errors in gas mass flowrate using the ISO/TR 11583 Equation with *C* given by C_{wet} as in equation (15): nitrogen and velocite: $\beta = 0.75$: horizontal tappings

6 OTHER PAPERS PUBLISHED SINCE THE BALLOT ON ISO/TR 11583 STARTED

Two important papers (besides [6]) have been published since the ballot on ISO/TR 11583 started: in October 2011 Steven et al [17] published data on wet-gas flow through orifice plates: the liquid was oil, water or a water/oil mixture. Both the oil and the water data are consistent with the uncertainty statements made in ISO/TR 11583: the errors in the oil data are within 2%; the water data are biased but the errors are less than 3%. It should be possible in due course to improve ISO/TR 11583 to include the revised equation from this paper.

In June 2012 Steven et al [18] published data on wet-gas flow through two 8-inch β = 0.6 Venturi tubes. The natural gas/oil data from the "ISO-compliant" Venturi tube (its upstream tapping is 1*D* from the start of the convergent, rather than 0.5*D*, but the effect of this is small) are consistent with ISO/TR 11583. Natural gas/oil data from a non-compliant Venturi tube (the radius of the corner upstream of the throat tapping is 14 times the maximum permitted for the compliant Venturi tube) are consistent with ISO/TR 11583. In the paper it is stated and graphs are given showing that a significant fraction of the natural gas/water data for the non-compliant Venturi tube lie outside the range promised by ISO/TR 11583. On the basis of these graphs it is stated that '<u>the results strengthen the position of ISO where they state that ISO TC30 TR11583 is not an appropriate document for use in the oil and gas industry</u>'. However, if the uncorrected errors in the same graphs are correct then the corrected errors are within the band promised by ISO/TR 11583. There is insufficient information given to enable the data for wet gas with a mixture of liquids to be recalculated, but it appears very likely that if the corrected errors were calculated correctly (a simple linear fit for H in terms of water liquid ratio should be used) that the errors would lie within the range given in ISO/TR 11583.

7 CONCLUSIONS

This paper has described the history of ISO/TR 11583:2012.

Each of the criticisms of the Venturi-tube correlations in the TR has been answered: the main criticism that it does not fit data outside the derivation and regression sets has been investigated:

- For the NAM Venturi tube ISO/TR 11583 fits the data collected at CEESI (which are different from the earlier data from SINTEF)
- For the K-Lab data it fits the vast majority of the data (a small number of the data points are interesting)
- It fails to fit the 12" Venturi tube data because it had a dry-gas discharge coefficient of 0.936; it is unreasonable to expect to fit such a Venturi tube
- It does fit the recently published data for the "ISO-compliant" 8" Venturi tube from CEESI
- In the opinion of the author of this paper it also fits the recently published data for the non-ISO-compliant 8" Venturi tube from CEESI

The predicted pressure loss ratio in Venturi tubes in dry gas according to ISO/TR 11583 is consistent with the prediction in ISO 5167-4.

The claim that the ISO/TR 11583 Venturi-tube correlation can be "improved" in a simple manner using the dry-gas discharge coefficient and the correlation then discredited has been shown to be wrong. A better way of improving the correlation using the dry-gas discharge coefficient has been described.

New data have been collected with Venturi tubes in nitrogen and gasoil and in nitrogen and velocite. For the nitrogen/gasoil data 99% of the points lie within the error bands that would have been expected for less viscous liquids. Of the nitrogen/velocite data excluding only the data for Fr_{gas} of 1.5 or below at 15 bar 96% of the errors lie within the error bands. Presumably for Fr_{gas} of 1.5 or below at 15 bar too much of the velocite adheres to the walls.

It is not intended to introduce a Venturi-tube correlation explicitly covering more viscous liquids to ISO/TR 11583. It was determined in order to quantify the effect of liquid viscosity. It has also been shown that the main effect of liquid viscosity is to change the wet-gas discharge coefficient.

Given the need to measure wet steam with Venturi tubes, it has been shown that the errors using horizontal tappings are not very different from those using vertical tappings.

In the CEESI wet-gas data for orifice plates using oil and water as the liquids both the oil and the water data are consistent with the statements made in ISO/TR 11583: the errors in the oil data are within 2%; the water data are biased but the errors are less than 3%.

ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the National Measurement Office's Engineering and Flow Programme, under the sponsorship of the United Kingdom Department for Business, Innovation and Skills.

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We would like to thank CEESI for the release of their data which were used in this paper.

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NOTATION

C	Discharge coefficient
C_{Ch}	Chisholm coefficient [Eqn (5)]
d	Diameter of throat of Venturi tube
D	Upstream diameter of Venturi tube
Fr_{gas}	Gas densiometric Froude number [Eqn (3)]
g	Acceleration due to gravity
H	Function of the surface tension of the liquid (see 2.3.2)
L_{down}	Distance between the downstream end of the Venturi tube divergent section (measured from the end of the cone not the flange) and the downstream pressure tapping used to measure the pressure loss
p	Absolute static pressure of the fluid
q_m	Mass flowrate
X	Lockhart-Martinelli parameter [Eqn (2)]
β	Diameter ratio: $\beta = d/D$
Δp	Differential pressure
$\Delta\varpi$	Pressure loss (without correction for the pressure loss that would have taken place if the Venturi tube had not been present)
ε	Expansibility [expansion] factor
ρ	Density of the fluid
ϕ	Over-reading correction factor [Eqn (1)]

Subscripts 1 and 2 denote the values at the upstream and throat tapping planes respectively

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APPENDIX A

DETAILED REPLY TO EACH POINT IN [6] referred to as de LEEUW et al

Reply to 3 of de Leeuw et al.

