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Paper 7.1

Venturi-Tube Performance in Wet Gas Using Different Test Fluids

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1 INTRODUCTION

It was known through various one-off tests that had been performed on wet-gas flowmeters that fluid properties influence the results. It was believed that factors such as surface tension could play a major role; however no data existed that quantified the effects in a systematic manner. Quantifying the effect is important given the increasing use of wet-gas meters for gas and liquid allocation measurement. With gas production scenarios now frequently involving multiple gas fields, it is important that confidence in the measurements made by wet-gas meters is increased as this will ultimately help to increase the viability of marginal gas fields.

To examine the effect of physical properties Venturi meters were tested in wet-gas conditions, where the fluids used have different physical properties from those of the current fluid combination (nitrogen-kerosene) used in the NEL wet-gas test facility.

Knowledge of the extent of any change in meter performance is significant because current wet-gas correlations which correct for the liquid presence are not able to account for large changes in fluid properties. Many correlations in existence were developed on test facilities that utilize only a single pair of test fluids. Consequently, the use of such correlations on meters exposed to different fluids during operation from those from the originating test facility may well introduce systematic errors in the estimates of the individual-phase flowrates.

At present the fluid combination used in the high-pressure wet-gas test facility at NEL is nitrogen-kerosene. The kerosene is a substitute fluid (tradename: Exxsol D80) with a relatively high flashpoint of 72 ^{o}C. This fluid combination was chosen to simulate as closely as possible (given safety and cost considerations) a natural gas/condensate system. Two internal studies were undertaken during the mid and late 1990s to determine the best gas-liquid system that could be used at NEL. The nitrogen-kerosene system was the result of those studies.

The physical properties of significance to this project were the gas and liquid densities, the liquid viscosity and the liquid surface tension. Changing the gas density is achieved by changing either the system pressure or the gas type (i.e. the molecular weight). The density difference between the liquid and the gas is generally around a factor of 10. The gas viscosity will also be different from one gas to another but will not change significantly relative to the much higher liquid viscosity (the difference can be on the scale of around 10 to 1000; however the ratio is dependent more on the liquid value). The liquid surface tension is generally considered important for drop formation and size.

For the test work three Venturi tubes were chosen, two of standard design (diameter ratio, β, 0.6 and 0.75) and one of non-standard design with a convergent angle of 10.5^{o} and diameter ratio 0.75 [1]. The additional fluid combinations chosen for testing were argon-kerosene and nitrogen-water, and the chosen gas-liquid density ratios matched the nitrogen-kerosene baseline system test values obtained when testing at 15 and 30 bar gauge, referred to in this paper as the low and medium density ratio tests. A “high density ratio” test would correspond to tests conducted on the baseline nitrogen-kerosene system at 60 bar gauge. Matching the other chosen fluid combinations to this condition was technically not possible.

Moreover, testing at the smaller gas-liquid density ratios results in larger measured Venturi-tube over-readings and therefore a greater chance of observing any small deviation in over-reading (compared with the baseline results) produced by the two alternative fluid combinations. Note that increasing the gas-liquid density ratio not only tends to reduce the measured over-reading but also decreases the spread in the over-reading data across a fixed range of the gas densimetric Froude number.

2 THE NEL HIGH-PRESSURE WET-GAS TEST FACILITY

2.1 The test facility

The test facility is based around a 6-inch nominal bore recirculating loop and a 12 m^3 gas/liquid separator. Although nominally 6-inch in diameter, the two parallel test sections (not shown on Figure 1 below) can accommodate line sizes ranging from 4-inch to 8-inch. The natural gas-condensate simulant fluids used are oxygen-free nitrogen and a kerosene substitute (Exxsol D80). At 20 ^oC the liquid phase has an approximate density of 802.5 kg/m^3 and a viscosity of 2.14 cP. The facility generally operates at an ambient temperature of 18 °C over a nominal pressure range of 15 to 63 bar gauge. This pressure range corresponds to a gas density range of 18.6 to 74.5 kg/m^3.

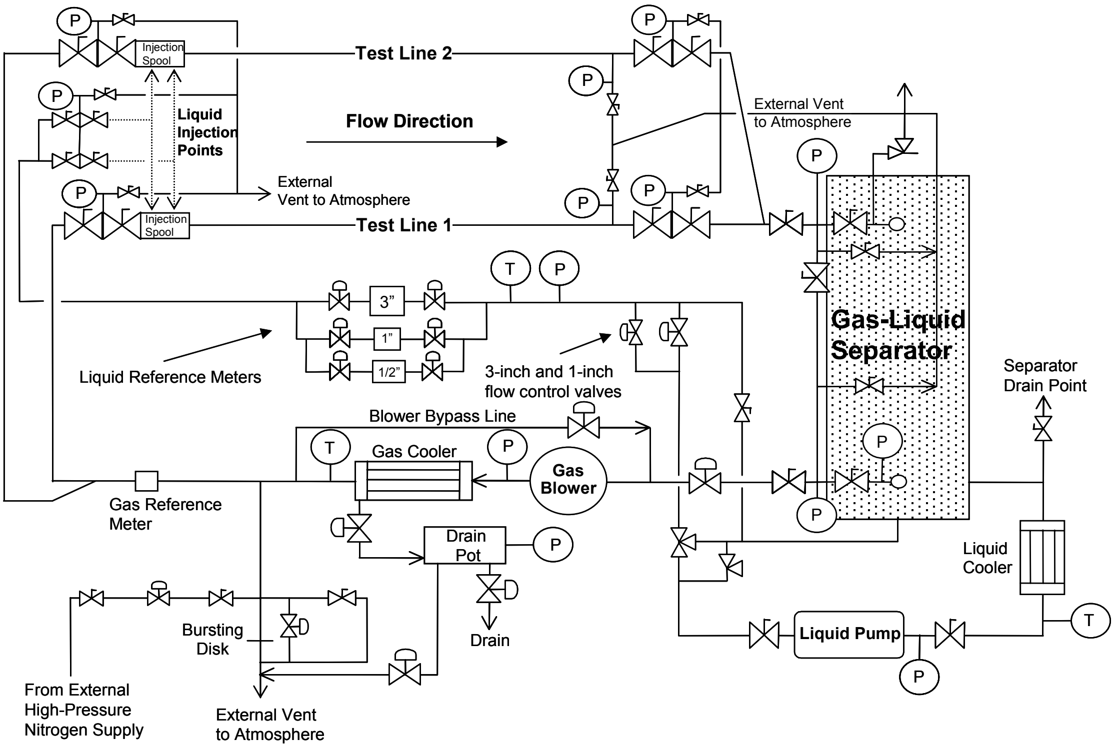

Figure 1. A schematic representation of the wet-gas test facility.

Referring to the schematic diagram in Figure 1, gas is drawn from the top of the separator and is driven around the test loop by a 200 kW blower. The maximum achievable, pressure-independent dry-gas flowrate is 1500 m^3/hr (minimum is 100 m^3/hr) at the minimum test line resistance (i.e. no test meter installed) when flowing through the separator. Liquid is injected using a 130 kW, 11 stage centrifugal pump through a specially designed spool over 60*D* upstream of the test section, up to a maximum flowrate of 80 m^3/hr (minimum is 0.2 m^3/hr). The gas and liquid phases mix at the injection point of each test line and pass through the test section in a form (i.e. flow pattern) dictated by the gas velocity and pressure. The two-phase mixture then passes back into the separator for separation and recirculation.

The gas and liquid stream temperatures are both maintained at a set level (to within $\pm$ 0.1 ^oC) using two chilled-water-controlled shell-and-tube heat exchangers. The accurate control of both stream temperatures allows an equilibrium mixture temperature to develop rapidly, within a small number of pipe diameters downstream of the liquid-injection point. This prevents large differences in the phase temperatures from existing at the test meter, e.g. when only a small amount of gas-liquid mixing occurs, in particular in a stratified (i.e. separated) flow regime. The gas flowrate is controlled by varying the speed of the blower, while the liquid injection flowrates are controlled using either a 1-inch or a 3-inch control valve. Liquid flowrate control can also, if necessary, be achieved manually at the injection point.

The gas reference flowrate is measured using traceable calibrated 6-inch turbine or ultrasonic meters, and the liquid reference flowrates are measured using traceable calibrated turbines of size ½-inch, 1-inch and 3-inch. For the test work described in this paper the maximum expanded uncertainty on the reference gas volumetric flowrate is $\pm$ 0.5% and for the liquid reference volumetric flowrate is $\pm$ 0.2% (both at the 95% confidence level). All temperature and pressure measurements are taken using traceable calibrated instrumentation. Two modified subsea video cameras can be used to monitor the two-phase flow in the test section. The camera view allows the transition from stratified flow to annular-mist flow to be observed.

2.2 The test-section layout

A diagram of the layout of the 4-inch test section used for this work is given in Figure 2. An eccentric reducer changes the pipe size from the upstream value of 6-inch to the 4-inch required for the Venturi tube. Following this is 29*D* of 4-inch schedule 40 pipe, of which the last 10*D* is machined, directly upstream of the Venturi tube (the final 2*D* of the 21*D* length is machined to ensure that there is no more than a very small step at the flange). The two upstream lengths, the Venturi tube and the pipe spool directly downstream of the Venturi tube are also aligned using dowel pins, thereby removing any significant steps from pipe to pipe.

