

Multi-Phase Flow Measurement by Using Multi-Path Ultrasonic Flow Meter

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As the demand for flow measurement of high viscosity and multi-phase is growing globally, operators have been looking for economical and robust flow meter technologies for allocation and control purposes. Despite the wide acceptance of the ultrasonic flow meter technology in single phase flow for fiscal metering and process control (primarily due to the advantage of its wide turn down ratio, no pressure drop etc.), people still remain sceptical about its application on complicated flow with high viscosity liquid or multi-phase conditions. The concern is mostly around the high attenuation of the ultrasonic signals in complex fluid and robustness in noisy environments.

This paper describes the study of an ultrasonic liquid custody transfer flow meter in a multiphase flow lab in Aracaju, Brazil where the flow conditions were changed from 0 to 100% water cut of crude oil. Gas volume fraction was varied from 0 to 80%. The purpose of the study was to identify the application boundaries for the liquid flow meter in real applications where water cut can be high and gas carry over is unavoidable.

The results showed that the ultrasonic transit time meter could withstand a high percentage water cut and can also tolerate significant amount of gas entrainment. The sophisticated diagnostic feature of the ultrasonic flow meter can even provide some important information regarding the flow regime, which could be beneficial for operators to optimize the operation

1.0 INTRODUCTION

The increased demand for metering high viscosity fluids is growing globally. This is primarily due to the fact that a higher percentage of the world oil reserve is heavy oil with high viscosity¹. Measuring viscous fluids have been fully recognised by experts in both multiphase and single-phase flow metering community as a challenging task by any flow meter technology. While a great deal of effort and progress have been made in expanding the application envelope of the ultrasonic flow meter (USM) technology to measure viscous fluids^{2, 3, 4, 5}, there is a great deal of scepticism and questions regarding the practicality or reliability of USM to meter multi-phase applications.

USM has been applied to gas and liquid flow measurement since the 1950's based on a few different principles, such as transit time, Doppler and cross-correlation. The transit time technique is much more commonly used today in industrial meters, so that it is the focus of this paper. Using multi-path transit time techniques, USM technology has even gained wide acceptance in the fiscal gas flow metering after almost a quarter of a century of effort and education. More importantly, it is due to fundamental advantages of USM in high accuracy, wide turn down ratio, unique diagnostics and zero pressure drop. Therefore USM brings great benefits in lowering cost to metering operations.

In recent years, the progress of liquid USM in meeting the requirements of API chapter 5.8 and OIML R117, class 0.3 standards, has encouraged the Oil & Gas industry to start implementing the use of ultrasonic flow meters for fiscal measurements of liquid flow. Although the same advantages of the USM in gas flow metering also apply in the liquid fiscal meter, the technical challenges are greater for manufacturers since liquid flow can be more complex than gas flow. As gas flow requiring fiscal metering is mostly methane flowing at different pressures, liquid can be crude oil with different API numbers or different refined products. In addition, different fluids are flowing in the same pipe line at different times or the same fluid is flowing through the same line at different temperature environments with changing values in viscosity over time. The nature of the operation could compromise the advantage of the USM unless the technology advances further to deliver a true viscosity independent flow meter that maintains custody transfer accuracy for a wide variety of hydrocarbon liquids. Even a demonstration of USM meeting the requirement of API Chapter 5.8 and OIML R117, 0.3 class accuracy standards in multiple fluids in laboratories cannot stop people from questioning if the fine-tuned calibration curve built from laboratory tests is reliable enough. So the question remains - can the meter truly work reliably at viscous fluids in the field?

In this paper, we report the test results of GE's 4 path Sentinel ultrasonic flow meter in a Petrobras' multi-phase flow loop in Aracaju, Brazil during the fall of 2010 to address the need of Petrobras. During the test, flow conditions were changed from single phase of oil to oil and water mixtures at a wide range of BSW. In addition, gas flow was also introduced into the flow stream.

The data and analysis obtained in this study address the above questions and concerns to a certain degree. The study also proves that our uniquely designed meter system is capable to reliably measure pipe flow of highly viscous fluid in the real world under harsh conditions. It may also shed some light on the future of USM in multi-phase flow applications.

2.0 TEST BACKGROUND

As one of the leading emerging markets, oil production in Brazil has increased very rapidly in recently years. The country has a large crude oil reserve to potentially become one of the top ranked oil producers in the world. Correspondingly, the market need in metering the flow of oil and refined oil products are expected to grow at the same speed in the region.

In Brazil, Petrobras is the largest oil production company and a major custody transfer flow meter user. In addition to the typical requirement defined by OIML 117, class 0.3 standard for liquid custody flow meters, Petrobras has its unique need in the robustness of flow meter to handle high contamination of water in crude oil even after the oil, water and gas separation. Based on the information from Petrobras metering facilities, the contaminated oil can have remaining water cut ranges from a typical few per cent up to 50% or even 60% in rare cases.

It has been an objective for Petrobras to identify liquid flow meters capable of operating at ideal conditions to meet OIML 117, class 0.3 and also operate at high water cut level with some reduced accuracy from the standard.

3.0 SELECTION OF FLOW METERS

High percentage water contamination has been considered as a difficult measurement for all types of flow meters. The contamination introduces large variations in almost all the physical parameters that different meter technologies are based upon, therefore exposing all the flow meters calibrated in laboratory conditions under a robustness test. The impact on turbine meters, a commonly used fiscal liquid flow meter, is especially large as previous study has shown⁶.

The most commonly used alternative to turbine flow meters are Coriolis meter and USM. Coriolis meters have been widely used to measure liquid flow after 2-phase of gas and liquid separation. It is insensitive to flow profile, can tolerate oil/water mixtures, but the entrainment of gas may generate significant errors. Despite advances in the Coriolis meter electronics that have enabled diagnostic information on the meter and flows in the past decade, Coriolis meters introduce a significant pressure drop. Sensitivity in zeroing of the meter also reduces Coriolis meter's turn down ratio.

In contrast, USM is non-intrusive, causes no pressure drop, and has high accuracy and wide turn down ratio in all pipe sizes. USM is especially more cost effective compared to Coriolis meters at pipe size larger than 6inch. The USM delivers custody transfer meter accuracy in well-developed flow profile conditions obtained by designing sufficient straight runs or installing a flow conditioner upstream of the meter. The USM is also known to be a robust meter in measuring difficult conditions in process applications. All of above USM features are attractive to Petrobras operators. Therefore it motivates Petrobras to select the right USM to meet the challenges in their operation. It requires the same meter to meet OIML 117, class 0.3 for 0.2% in single phase of flow and to operate reliably at reduced accuracy in water contaminated oil in the same pipe line.

Technically, the USM meter faces following risks in Petrobras' application:

- High attenuation due to high viscosity of 2-phase liquid that can be much higher than the single phase viscosities of oil and water.
- Flow profile changes due to large variation in viscosity.
- Thermal condition changes at pipe wall due to high viscosity of fluid
- Non-homogeneity in density distribution or flow regime
- Impact of gas entrainment, worsen all of above.

4.0 NON-CONVENTIONAL 4-PATH SENTINEL DESIGN

GE's process USM technology is well known in downstream applications of the oil and gas industry for about 30 years. It all started with clamp-on USM and then wetted meter with diameter paths only. The USM has been applied to many difficult applications of gas and liquid flows with low or high pressure, cryogenic or extreme high temperature, and sometimes unknowingly even multi-phase flow. The recent release of a 4-Path Sentinel fiscal liquid USM flow meter, combines robustness knowledge and experience of process metering with a non-conventional multi-path chordal design certified to meet OIML 117, class 0.3 as a fluid viscosity independent flow meter.

4.1 Historical Data of Sentinel

With respect to high viscosity fluids, Sentinel is certified to measure single phase liquids with kinematic viscosity up to thousands of centistokes which minimizes the first risk listed above. The meter has been certified to blindly measure different flows of fluids without adjusting calibration curves (see figure 1a and 1b) which addresses the 2nd risk above. The meter is also tested in a dynamic flow of a crude oil with kinematic viscosity of 600cSt. That was an outdoor test without temperature control of the fluid or pipe insulation during winter time (see figure 2a and 2b) at Southern France so that ambient temperature changed more than 10°C from the start to end of the test and fluid viscosity varied from 600cSt to 280cSt during the test. All of success of these results seems to down play the risks of Sentinel meter on the top 3 risks listed above.

Is it possible for the design to also allow this single phase flow performance to be expanded and overcome the obstacles of the last 2 risks?



16" Sentinel LCT at SPSE

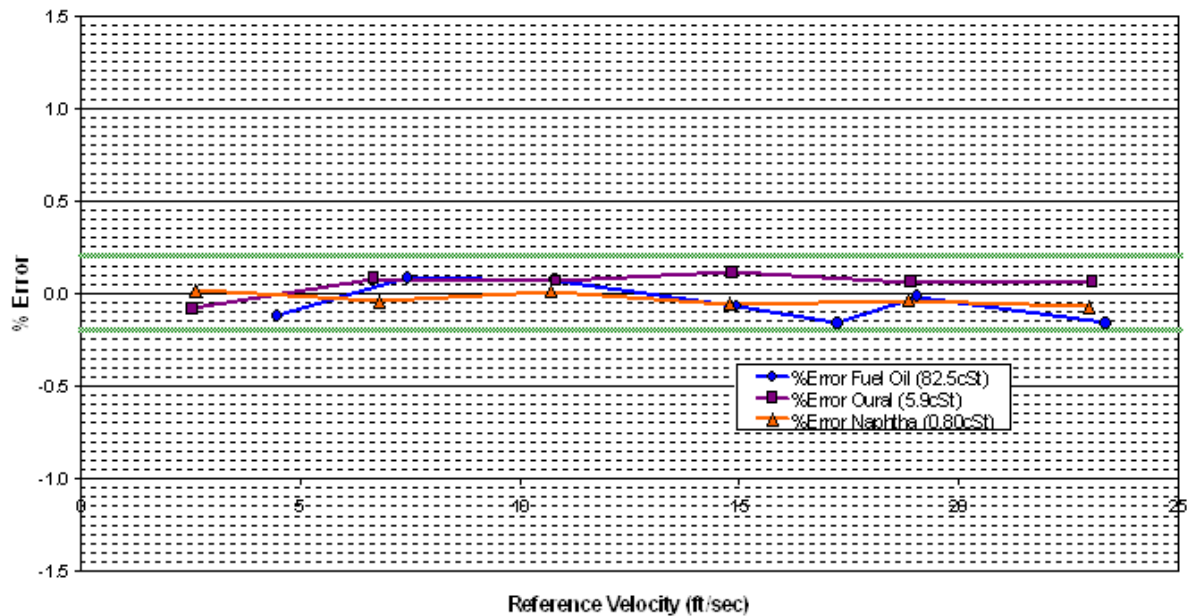


Figure 1 The 16inch flow cell tested at SPSE in Foss, France. With the same calibration curve built as a function of velocity ratio between inner and outer chords (reverse of a common known flat ratio), the meter was witnessed by NMI to meet OIML R117, class accuracy 0.3 in 3 different fluids of Naphtha(0.8 cSt), Oural(5.9 cSt) and Fuel oil(82.5 cSt).



