Use of Venturi Meters in Multiphase Flow Measurement

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SUMMARY

This paper describes a project to investigate the performance of Venturi meters in multiphase flows. A range of Venturi meters spanning three diameter ratios and three inlet convergent angles was evaluated across a comprehensive range of multiphase flow conditions in the multiphase flow measurement facility at NEL.

The Venturi meters were evaluated in an uninterrupted 4-inch horizontal pipe run, without any mixing. The first stage of the project focused on development of appropriate instrumentation, using standard differential pressure transmitters and a clamp-on gamma densitometer, followed by the full evaluation of the meters.

Based on the results of this programme, one Venturi meter was selected for final evaluation using further refined instrumentation to collect data at a higher frequency. Evaluation of this final meter together with more detailed analysis of the data completes this paper.

1 INTRODUCTION

A range of Venturi meters spanning three diameter ratios and three inlet convergent angles was evaluated in the multiphase flow measurement facility at NEL. The multiphase flows used for the tests consisted of mixtures of stabilised crude oil, magnesium sulphate solution and nitrogen gas, across a range of test conditions. Multiphase test conditions are normally specified in terms of liquid flowrate, gas volume fraction (GVF) and the fraction of water in the liquid (water cut); the ranges of these conditions spanned the operating envelope of the multiphase test facility and correspond closely to the conditions used for evaluation of commercial multiphase meters in separate tests carried out by NEL.

The first stage of the project focused on development of appropriate instrumentation to meet the needs of the research programme. This included differential pressure measurement, density measurement, data sampling method and correct averaging of the measurements to give the Venturi discharge coefficients. Flow measurements in multiphase flow are strongly affected by the highly unsteady nature of the flow over much of the test envelope. For example the Venturi differential pressure can have peaks registering an instantaneous differential pressure more than 5 times the average value during a slug flow. To achieve a reliable discharge coefficient measurement requires a large number of data samples.

All the Venturi meters were tested using a mixture of stabilised Forties crude oil and kerosine as the oil phase. The water phase used for all but two of the Venturi meters was 50 g/litre magnesium sulphate solution, and for the remaining two was 100 g/litre magnesium sulphate solution (the water phase was changed for a separate project). Two Venturi meters were additionally tested using stabilised Oseberg crude oil.

The results of these tests are summarised in this paper. Based on these results one Venturi meter was selected for final evaluation using further developed instrumentation to allow higher frequency data acquisition and the results of this final evaluation together with more detailed analysis of the data completes this paper.

2 EXPERIMENTAL PROGRAMME

2.1 Venturi Meter Theory

The volumetric flowrate through a Venturi meter is given by the following expression:

$$Q = CA\sqrt{\frac{2\Delta P}{\rho\left(1-\beta^{4}\right)}} \qquad (1)$$

In a multiphase flow, where the measurements of differential pressure and density both fluctuate it is not satisfactory to use the ratio of $\Delta P/\rho$ in this expression. This may be avoided by calculating the mass flowrate

$$M = \rho Q \qquad (2)$$

from which it follows that

$$M = CA\sqrt{\frac{2\rho\Delta P}{\left(1-\beta^{4}\right)}} \qquad (3)$$

In practice, the mass flowrate is an average value over the measurement period. Equation (3) becomes, by correct summation over the measurement period:

$$\overline{M} = CA\sqrt{\frac{2}{\left(1-\beta^{4}\right)}} \leftrightarrow \overline{\sqrt{\rho\Delta P}} \qquad (4)$$

Therefore the correct quantity to calculate from the measured parameters of density, r, and differential pressure across the Venturi, ΔP, is the average of the square root of $\rho\Delta\Pi$ evaluated for each individual measurement sample.

In this situation we have reference volumetric flowrates for each of the individual streams of oil, water and gas and, knowing their densities at measured pressure and temperature, the reference total mass flowrate may be calculated from

$$M = \rho_{oil} Q_{oil} + \rho_{water} Q_{water} + \rho_{gas} Q_{gas} \tag{5}$$

Having the average reference mass flowrate, $\overline{M}$, and the measured value of rDP from the Venturi meter enables calculation of the discharge coefficient from:

$$C = \frac{\overline{M}}{A} \sqrt{\frac{\left(1-\beta^{4}\right)}{2}} \left(\sqrt{\rho \Delta P}\right)^{1} \tag{6}$$

where A is the throat area and b is the ratio of throat diameter to full pipe diameter, which will be specific to each Venturi meter tested.

2.2 Instrumentation

In a single phase flow the density of the fluid will be known and therefore it is only necessary to measure the differential pressure in order to be able to calculate the flowrate. In multiphase flow, however, although the densities of the individual component phases are known, the density of the multiphase mixture is not known. Therefore it is necessary to measure the density of the fluid mixture entering the Venturi meter. This was done using a gamma densitometer containing a ^{137}Cs gamma source, clamped onto the pipe upstream of the Venturi meter.

Differential pressure was measured between tappings located upstream and at the Venturi throat, using a Rosemount differential pressure transmitter. These devices are used in the multiphase measurement laboratory and were available in a number of calibrated pressure ranges, enabling the selection of appropriate transmitters for each Venturi, since often two pressure ranges were required to span the range of differential pressures which could be encountered across the whole test programme. There was always a need to balance accuracy of measurement with the total range which could be experienced in a multiphase flow. The Rosemount transmitters have proved to be very robust in multiphase flow, but have signal output which is damped, giving a maximum frequency response of 5 Hz.

Pressure and density measurements were collected using a high speed A to D conversion board in a PC, at the maximum frequency of the pressure transmitters (ie 5 Hz). A much higher data logging frequency was planned for the final stage of the project.

Each test condition was recorded for 10 minutes, giving a total number of 3000 measurements per test point.

2.3 Orientation

Typically multiphase flowmeters may be arranged in a vertical or a horizontal flow configuration. Most multiphase flowmeters using Venturi meters are arranged with a vertically upward flow through the Venturi meter. In nearly all cases the multiphase flow mixture passes from horizontal to vertical through a blinded tee just upstream of the metering section. Mixing is beneficial in distributing the gas and liquid across the pipe cross-section such that density measurement is reasonably reliable. This is more easily achieved in vertical flow since gravity does not act to separate the gas and liquid. So for density measurement, a vertical flow orientation is preferred.

For differential pressure measurement, however, vertical flow is less satisfactory. Unless the tapping lines to the pressure transmitters contain a fluid of the same density as the multiphase mixture in the flow conduit, there will be a hydrostatic pressure differential to consider in addition to the Venturi pressure differential. In the case of a large diameter ratio Venturi meter at low flowrate, the hydrostatic pressure differential may be significant compared with the Venturi differential pressure. If the impulse lines were always liquid or gas filled the hydrostatic differential can be calculated, knowing the mixture density, but it is unsatisfactory to correct one measurement with another in this way. Furthermore, it is difficult to ensure that the impulse lines remain filled with a particular fluid phase and so the applied correction itself may be in error. It is easy to obtain Venturi differential pressure measurements with errors higher than ±50% for low Venturi differential pressure. Therefore, for differential pressure measurement, a horizontal flow orientation is preferred.

In practical tests it was found that a horizontal configuration gave much more satisfactory results than a vertical configuration, since the errors in differential pressure measurement in vertical flow vastly outweigh the difficulties of making a reliable density measurement in horizontal flow. The most satisfactory horizontal flow results were obtained in a long straight horizontal pipe where the density at the gamma densitometer was consistent with the density at the Venturi throat, with the densitometer arranged to give a vertical measurement through the pipe cross-section.

2.4 Data Collection Frequency and Averaging

A typical example of density and differential pressure measurement is shown in Figure 1, where signals from the instruments, in mV, are plotted against time in msec.

Calculating in mV, the average and standard deviations of the measurements are:

	Average	Standard deviation
Venturi differential pressure, ΔP	1046.4	102.0
Density	1863.7	515.9
Density x ΔP	1987768	807047

The 95% confidence interval of the measurements will depend on the number of samples taken according to the equation

$$\text{confidence interval} = t_{95}\frac{\sigma}{\sqrt{n}} \qquad (7)$$

The confidence interval for density × Venturi ΔP is shown below and as a proportion of the average measurement.

Number of samples	Confidence interval	Confidence interval / average
100	159795	8.0%
1000	50072	2.5%
3000	28880	1.5%
10000	15818	0.80%
30000	9133	0.46%

This is an extreme example, and in many cases the signals are unlikely to vary quite so much. However it is clear from this example that typically 3000 data samples are required to give an acceptable uncertainty in the value of the Venturi discharge coefficient (ie less than ±1%), where the uncertainty is half that of the density $\times \Delta P$ value because of the square root. 3000 samples may be collected by recording at 5 Hz for 10 minutes. To achieve an uncertainty of ±0.25% would require a further 10-fold increase in the number of samples collected and this was considered in the final stage of the project.

2.5 Installation

The Venturi meters were all installed in a similar horizontal orientation consisting of:

- an adaptor from class 150 to class 600 flanges 0.6 m
- a spool piece with bore machined to match the Venturi tube 1.0 m
- the Venturi meter 1.0 m
- a pressure recovery spool piece 1.0 m
- an adaptor from class 600 to class 150 flanges 0.6 m

The whole assembly was then installed in the 4-inch horizontal line of the NEL multiphase flow facility. The clamp-on gamma ray densitometer was located on the conditioning spool piece upstream of the Venturi meter. The installation is illustrated in Figure 2 and the exact measurements of each Venturi meter are given in the table below.