1 In the text of ISO/TR 11583 (outside the references) the word 'model' is only used with reference to the work of Chisholm and of Murdock. More modern work is referred to as either an equation or a correlation.

2 The equations for both the Venturi over-reading and the orifice over-reading are based on data mainly from one lab (NEL in the former case, CEESI in the latter) with supporting data from another and a small amount of data beyond that. If the community decides to share its data to a larger extent that will improve equations. The de Leeuw equation (often used for the Venturi overreading) is based on one set of data from one Venturi tube in one lab: the equations in ISO/TR 11583 are based on much larger databases.

3 The understanding of the effect of the physical properties of hydrocarbon fluids is incomplete and this is reflected in ISO/TR 11583. The fluids on which the correlation has been tested are listed. The effect of gas density is covered in ISO/TR 11583. Tests have been undertaken (see 5) to examine the effect of liquid viscosity. Many hydrocarbons have similar surface tension. ISO/TR 11583 is written in terms of mass flow.

4 On the basis of the data it appears that the minimum number of parameters has been used.

5 In the theoretical limiting cases the correlation does, I think, give good results:

a) As X tends to 0 the equation tends to the dry-gas equation with C = 1, typical of dry-gas Venturi tubes: the mean value of the dry-gas discharge coefficient for all the points in the wet-gas database used by NEL is 0.999; figure 7 of de Leeuw et al appears to have a similar mean.

b) As $Fr_{\text{gas}} \rightarrow \infty$ $\mathbf{n} \rightarrow 0.583 - 0.18\beta^2$, which takes values in the range 0.482 to 0.554, much closer to the theoretical value of 0.5 than de Leeuw's value of 0.606.

c) $\phi \geq 1 + X$.

d) In dense phase $\rho_{\text{gas}} = \rho_{\text{liquid}}$ and so $Fr_{\text{gas,th}} \rightarrow \infty$ and $C \rightarrow 1$. Moreover, $\phi = 1 + X$, in accordance with the theoretical limit.

6 The WG would have been happy to receive technical comments to improve ISO/TR 11583. In practice the comments from some countries did not provide proposed revisions.

7 In flow measurement it is common practice for discharge coefficient to depend on Reynolds number. Here it depends on Froude number.

8 The correlation is based on two-component data. There is only one set of data on three-component flow in the public domain that can be analysed. The correlation fits these data (see 3.2.4).

9 The report gives a correlation based on available data.

10 Venturi tubes of the same quality as those in ISO 5167-4 are required: see 6.2 of ISO/TR 11583. So according to Table B.2 of ISO 5167-4 C should be in the range 0.98 to 1.04. In practice the discharge coefficient range in ISO 5167-4 is a little high: most commercial Venturi tubes are in the range 0.98 to 1.02.

The location of the third tapping has been specified (6.4.5 of ISO/TR 11583). See 3.3. There is no contradiction with ISO 5167-4.

11 ISO/TR 11583 is essentially about the use of Venturi tubes and orifice plates, and so the sections on liquid measurement are brief. Reference is made to papers by van Maanen and by de Leeuw et al both from 2001. Comments that were submitted on the draft of ISO/TR 11583 were brief and contained no ‘Proposed change by the MB’.

12 The correlation is not a ‘pure empirical data fit’: the difference between the wet-gas discharge coefficient and the dry-gas discharge coefficient is probably due to the presence of a liquid layer on the wall [19] that suppresses humps in the data and reduces *C*. The correlation does have the correct limiting behaviour: 1.00 is a good approximation of the dry-gas discharge coefficient. The mean value of the dry-gas discharge coefficient for all the points in the wet-gas database used by NEL is 0.999. Figure 7 of de Leeuw et al appears to have a similar mean.

13 The differential pressure should indeed be much lower than the line pressure.

14 Limits are not obvious for any of these:

a) the correlation works for the line diameters tested (up to a rather small amount of data in 10” pipe);

b) there is not likely to be a maximum Reynolds number (its effect on the measurements is small);

c) generally the errors reduce as fluid density ratio increases; so a maximum limit on density ratio would probably result in the correlation not being used for flows where it would work;

d) most oils in which tests could be done have fairly similar surface tension; so it is difficult to obtain a maximum. 6.4.1 of ISO/TR 11583 lists the fluids used for the tests.

e) NEL subsequently did tests to look at the effect of liquid viscosity. 6.4.1 of ISO/TR 11583 lists the fluids used for the tests and warns that the correlation may not work for much more viscous fluids. In practice it works for the gasoil tests and for almost all the velocite tests.

15 This limit is necessary for the application of the correlation: maybe too low a value of $Fr_{\text{gas,th}}$ means that there is insufficient axisymmetry.

Reply to 4.1 of de Leeuw et al.