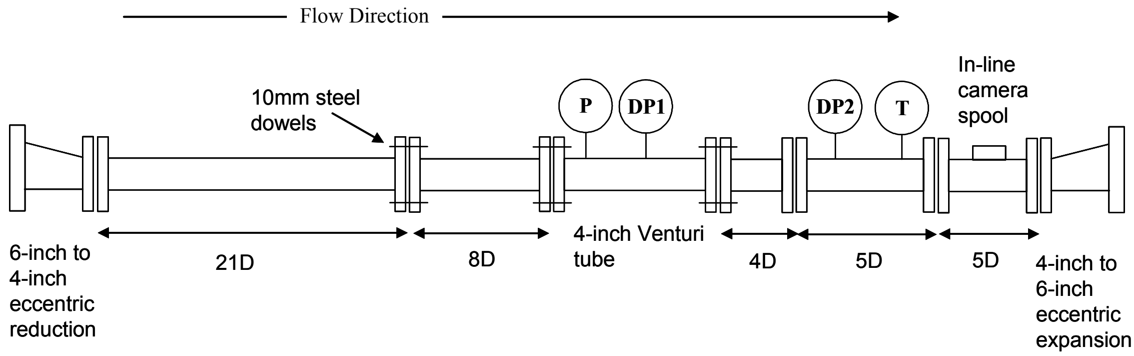

Figure 2. Layout of the 4-inch Venturi-tube test section for all fluid combination tests.

Downstream of the Venturitube a single pipe spool is used to allow the taking of measurements of temperature and of an additional differential pressure. The differential-pressure measurements consist of the standard upstream-throat measurement and an upstream-downstream measurement which gives a value for the overall pressure loss across the Venturi tube. One static pressure is measured. A 4-inch camera spool is also used to allow the gas-liquid flow pattern to be observed if required. After this spool the line is returned to its nominal 6-inch size via another eccentric expansion.

3 WET-GAS TERMINOLOGY

The following provides descriptions of the relevant wet-gas parameters used in this paper for the representation and interpretation of the wet-gas test results.

<u>Dry-gas flow coefficient</u>: This parameter is required to calculate the Venturi-tube over-reading defined below. It is essentially a combination of three terms, the Venturi-tube discharge coefficient, the velocity of approach factor and the gas expansibility. This parameter is determined via a dry-gas calibration of the Venturi tube under test and is calculated using the following expression:

$$Flow\,Coefficient,\, K_{gas} = \frac{m_{gas}}{A_d\sqrt{2\rho_{gas}\Delta p_{gas}}} \tag{1}$$

where m_{gas} is the reference gas mass flowrate, A_d is the throat area of the Venturi tube, ρ_{gas} is the gas density at the Venturi tube and Δp_{gas} the measured upstream-throat dry-gas differential pressure.

Gas and liquid densimetric Froude numbers: These parameters are useful in two-phase flow systems in that they can be used to produce flow-pattern maps that represent the wide range of regimes encountered in horizontal pipe systems. The dimensionless Froude number is derived from the ratio of inertial forces to gravity forces and was first used in relation to wet gas and Venturi tubes by de Leeuw [2]. It was found by de Leeuw that the Venturi-tube over-reading is a function of the gas densimetric Froude number. These parameters are calculated using the following expressions:

$$Gas\ Froude\ Number,\, Fr_{gas} = \frac{m_{gas}}{\rho_{gas} A_D\sqrt{gD}}\sqrt{\frac{\rho_{gas}}{\rho_{liquid}-\rho_{gas}}} \tag{2}$$

$$Liquid\ Froude\ Number,\, Fr_{liquid} = \frac{m_{liquid}}{\rho_{liquid} A_D\sqrt{gD}}\sqrt{\frac{\rho_{liquid}}{\rho_{liquid}-\rho_{gas}}} \tag{3}$$

where ρ_{liquid} is the reference liquid density, m_{liquid} is the reference liquid mass flowrate, A_D is the upstream pipe area, g is the acceleration due to gravity and D the upstream pipe diameter.

Lockhart-Martinelli parameter: This is a useful parameter for the representation of two-phase flow in pipes and differential-pressure flowmeters. Originally the parameter was defined in terms of the frictional pressure drops in a straight horizontal pipe of both gas and liquid phases in a flowing two-phase mixture, as if the phases flowed alone in the pipe. Since the work of Murdock [3] the parameter has been used in terms of the pressure drop due to a change of velocity of gas and liquid phases passing through a differential-pressure meter. In this work the parameter has been calculated as the ratio of the liquid to gas densimetric Froude numbers, which reduces to the following expression:

$$Lockhart-Martinelli\ Parameter,\, X = \frac{Fr_{liquid}}{Fr_{gas}} = \left(\frac{m_{liquid}}{m_{gas}}\right)\sqrt{\frac{\rho_{gas}}{\rho_{liquid}}} \tag{4}$$

Venturi-tube over-reading: The presence of liquid in a gas flow produces additional pressure drop through a differential-pressure meter, which, if the flow were assumed to be completely dry would cause an overestimate of the gas flowrate; therefore the meter is said to "over-read". The over-reading parameter is therefore calculated as the ratio of the square root of the measured two-phase pressure drop, $\Delta p_{two\text{-}phase}$, to the square root of the pressure drop that would be measured by the meter if the gas phase flowed alone in the pipe, Δp_{gas}. In this work the parameter is calculated using the following expression:

$$Venturi-tube\ Overreading = \sqrt{\frac{\Delta p_{two-phase}}{\Delta p_{gas}}} = \frac{K_{gas} A_d\sqrt{2\rho_{gas}\Delta p_{two-phase}}}{m_{gas}} \tag{5}$$

where K_{gas} is the dry-gas flow coefficient obtained from a dry-gas calibration as noted above. The flow coefficient is generally used as a function of the gas Reynolds number at the test meter but could also be a single value to simplify the calculation procedure in operation.

Venturi model of de Leeuw: de Leeuw [4] published the first Venturi-tube-specific correlation to correct for the presence of liquid in a gas stream. The model used was based on that of Chisholm [5, 6], but was modified to account for the influence of the gas densimetric Froude number as well as the gas-liquid density ratio. The model is given by the following expressions:

$$Venturi-tube\ Overreading = \sqrt{\frac{\Delta P_{two-phase}}{\Delta P_{gas}}} = \sqrt{1 + CX + X^2} \tag{6}$$

where

$$C = \left(\frac{\rho_{liquid}}{\rho_{gas}}\right)^n + \left(\frac{\rho_{gas}}{\rho_{liquid}}\right)^n \tag{7}$$

and

$$n = \begin{cases} 0.41 & 0.5 \le Fr_{gas} \le 1.5 \\ 0.606\left(1 - e^{-0.746 Fr_{gas}}\right) & 1.5 \le Fr_{gas} \end{cases} \tag{8}$$

4 WET-GAS TEST RESULTS

4.1 Test conditions

Three 4-inch Venturi tubes were tested in the NEL wet-gas test facility using three gas-liquid combinations: nitrogen-kerosene, argon-kerosene and nitrogen-water. The Venturi tubes and fluid combinations were chosen for reasons given in section 1 above [1].

As noted in section 1, two standard-design Venturi tubes were selected with diameter ratios of 0.6 and 0.75, while a third Venturi tube was chosen that had a standard design except that the convergent section has an angle of 10.5°. The convergent angle in the standard design is 21°.

The test conditions (gas and liquid flowrates) for each Venturi-tube/additional-fluid combination were determined such that they matched (relative to the nitrogen-kerosene tests) in terms of the gas-liquid density ratio, Lockhart-Martinelli parameter and gas densimetric Froude number. This allowed a direct comparison of the results obtained. The experimental range in the gas densimetric Froude number was 1.5 to 4.5 (depending on the gas-liquid density ratio) and in the Lockhart-Martinelli parameter was 0 to 0.3. Each meter was tested at two gas-liquid density ratios of approximately 0.024 and 0.046.

4.2 Wet-Gas Test Data

4.2.1 Venturi tube with β = 0.6 and a standard convergent

Figures 3 to 6 show the over-reading data obtained. The following points summarize the results obtained for this meter:

- Only small differences are observed between the nitrogen-kerosene and argon-kerosene data sets at both gas-liquid density ratios tested. The maximum differences in the over-reading data sets range from -0.023 to 0.016 (relative to the nitrogen-kerosene over-reading data) from low to high gas densimetric Froude numbers (and occur at the maximum tested Lockhart-Martinelli parameter value of 0.3).

- The differences between the nitrogen-kerosene/argon-kerosene data sets and the nitrogen-water data set are more significant. All of the nitrogen-water over-reading data clearly lie on or below the nitrogen-kerosene/argon-kerosene data, with a maximum difference of -0.09 for the low-density-ratio data at a gas densimetric Froude number of 2.5. Again the Lockhart-Martinelli parameter value is 0.3. The maximum difference in the over-reading data at the medium density-ratio was -0.08, also at a gas densimetric Froude number of 2.5 and Lockhart-Martinelli parameter value of 0.3. Figure 7 shows how these differences vary as a function of the gas densimetric Froude number.