$\phi 24''$ Sentinel LCT Test in SPSE

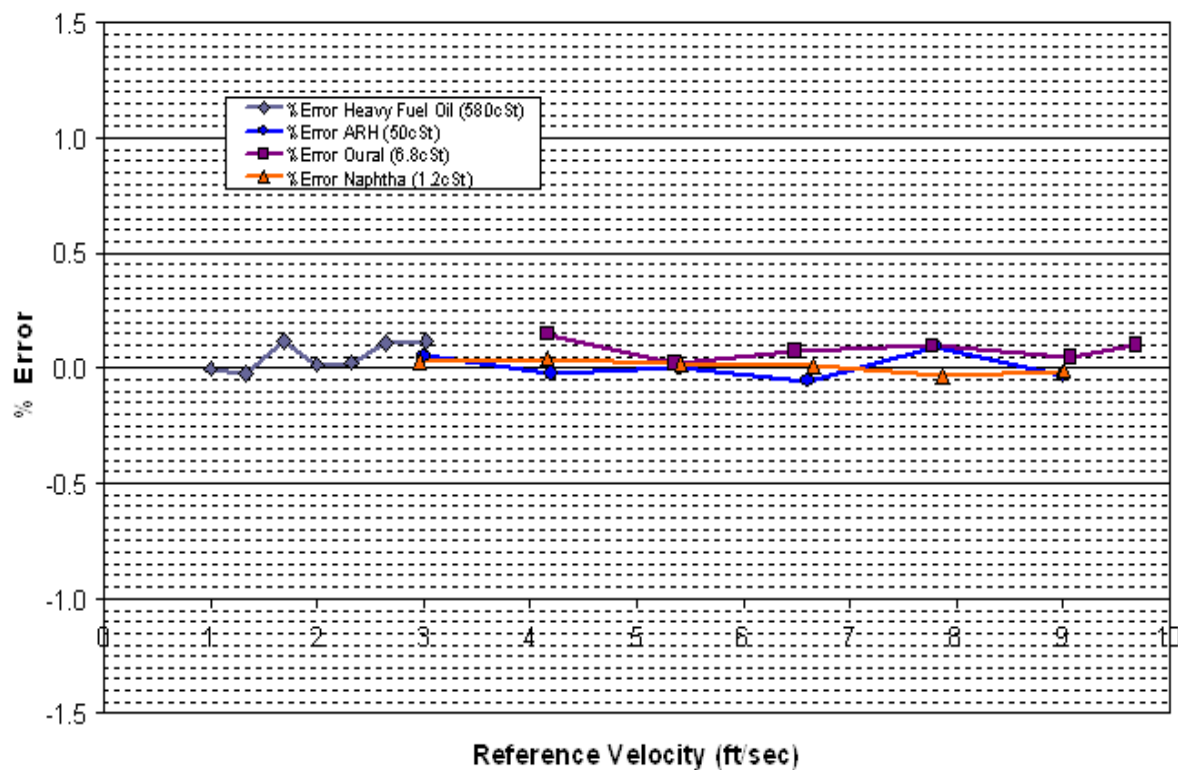


Figure 2 A 24inch flow meter was tested at SPSE with 4 different fluids, Fuel oil (580cSt), Naphtha (6.8cSt), Oural (1.2.cSt) and ARH (50cSt). (a) Meter used for the test. (b) Data obtained with 1 calibration curve. Without a temperature control in the outdoor loop, the fluid temperature varied in a wide range during the test.

4.2 Robustness of Electronics and Transducer Assembly

Obviously, sufficient signal penetration is critical to a USM meter performance so that the meter needs a wide dynamic range to handle good flow and bad flow without changing hardware. Sentinel has 2 levels of transmitting voltages in addition to its wide range amplifier. It is known that lower signal frequency subjects to less signal attenuation, and higher frequency signal generally offers better time resolution for better meter accuracy. The same meter required to do both would need broad bandwidth transducers and signal processing techniques to meet both ends. GE's BWT (Bundled Waveguide Technology) transducer assembly not only allows the meter to operate at fluid extreme temperatures from -200°C to $+400^{\circ}\text{C}$, it allows the meter to transmit different frequencies without changing transducers. Even in the case when a transducer replacement is absolutely required, the meter accuracy can be maintained to meet OIML 117 without re-calibration (see figure 3 and table 1).



Figure 3: Verification Test of Sentinel meter maintaining accuracy after a transducer replacement in a 24inch meter at SPSE laboratory in February 2010. The replacement doesn't require a flow shut down, and it generally take an operator less than 30minutes to complete the replacement.

Original Transducer			Replaced Transducer			Original Transducer		
-0.05	-0.04	0.09	0.02	-0.05	-0.06	-0.02	0.07	0.06
0.08	0.03	0.002	-0.06	0.03	0.18	0.03	-0.12	0
0.09	0.008	0.03	-0.15	0.02	-0.1	-0.05	-0.01	0.02
0.04	0.00	0.04	-0.06	0.00	0.01	-0.01	-0.02	0.03

Table 1 A flow meter accuracy in percentage is shown from left to right columns as before a transducer replacement, after the replacement and after replacing the original transducer back. 3 groups of data per case and 3 repeating points per group. A flow rate of $900\text{m}^3/\text{hr.}$ of heavy fuel oil and a large ball prover of 15m^3 were used for the test. The result was certified by NMI to meet OIML 117, class 0.3 standard.

4.3 Non-Conventional 4-Path Design

Thermal gradient is expected in laminar flow ⁴ or could even occur more often in multi-phase flow. The 4-path design configuration in Sentinel seems to be robust enough to handle that application.

Gaussian integration technique is a numerical integration method commonly used in the multi-path flow meter design based on an understanding that the numerical summation of n pre-defined points (chords in this case) with pre-determined weights provides an accurate integration over an arbitrary function that can be expressed in a polynomial in the order of $2n-1$ ³. There are a number of choices of Gaussian quadrature to select the locations of the chords and corresponding weights to obtain the integration for any function that can be accurately expressed by a 7th polynomial.

Despite the effectiveness of the Gauss method in eliminating profile dependence of the ultrasonic flow meter in earlier years, there are remaining challenges to overcome with the complicated pipe boundary layer conditions. The fact remains that under those conditions, the pipe flow profile cannot be exactly expressed by a 7th or even a 9th polynomial which makes it difficult to maintain the needed performance of custody transfer flow meter applications. Furthermore, the limitation of reproducing mechanical tolerance precision in meter body fabrication also introduces a variety of deviations from the predefined chord locations. This changes the relationship between the weights of each chord and imposes uncertainty in the flow calculations. As a common practice, even for the multi-path flow meter with at least one path being off diameter chord, a flow calibration is a necessary step to deliver high meter accuracy. To summarize:

- Multi-path ultrasonic flow meter requires flow calibration for custody transfer use
- The calibration curve is still Reynolds number dependent to a certain degree
- The Re number dependency is generally caused by mechanical configuration and tolerance of the meter body.

While most ultrasonic flow meters apply the traditional multi-path design employing Gaussian - Quadrature methods, we chose a different path to overcome some of the inherent limitations of that technique. Our approach combines numerical simulation methods with the symmetry of pipe flow profiles. As it is illustrated in figure 4, the meter factor K_{chord} described the ratio between the mean axial velocity and each chord velocity. There is clearly a chord existing around mid-radius that has its Chord almost independent of Reynolds number. The figure also clearly shows that for any inner chord closer to the pipe diameter, there is an outer chord closer to the wall responding to flow profile change in the opposite way as Reynolds number changes. Therefore, we can match the inner and outer chord to have combined result independent from the profile changes (see theoretical graph in figure 5 and flow test result in figure 6). This unique design allows the outer chord to be further away from the pipe wall to minimize the wall roughness effect on ultrasonic signals. The result is that meter performance design is insensitive to the changes of fluid and provides more reliable flow meter accuracy in real world applications where flow conditions are not as ideal as the flow calibration laboratory.

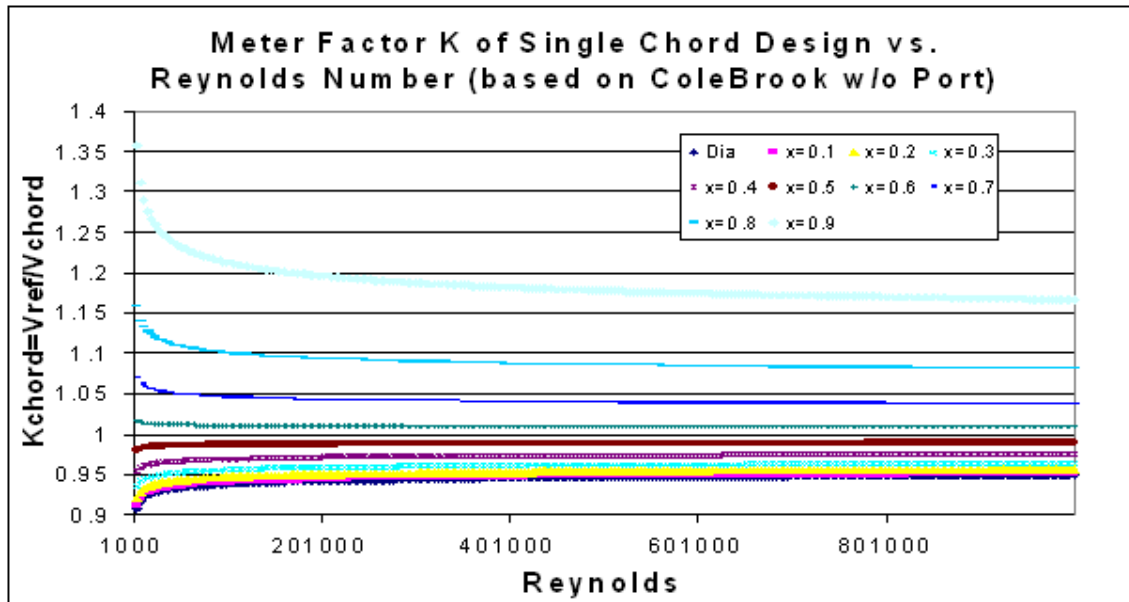


Figure 4 Single path meter as a function of Re where $x = 0$ is the diameter chord and $x = 0.9$ is the chord next to the pipe wall.

