An Ultrasonic Meter for Stratified Wet Gas Service

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Abstract

Recent tests of ultrasonic meters in wet gas service have shown that the most consistent connection between internal parameters of a 4-path SeniorSonic meter and LVF (Liquid Volume Fraction) is seen in mist flow. However, it has proved difficult to achieve this flow regime in practice. Mist flow is seen at high gas velocities and high pressure, and is found only at the edge of the operating envelope of all available wet gas test facilities.

The most common flow regime encountered during testing has been stratified. It can be expected that natural gas/condensate systems will also operate to a large extent in this flow regime. An ultrasonic meter capable of giving gas and liquid flow rates in stratified flow is therefore essential if this type of metering is to be applicable over the full range of wet gas operating conditions.

A 2-path JuniorSonic meter was adapted to measure in stratified flow. Level was measured using a vertical beam reflected from the liquid surface. Actual gas velocity was obtained using a horizontal beam across the centre of the pipe, which remained free of liquid under all test conditions. Using the assumption that the surface of the liquid stream is horizontal, the level can be related to the area occupied by the liquid. This leads directly to the relationship:
Equivalent dry gas flow rate = actual gas velocity x (pipe area – liquid area).
A simple slip model, based on density ratio, can give an estimate of the liquid velocity and hence the LVF and liquid flowrate.

Tests were conducted in the wet gas test facility at NEL (Ref. 3) with two components, Nitrogen/Exxsolve, to simulate the two-phase flow. The text matrix covered pressures of 25 and 50 bar, velocity from 2 to 12 m/s and LVF from 0.1 to 5%. Results show that this simple meter performed well over this complete range. The dry gas flow rate could be obtained with an uncertainty of 3 % of reading, and LFV to within 0.5% LVF absolute, even with liquid hold-up (area) in excess of 25%,

This work was undertaken by a JIP, with members from BG International, BP, Conoco, Elf, Phillips Petroleum, Statoil and Daniel, to investigate the performance of ultrasonic meters in wet gas service.

Introduction

The aim of the Ultraflow project is to develop an ultrasonic wet gas flow meter which, making use of existing hardware, can measure both liquid content and gas flow rate in a wet gas service. It was anticipated that the internal parameters of a conventional ultrasonic gas flow meter would provide the additional information required to measure both phases simultaneously. This expectation was built on the observation during trials at Bacton (Ref. 1) that parameters such as Gain, Standard Deviation, Signal to Noise Ratio and Velocity of Sound all reacted in different ways to an increase in LVF. It was hoped that a model (in software) could be found to fit the changes in internal parameters to the LVF, enabling the liquid content to be measured and used to correct the gas flow rate to an “equivalent” dry gas flow rate.

Various tests at British Gas, CEESI (Colorado) and NEL (Ref. 2 & 3) confirmed the reaction of the internal parameters to changes in gas LVF. However, it has proved difficult to construct a universal model relating this behaviour directly to liquid content. The tests at each site showed consistent behaviour, but unrelated to the parameter changes seen at the other sites. Other factors, such as meter design, density, viscosity, surface tension, drop size, pipe geometry and ambient temperature, were apparently of sufficient influence to prevent a simple universal relationship between ultrasonic meter parameters and liquid content to emerge.

The last conclusion in (Ref. 3) stated
“If it is difficult to achieve mist flow in practice, it might be better to ensure stratified flow and design a meter suitable for stratified two-phase flow measurement”
This suggestion forms the basis of the present paper.

Measurements

The measurements were carried out using a 6” Daniel JuniorSonic ultrasonic meter. This is a two-path reflection device, normally installed in a horizontal pipe such that both beams are at 45° to the vertical, to avoid the pipe bottom. For these tests the meter was rotated by 45°, resulting in one beam being horizontal and the other vertical. The vertical beam reflects off the surface of the liquid film flowing along the bottom of the pipe. The ultrasonic path length decreases as the height of the liquid film increases. This gives a shorter transit time and an apparent increase in the measured velocity of sound that can be used to calculate the film thickness (Fig. 1) and hence the liquid hold-up (Fig.2). The horizontal beam sees only dry gas, providing a reference velocity of sound to compare with the vertical value and also a direct measurement of the actual gas velocity in the pipe.