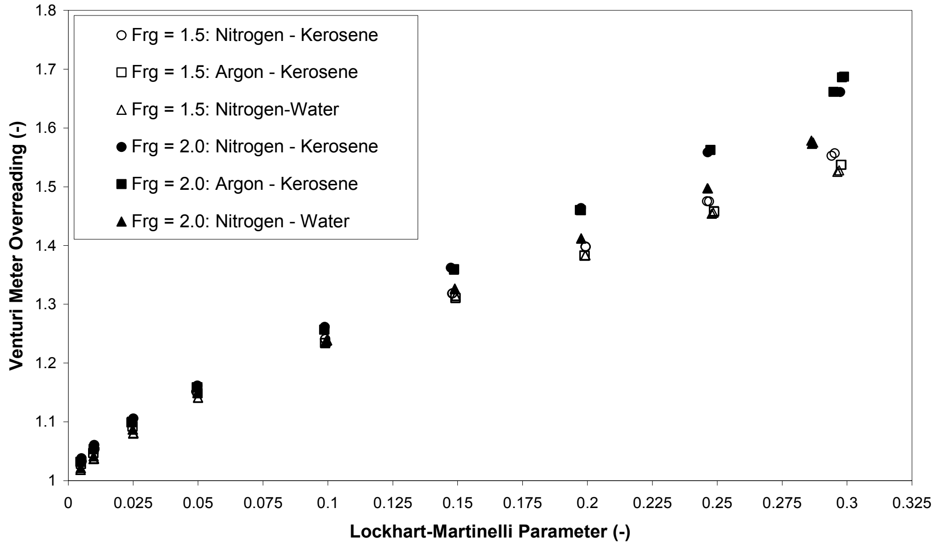

Fig. 3 Over-reading for standard Venturi $\beta = 0.6$, gas-liquid density ratio 0.024, $Fr_g \leq 2.0$

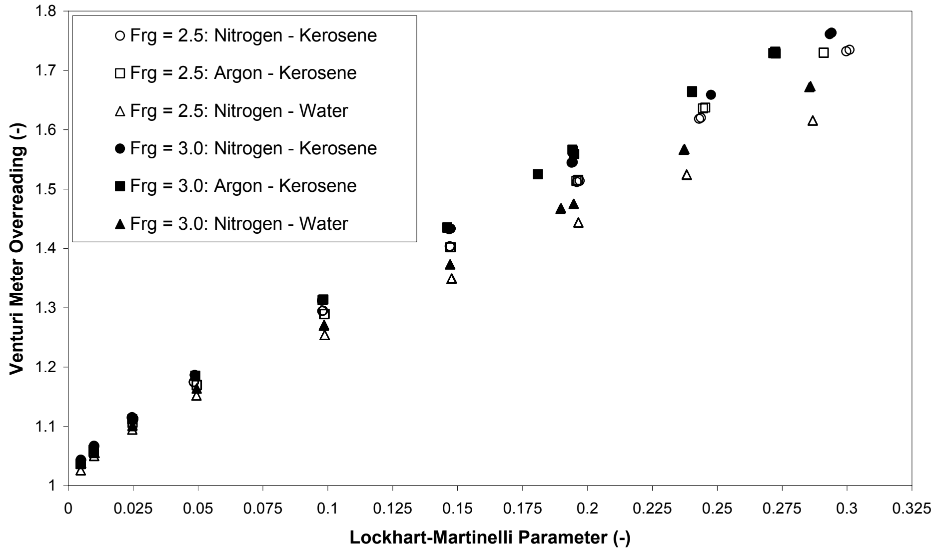

Fig. 4 Over-reading for standard Venturi $\beta = 0.6$, gas-liquid density ratio 0.024, $Fr_g \geq 2.5$

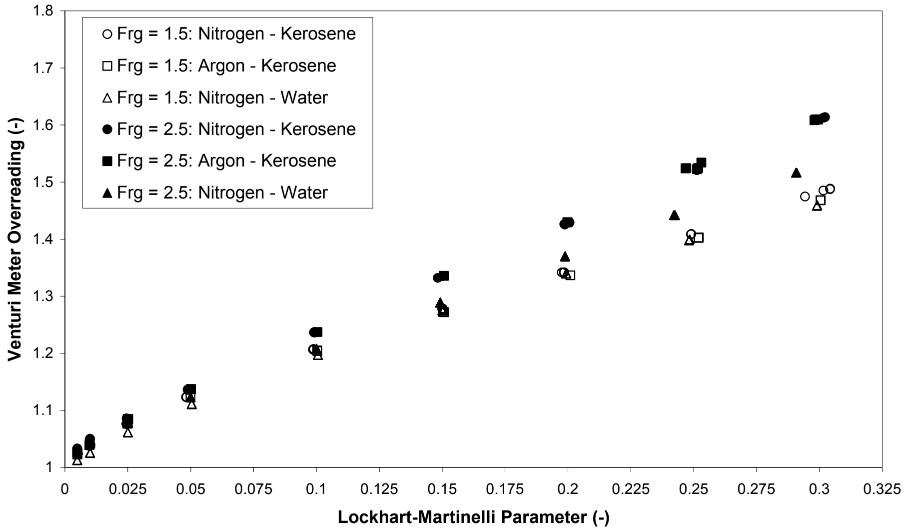

Fig. 5 Over-reading for standard Venturi $\beta = 0.6$, gas-liquid density ratio 0.046, $Fr_g \leq 2.5$

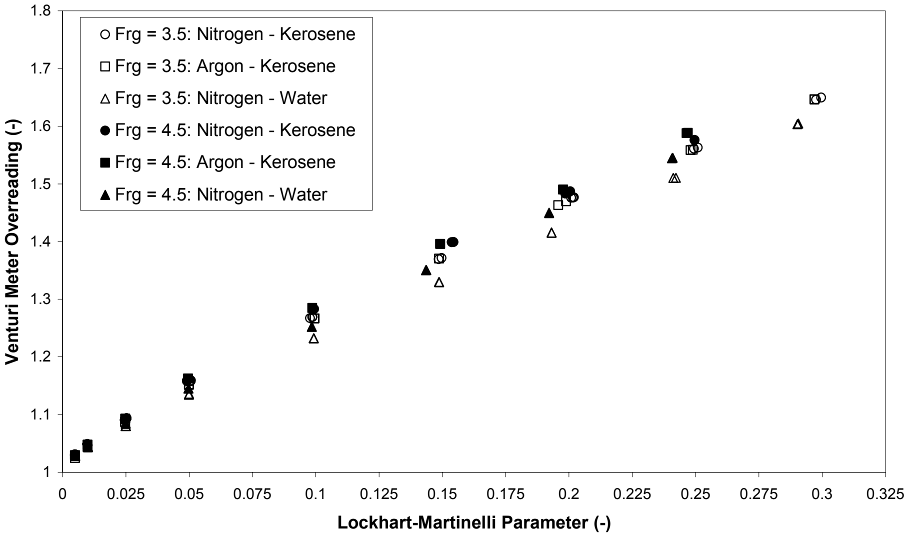

Fig. 6 Over-reading for standard Venturi $\beta = 0.6$, gas-liquid density ratio 0.046, $Fr_g \geq 3.5$

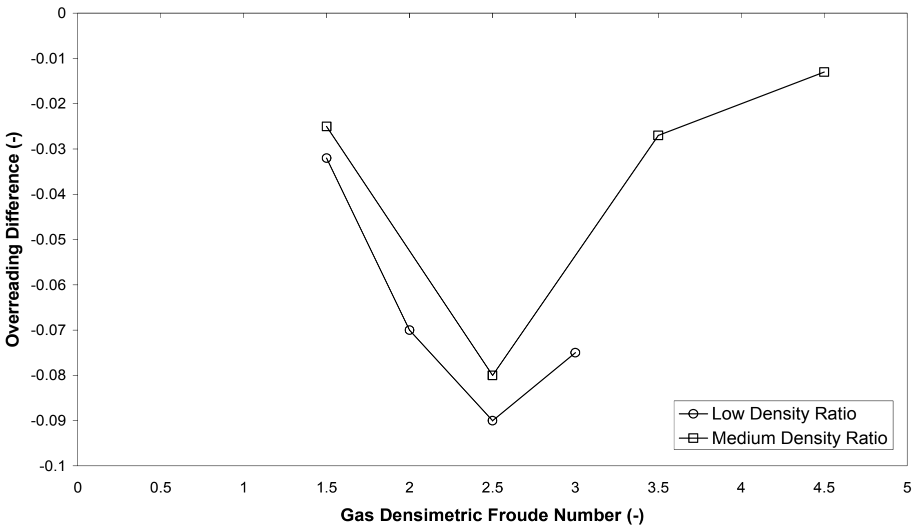

Fig. 7. $\beta = 0.6$, standard convergent: over-reading differences at $X = 0.3$ relative to nitrogen-kerosene

4.2.2 Venturi tube with β = 0.75 and a standard convergent

Figures 8 to 11 show the over-reading data obtained. The following points summarize the results obtained for this meter:

- The influence of the alternative gas used (argon) is similar to that found for the Venturi tube with a diameter ratio of 0.6. The differences between the over-reading data lie within a band of $\pm$ 0.02 (with the largest spread at a Lockhart-Martinelli parameter value of 0.3) relative to the nitrogen-kerosene data. This is close to the experimental uncertainty of the over-reading data.