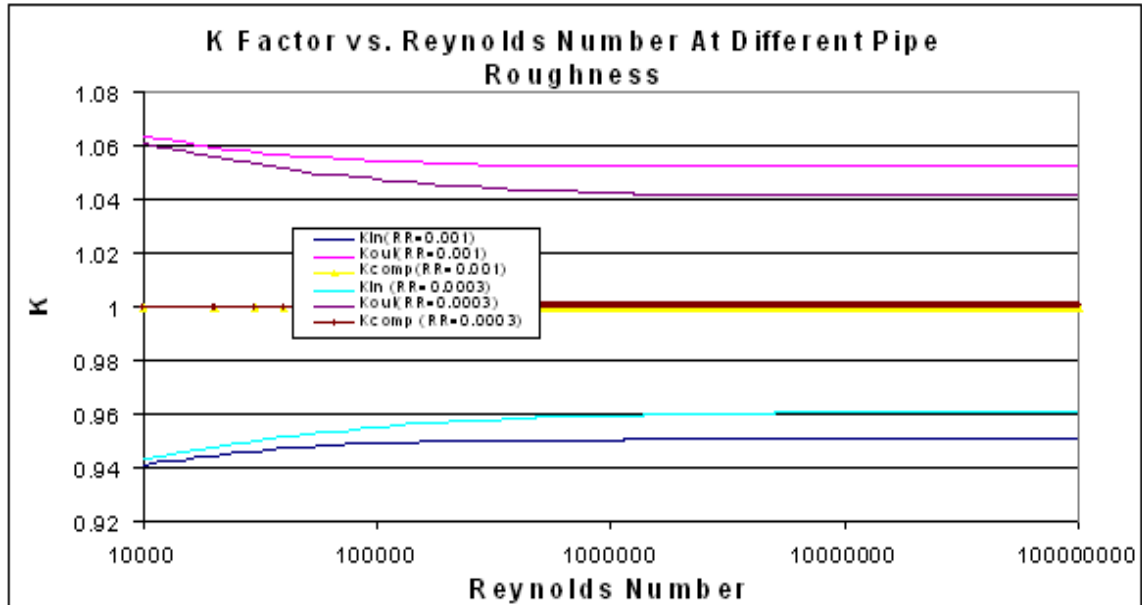


Figure 5 Meter factors of single chord $x=0.34$ and $x=0.7$ are strongly dependent on Re and relative roughness of the pipe wall. The meter factor of a composite velocity with both chords is nearly a constant at these changing conditions.

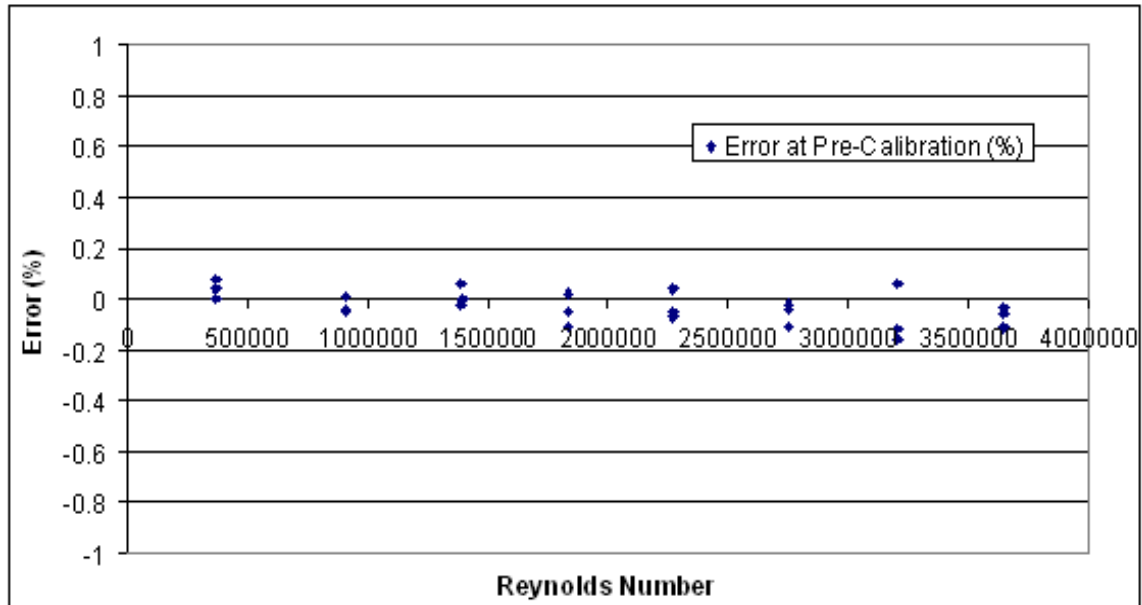


Figure 6 A water flow test data of a 16inch flow meter using the non-conventional design where the 0.34 and 0.7 chord locations at 45degree incident angle relative to the pipe axis were made. Pre-calibration data of the 16inch flow cell obtained in Alden lab in Mass, USA proves the meter linearity supports the design principle.

For the test conducted in Petrobras' Aracaju laboratory, considering the high uncertainties in flow conditions, we decided to test 2 models of Sentinel at 2 different frequencies for comparison. One is Sentinel LCT that transmits higher frequency signal pulses and the other is Sentinel LNG that transmits low frequency signal pulses.

5.0 TEST CONDITIONS AND RESULTS

Petrobras multiphase flow lab in Aracaju is shown in the figure 7. The fluid of gas, oil and water were mixed upstream from the meter testing section. The oil was crude API 26 and most water tested had salinity of 80g/l and later the water salinity was changed to 40g/l. The fluid pressure was kept relatively constant between 5bar and 19bar, temperature of the fluid was also kept relatively constant between 28°C and 50°C. Two of 6inch GE meters were installed in series shown in figure 8. The Sentinel LCT meter has pipe ID of 6.0544" and Sentinel LNG has pipe ID of 6.3456". The two meters were separated by 20D distance apart and the LCT was upstream from the LNG meter. The two meters are fundamentally the same except having different lengths in transducer buffer between the fluid and piezo element. The longer BWT buffers in the LNG allows the meter to be operated at fluid temperatures between -200°C to 400°C. The BWT can also transmit different transducer frequencies for measuring more difficult flow of fluid. However, the signal frequency of LNG was kept unchanged during this test to compare with the result of the LCT operated at a higher frequency. The liquid flow reference meter was a Coriolis meter with accuracy of about 1% in this loop. During the test, the BSW of the fluid was varied from 3 to 100%.

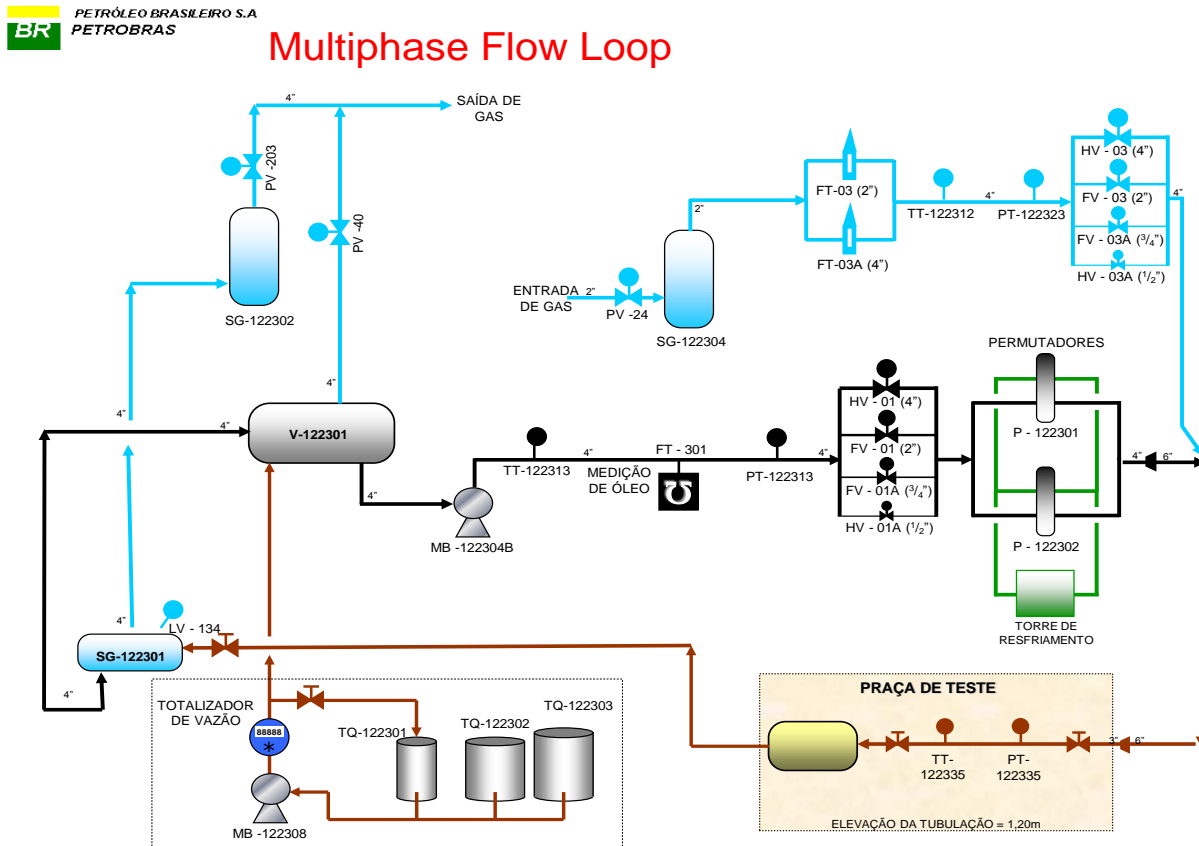


Figure 7: Layout of Petrobras multi-Phase loop in Aracaju, Brazil



Figure 8: Sentinel LCT and Sentinel LNG were installed in series with 20D space between the two meters. LCT was upstream to LNG.

Both flow meters had passed OIML 117 class 0.3 standard tests in water and oil flow calibration checks at the Metroval flow laboratory in Brazil before being shipped to Aracaju. Due to lack of adequate reference for custody metering, the multi-phase flow test at Aracaju was focused on the influence of the water contamination and gas entrainment. Liquid flow rate was scheduled to vary from $20\text{m}^3/\text{hr.}$ to $80\text{m}^3/\text{hr.}$ as the fluid changed from oil (3% BSW) to water (92%BSW) whenever possible. The actual flow rates were somehow different from the plan due to laboratory limitations. The 4 signal paths labelled 1 to 4 represents chord location from top to bottom in both meters. The highest fluid viscosity at 0% of GVF is near the inversion point, so the most difficult measurement is expected around 60% BSW.