The meter was mounted in the NEL wet gas test facility, which has been adequately described elsewhere (Ref. 3). Test conditions covered a wide range of liquid volume fractions and gas velocities and took place at two line pressures, 25 bar and 50 bar. The nominal test matrix requested was:

Gas velocity (m/s)	2, 5, 8, 12
Liquid volume fraction (%)	0.1, 0.2, 0.5, 1, 2, 3, 5

In practice the maximum gas velocity and maximum LVF that could be achieved were determined by loss of the vertical signal, caused by the interface becoming indistinct. At gas velocities up to 5 m/s it was possible to measure up to the maximum 5% LVF, at 8 m/s up to 2% LVF and at 12 m/s up to only 0.3% LVF. This practical limitation appeared to coincide with the onset of mist flow so the entire stratified flow envelope is covered by this technique. Note, however, that the onset of mist flow was deduced from visual observation. The horizontal beam (at h/D = 50%) showed no change under conditions where the vertical beam stopped responding, at 25% area, (h/D = 30%). Thus any mist must have remained close to the stratified interface.

The 25 bar tests were completed first. This identified some anomalies around the 5 m/s measurements, which were then further investigated with additional test points at 4 m/s and 6 m/s. This extended test matrix was also applied at 50 bar.

Results

As with previous tests, the ultrasonic flow meter, an actual volume meter, gives an over-reading of the gas flow that increases with increasing LVF. In this case only the horizontal beam could be used to measure gas velocity. For the vertical beam, the irregular surface of the liquid flowing in the pipe caused such large fluctuations in the difference between the upstream and downstream transit times, that a reliable gas velocity measurement was not possible. Note, however, that this has little effect on the velocity of sound measurement, since this uses the total transit time and not the small difference in transit times required for the gas velocity. This is important since the vertical velocity of sound value leads directly to liquid hold-up by applying simple trigonometry and assuming the liquid level is horizontal (Fig.1 & 2). The calculations are complex and resource consuming in real time, however a simple curve fit can give sufficient accuracy.

The over-reading, called the **wet error**, is shown in **Figures 3 and 4** for 25 bar and 50 bar respectively. In both cases, the wet error increases smoothly with increasing LVF, reaching values up to 25% at the highest achievable LVF of 5%.

The wet error is caused by the liquid holdup; the greater the restriction in the pipe, the higher the wet error. By measuring the holdup, the wet error can be corrected. The resulting residual error, obtained by subtracting the area % (i.e. holdup) from the wet error, is the final error in the “effective” dry gas flow rate. The **residual error** at 25 bar and 50 bar respectively is shown in **Figures 5 and 6**.

To estimate the LVF or liquid flow (Q_{liq}) requires a slip model to estimate $S = V_{gas} / V_{liq}$, the ratio of gas to liquid velocity. The test results can be use to give a reasonable estimate of slip based on S = Area/LVF. The JIP project manager, Dave Brown, made use of a Shell model to predict the slip, and the author proposed a very simple model based on gas and liquid density (App 1). All three of these **slip values** are shown on **Figures 7 and 8**, for the 25 bar and 50 bar results respectively. The **LVF** based on this model (App 1) is shown in **Figure 9**, compared to the actual value, together with the errors.

Analysis

Measurements

A comparison of Figures 3 and 4, wet error, with Figures 5 and 6, residual error, shows that the area correction is capable of correcting wet gas errors of up to 25% down to residual errors of generally less than 3%. The main aim of the JuniorSonic tests was to provide a convincing demonstration that this correction is possible.

For a given LVF, the residual errors first increase with increasing gas velocity and then decrease. Maximum values occur at an LVF of 3%, around 5 m/s at 25 bar and 4 m/s at 50 bar. Extra attention was paid to these particular flow conditions, with measurements being repeated and additional points investigated. The anomalous residual error values are real and repeatable. Clearly some sort of flow transition is indicated. This has also been seen in previous tests. However, no proper explanation is available since there is no evidence of a flow regime transition under these conditions.

From Figures 5 and 6 it can be seen that, with very few exceptions, residual errors are positive. A small depression along the center of the liquid stream compared to the edges could produce this result. The assumption of a horizontal surface, which was used to convert the liquid film thickness to the area, is probably not justified. It is possible that a better model for the liquid cross-section, taking curvature, waves, surface roughness and gas and liquid entrainment into account, could reduce the residual errors further and even offer an explanation for the anomalous results discussed above.