- The influence of the alternative liquid used (water) is again noticably more significant. The nitrogen-water over-reading data tend to lie below the other data sets across the whole range of Froude numbers tested. At a Lockhart-Martinelli value of 0.3 the differences in the over-reading data sets varied from -0.012 to -0.07 for the low-density-ratio tests and -0.02 to -0.0675 for the medium-density-ratio tests. Figure 12 shows how these differences vary as a function of the gas densimetric Froude number.

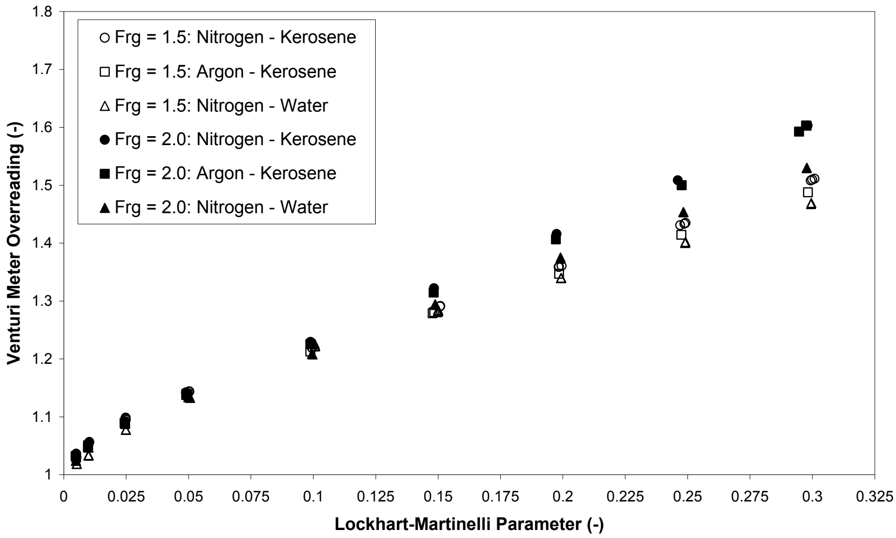

Fig. 8 Over-reading for standard Venturi β = 0.75, gas-liquid density ratio 0.024, $Fr_g \leq$ 2.0

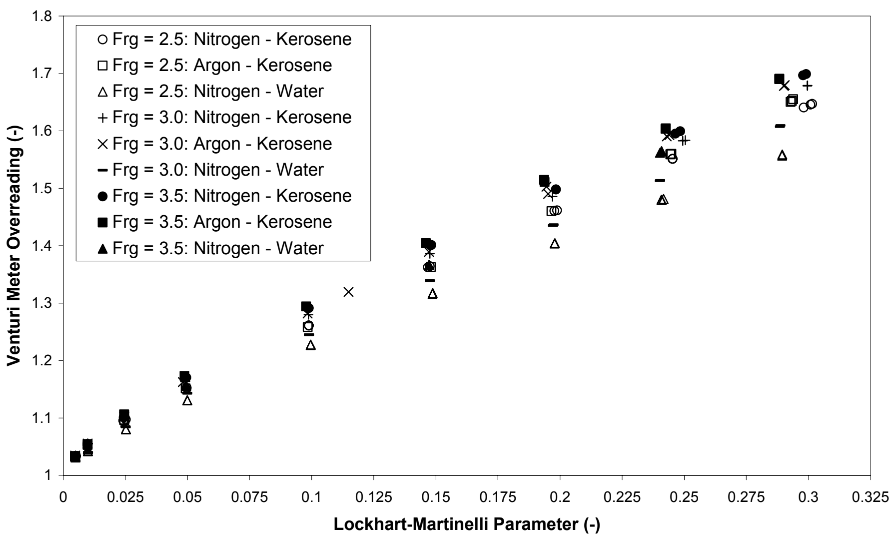

Fig. 9 Over-reading for standard Venturi β = 0.75, gas-liquid density ratio 0.024, $Fr_g \geq$ 2.5

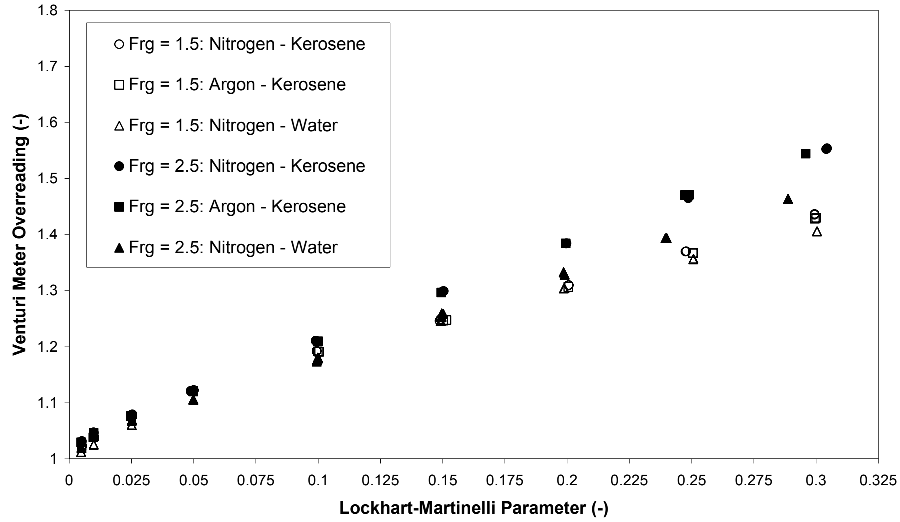

Fig. 10 Over-reading for standard Venturi β=0.75, gas-liquid density ratio 0.046, $Fr_g \leq$ 2.5

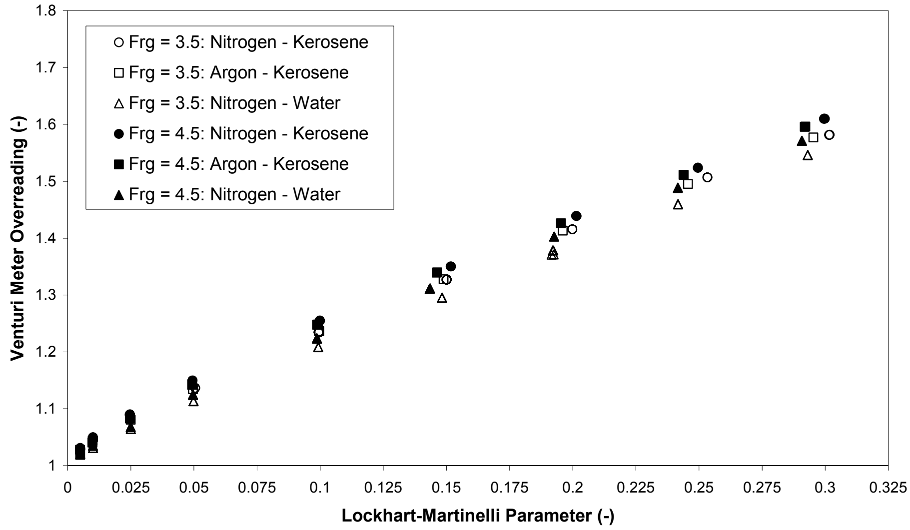

Fig. 11 Over-reading for standard Venturi β=0.75, gas-liquid density ratio 0.046, $Fr_g \geq$ 3.5

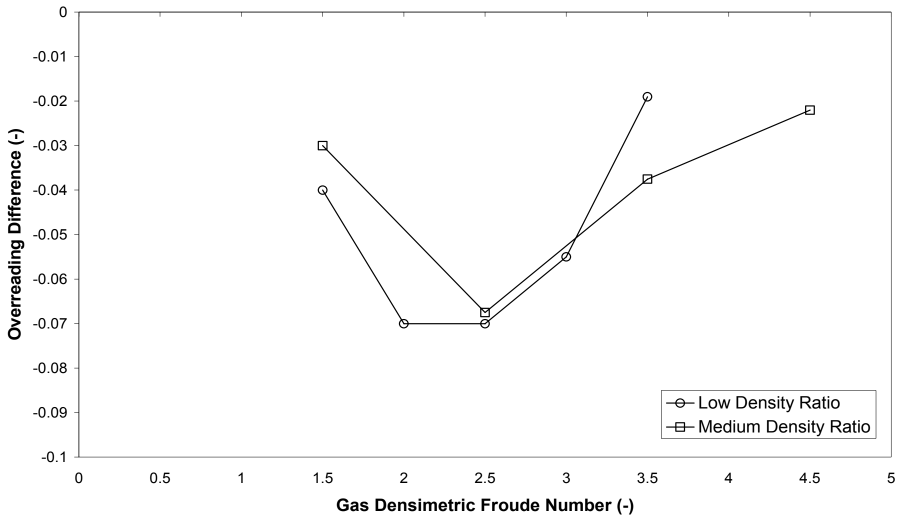

Fig. 12. β = 0.75, standard convergent: over-reading differences at X = 0.3 relative to nitrogen-kerosene

4.2.3 Venturi tube with β = 0.75 and a 10.5° convergent

Figures 13 to 16 show the over-reading data obtained. The following points summarize the results obtained for this meter:

- For this Venturi tube the effect of changing gases was the smallest of all three meters tested. The differences in the over-reading data sets were generally less than 0.01 in magnitude.