5.1 Results of 2 Phase Liquid

The test results at 0% GVF are plotted in figure 9a to 9e. They show that both meters could tolerate 3% to 10% BSW very well. The signals from both meters captured at 10% BSW are plotted in figure 10a and 10b. They look like typical signals obtained in single phase flow. From the real time data log of both meters at conditions when flow rate was decreased (figure 11 and figure 12) from $60\text{m}^3/\text{hr.}$ to $40\text{m}^3/\text{hr.}$, the data apparently showed that fluids mixed well at these two conditions. The SOS measurements were consistent and very stable, which indicated good

homogeneity in the fluid. The chord velocities are showing a typical flow profile of laminar with chord velocity ratios greater than 1.7. An encouraging fact is that the flow rates between the 2 meters were consistent with differences of only 0.2%, 0.24% and 0.4% when BSW was 3% and velocity was greater than 0.5m/s.

It is interesting to note that the SOS from all four channels of each meter clearly showed that a thermal gradient existed from top to bottom of the flow. Even when the flow rate was changed from one test point to another (See figure 11 and figure 12). As a consequence, the flow of the top path moved faster than the bottom in both meters (see figure 13). All of the results prove that both meters performed well under following conditions:

- The flow profile was laminar
- Thermal gradient were present during the measurement
- Thermal condition and profile changed during that period of time.

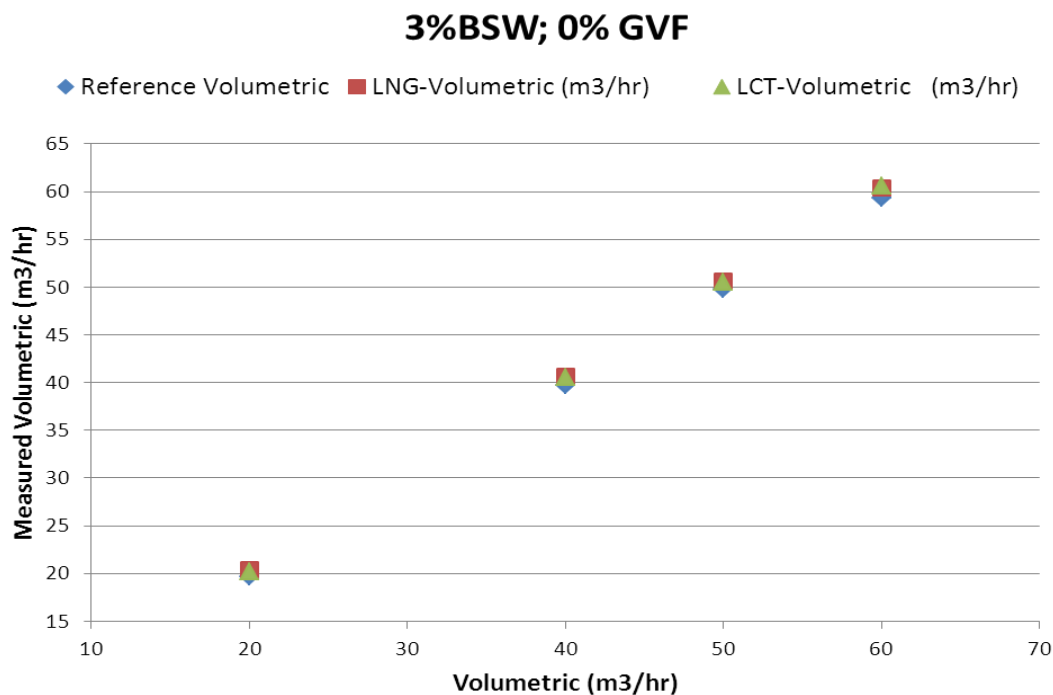


Figure 9a: Both meters working well. The difference between them were 0.2% to 0.4%

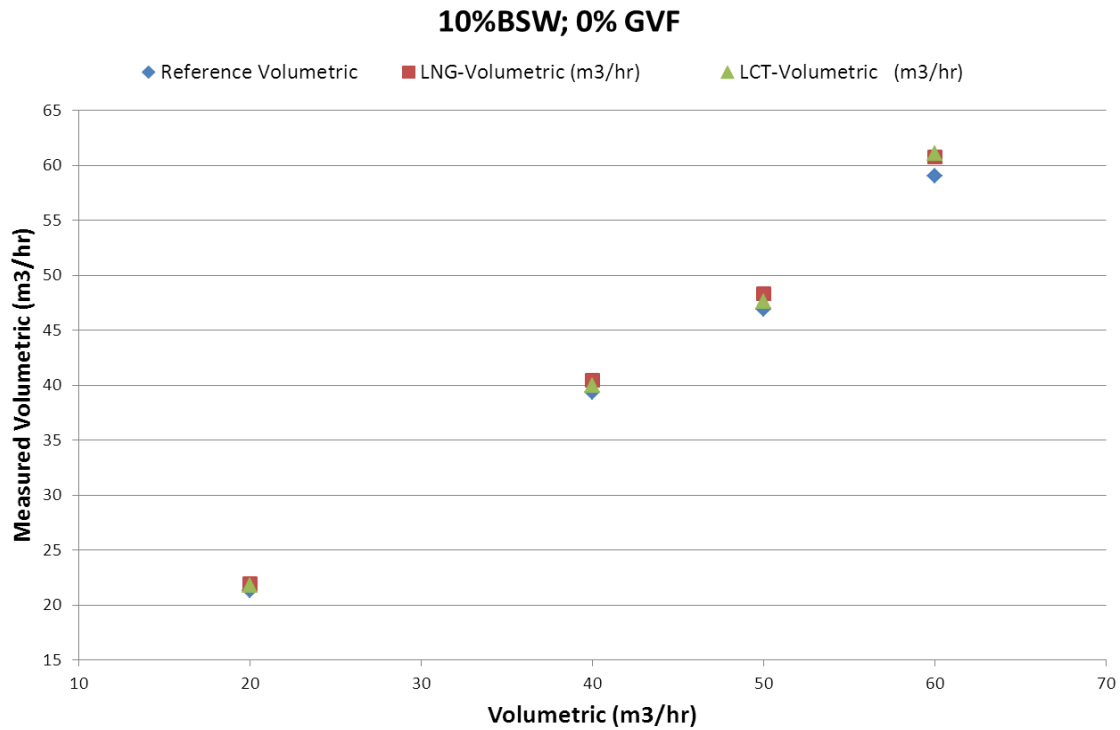


Figure 9b: Both meters were fine. Difference between the 2 meters was less than 1.5% at worst.

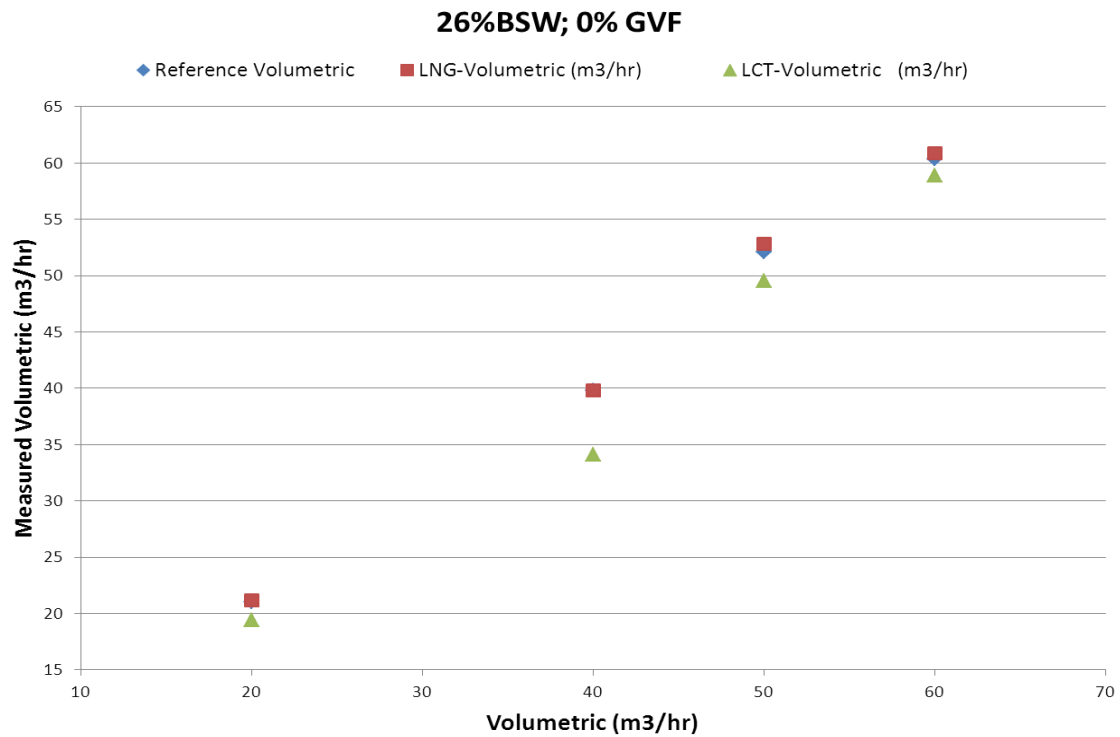


Figure 9c: The LCT started to have problems as the signal attenuation becomes high for high frequency signal.