It was hoped, before these tests, that the vertical beam could be used not only for the film thickness measurement but also for a second gas velocity measurement as a check on the horizontal value. This proved impossible since the fluctuations in transit time (Standard Deviation) caused by the uneven liquid surface far outweigh the small transit time difference between the upstream and downstream directions required for the gas velocity measurement. These fluctuations remain small compared to the total transit time, so the velocity of sound measurement and subsequent film thickness calculation is not affected.

Figures 7 & 8 show that in general the Shell slip values are high, while the Area/LVF are low compared with the density ratio model. Figure 9 shows the LVF calculated using the density ratio model, and it is seen that the errors are reasonably random. The average error is less than 0.5% LVF for these relatively short term tests, thus longer time averages would probably yield better results. The slip model could be improved by taking into account the liquid area and gas velocity, low values tending to higher slip than that given by the simple density ratio.

Further improvement in both the liquid and gas flow could come by considering velocity profile effects in both fluids.

Modelling

Many multi-phase models exist, for example: Shell, PLAC, and Taitel & Duckler. All these models use gas and liquid flow rates as input to calculate liquid hold-up and flow regime. They are useful as a check on the measurements but cannot be applied directly to wet gas flow metering. The density ratio model shows the best agreement with the ultrasonic measurements over the full range of test conditions. This is also the only model where the measured variables can be used as input to calculate gas and liquid flow rates, as shown in Appendix 1.

The Shell model shows good agreement with the JuniorSonic values up to a film thickness of around h/D =25 %. For thicker films, the calculated height is lower than the measured value. This is because the Shell model switches from a calculation based on stratified flow to one based on annular mist flow where slip and hence liquid holdup are lower. The criteria in this Shell model for switching from one flow regime to another unfortunately cannot be adjusted. It is clear that the flow regime change is not appropriate in the present case.

Referring to Appendix 1, the model implies a velocity profile in the liquid film since the velocity at the base of the film is reduced by friction with the pipe wall while the velocity at the interface is increased by interaction with the faster gas stream. Thus some form of velocity profile correction should be able to improve the accuracy of the calculated liquid flow above that of the simple density ratio model. The same is true of the gas flow, which could also be improved by a velocity profile correction.

It is possible that a better model for liquid cross-section, and gas velocity profile, could reduce the gas residual errors and perhaps explain the anomalous results. The liquid flow rate calculation would also be made more robust and general purpose with a physical model that includes surface curvature, waves, gas and liquid properties and a liquid velocity profile.

Conclusions

1. Two direct measurements, Liquid level and Gas velocity, allow the area occupied by the gas (pipe-liquid) and hence the gas flow rate to be calculated.

2. A simple slip model, based on the liquid to gas density ratio, allows the liquid velocity, liquid flow rate and LVF to be calculated

3. The uncertainty is better than 3% for the gas flow rate and 0.5% absolute for the LVF, over the range 25 – 50 bar, 2 - 12 m/s gas velocity, and 0.1 – 5% LVF, which lead to liquid hold-up in excess of 25%.

4. The results could be improved by considering:
- The interface is curved and wavy, not flat
- The velocity profile in the gas
- The velocity profile in the liquid
- The effects of hold-up and gas velocity on slip

Acknowledgements

The permission of the JIP, with members from BG International, BP, Conoco, Elf, Phillips Petroleum, Statoil and Daniel, to publish this paper is gratefully acknowledged. The JIP project manager, Dave Brown, took an active part in the collection and analysis of the experimental data and made the Shell model calculations available, and his guidance was invaluable to the success of the project.