Venturi meter	Nominal diameter ratio	Inlet cone angle (degrees)	Full bore diameter (mm)	Throat diameter (mm)	Diameter ratio
1	0.40	21	102.20	40.86	0.3998
2	0.60	21	102.21	61.33	0.6000
3	0.75	21	102.19	76.73	0.7509
4	0.40	31.5	102.23	40.94	0.4005
5	0.60	31.5	102.26	61.36	0.6000
6	0.75	31.5	102.31	76.76	0.7503
7	0.40	10.5	102.22	40.91	0.4002
8	0.60	10.5	102.20	61.31	0.5999
9	0.75	10.5	102.26	76.76	0.7506
10	0.40	21	102.26	40.88	0.3998
11	0.75	21	102.31	76.74	0.7501

2.6 Test Matrix

The typical minimum test matrix for each meter is shown in the table below. This covered the full range of liquid flowrates and gas volume fractions at 4 water cuts (less than 10% water, 40% water, 75% water and 100% water). Some meters were tested over a wider range of test conditions including some additional water cuts (25% water, 60% water and 90% water). The matrix for Venturi meters of diameter ratio 0.40 was reduced to remove points of excessively high Venturi differential pressure since the maximum differential pressure measurement range available was 50 psi (3.45 bar).

	GVF (%)											
Liquid (m^3/hr)	10	25	40	50	60	70	80	85	90	92.5	95	97.5
14						(X)	(X)	X	X	X	X	X
22						X	X	(X)	X	X	X	
32			X	(X)	X	(X)	(X)	X	(X)	X		
43			(X)	X	(X)	X	X	X				
65		X	(X)	(X)	X	(X)	X					
86	X	(X)	(X)	X	X							
108	(X)	X	X									

Repeated at water cuts of 5, (25), 40, (60), 75 and 90%.

Bracketed values tested for only selected meters, other values for all meters.

2.7 Test Fluids

The combination of fluids used for the tests were as follows:

Venturi meter	Diameter ratio (β)	Inlet cone angle (°)	Oil phase	Water phase
1	0.4	21	Forties	50 g/litre
2	0.6	21	Forties	50 g/litre
"	"	"	Oseberg	50 g/litre
"	"	"	Oseberg	100 g/litre
3	0.75	21	Forties	50 g/litre
4	0.4	31.5	Forties	50 g/litre
5	0.6	31.5	Forties	50 g/litre
6	0.75	31.5	Forties	50 g/litre
7	0.4	10.5	Forties	100 g/litre
8	0.6	10.5	Forties	100 g/litre
"	"	"	Oseberg	100 g/litre
9	0.75	10.5	Forties	50 g/litre
10	0.4	21	Forties	50 g/litre
11	0.75	21	Forties	50 g/litre

The properties of the single-phase fluids were typically (at 20ºC):

Forties crude oil:	Density = 862.8 kg/m^3 Viscosity = 14.65 cP
Oseberg crude oil:	Density = 878.2 kg/m^3 Viscosity = 31.25 cP
50 g/litre $MgSO_4$ solution:	Density = 1029.3 kg/m^3 Viscosity = 1.178μ_w Concentration = 62.4 g/litre
100 g/litre MgSO4 solution:	Density = 1051.6 kg/m^3 Viscosity = 1.340μ_w Concentration = 106.2 g/litre

The exact density for each fluid was evaluated as a function of temperature for each test.

3 RESULTS FOR INITIAL EVALUATION

3.1 Results for all meters

Figure 2 shows the discharge coefficient plotted against reference gas volume fraction (GVF) for all the meters together. Each group of Venturi meters of similar diameter ratio gave a similar curve of discharge coefficient against GVF although there is quite a marked difference between the curves. The discharge coefficient apparently increases as the diameter ratio is increased, although it is not clear why this should occur.

3.2 Results for meters of β = 0.40

Figure 3 shows the discharge coefficient against GVF for the Venturi meters of diameter ratio 0.40. The values of discharge coefficient show a consistent behaviour for all three Venturi meters having different inlet cone angles, with the discharge coefficient for the meter with the shallow inlet angle (Venturi No 7) slightly lower than for the other meters. This is expected since the longer inlet length leads to a higher irreversible (frictional) pressure loss between the upstream and throat tappings, than for a standard Venturi operating at the same flowrate. Venturi No 10 was similar to No 1 but without the diffuser section, and this is seen to give similar results to Venturi No 1.

Figures 4, 5 and 6 show discharge coefficient against GVF for the Venturi meters with inlet angles of 21º, 31.5º and 10.5º respectively, shown by water cut. There is a small, but noticeable effect of water cut on the discharge coefficients. This is most apparent in Figure 5 where the discharge coefficient for 60% water cut can be seen to be lower than the other values, but also in Figures 4 and 6 for 40% water cut. It is known that in this intermediate water cut zone between oil continuous and water continuous mixtures, the apparent viscosity, and hence frictional pressure loss is greater than it would be for a single liquid phase. For the test fluids used at NEL it is known that the peak in viscosity occurs at around

60%water cut and so this would be expected to give the lowest discharge coefficient. The effect is largest at high gas fraction and this is consistent with the expectation that liquid viscosity will have the largest effect in the thin liquid films which occur in annular flow.

Above 80% GVF, the difference in discharge coefficient between liquid phases of 60% water cut and of oil can be 5%, with a consequent similar magnitude of error in the calculated value of mass flowrate if a Venturi were used in this flow without compensation for the viscosity enhancement effect.

3.3 Results for meters of β = 0.60

Figure 7 shows the discharge coefficient against GVF for the Venturi meters of diameter ratio 0.60. The values of discharge coefficient show a consistent behaviour for all three Venturi meters with different inlet cone angles. Once again the discharge coefficient for the meter with the shallow inlet angle (Venturi No 8) is slightly lower than for the other meters. There is more scatter in the measurements from these three Venturi meters compared with those of diameter ratio 0.4. This is due to two effects. Firstly the differential pressures were significantly lower, and even using pressure transmitters of lower range to cover the points at the lowest differential pressures, the uncertainties in measuring differential pressure in a multiphase mixture increase at low differential pressure. Secondly, a greater range of test conditions could be covered than for the smaller diameter ratio meters, particularly at high gas fractions, since the overall pressure loss was significantly smaller. There is typically more fluctuation observed in multiphase flows at high gas fractions and greater scatter in the measurements is to be expected.

Figures 8, 9 and 10 show discharge coefficient against GVF for the Venturi meters with inlet angles of 21º, 31.5º and 10.5º respectively, shown by water cut. Similarly to the smaller diameter ratio meters there is a clear influence of water cut on the discharge coefficients, particularly at 40% and 60% water cut (60% water cut tested for Venturi 2 only).

3.4 Results for meters of β = 0.75

Figure 11 shows the discharge coefficient against GVF for the Venturi meters of diameter ratio 0.75. The values of discharge coefficient show a similar behaviour for all three Venturi meters having different inlet cone angles. The values of discharge coefficient are more scattered still than was observed for the meters of diameter ratio 0.6, although the tests covered similar ranges of flow conditions. In these three Venturi meters the differential pressure measurements are often extremely small which lead to large uncertainties in the measurements.

Figures 12, 13 and 14 show discharge coefficient against GVF for the Venturi meters with inlet cone angles of 21º, 31.5º and 10.5º respectively, shown by water cut. Even with the greater scatter in the measurements, it is still possible to distinguish the effect of water cut. This is most clearly shown for Venturi No 6, in Figure 13, where approximately 10% difference in discharge coefficient is demonstrated between 5%/40% water cut and 75%/100% water cut.

4 RESULTS FOR FINAL EVALUATION

4.1 Experimental Tests

The final Venturi meter, Venturi No 2, was assembled in the same configuration described in Section 2.5, but using undamped Gulton-Statham differential pressure transmitters. The full test matrix shown in Table 2 was used for the evaluation of this meter. The test matrix was sorted by the maximum differential pressure observed in the original tests at 5 Hz data collection frequency so that pressure transmitters of differential pressure range 0 to 20 psi and 0 to 50 psi could be used. This allowed more accurate measurement of low differential pressure than would have been possible using a single 0 to 50 psi transmitter range.

The response time of these transmitters was less than 7 msec, which is equivalent to 142 Hz. To achieve the 30,000 data samples as discussed in Section 2.4 therefore required data to be collected over a period of 3_ minutes for each data point. The discharge coefficient against GVF is shown in Figure 15.

4.2 Modelled Data

The behaviour of the Venturi meter in its evaluation described in the previous section has been modelled according to the following process.

The mass flowrate is calculated from equation (4) where the discharge coefficient has been fitted as a function of the reference gas volume fraction (GVF) and liquid Reynolds number (Re_L) with different polynomial fits obtained for each water cut. The combination of GVF and Re_L which yielded the best fit was GVF/ReL. This was used since the discharge coefficient depends on both GVF and Re_L, but it must be emphasised that this is an empirical relationship. The GVF dependence of (apparent) discharge coefficient is most likely related to the use of a live density measurement in place of a volume or area density measurement. If the multiphase flow were fully homogenised it is likely that the discharge coefficient would be close to 1. It should be noted that in practice the GVF and liquid Reynolds number will be outputs from the measurement model and therefore an iterative situation will be required.