In flow measurement it is common practice for discharge coefficient to depend on Reynolds number. Here it depends on Froude number.

ISO/TR 11583 is for uncalibrated Venturi tubes of good quality (just as ISO 5167 is): see 6.2 of ISO/TR 11583.

Reply to 4.2 of de Leeuw et al.

See 5 b) of Reply to 3 of de Leeuw et al above.

Reply to 5.1 of de Leeuw et al.

This section of de Leeuw et al is, according to the author of this paper, incorrect. Figure 2 of de Leeuw et al is for $Fr_{\text{gas}} = 1.5$; however in dense phase $\rho_{1,\text{gas}} = \rho_{\text{liquid}}$ and so $Fr_{\text{gas,th}} \rightarrow \infty$ and so in ISO/TR 11583 $C \rightarrow 1$. Moreover, $\rho_{1,\text{gas}} = \rho_{\text{liquid}}$ gives $\phi = 1 + X$ in ISO/TR 11583, in accordance with the theoretical limit.

Reply to 5.2, 6 and 7 of de Leeuw et al.

See 3.2 above.

Reply to 7 of de Leeuw et al.

The question of the effect of temperature on *H* will, presumably, apply to Richard Steven's new orifice over-reading formula.

See also 3.2.4 above.

Reply to 8.1 of de Leeuw et al.

ISO/TR 11583 only gives brief information on liquid measurement methods. Its main emphasis is on orifice and Venturi tube measurements. Had any of this material been supplied to the WG it could have been incorporated. It could form part of an amendment.

Reply to 8 of de Leeuw et al.

See 3.3 above.

Reply to 10 of de Leeuw et al.

de Leeuw et al has not revealed any problems with ISO/TR 11583 that should prevent its publication.

If the authors of de Leeuw et al wish to present data that can be used by ISO to improve ISO/TR 11583 then an amendment or a revision could be issued.

6. There is interest in measuring wet steam. In the course of an e-mail correspondence about measuring wet steam NMIJ wrote: 'Congratulation on the TR 11583. You did a great job. We hope we can contribute to it in the future.' [20]

APPENDIX B OVER-READINGS IN NEW EXPERIMENTAL WORK

The over-readings for the data described in 5 are given in Figures B.1 – B.11. The data for β = 0.6 for each liquid are given first, then the data for the other values of β.