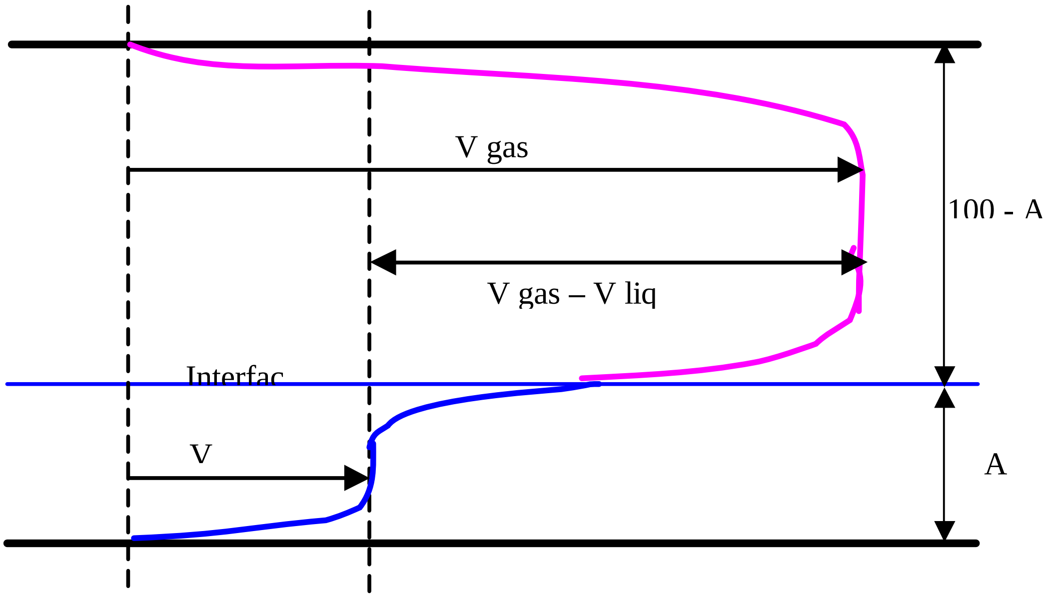
References

[1] K. J. Zanker & W. R. Freund Jr. Developments of multi-path transit time ultrasonic gas flow meters, NSFMW 1994

[2] G. J. Stobie & K. J. Zanker. Ultrasonic wet gas measurement – Dawn gas metering – A Real world system, NSFMW 1998

[3] K. J. Zanker & G. J. Brown, The performance of a multi-path ultrasonic meter with wet gas. NSFMW 2000

Appendix 1: Density Ratio Model



If we assume the shear stress is the same on either side of the interface we have

$$r_{liq} \times V_{liq}^{2} = r_{gas} \times (V_{gas} - V_{liq})^{2} \qquad \text{Giving} \qquad S = \frac{V_{gas}}{V_{liq}} = 1 + \sqrt{\frac{r_{liq}}{r_{gas}}}$$

$Q_{gas} = V_{gas} * (100 - A)$ where V_{gas} and A are measured directly

$Q_{liq} = V_{liq} * A = (V_{gas} / S) * A$

$$LVF\% = 100 \times \frac{Q_{liq}}{Q_{gas}} = 100 \times \frac{V_{lia} \times A}{V_{gas} \times (100 - A)} = \frac{100}{S} \times \frac{A}{(100 - A)}$$

Typical values for these tests are shown below:

P	Den Gas	Den Liq	Dliq/Dgas	SqRt	1+
bar	kg/m3	kg/m3			S
25	30.1	802.4	26.66	5.16	6.16
50	58.3	802.4	13.76	3.71	4.71