Having evaluated the total mass flowrate, __, the next stage is to calculate the quality (= gas mass fraction) in order to calculate the M gas and liquid flowrates. The quality, χ, is calculated from:

$$\chi = \left\{ 1 + \frac{\rho_L (\rho_{TP} - \rho_G)}{S_{\rho G} (\rho_L - \rho_{TP})} \right\}^{-1} \tag{8}$$

where rTP is the measured two-phase (line) density for consistency with the experimental data set and S is the slip ratio, defined by

$$S = \frac{Q_G}{Q_L} \left(\frac{1 - \varepsilon}{\varepsilon} \right) \tag{9}$$

The slip ratio represents the ratio between the in situ gas velocity and the in situ liquid velocity. The void fraction, ε, is calculated from

$$\varepsilon = \frac{\rho_{TP} - \rho_L}{\rho_G - \rho_L} \qquad (10)$$

Using the reference volumetric flowrates Q_G and Q_L, the known single phase densities and the measured density, rTP, the void fraction, e, and slip ratio, S, can be calculated. The best correlation of S was found to be against the parameter GVF/$Re_L^{0.25}$ for which all the slip ratio values at different water cut collapse on to one curve for oil-continuous flow and another for water-continuous flow.

The Reynolds number is calculated by the following method. Since in all cases the mass flowrate is dominated by the liquid phase the liquid Reynolds number is used. This is evaluated based on the full pipe diameter, D:

$$\mathrm{Re}_L = \frac{Q_L \rho_L D}{1000 A \mu_L} \qquad (11)$$

where *Q*L is the reference liquid flowrate in litre/sec, rL is the liquid density in kg/m^3 and µL is the liquid viscosity in Pa.s. The viscosity of the liquid phase is determined according to the methodology developed by Corlett (1998). For oil-continuous flow (ϕ = percentage water cut < 64):

$$\mu_L = \frac{\mu_{oil}}{(1 - \phi / 1000)^{1.2}} \qquad (12)$$

For water-continuous flow (f = percentage water cut > 64):

$$\mu_L = \mu_{water} \qquad (13)$$

The best results are obtained in the water cut range 0 < ϕ < ~50 where the liquids are oil-continuous and reasonably well mixed. As the inversion point is reached, around 64% water in these tests, the liquid phase distribution can switch between oil-continuous and water-continuous and so the viscosity, and hence the liquid Reynolds number can vary over a wide range.

For water-continuous mixtures, viscosity, and hence liquid Reynolds number can usually be less well characterised. The oil and water can either give temporary mixtures and liquid films with high viscosity or can separate and give an effective viscosity even lower than that of the water phase. Therefore characterisation of the rheological properties of the liquid phases in the three-phase mixture flowing through the Venturi meter is of key importance in the modelling of the meter.

Finally, the liquid and gas volumetric flowrates are calculated from:

$$liquid\,volume\,flowrate = Q_L = \frac{M(1-\chi)}{\rho_L} \tag{14}$$

$$gas\,volume\,flowrate = Q_G = \frac{M\chi}{\rho_G} \tag{15}$$

The errors in liquid and gas volumetric flowrates are calculated from:

$$\%\,liquid\,volume\,flowrate\,error = \frac{100\times(Q_{L,measured} - Q_{L,reference})}{Q_{L,reference}} \tag{16}$$

$$\%\,gas\,volume\,flowrate\,error = \frac{100\times(Q_{G,measured} - Q_{G,reference})}{Q_{G,reference}} \tag{17}$$

The errors in modelled liquid volume flowrate are shown in Figures 16 and 17, and the overall results of the modelling of the Venturi performance data are shown below. The arithmetical average error (showing the bias) and standard deviation of the errors (showing scatter)

Water cut	Liquid		Gas	
	Average error	Standard deviation of errors	Average error	Standard deviation of errors
5	0.09	3.05	0.71	9.11
25	0.18	3.52	-0.35	7.29
40	0.10	4.46	3.20	7.61
60	-0.05	5.73	6.32	7.87
75	0.06	2.82	1.28	12.05
90	-0.31	2.72	4.76	13.38

are calculated for both liquid and gas flowrates.

5 CONCLUSIONS

Eleven Venturi meters have been characterised in multiphase flows across the whole test envelope available in the NEL multiphase flow facility. These conditions spanned the range 10% to 95% gas volume fraction and 5% to 100% water cut, with liquid volumetric flowrate ranging from 14 to 108 m^3/hr.

The discharge coefficient was evaluated for each test condition based on the mass flowrate from the reference metering system (the sum of mass flowrates of the individually metered single phase flows of oil, water and gas). Measurements of differential pressure between the Venturi meter throat and the upstream tapping and of the density from a gamma ray densitometer were made to complete this calculation.

Discharge coefficient calculated by this method showed a significant variation with reference gas volume fraction and a smaller effect with reference water cut. This latter effect was most significant at water cuts close to the inversion between oil-continuous and water-continuous dispersion (40% to 60% water cut). A small difference was also observed in discharge coefficient between the Venturi meters with shallow inlet cone angle and the other Venturi meters, except at the largest diameter ratio, where scatter in the measurements obscured any difference.

For measurements in multiphase flows across the studied range of conditions, the most appropriate choice of diameter ratio is 0.60. The smaller diameter ratio gave too high a pressure drop and thus restricted the useful operating range, while the larger diameter ratio gave too small a pressure differential for reliably accurate measurements to be made.

There does not appear to be any advantage in varying the inlet cone angle from the standard value of 21º. No significant difference was observed between the Venturi meters with 21º inlet angle and those with 31.5º. The shallow inlet angle led to increased pressure loss without improvement in measurement accuracy. The diffuser section was shown to be essential in mitigating permanent pressure loss over the Venturi measuring system, except in conditions of gas volume fraction above 90% where there was little pressure recovery, with or without the diffuser section.

The standard Venturi meter No 2 with diameter ratio 0.60 and inlet cone angle of 21º was selected for the final evaluation using instrumentation which was revised to allow data recording at a significantly increased frequency. The results of this evaluation were modelled empirically: there was good agreement between modelled and reference volume flowrates.

REFERENCE

1 Viscosity of oil and water mixtures. A. E. Corlett, NEL Report No 263/97, 1998.

NOMENCLATURE

A	Venturi meter throat area	m2
C	Venturi discharge coefficient	-
D	Pipe diameter	m
M	Mass flowrate	kg/s
n	Number of samples	-
Q	Volume flowrate	m3/s
Re	Reynolds number	-
S	Slip ratio	-
t_{95}	Student's t-distribution for 95% confidence interval	-
β	Venturi diameter ratio (throat diameter/upstream diameter)	-
ΔP	Differential pressure	Pa
ε	Void fraction	-
μ	Viscosity	Pa.s
ρ	Density	kg/m^3
σ	Standard deviation	-
ϕ	Water cut (percentage water in liquid)	-
χ	Quality (gas mass fraction)	-