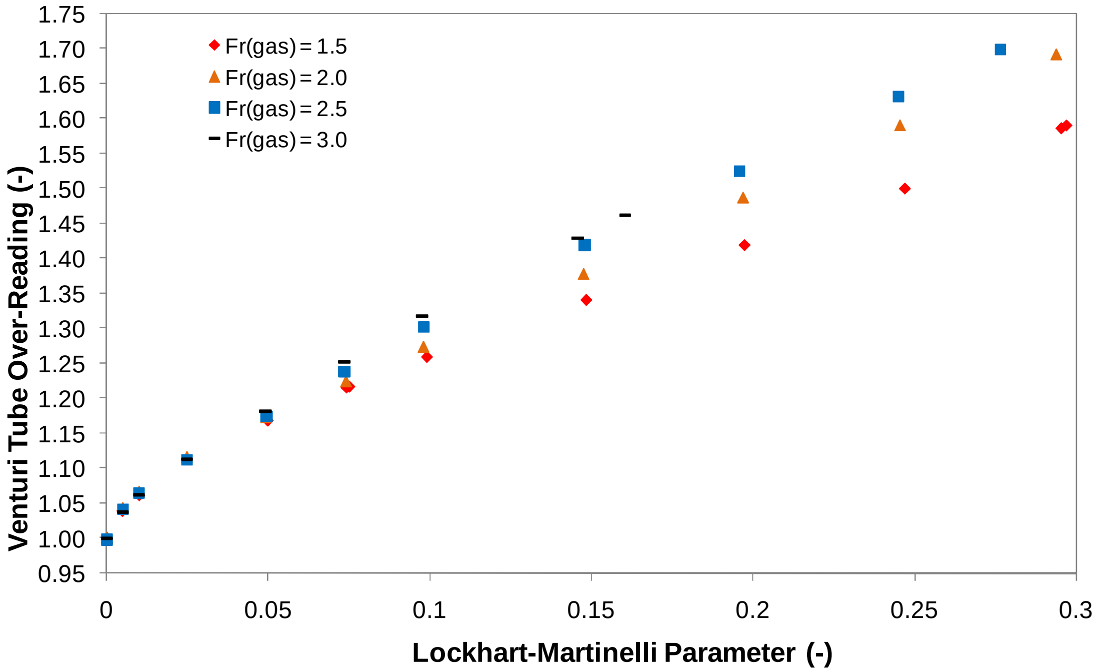

Figure B.1 Over-reading with nitrogen and gasoil: β = 0.6: 15 barg

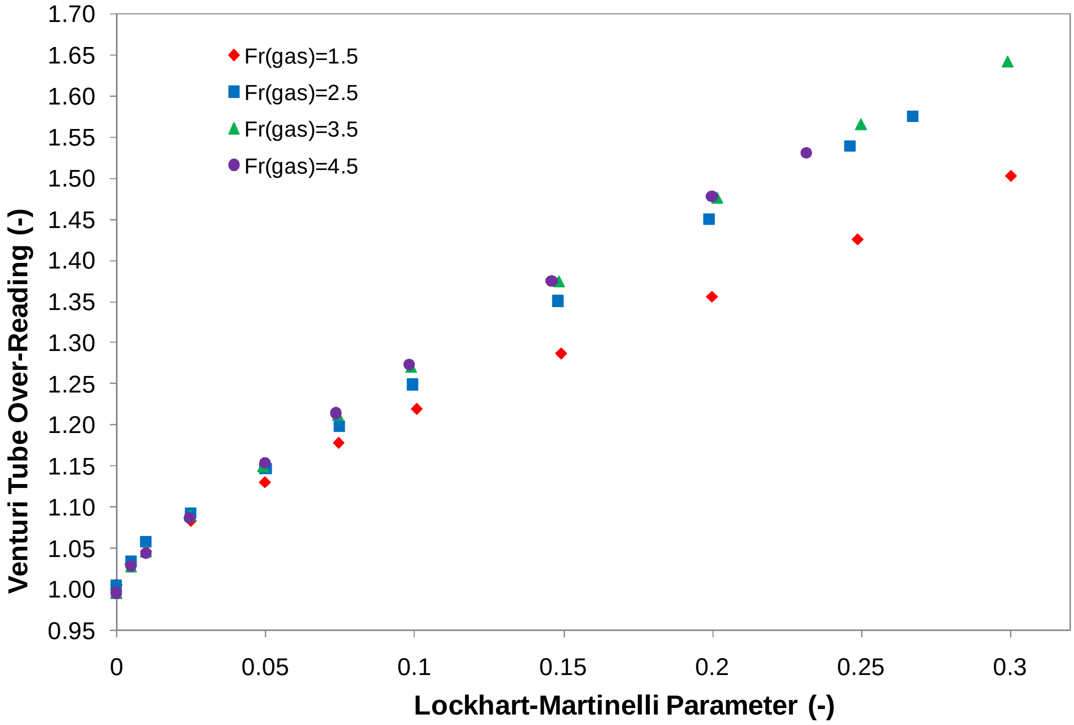

Figure B.2 Over-reading with nitrogen and gasoil: β = 0.6: 30 barg

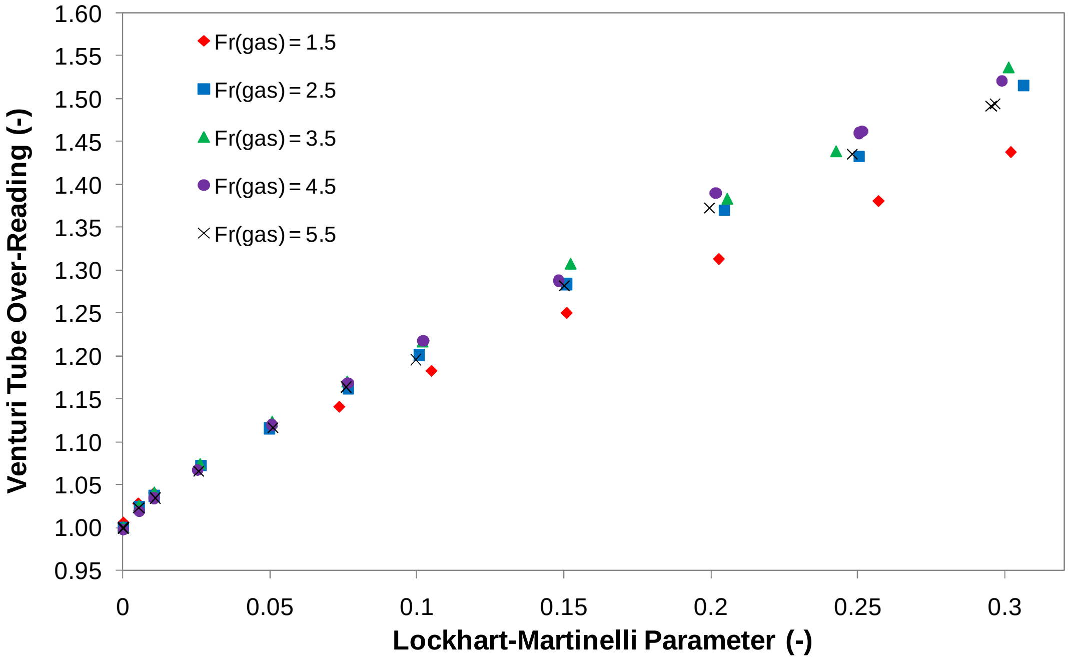