Figure 1. Bounce off the Stratified Liquid Surface

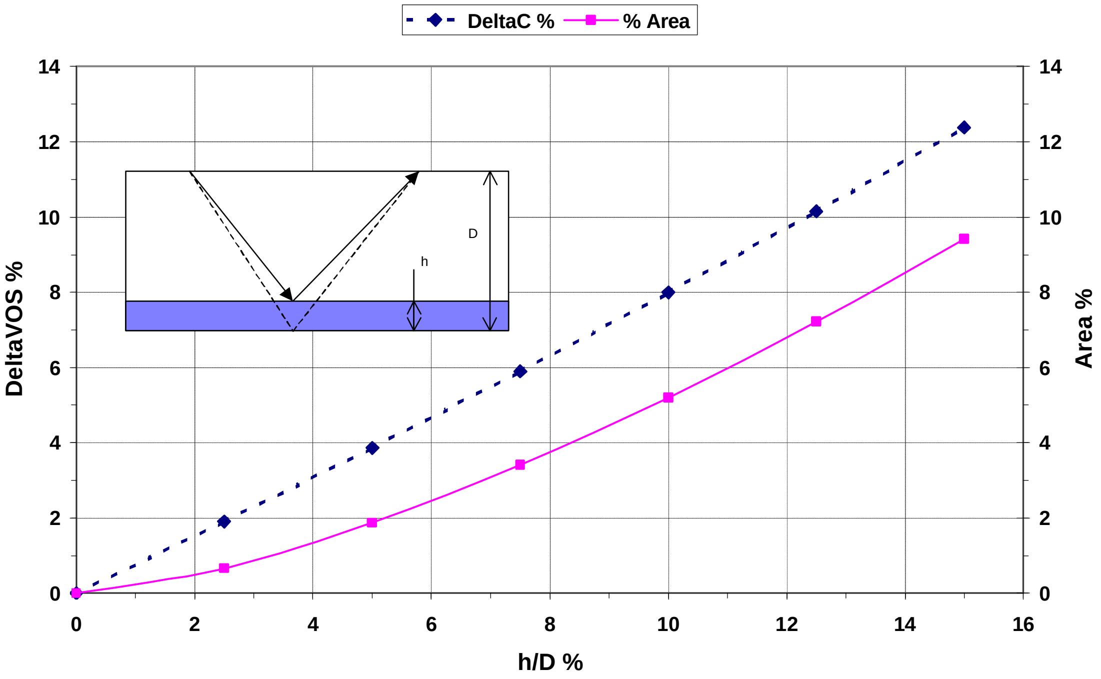


Figure 2. Hold-up (Area) - Delta VOS

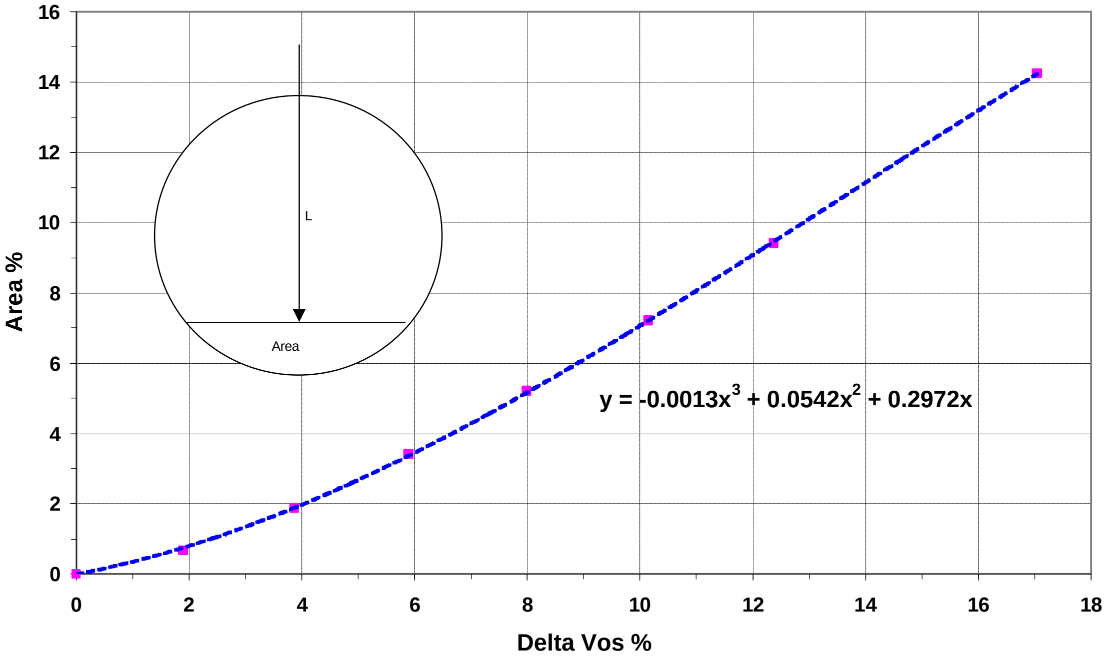