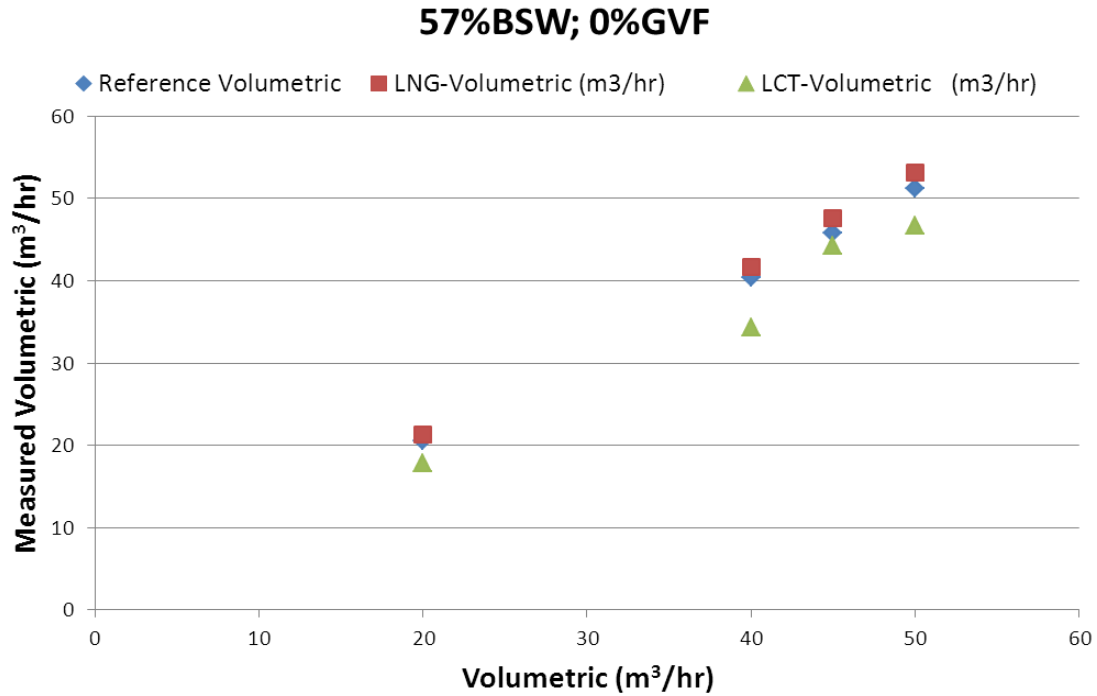


Figure 9d: *This is the most difficult testing condition in terms of signal attenuation.*

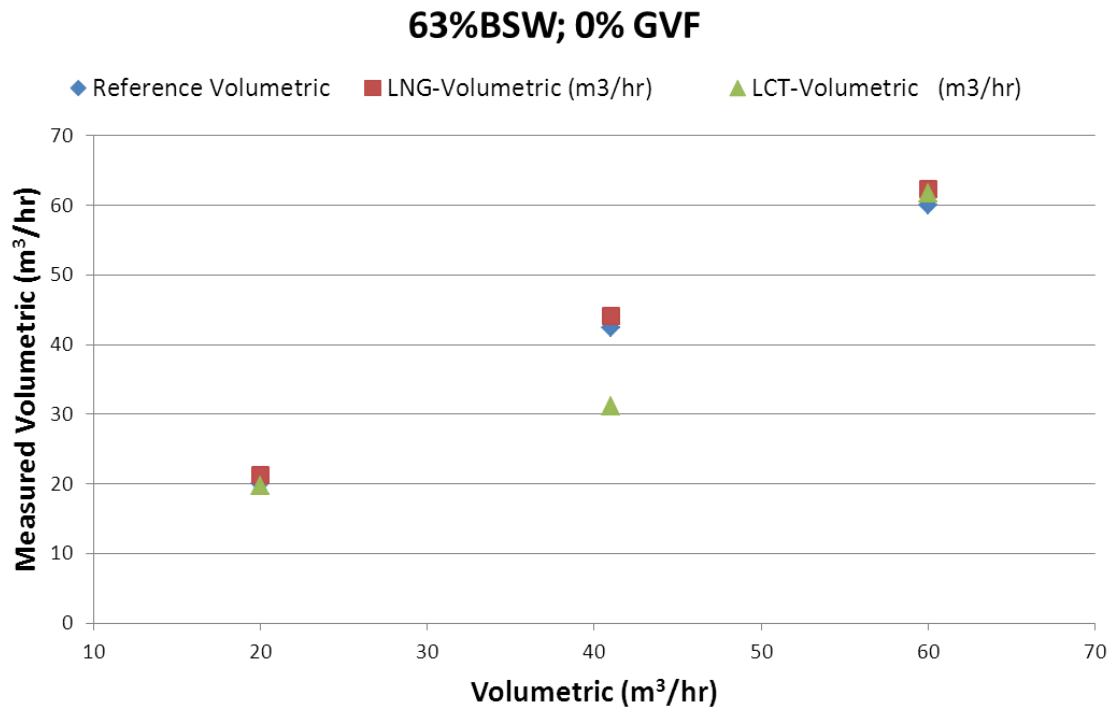


Figure 9e: *Another difficult point when GVF=0. LCT measurement becomes intermittent depending on the viscosity of the fluid at the time of the test.*

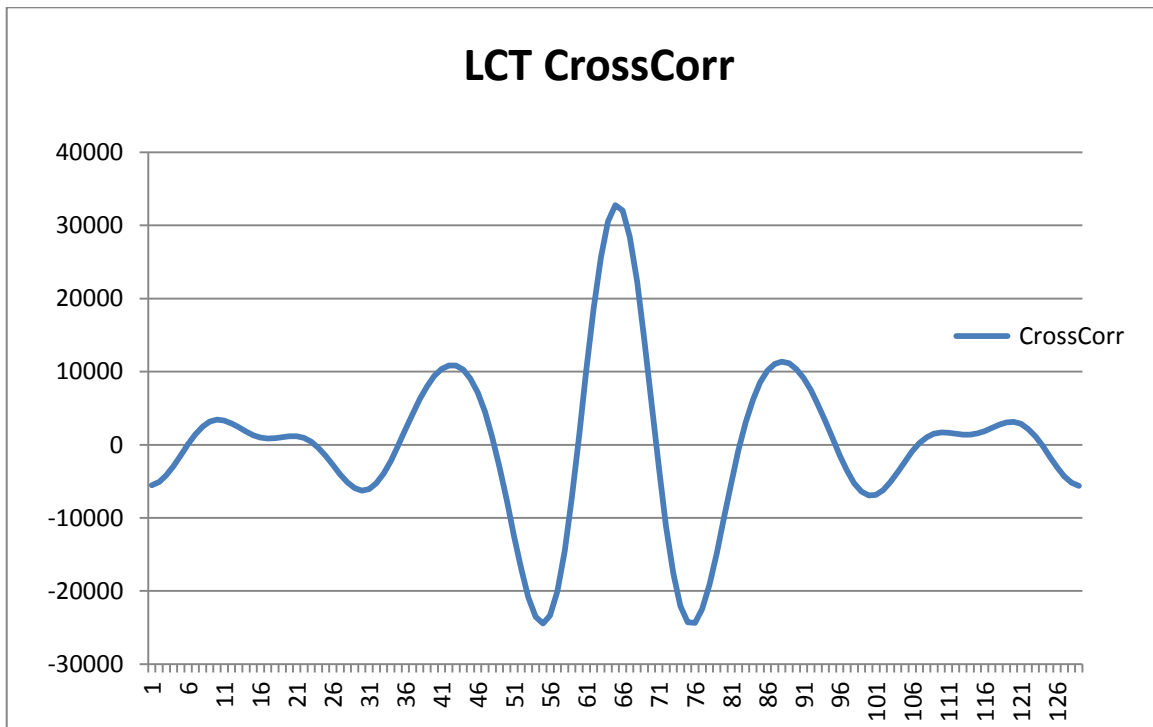
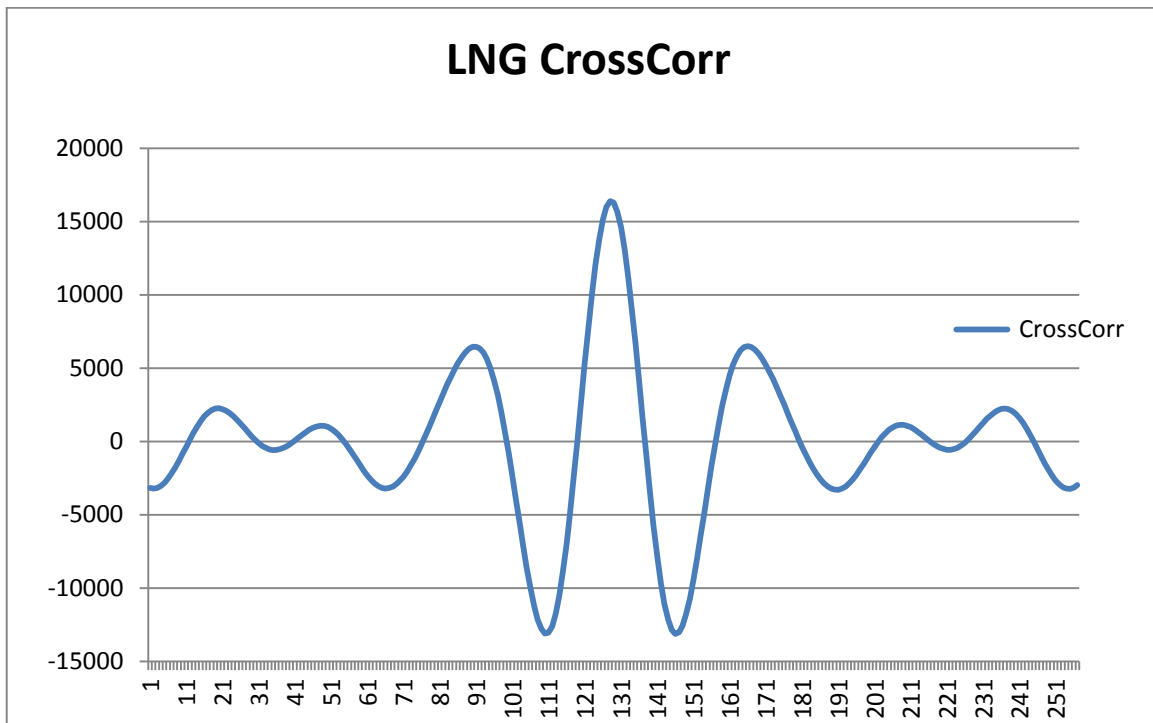


Figure 10: Signals from the LCT and LNG meter captured at flow of fluid with 10% BSW show a typical liquid flow feature to maintain meter's timing resolution.

When BSW was at 26%, the LCT sometimes lost signal due to attenuation. Its performance started to deteriorate. The LNG meter continued measuring well (see figure 9c). From the meter gain in our diagnostic data, we found that SOS measurements in the LCT sometimes went to error. Nevertheless, the output of the LNG meter still provides reasonable readings against the Coriolis throughout the entire range of BSW conditions.