Figure B.3 Over-reading with nitrogen and gasoil: β = 0.6: 60 barg

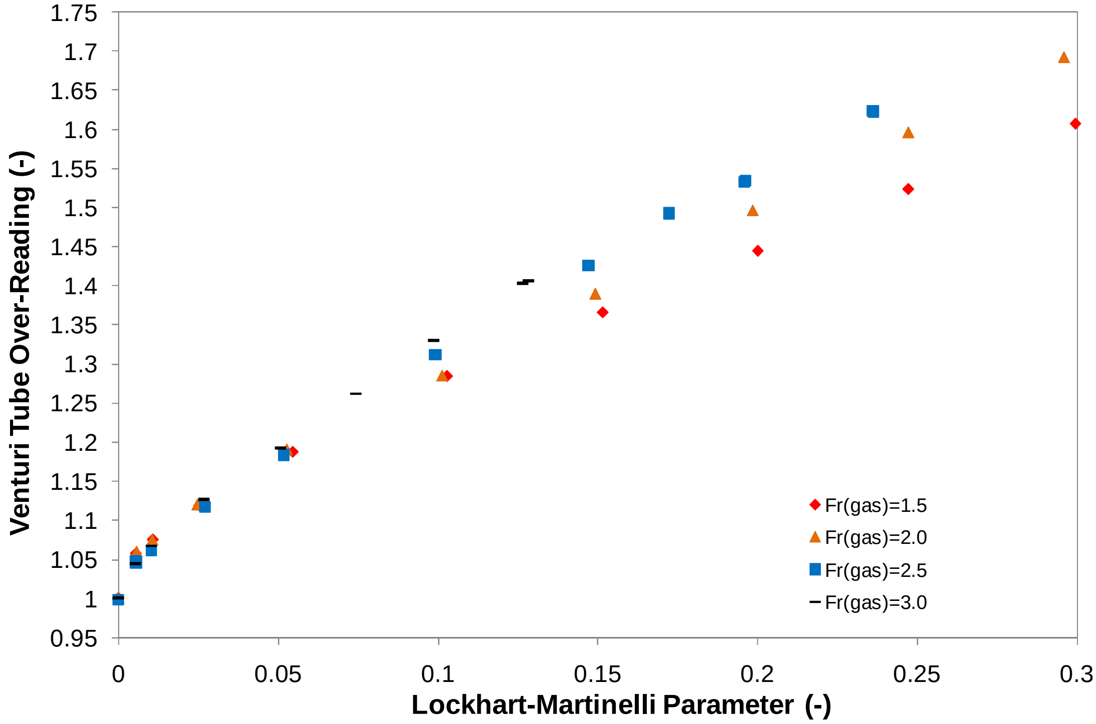

Figure B.4 Over-reading with nitrogen and velocite: β = 0.6: 15 barg

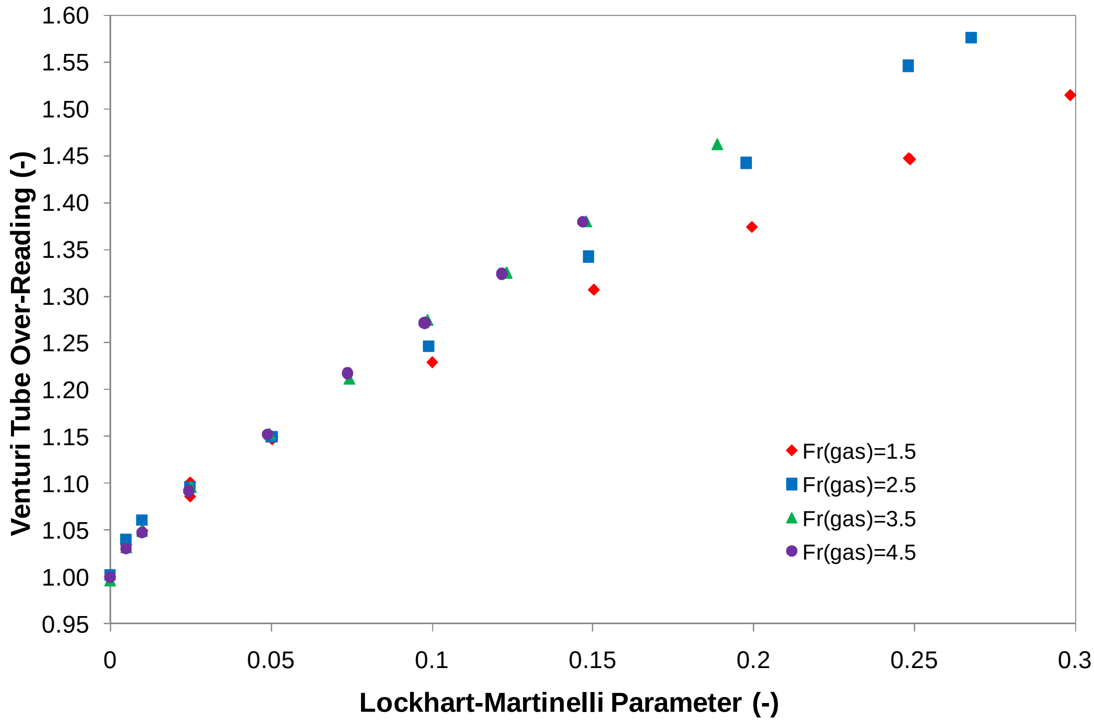