Figure 3: Wet error v LVF at 25 bar

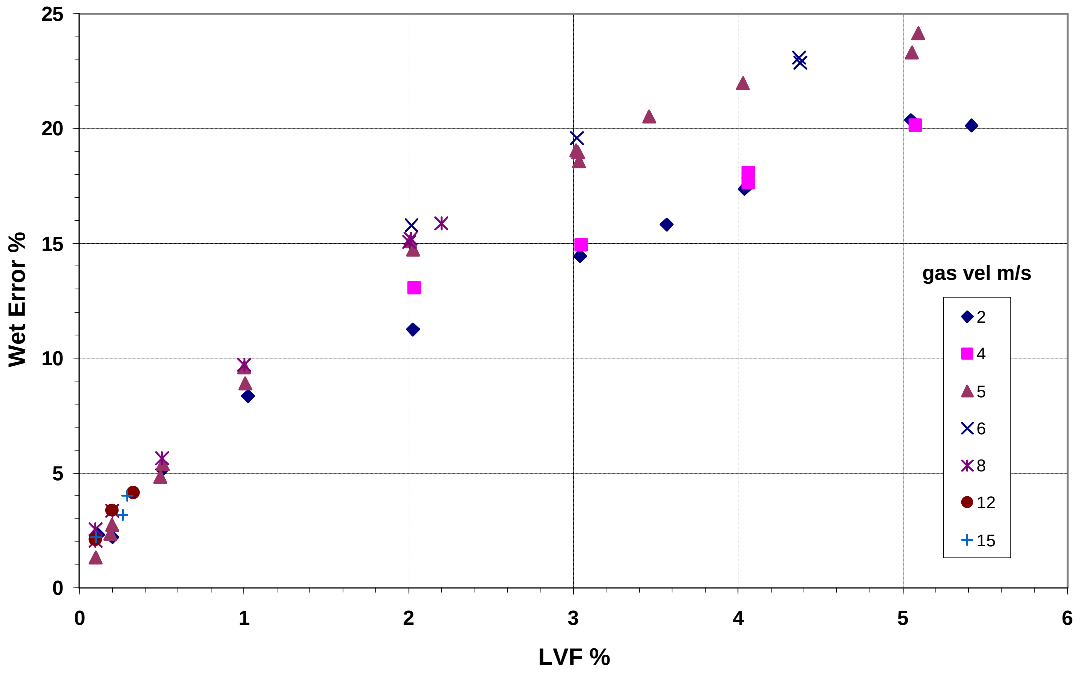


Figure 4. Wet Error v LVF at 50 bar

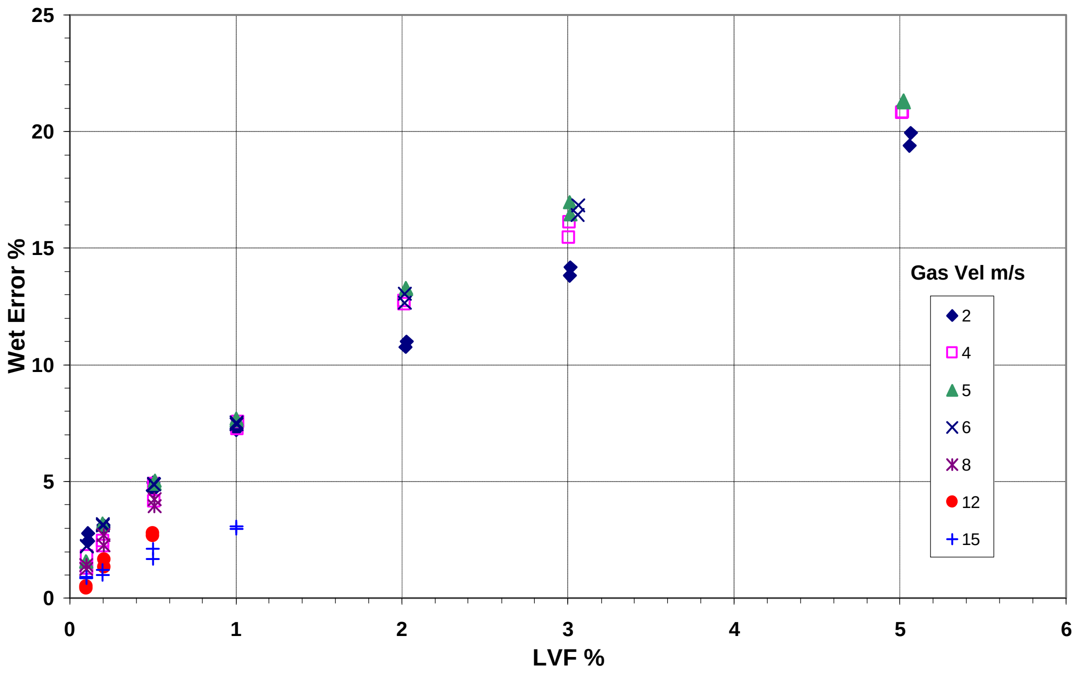