- For the alternative liquid used the trend is the same as for the other meters tested. The over-reading data sets all lie below the kerosene data sets over the Lockhart-Martinelli and gas densimetric Froude number ranges tested. Differences in the data sets at a Lockhart-Martinelli value of 0.3 vary from -0.03 to -0.095 at the low density ratio and -0.005 to -0.045 at the medium density ratio. These differences can be seen as a function of Froude number in Figure 17.

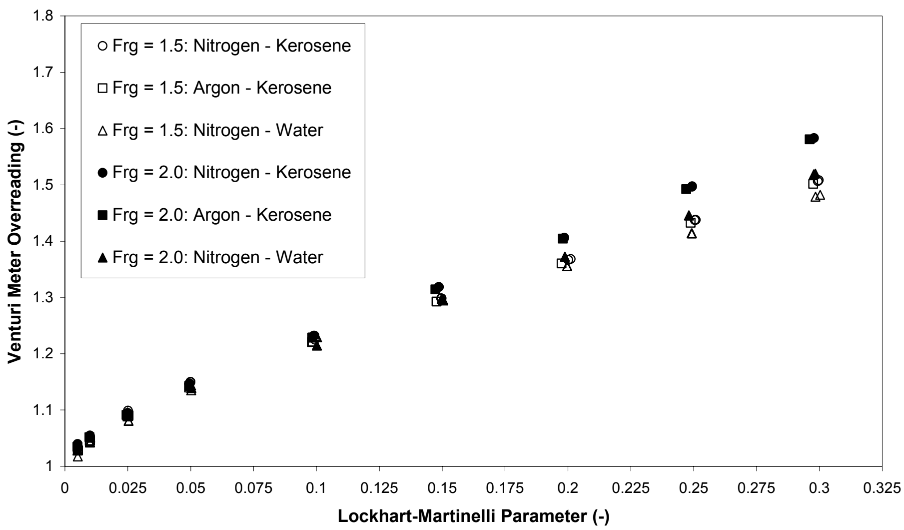

Fig. 13 Over-reading for 10.5° convergent β=0.75, gas-liquid density ratio 0.024, $Fr_g \leq 2.0$

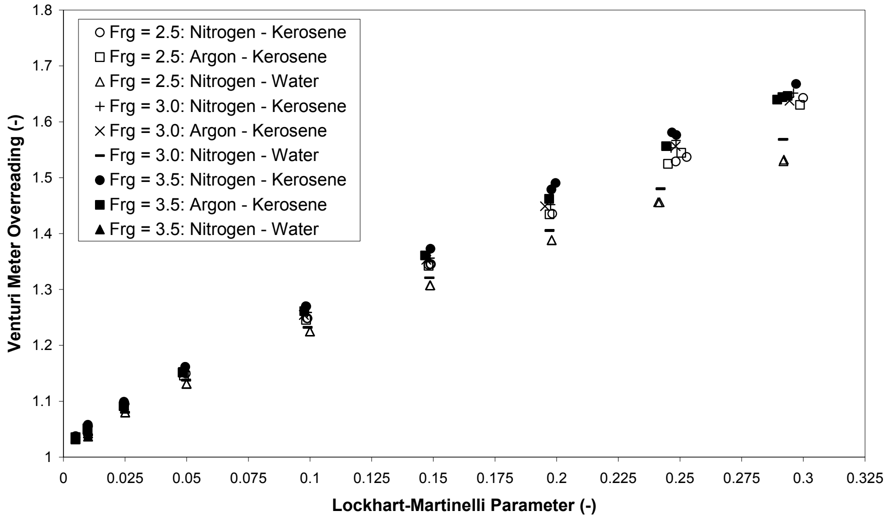

Fig. 14 Over-reading for 10.5° convergent β=0.75, gas-liquid density ratio 0.024, $Fr_g \geq 2.5$

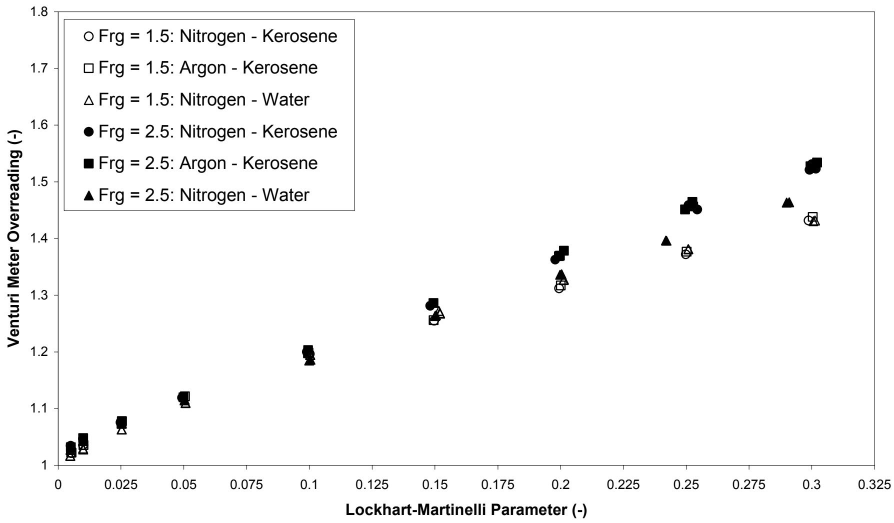

Fig. 15 Over-reading for 10.5° convergent β=0.75, gas-liquid density ratio 0.046, $Fr_g \leq 2.5$

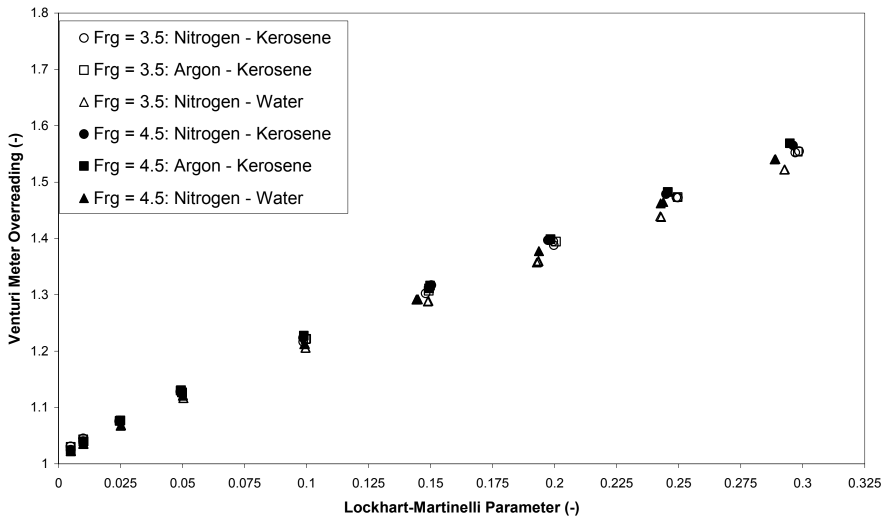

Fig. 16 Over-reading for 10.5° convergent β=0.75, gas-liquid density ratio 0.046, $Fr_g \geq 3.5$

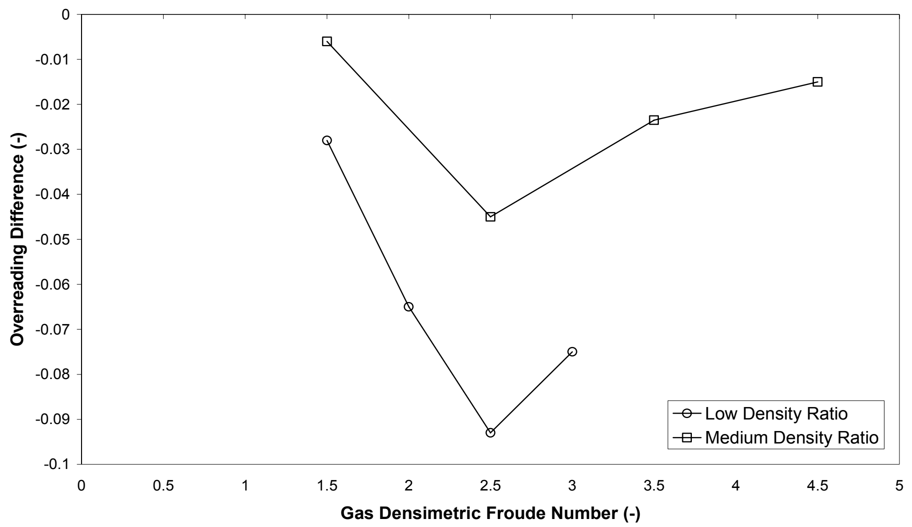

Fig. 17. β = 0.75, 10.5° convergent: over-reading differences at X = 0.3 relative to nitrogen-kerosene

5 NEL EXPERIMENTAL DATA REDUCTION USING THE DE LEEUW VENTURI MODEL

There are very few published Venturi-tube wet-gas data. From his experimental data de Leeuw [2, 4] formulated a correlation (Equations 6 to 8), based on that of Chisholm [5, 6], which was derived for orifice meters. In an attempt to provide an improved understanding of the NEL experimental data (obtained both from this test programme and from some of the projects over the last few years) the data have therefore been fitted using this particular Venturi-tube-specific model. This data-fitting exercise would tell us both how well the NEL data compares with the de Leeuw model and the capability of the model to represent the data.