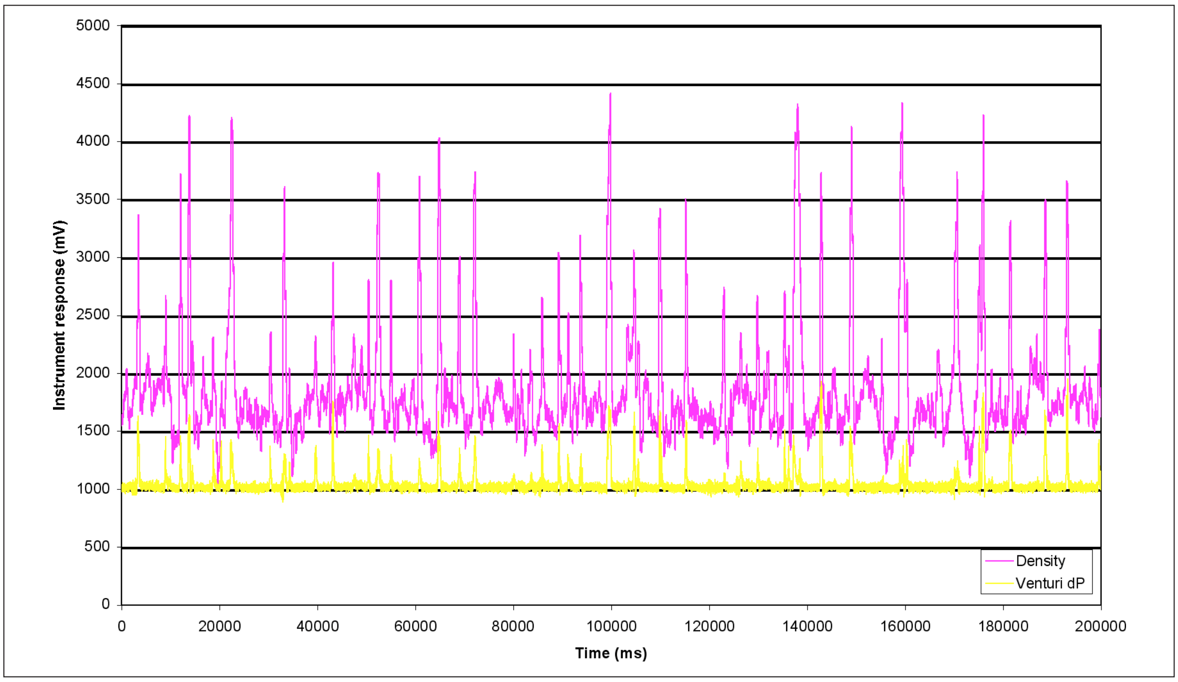

Figure 1: Typical density and Venturi differential pressure signals

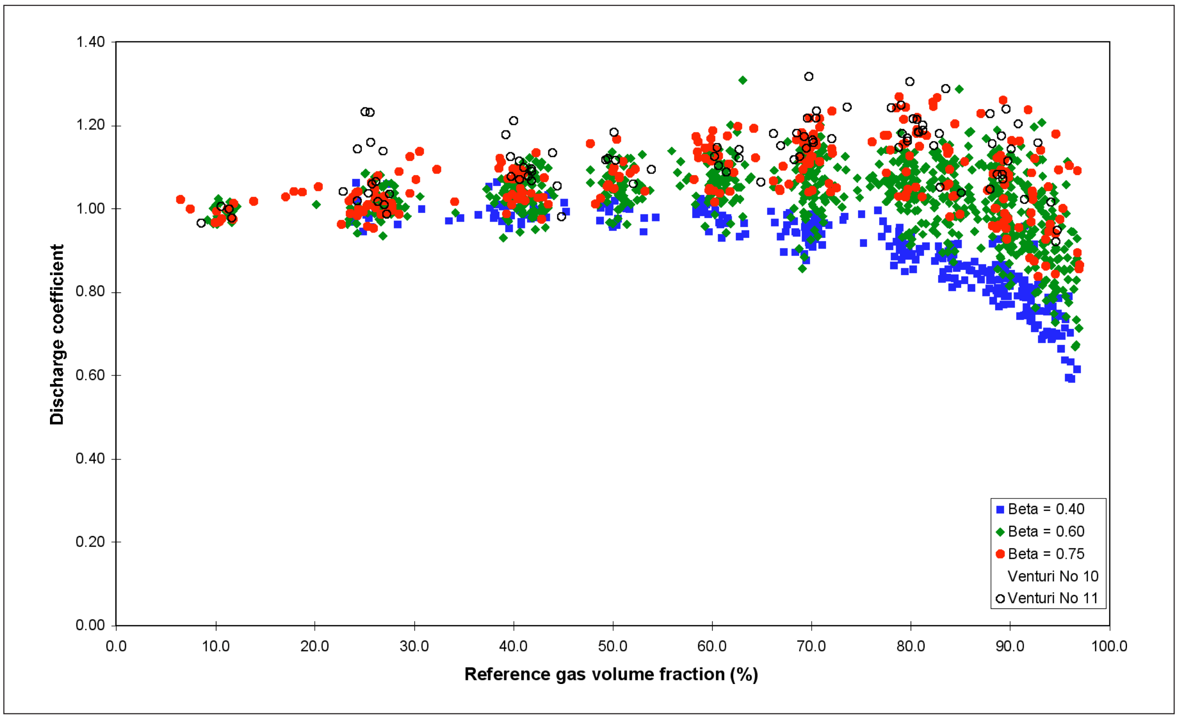

Figure 2: Discharge coefficient vs GVF for all Venturi meters in multiphase flow

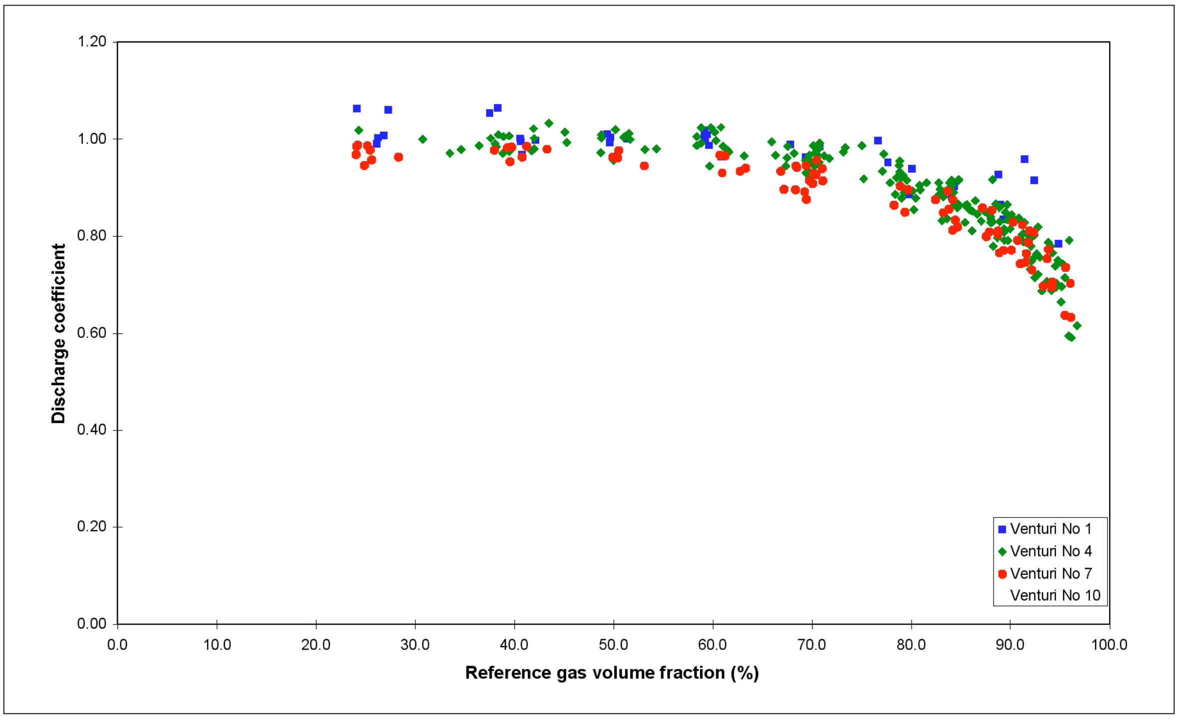

Figure 3: Discharge coefficient vs GVF for all Venturi meters of b = 0.40 in multiphase flow

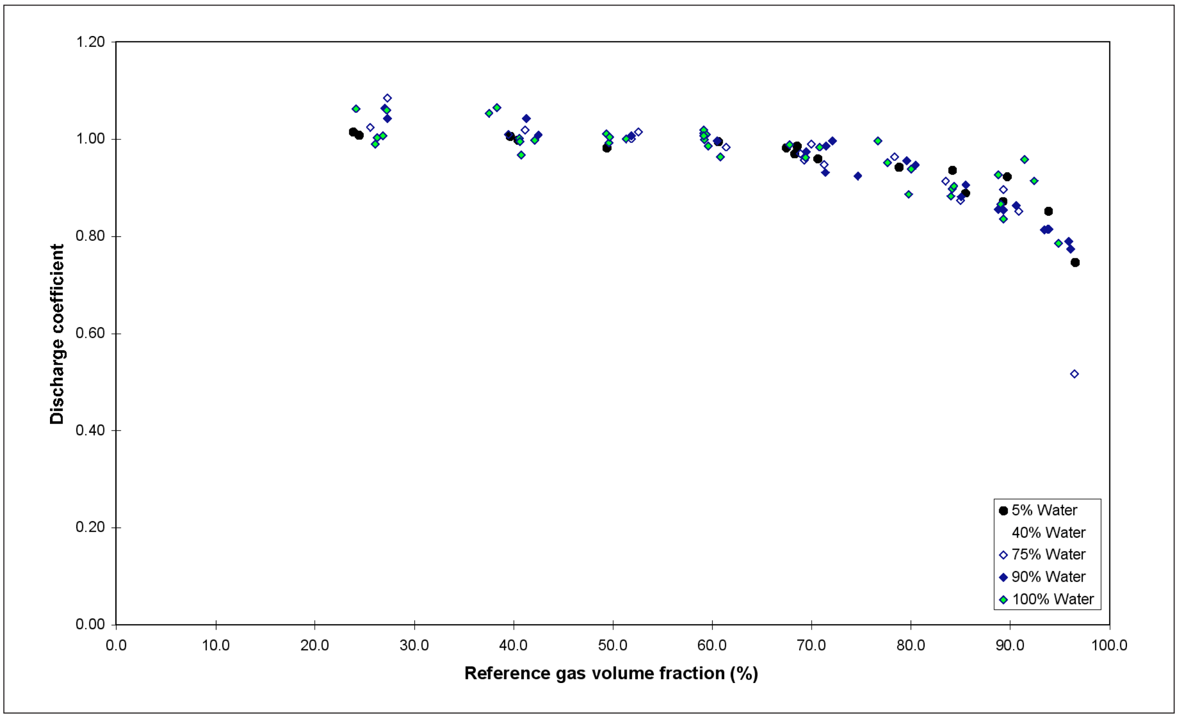

Figure 4: Discharge coefficient vs GVF for Venturi meter 1 in multiphase flow, showing effect of water cut