Figure 5: Residual Error v LVF at 25 bar

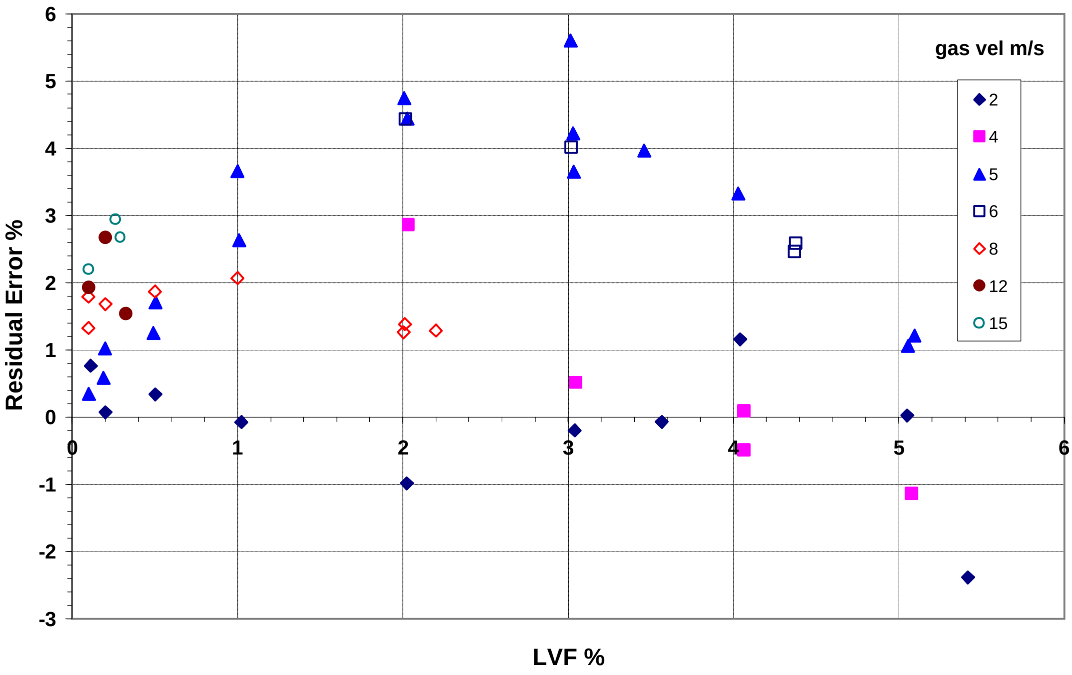


Figure 6. Residual Error v LVF at 50 bar

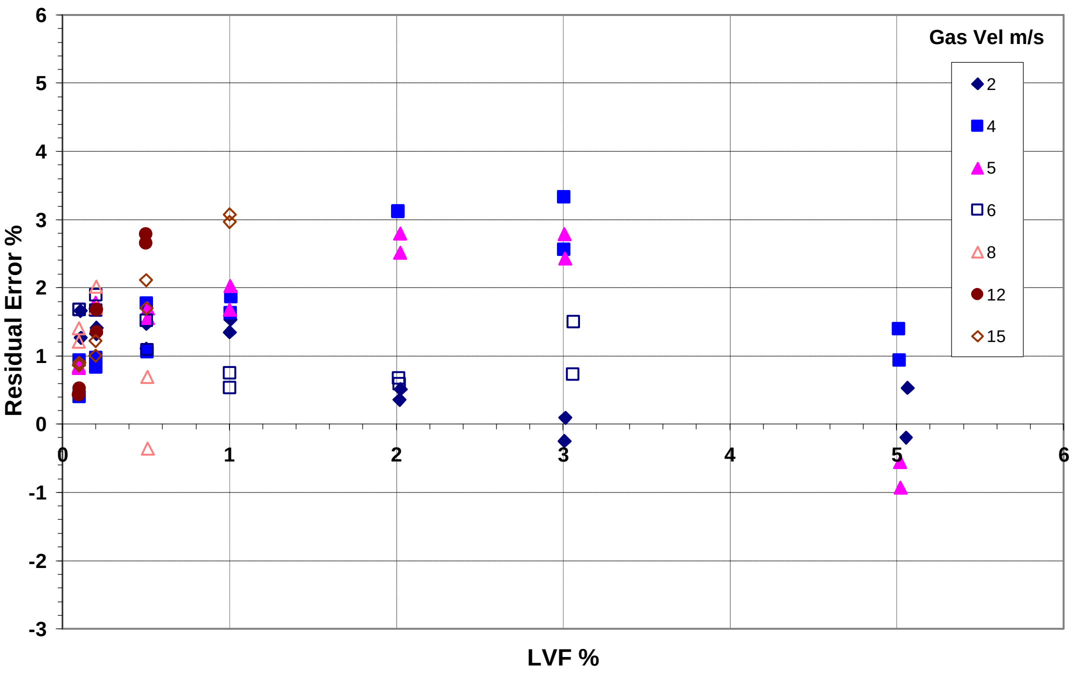