To fit the NEL experimental data to the de Leeuw model primarily required determining the value of parameter C in equation 6 from the Venturi-tube over-readings and Lockhart-Martinelli parameter data (presented in Section 4). This was achieved by minimizing the square root of the mean of the sum of squares of the relative errors between the experimental over-readings and the over-reading values predicted by the model at the same Lockhart-Martinelli parameter values. In addition to fitting the parameter C in the de Leeuw Venturi model the parameter n has also been determined for comparative purposes. This was determined by solving the relationship between C, the gas-liquid density ratio and n in equation 7, once the best fit values of C were determined.

The values of n and the quality of the fits obtained for each Venturi-tube/fluid combination at the low and medium density ratios tested are presented in Figures 18 to 23 using the relative errors between the experimental over-readings and the final values from the model.

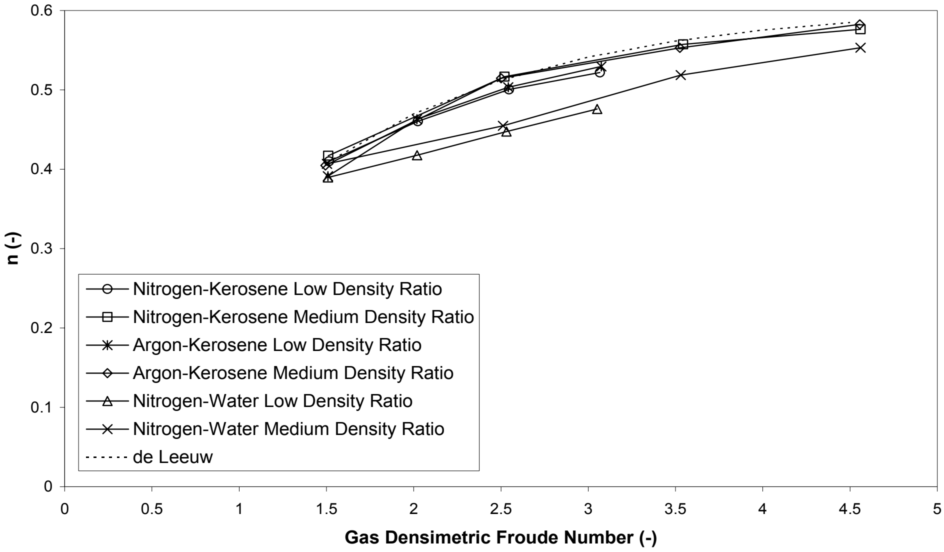

Figure 18. β = 0.6, std convergent: refitted de Leeuw model parameter *n*

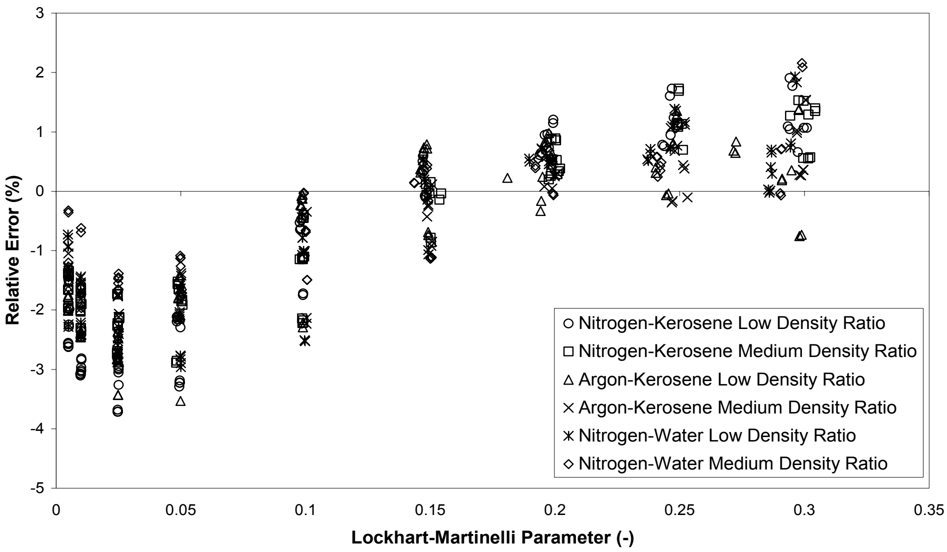

Figure 19. β = 0.6, std convergent: errors relative to the refitted de Leeuw model

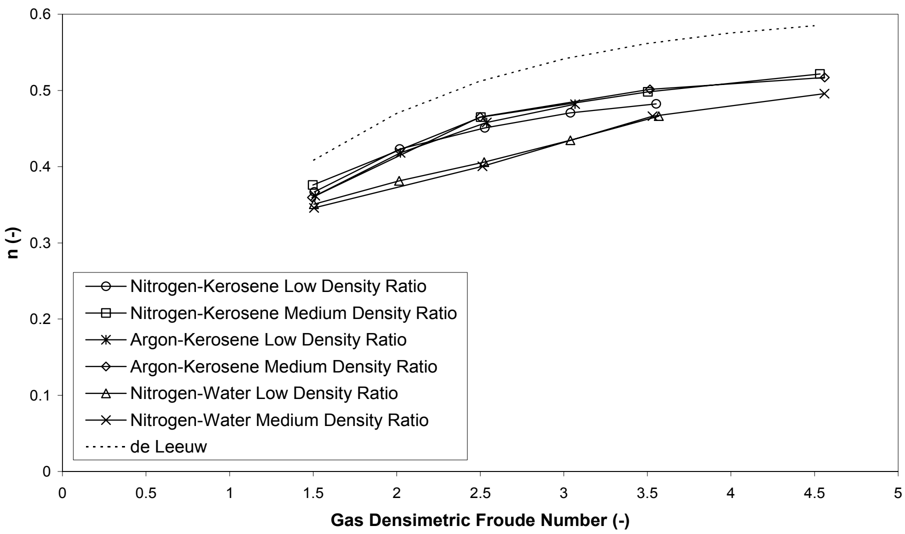

Figure 20. β = 0.75, std convergent: refitted de Leeuw-model parameter *n*

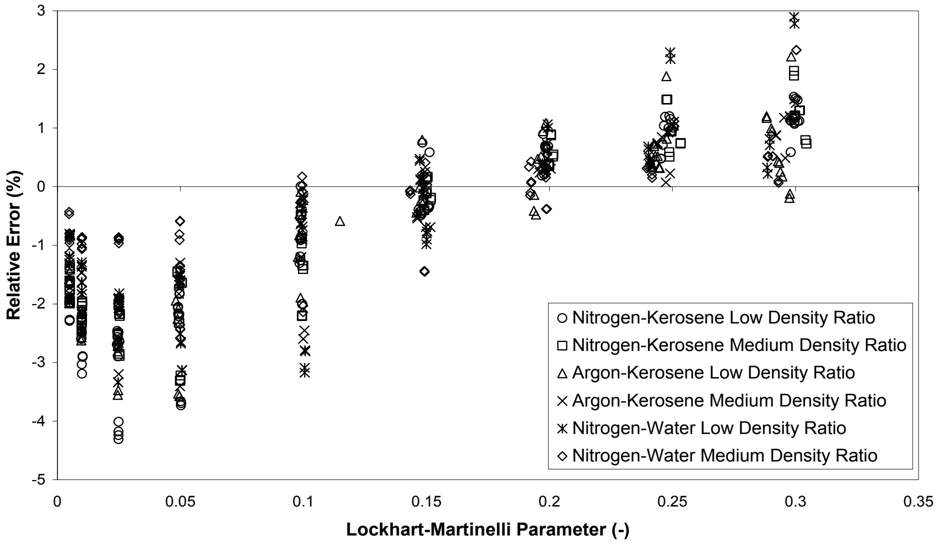

Figure 21. β = 0.75, std convergent: errors relative to the refitted de Leeuw model