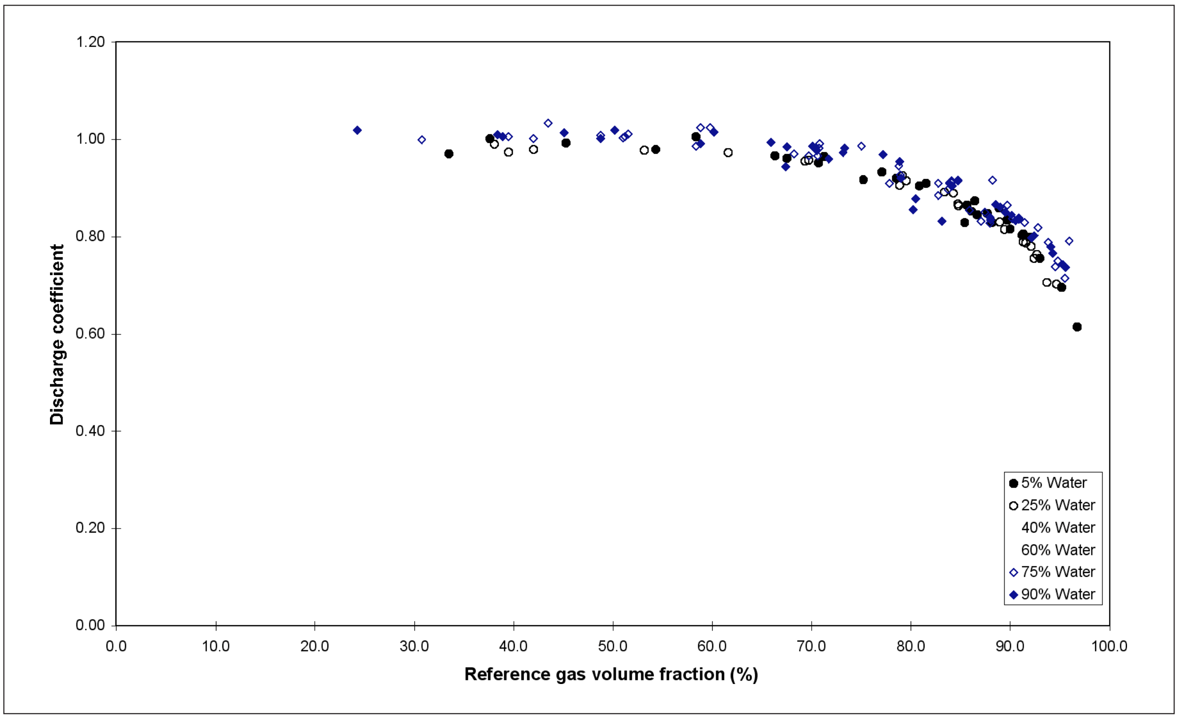

Figure 5: Discharge coefficient vs GVF for Venturi meter 4 in multiphase flow, showing effect of water cut

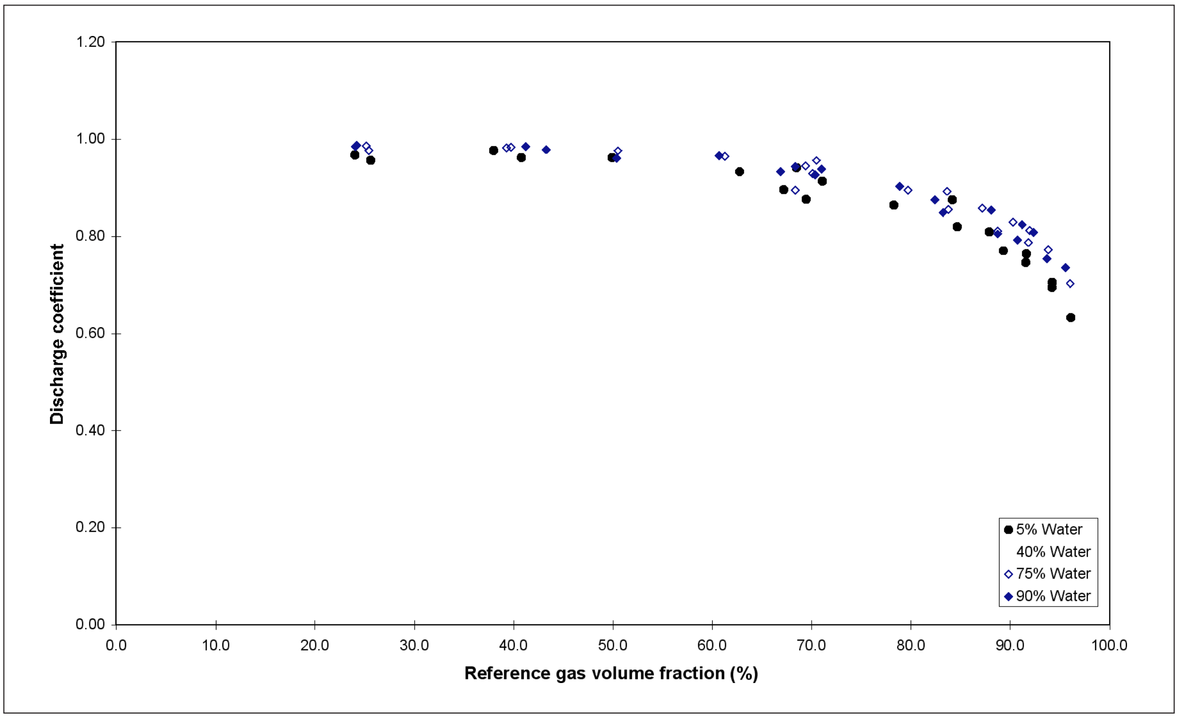

Figure 6: Discharge coefficient vs GVF for Venturi meter 7 in multiphase flow, showing effect of water cut

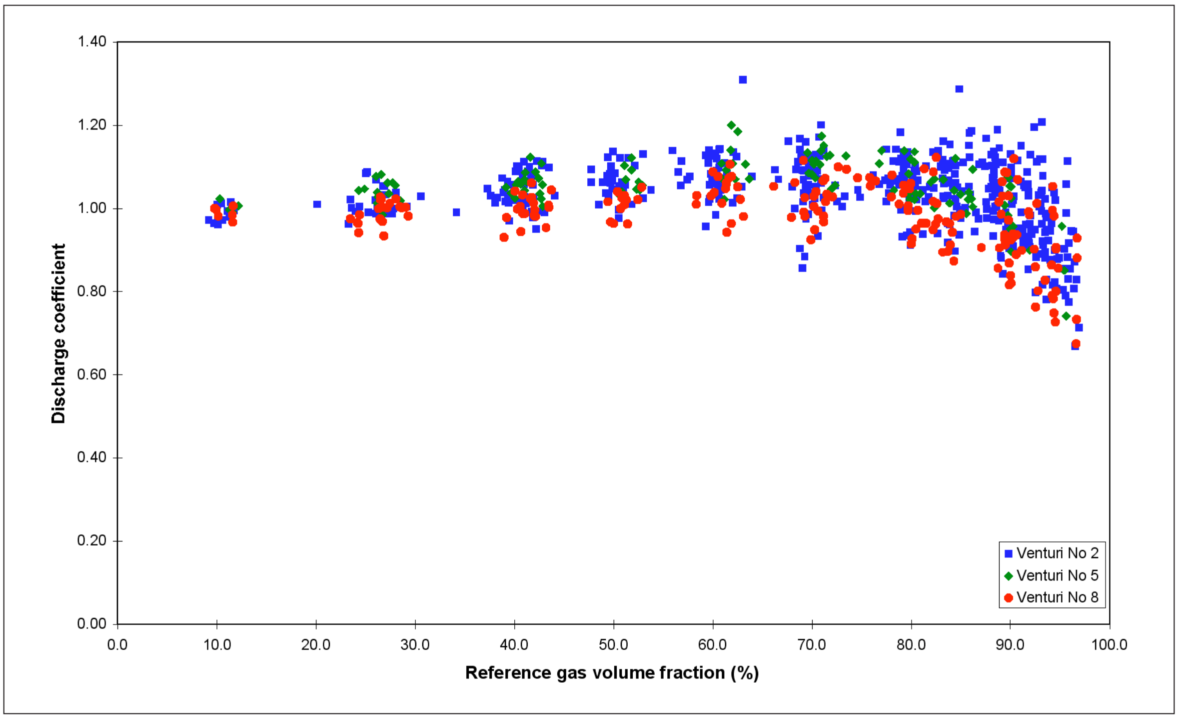

Figure 7: Discharge coefficient vs GVF for all Venturi meters of b = 0.60 in multiphase flow