Figure 7. Slip models for 25 bar

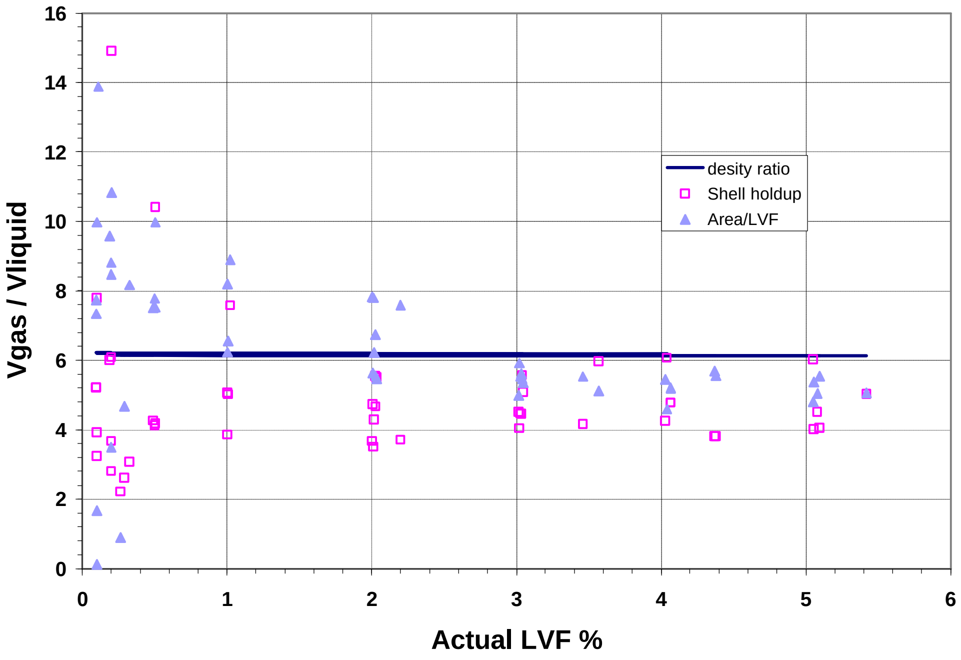


Figure 8. Slip models for 50 bar

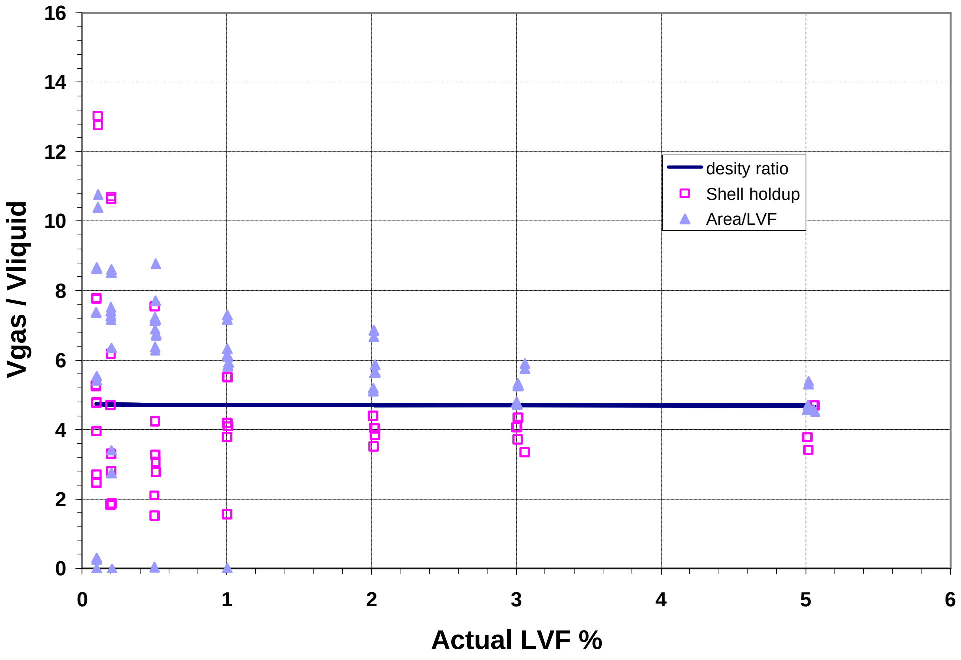


Figure 9. Calculated LFV and Error