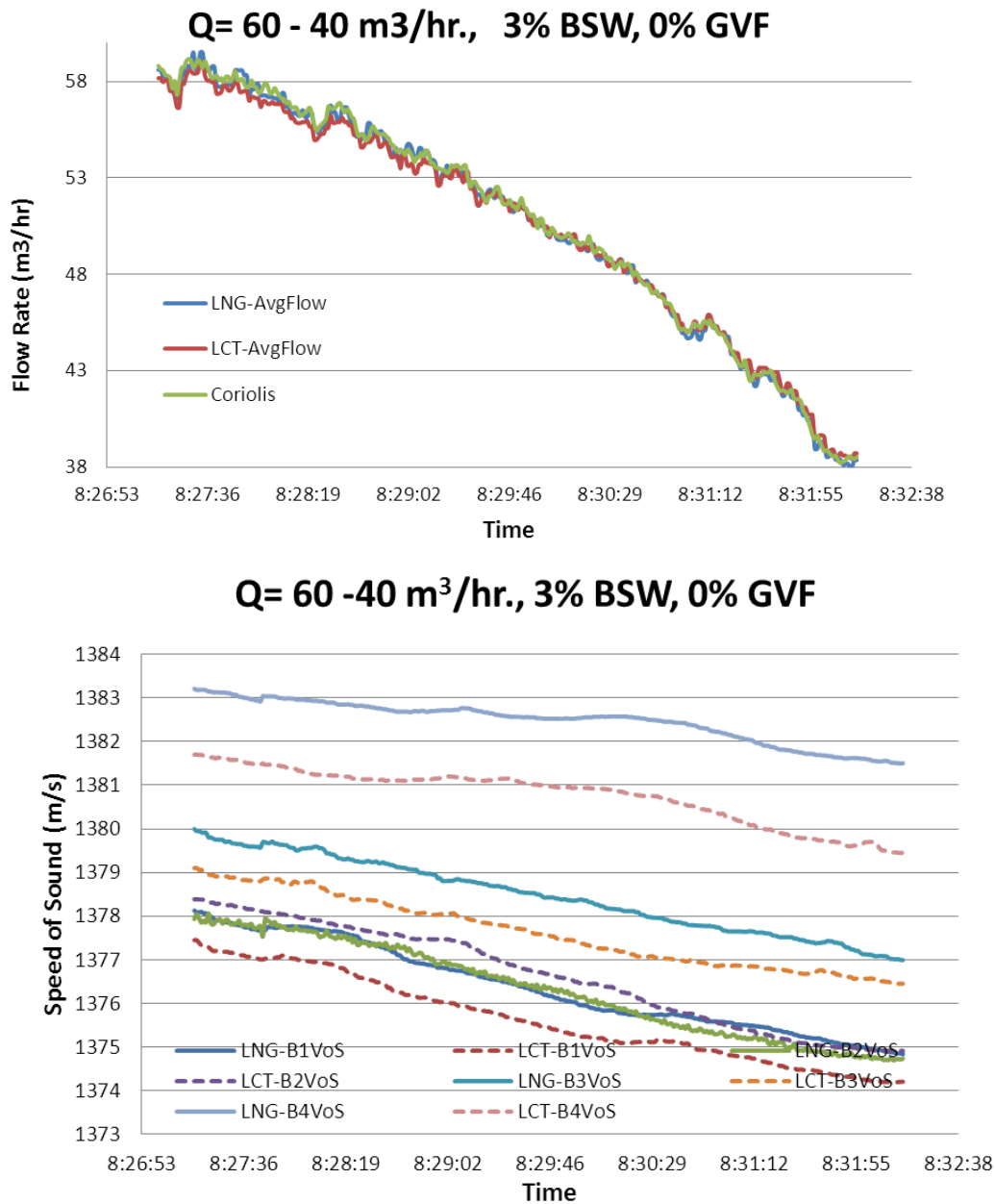
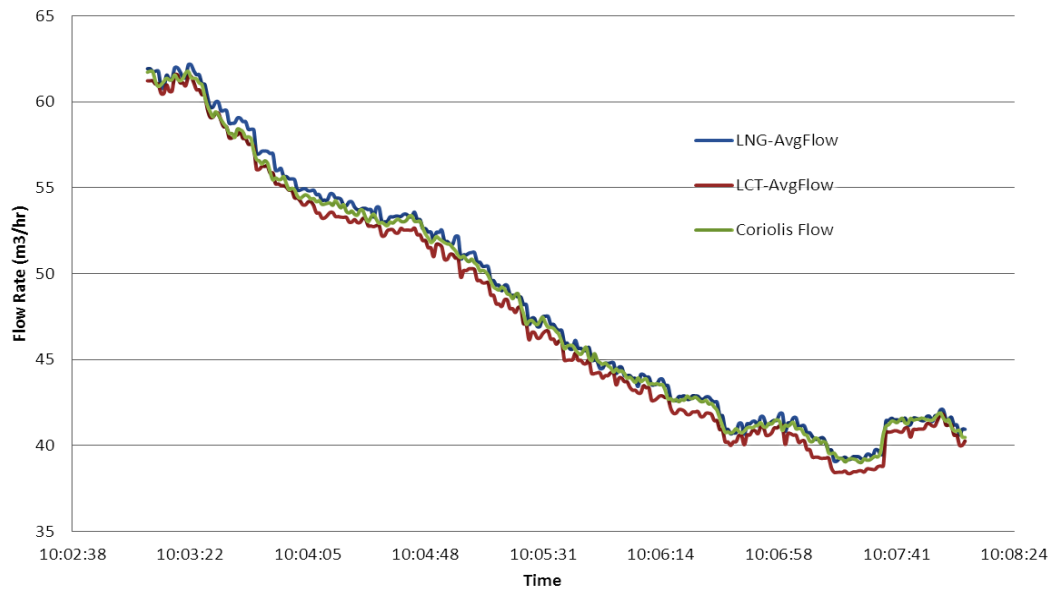


Figure 11: The LNG and LCT followed flow rate changes in relative pure oil (3% BSW) consistently. The higher sound speed values in the lower path of both meter indicated a presence of a vertical thermal gradient in the loop.

Q= 60 to 40m³/hr, 10% BSW, 0% GVF



Speed of Sound of Each Path at Q= 60 to 40m³/hr, 10% BSW

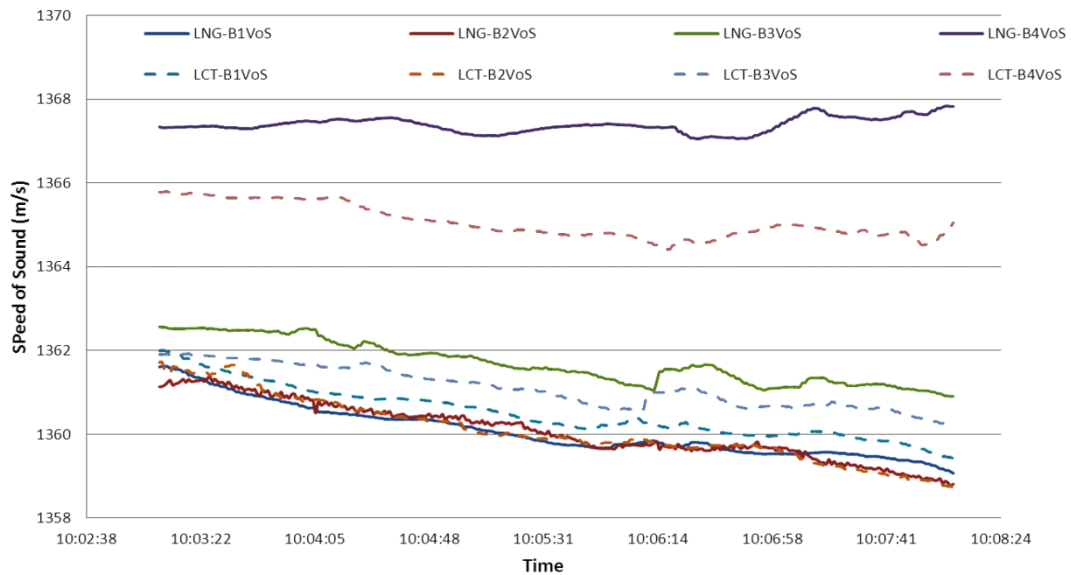


Figure 12: Both meters responded to flow rate changes at 10% BSW. LCT started to read lower.