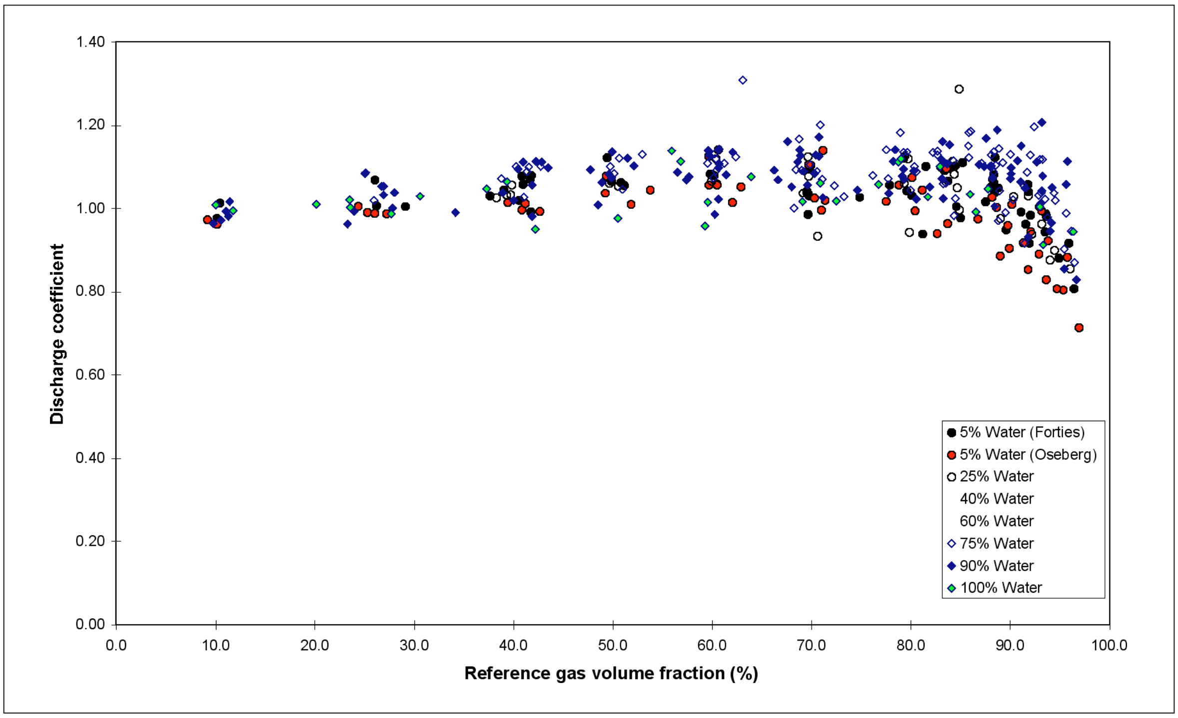

Figure 8: Discharge coefficient vs GVF for Venturi meter 2 in multiphase flow, showing effect of water cut

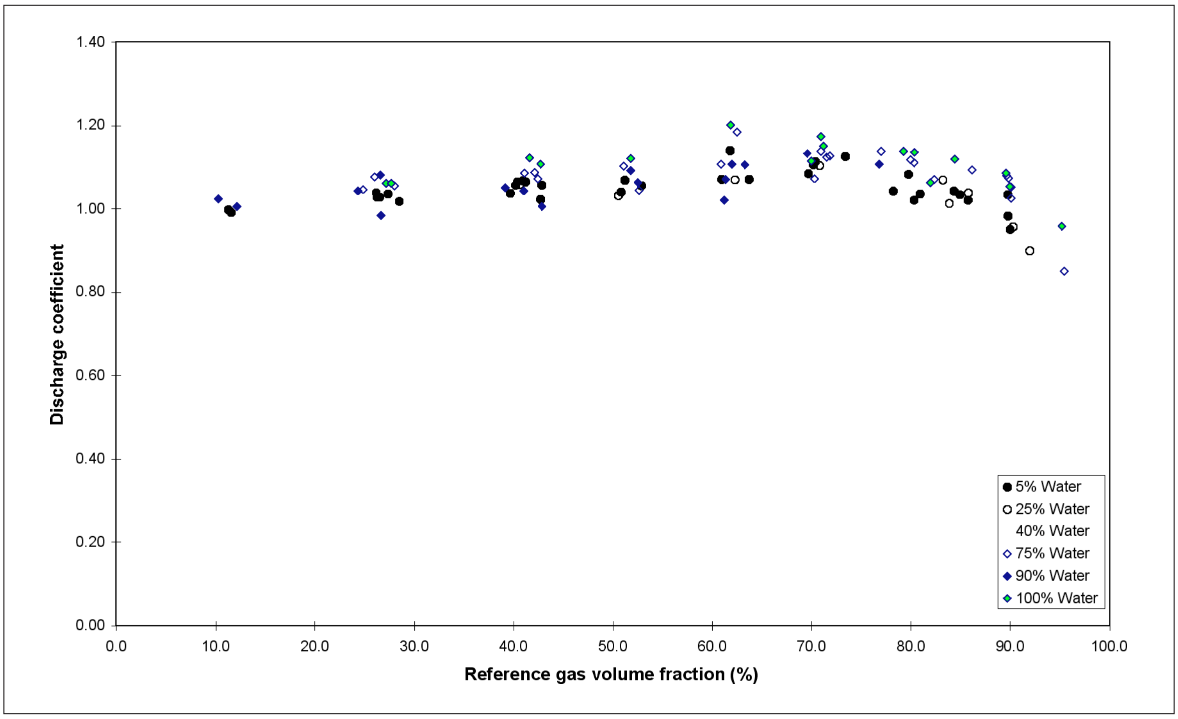

Figure 9: Discharge coefficient vs GVF for Venturi meter 5 in multiphase flow, showing effect of water cut

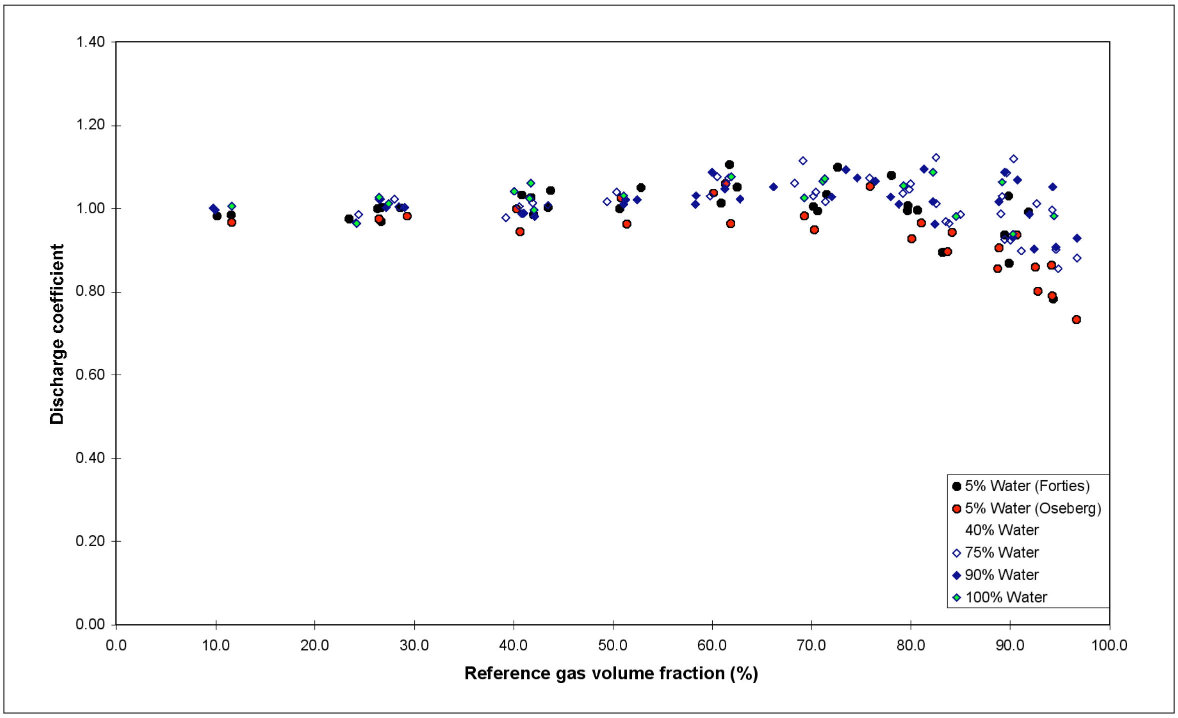

Figure 10: Discharge coefficient vs GVF for Venturi meter 8 in multiphase flow, showing effect of water cut