Figure B.5 Over-reading with nitrogen and velocite: $\beta = 0.6$: 30 barg

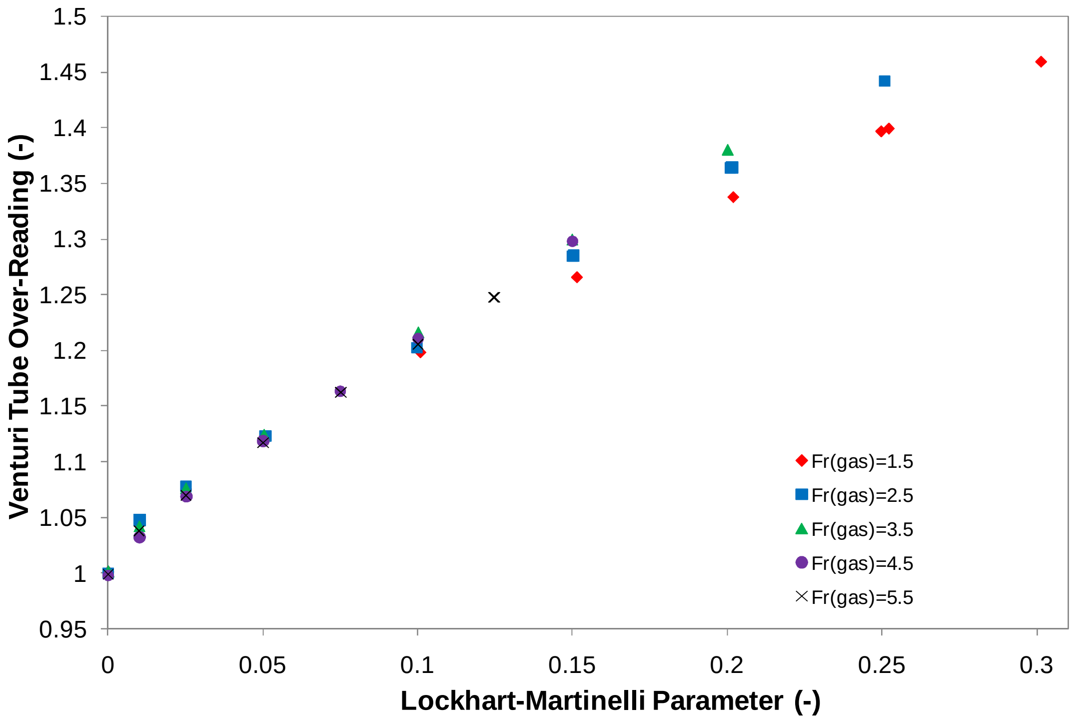

Figure B.6 Over-reading with nitrogen and velocite: $\beta = 0.6$: 60 barg

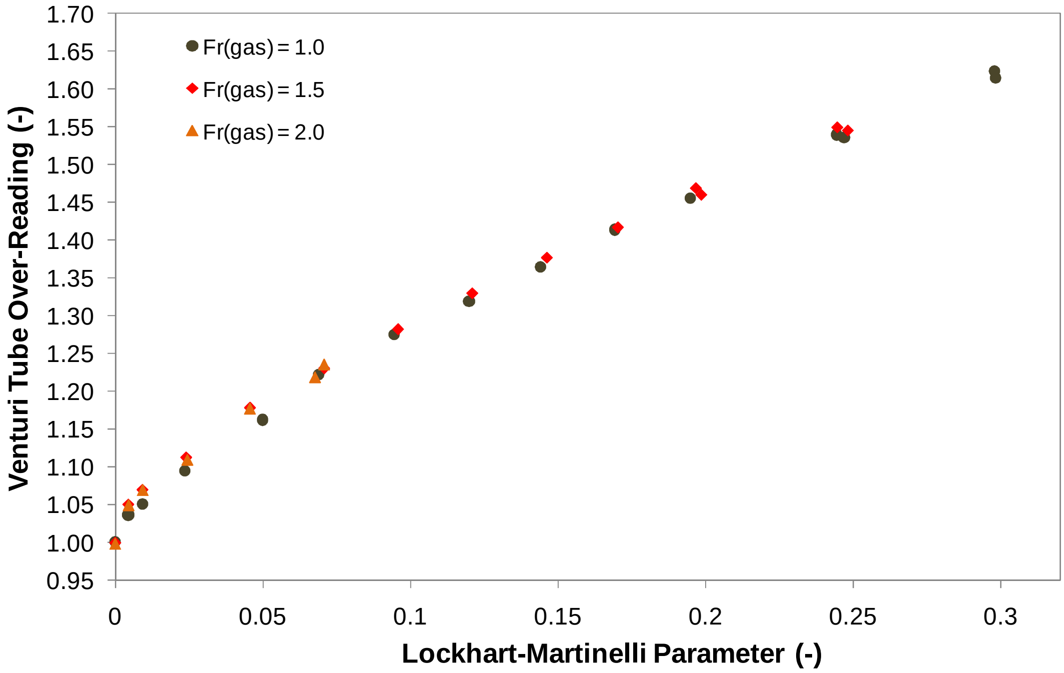