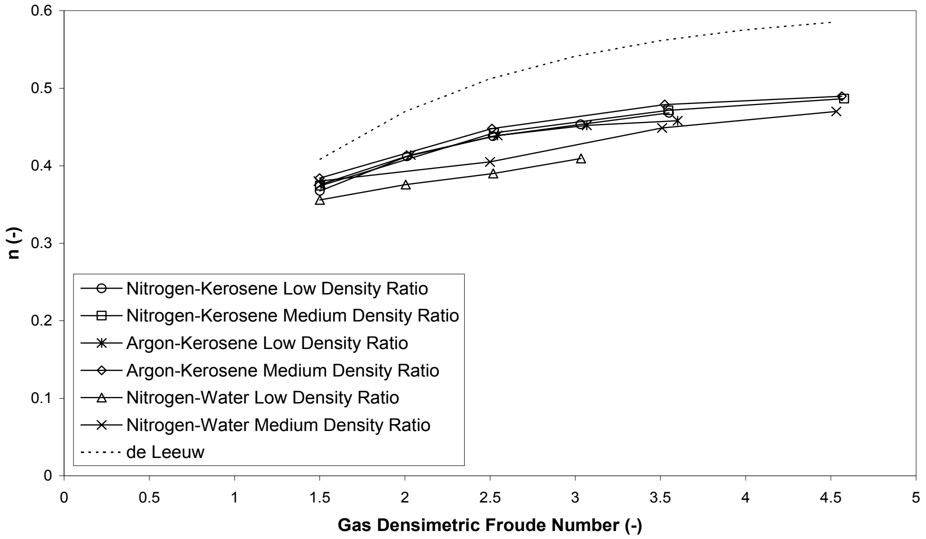

Figure 22. β = 0.75, 10.5° convergent: refitted de Leeuw-model parameter *n*

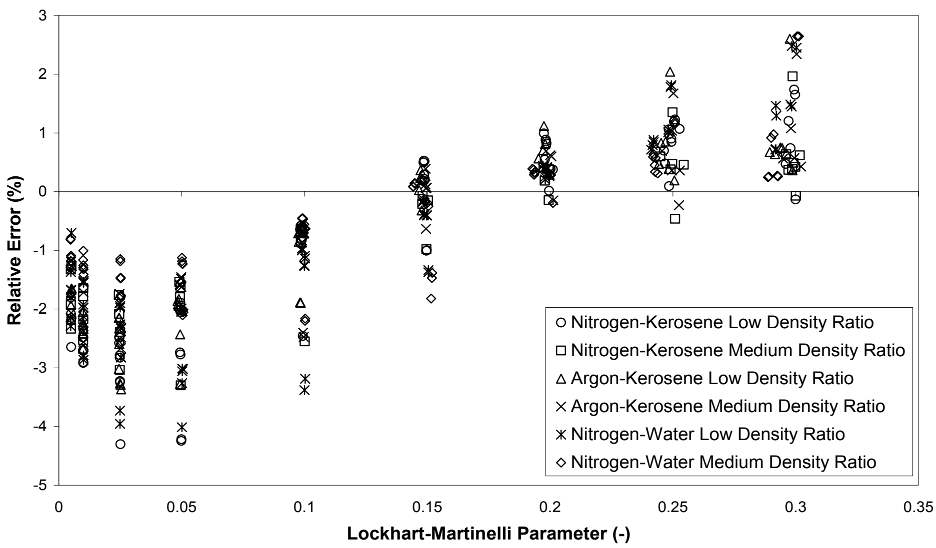

Figure 23. β = 0.75, 10.5° convergent: errors relative to the refitted de Leeuw model

What is clear from these Figures is that the model does not functionally fit the experimental data particularly well. There is a definite bias in the relative errors across the Lockhart-Martinelli range tested for each Venturi tube, i.e. no signs of random scatter in the errors around zero. Furthermore the relative error values are larger than anticipated, particularly at small values of the Lockhart-Martinelli parameter. The values of *n* obtained for each Venturi tube are presented as a function of the gas densimetric Froude number and the gas-liquid density ratio. These figures also include the values of *n* that would be obtained from the published de Leeuw model over the same gas densimetric Froude number range. The values of *n* all lie below those predicted by de Leeuw although good agreement with de Leeuw's value of *n* was obtained for nitrogen-kerosene and argon-kerosene for β = 0.6 (de Leeuw's values of *n* were generated on a 4-inch Venturi tube with β = 0.4). Moreover the nitrogen-water values are smaller than the nitrogen-kerosene and argon-kerosene values and have different trends both in terms of the gas densimetric Froude number and the gas-liquid density ratio. There are minimal differences in the value of *n* between the nitrogen-kerosene and argon-kerosene data sets.

The results noted above suggest that to improve the quality of the fits some form of modified model is necessary. To this end the following function was developed that includes three additional variable parameters (*a*, *b* and *m*). The modified model attempts to improve the representation of the observed "curvature" in the NEL experimental data sets at low values of the Lockhart-Martinelli parameter while reducing this effect on the fit as the Lockhart-Martinelli parameter increases.

The modified model is given as equation 9 below.

$$Venturi-tube\ Overreading=\sqrt{\frac{\Delta p_{two-phase}}{\Delta p_{gas}}}=\sqrt{1+CX+X^2}+a(C-2)X^m e^{-bX} \qquad (9)$$

It was determined after some initial trial fits that the value of *m* could be fixed at 1 without producing any detrimental effect on the overall performance of the modified function; so in fact only two additional variables have been added to the original model. The modified model was fitted using the same basic approach as described above; however some changes to the procedure were required owing to the two extra parameters present. These procedural changes involved initially fitting the parameters *C*, *a* and *b* simultaneously. Then taking the average value of all the individual *b* parameters at each density ratio and gas densimetric Froude number (for a given Venturi-tube and fluid combination) parameter *b* was then fixed. Next the data was refitted using only *C* and *a* as the adjustable parameters and the average *a* values determined and fixed as for *b*. Finally the data were refitted again using only the *C* parameter as a variable. The average values of *a* and *b* determined during the fitting process are presented in Table 1 below. For the Venturi tubes with standard convergent the average value of *b* is fairly constant, while parameter *a* varies by a larger amount, particularly for the meter with β = 0.75. There is less consistency in the parameter values for the Venturi tube with convergent angle 10.5°, with the *b* parameter value for the nitrogen-water combination being considerably less than those for the nitrogen-kerosene and argon-kerosene tests. The low *b* value is due to very low values of *b* at the low gas densimetric Froude numbers (1.5 and 2) pulling down the average.

Venturi Tube	Fluid Combination	*a* (average)	*b* (average)
β = 0.6, standard convergent	nitrogen-kerosene	1.013010	32.288919
β = 0.6, standard convergent	argon-kerosene	0.958996	33.155635
β = 0.6, standard convergent	nitrogen-water	0.909893	32.680548
β = 0.75, standard convergent	nitrogen-kerosene	1.308043	33.232230
β = 0.75, standard convergent	argon-kerosene	1.249512	33.154408
β = 0.75, standard convergent	nitrogen-water	1.110517	33.619659

β = 0.75, 10.5° convergent	nitrogen-kerosene	1.474415	35.82879
β = 0.75, 10.5° convergent	argon-kerosene	1.262837	34.49121
β = 0.75, 10.5° convergent	nitrogen-water	1.114199	25.87543

Table 1. Modified de Leeuw-model average *a* and *b* parameter values.

The results of the fitting process are shown in Figures 24 to 29. It is immediately clear that the new function better represents the experimental data. However a small element of bias still remains, but this is partly due to the fitting approach used. In finding new values of *C*, *a* and *b* parameter *n* was also redetermined and the new values are presented.

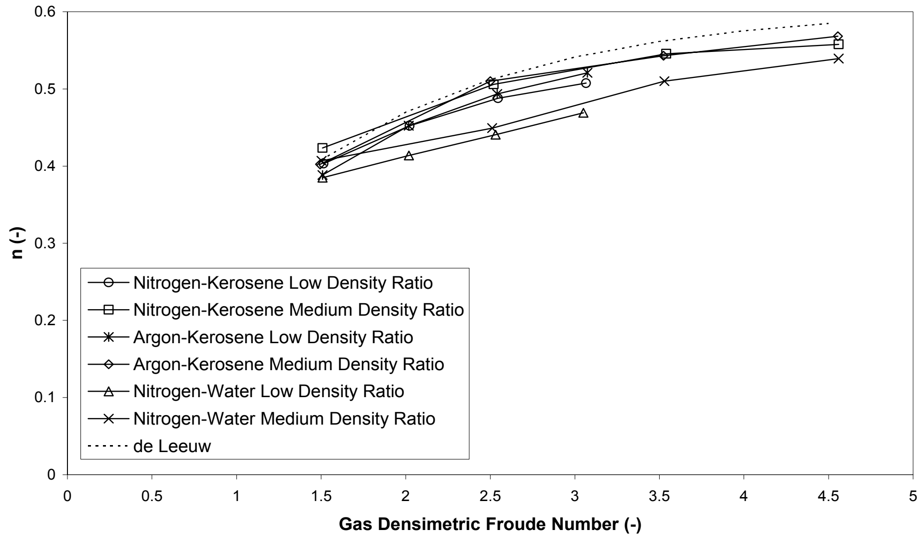

Figure 24. β = 0.6, std convergent: modified de Leeuw-model parameter *n*

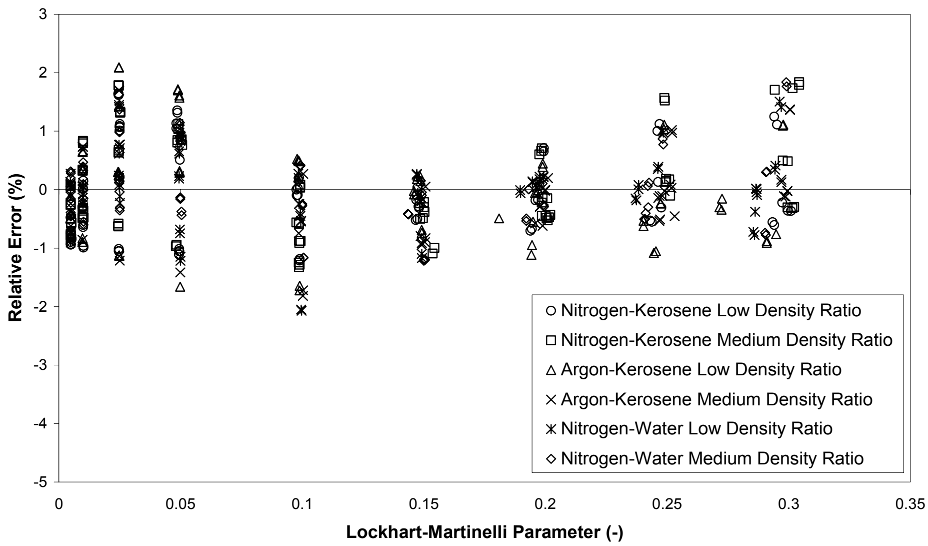

Figure 25. β = 0.6, std convergent: errors relative to the modified-de Leeuw model