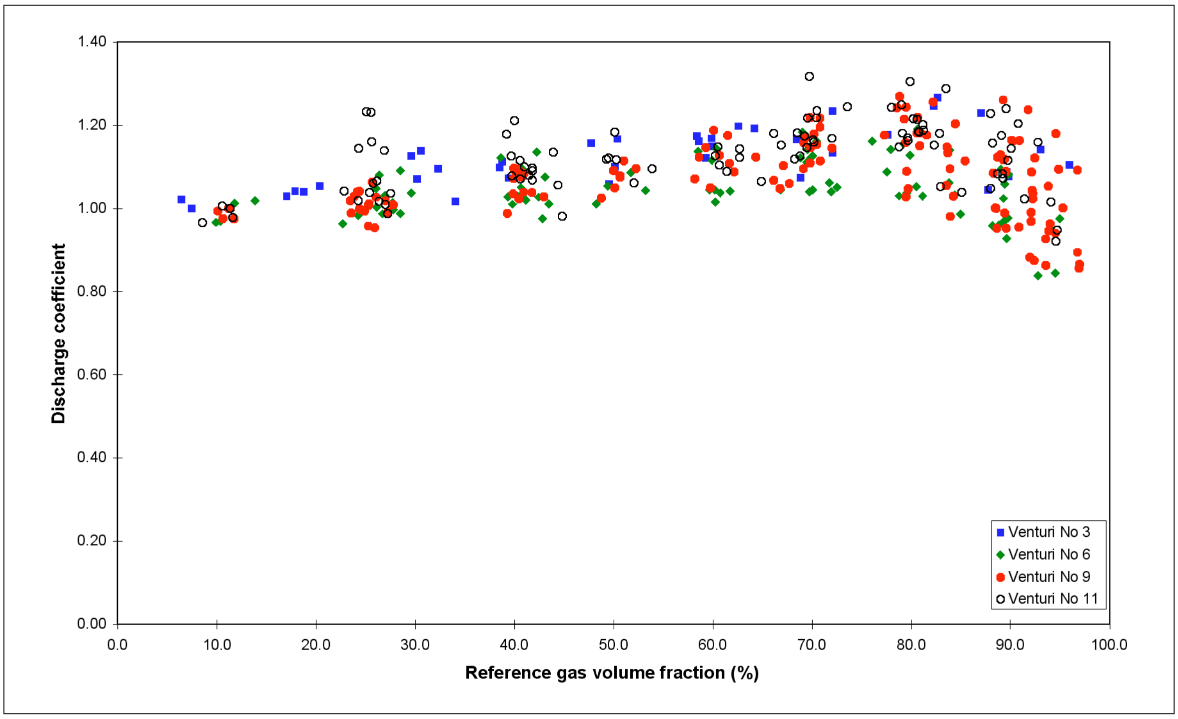

Figure 11: Discharge coefficient vs GVF for all Venturi meters of b = 0.75 in multiphase flow

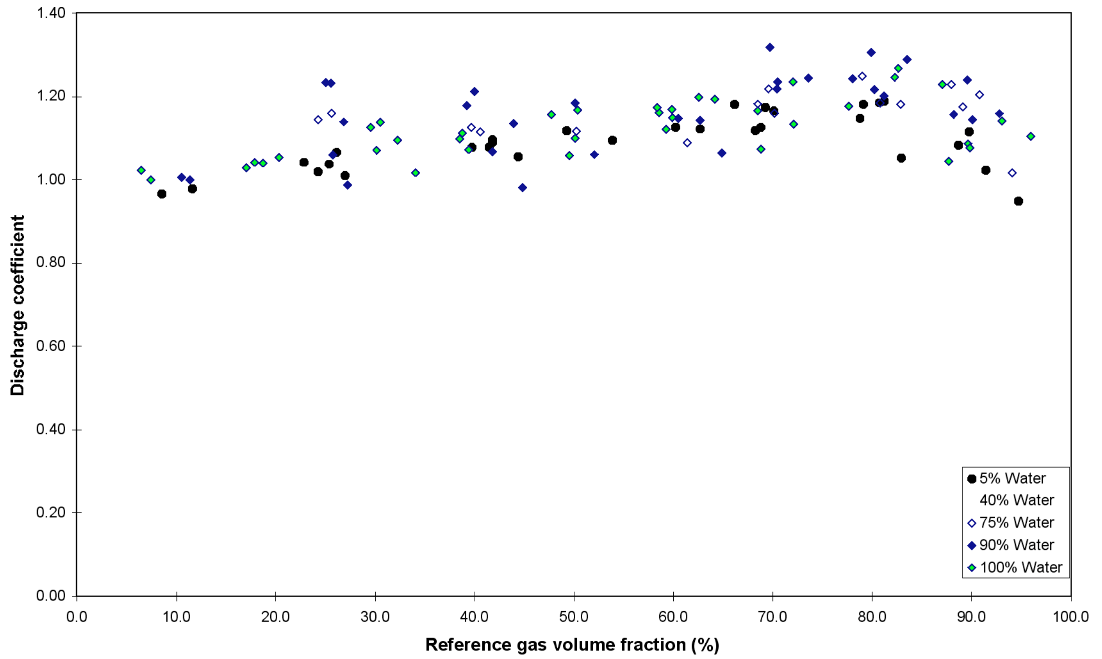

Figure 12: Discharge coefficient vs GVF for Venturi meter 3 in multiphase flow, showing effect of water cut

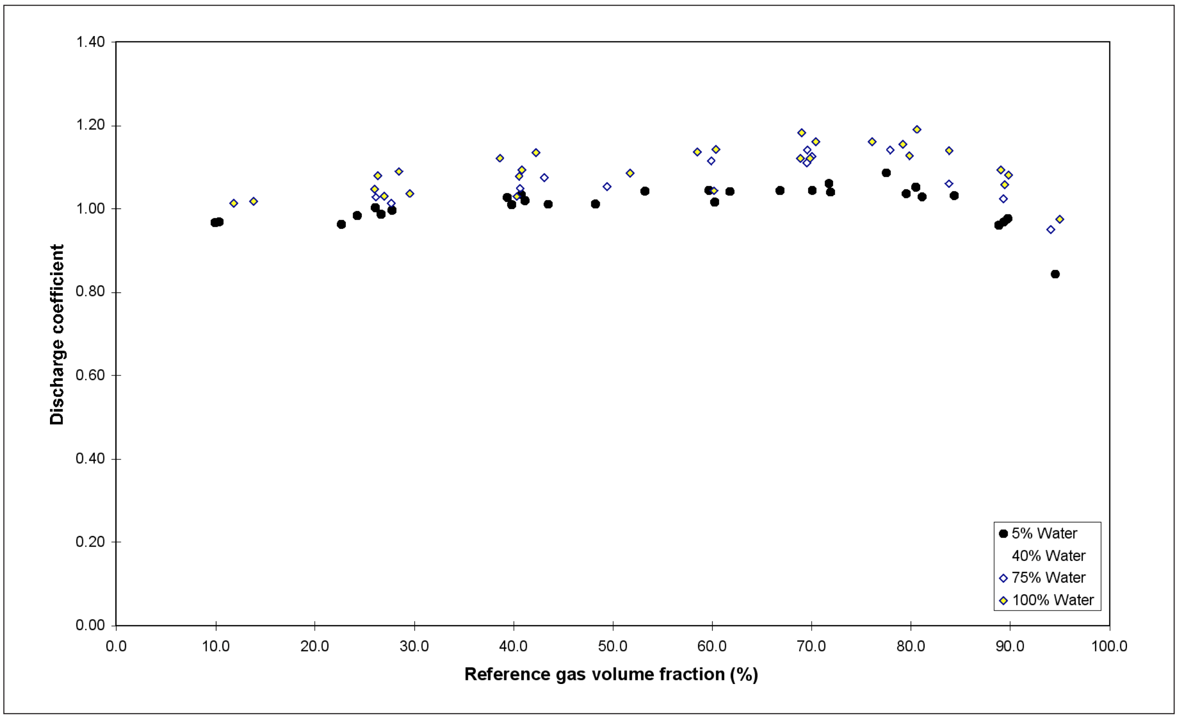

Figure 13: Discharge coefficient vs GVF for Venturi meter 6 in multiphase flow, showing effect of water cut

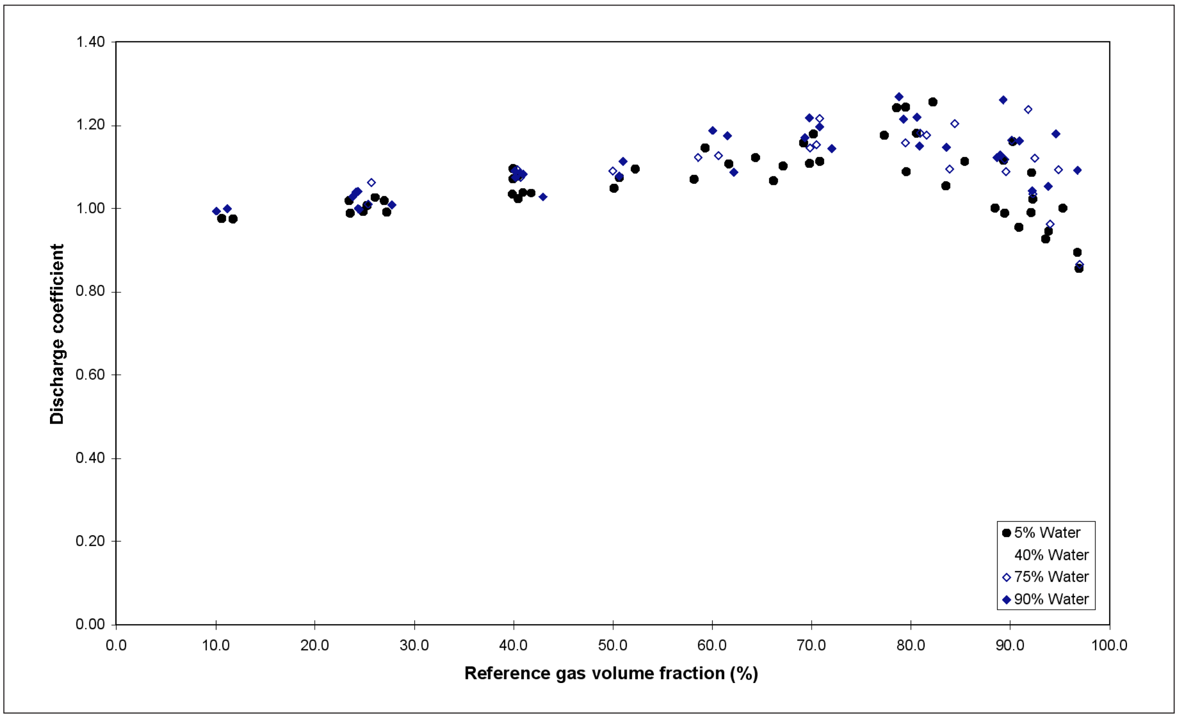

Figure 14: Discharge coefficient vs GVF for Venturi meter 9 in multiphase flow, showing effect of water cut