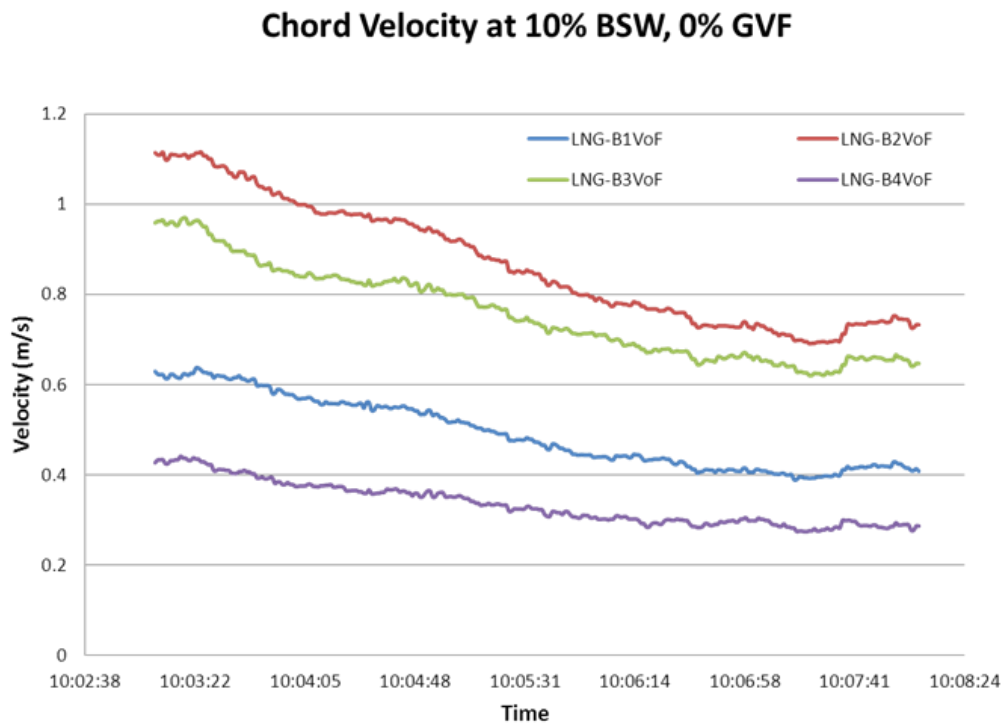
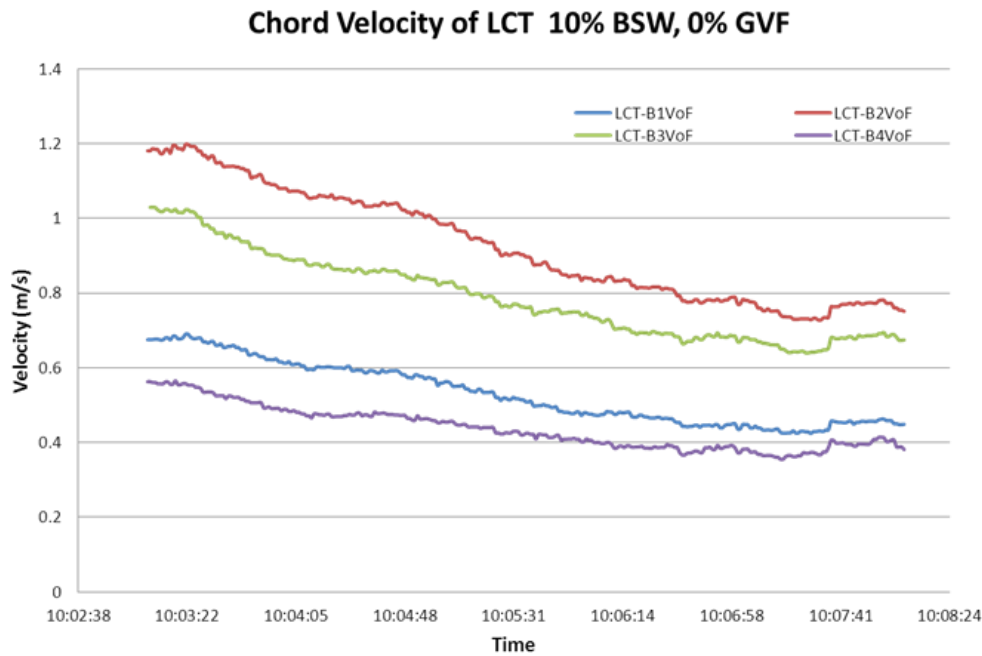
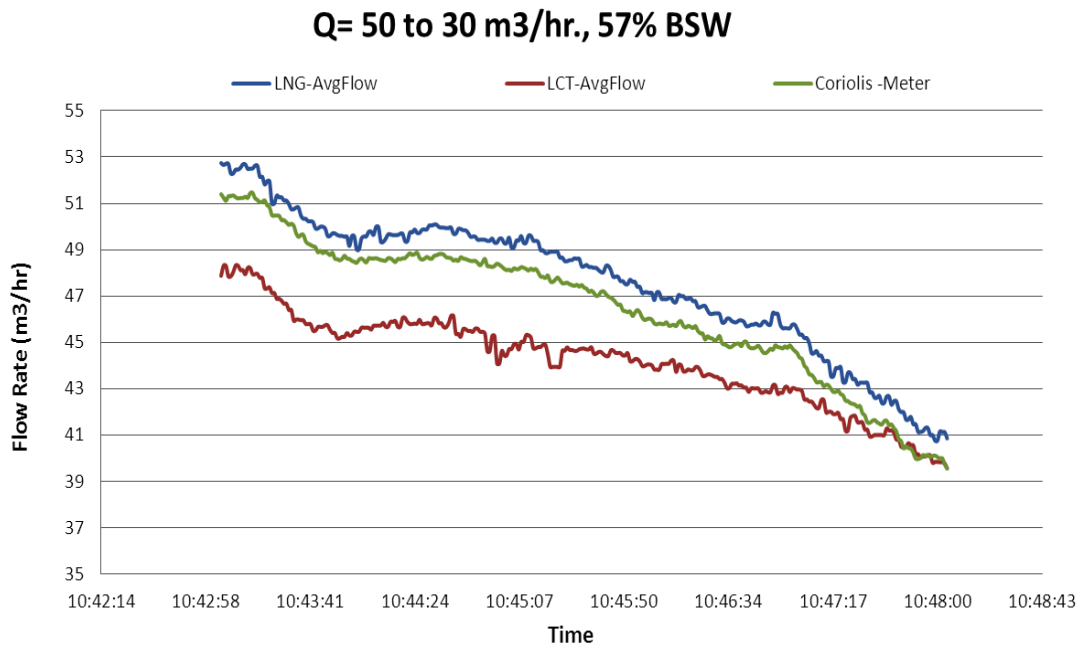


Figure 13: The chord velocities in both meters demonstrated that flow profile was unsymmetrical due to the vertical thermal gradient. Fluid in the top part of the pipeline flowed faster than the bottom as $V1 > V4$ and $V2 > V3$ during the period of time.

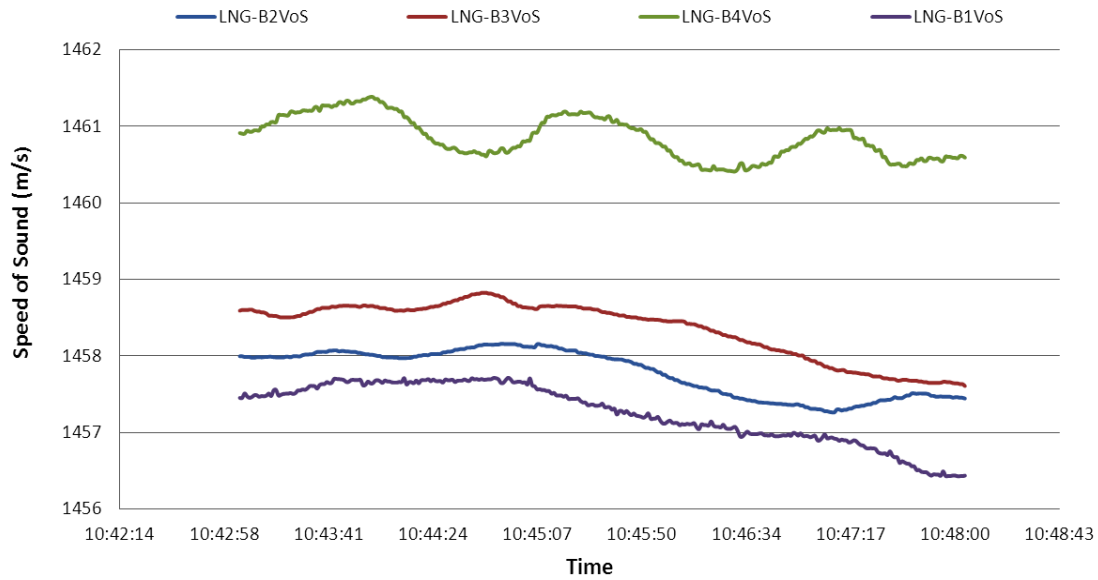
The highest fluid viscosity of the mixture is expected to be near the inversion point which is about 60% BSW. One would expect the measurement at the condition is likely to be problematic. By looking at the meter gains at testing conditions of 57%BSW and 63%BSW, we found that the meter gain on the same chord location of the same meter did not change much between the two conditions.

It is clear that the LNG meter uses lower frequency signal that can work in pure oil to highly water contaminated oil reliably. The LCT meter with higher signal frequency lost meter accuracy consistency when BSW is at 26%. Somehow, the meter went back to track at higher water cut with better speed of sound consistency (see figure 14 and 15). The phenomena show the importance of diagnostic features that can help users to justify the use and ascertain the reliability of the data. In the case of 63% BSW, even though the test data results have values close to the Coriolis, the chord velocities at the lower paths fluctuated at high magnitude, which was likely caused by slugs moving at the lower part of the pipe (see figure 15a and 15b). Since the SOS of the lower paths were more stable at 63% of BSW than at 57% of BSW, it might be an indication that slug size decreased as the BSW increased from 57% to 63%.