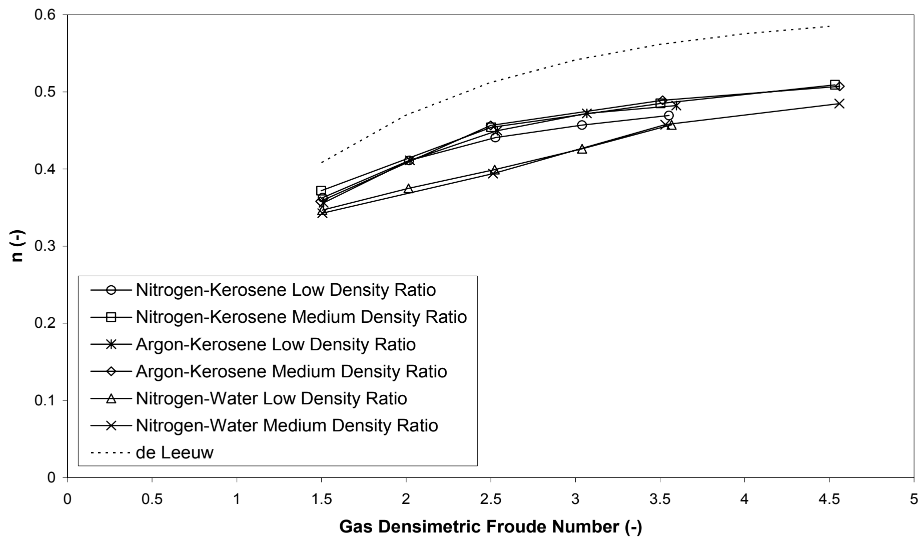

Figure 26. β **= 0.75, std convergent: modified de Leeuw-model parameter** ***n***

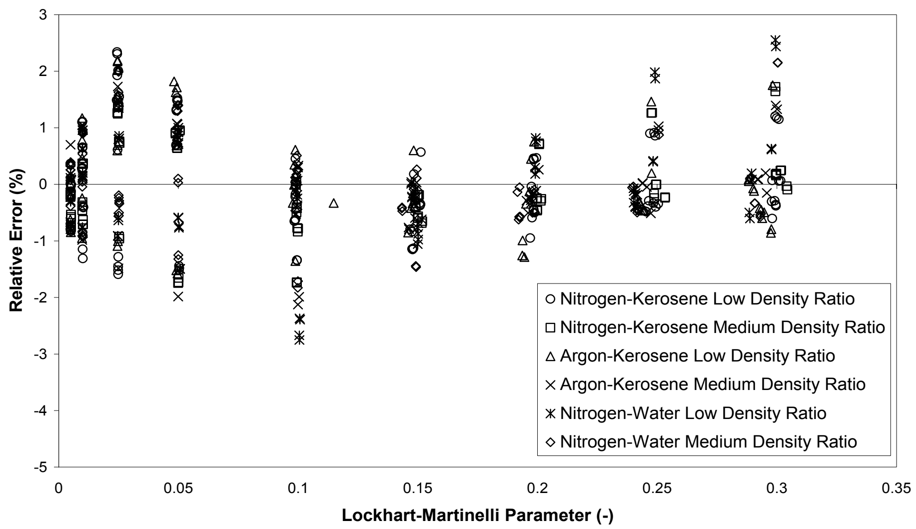

Figure 27. β **= 0.75, std convergent: errors relative to the modified-de Leeuw model**

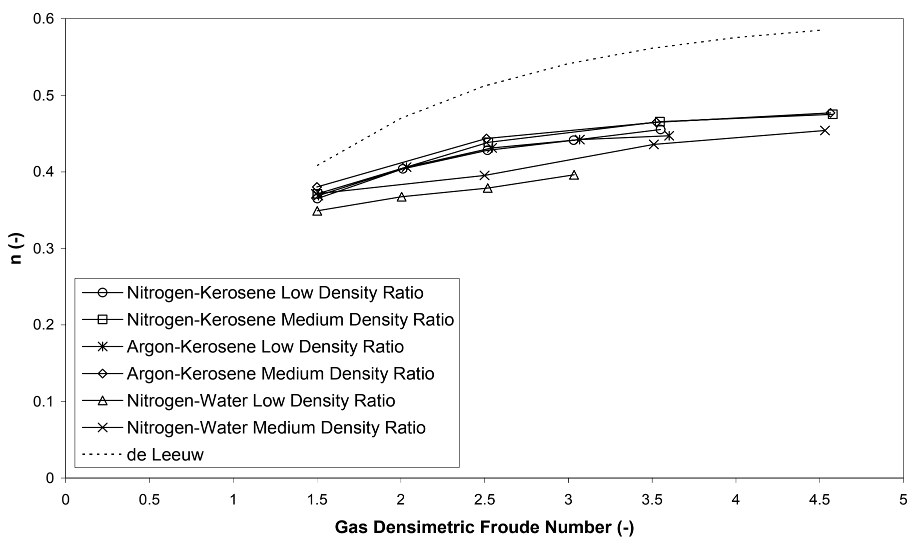

Figure 28. β **= 0.75, 10.5° convergent: modified de Leeuw-model parameter** ***n***

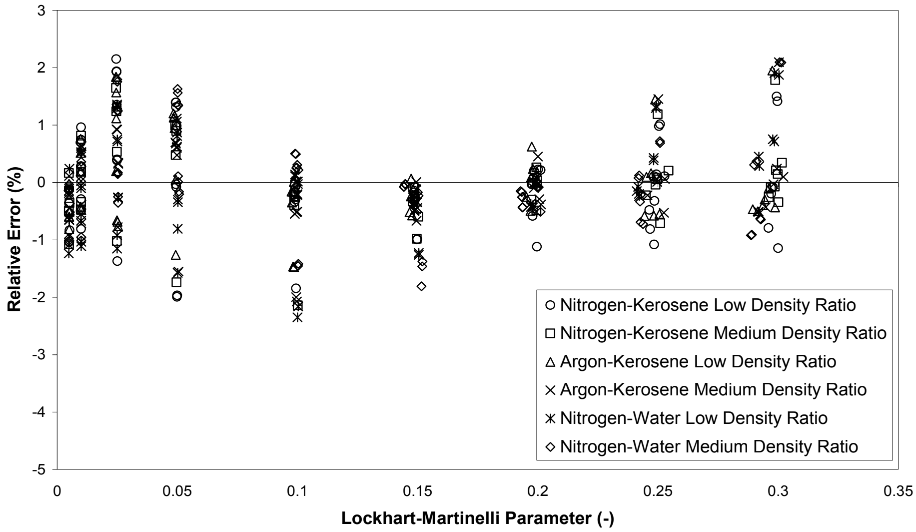

Figure 29. β = 0.75, 10.5° convergent: errors relative to the modified-de Leeuw model

6 CONCLUSIONS

Three 4-inch Venturi tubes have been tested in the NEL wet-gas test facility using three gas-liquid combinations: nitrogen-kerosene, argon-kerosene and nitrogen-water. Two gas-liquid density ratios were used for the tests with a gas densimetric Froude number range of 1.5 to 4.5, and a Lockhart-Martinelli parameter range of 0 to 0.3.

The alternative gas tests indicated a very small effect on the Venturi-tube performance, especially for the Venturi tube with convergent angle 10.5°. Using an alternative liquid, however, indicated a change in performance significant enough to produce large errors if not accounted for in a practical installation.

Fitting the experimental data obtained during the test programme using the Chisholm/de Leeuw model produced less than optimal Venturi-tube over-reading predictions, with relative errors in the range -4% to +3%. Consequently a modified model was developed which improved the representation of the experimental data to within $\pm$ 2% for more than 95% of test data points.

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NOTATION

A_D	Upstream pipe area	m^2
A_d	Throat area of Venturi tube	m^2
D	Diameter of entrance cylinder	m
Fr	Froude number	-
g	Acceleration due to gravity	m/s^2
K	Flow coefficient	-
m	Mass flowrate	kg/s
p	Absolute static pressure	Pa
Δp	Differential pressure	Pa
X	Lockhart-Martinelli parameter	-
β	Diameter ratio (= d/D)	-
ρ	Density	kg/m^3

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