Figure B.7 Over-reading with nitrogen and velocite: $\beta = 0.4$: 15 barg

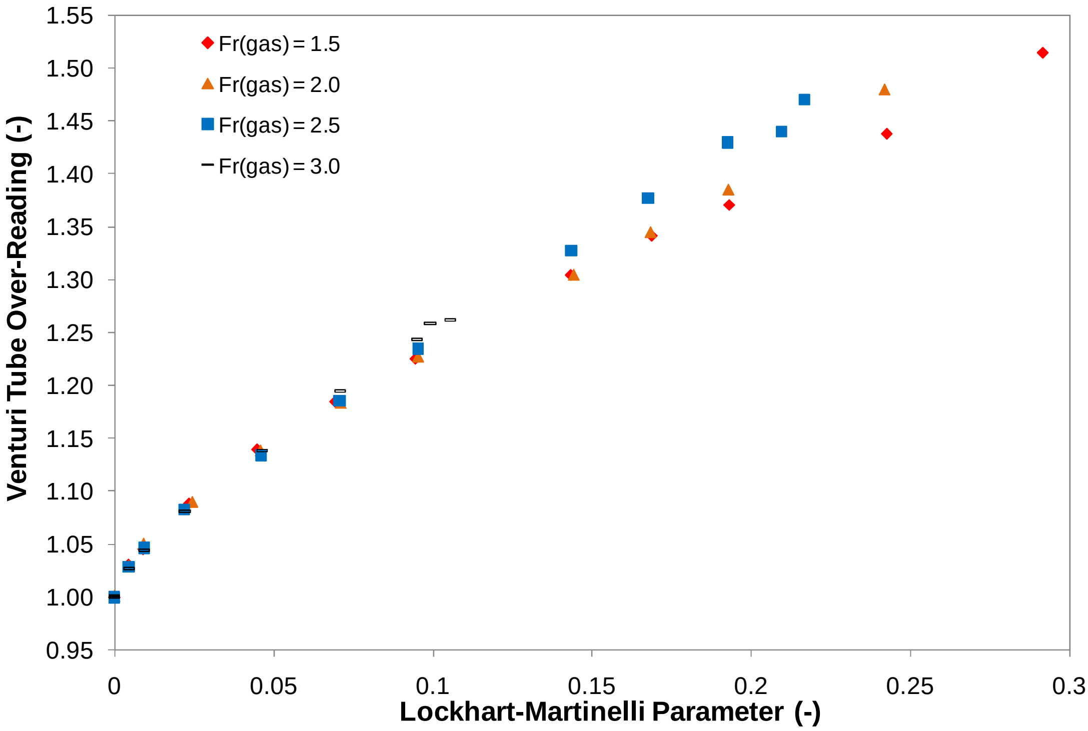

Figure B.8 Over-reading with nitrogen and velocite: $\beta = 0.4$: 30 barg

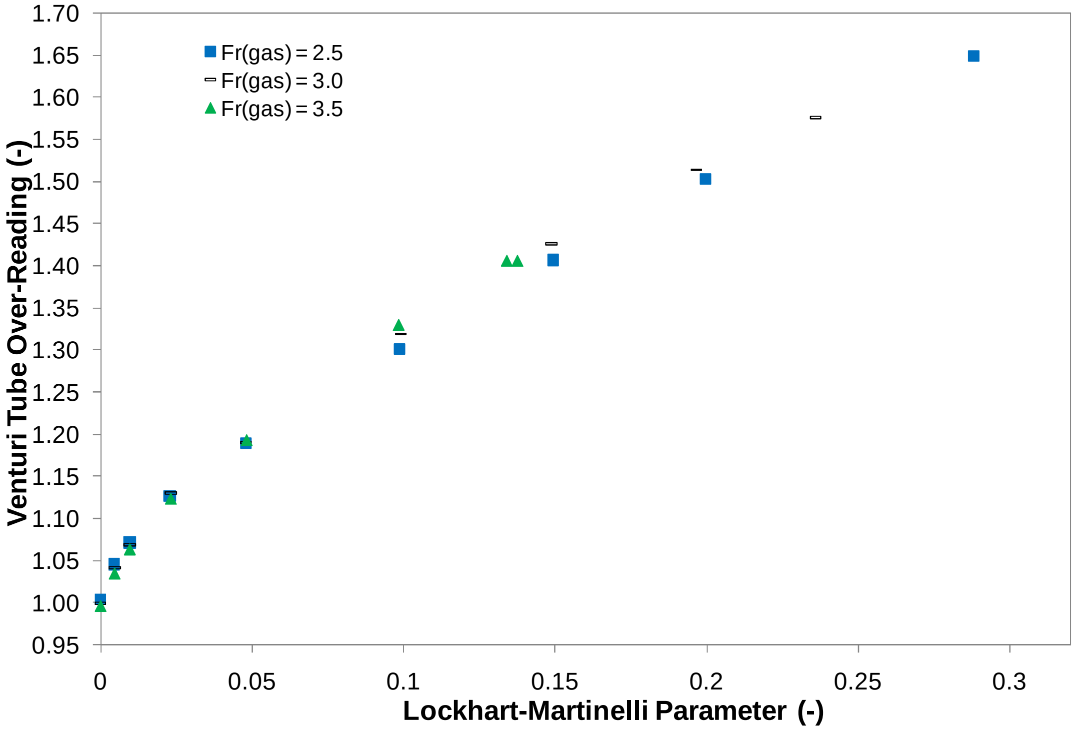

Figure B.9 Over-reading with nitrogen and velocite: β = 0.75: 15 barg