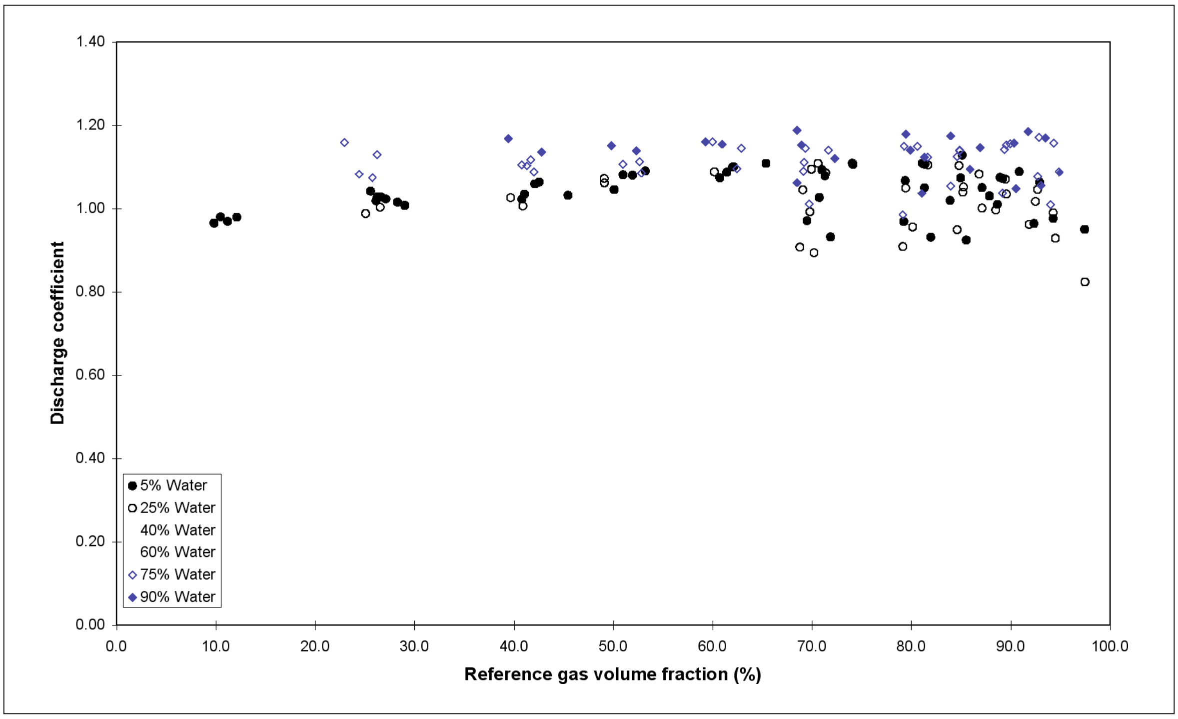

Figure 15: Discharge coefficient vs GVF for Venturi meter 2 in multiphase flow using 142 Hz instrumentation

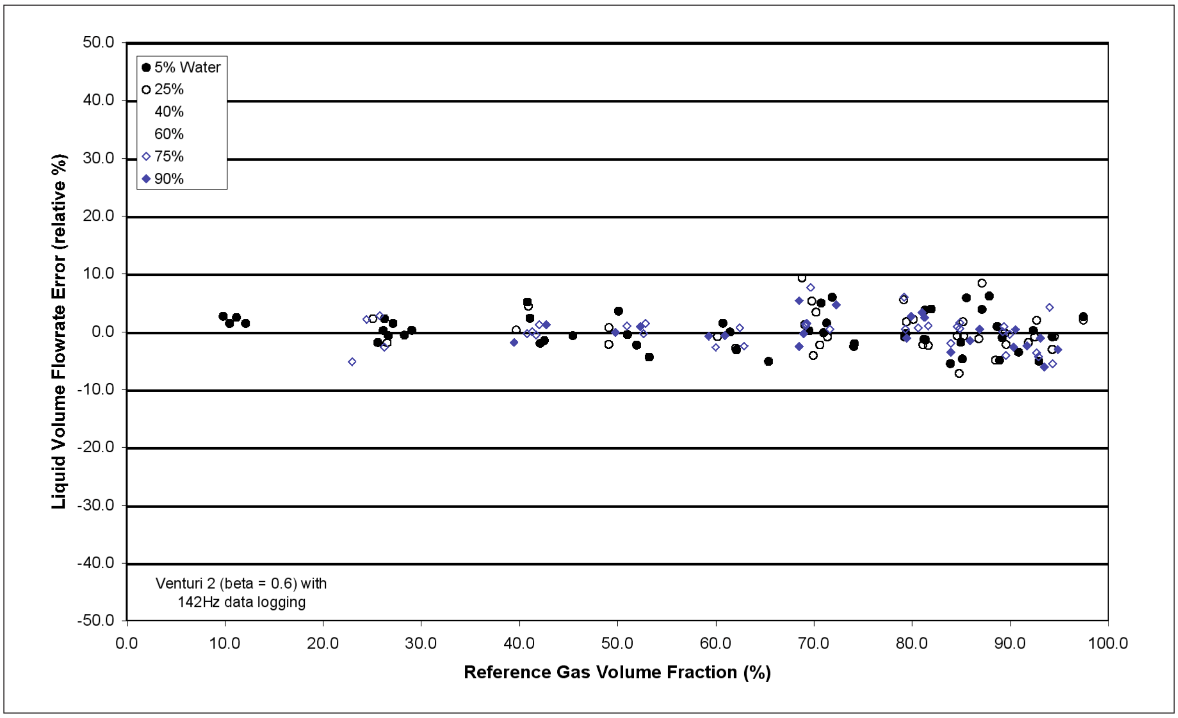

Figure 16: Error in modelled liquid volume flowrate vs reference GVF

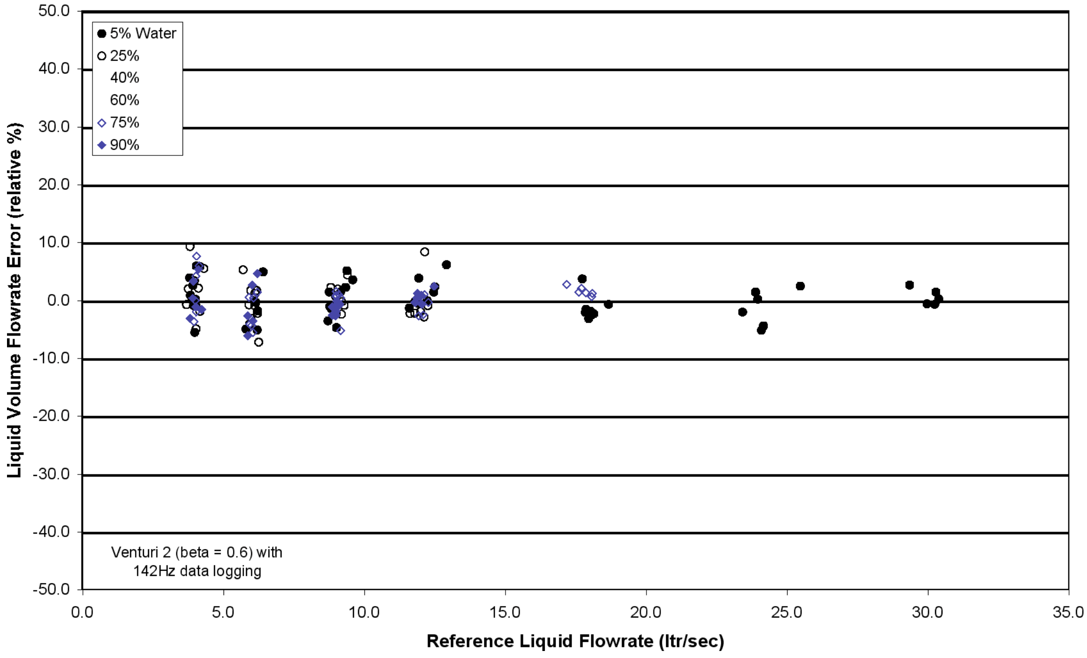

Figure 17: Error in modelled liquid volume flowrate vs reference liquid flowrate