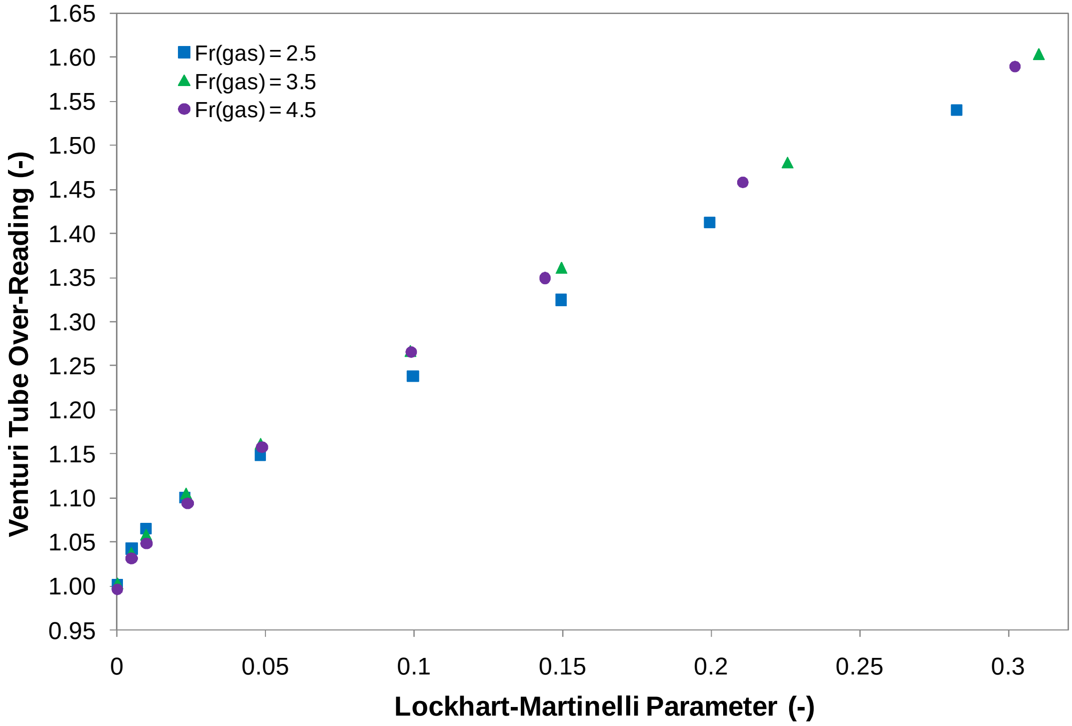

Figure B.10 Over-reading with nitrogen and velocite: β = 0.75: 30 barg

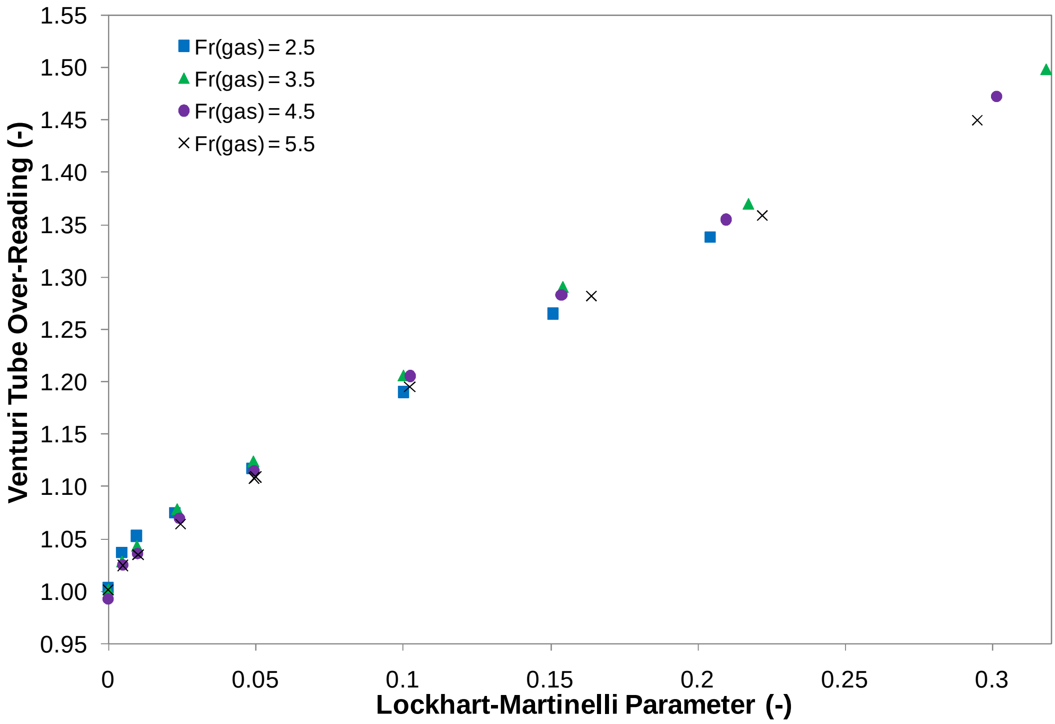

Figure B.11 Over-reading with nitrogen and velocite: $\beta = 0.75$: 60 barg