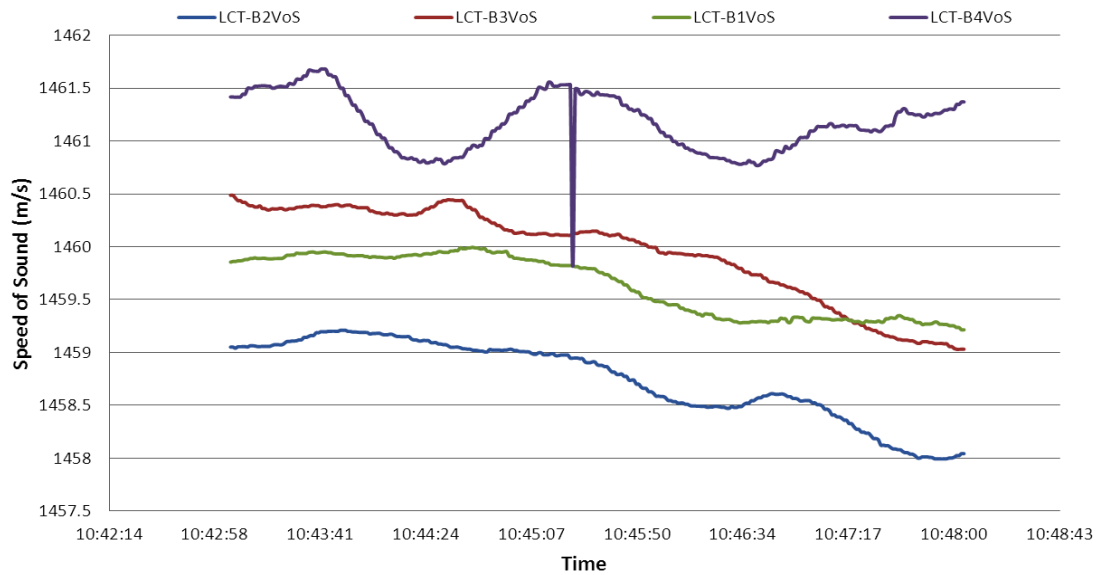
14a

Q= 50 to 30 m³/hr., 57% BSW



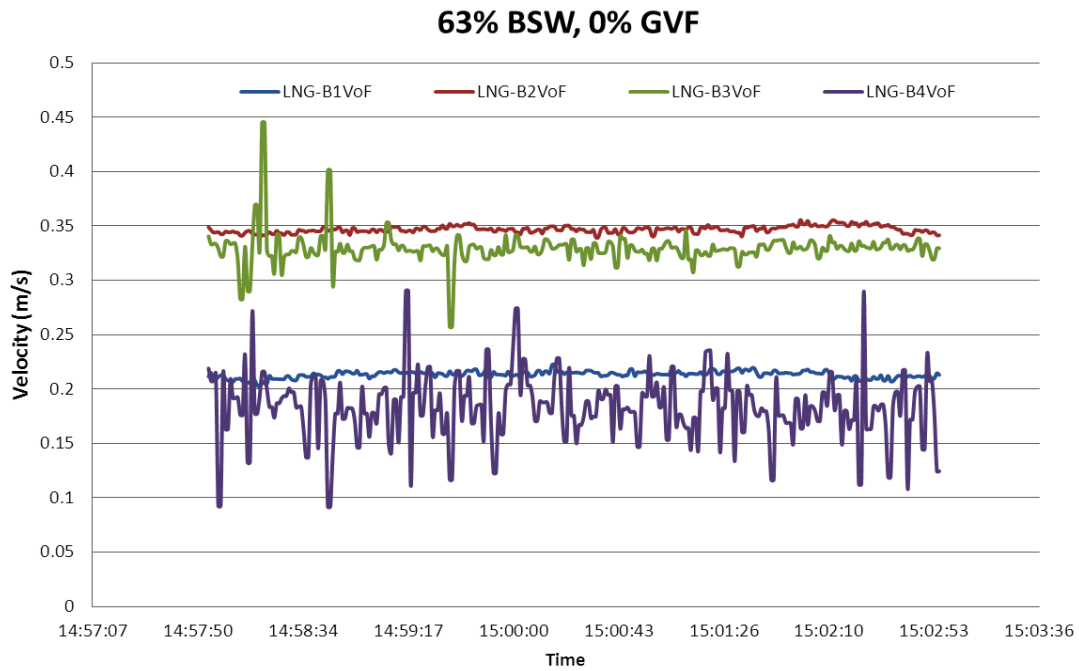
14b

57% BSW

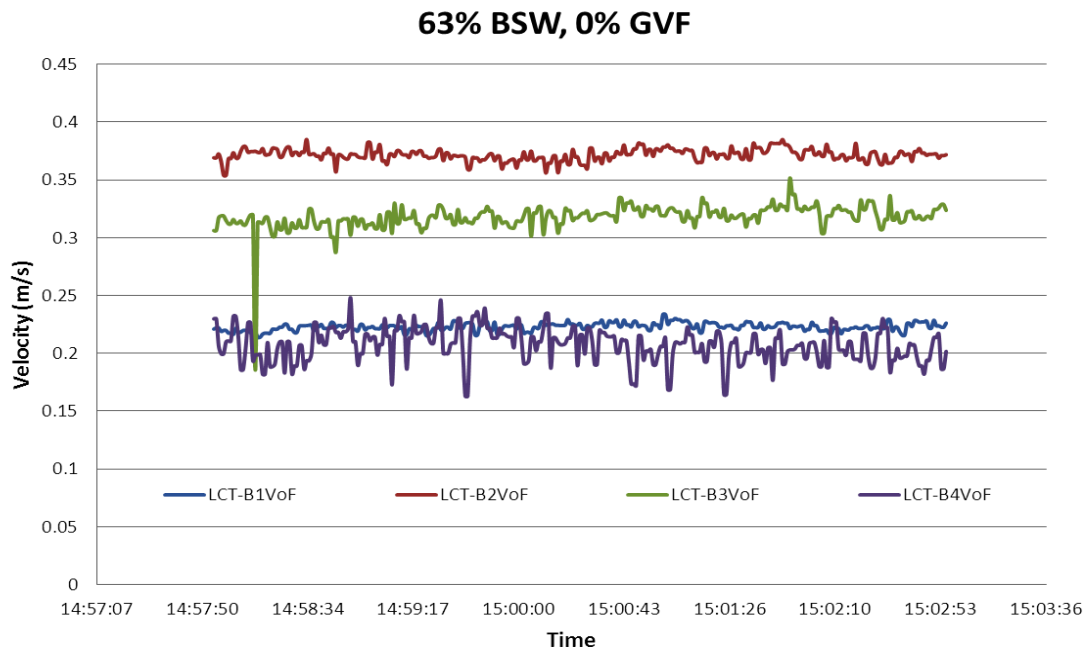


14c

Figure 14: The LCT meter started to work again at this “difficult” conditions comparing with 26% BSW. Note some periodicity in the speed of sound of bottom channel from both meters. They appeared to be caused by slugs.

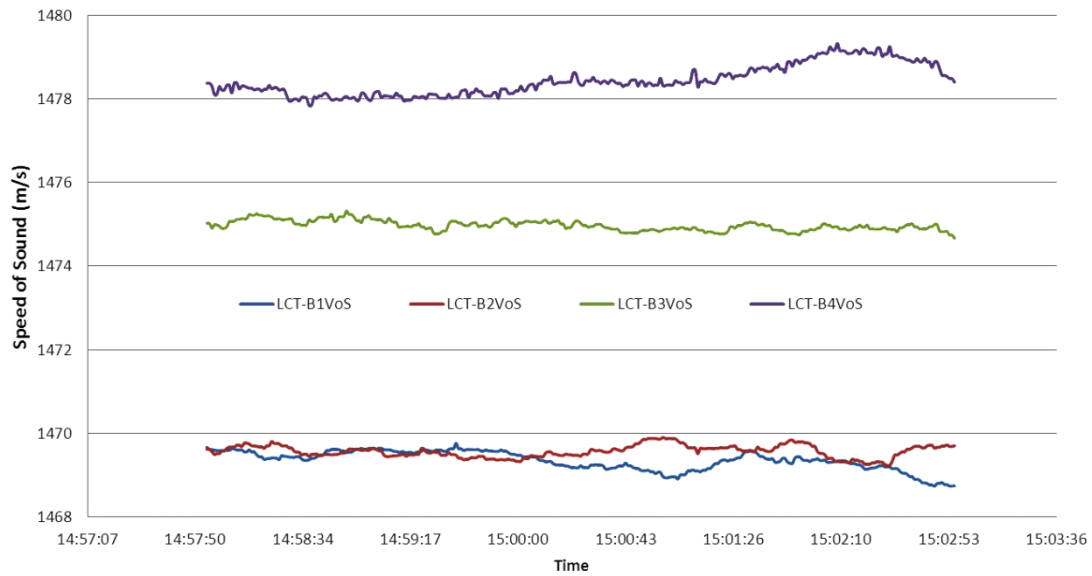


15a



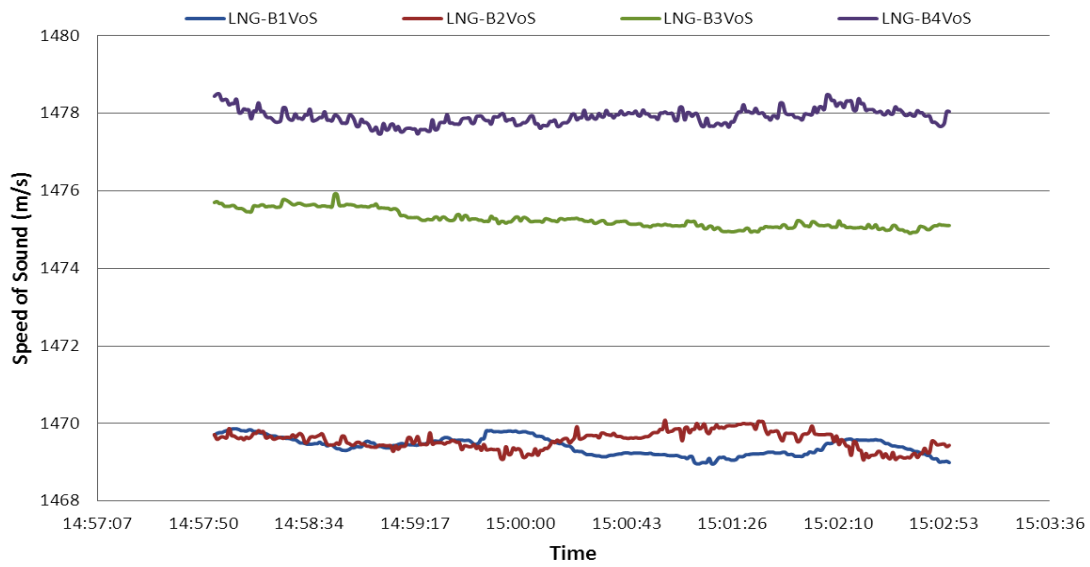
15b

63% BSW, 0% GVF



15c

63% BSW, 0% GVF



15d

Figure 15: Data obtained at 63%BSW, 0%GVF. Data in sound speeds (c and d) seems to show that flow is highly attenuative but mostly homogenous. The velocity at bottom paths (a and b) suggesting some slugs might be present at the lower part of the pipe.

5.1 Results of 3 Phase Liquid

After natural gas was introduced into the oil and water mixture, liquid flow rate becomes very unstable, causing top meter paths to fail in both meters. So the data become very noisy, especially at high percentage GVF (see figure 16). The flow regimes are mostly stratified and waving so that the bottom path in LNG continued working throughout the entire tested range of GVF which can provide trend of the flow rate changes (see figure 17a to 17f).

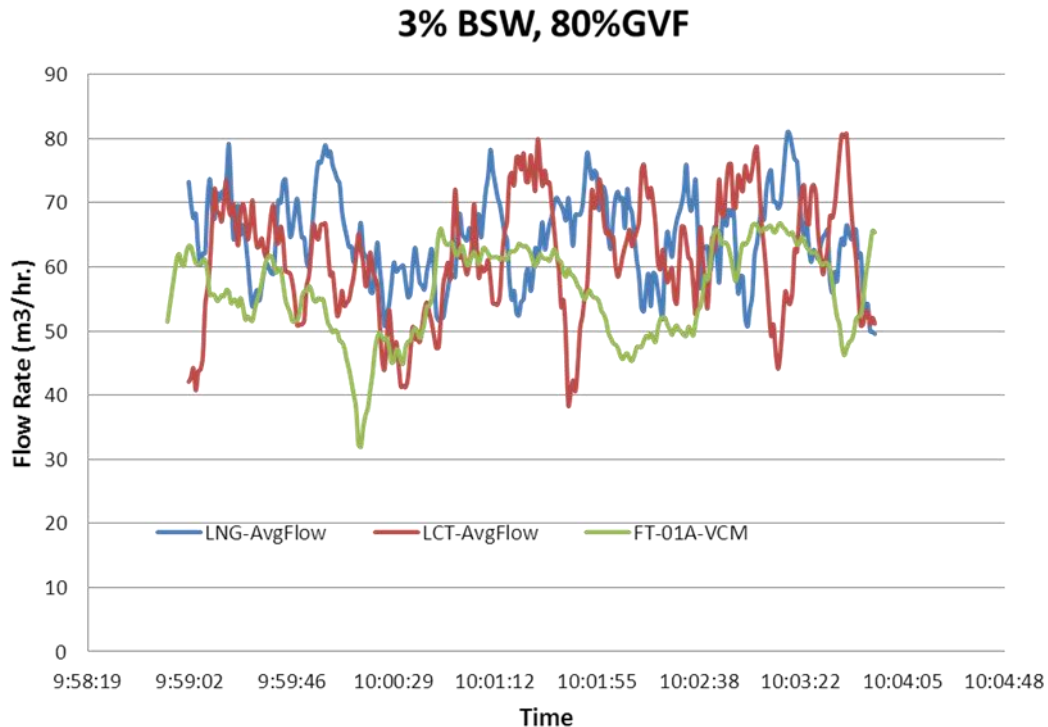


Figure 16: Data logged at 3% BSW and 80% GVF. Flow rate of liquid is unstable shown by the Coriolis meter. The both USM were higher than the Coriolis meter.

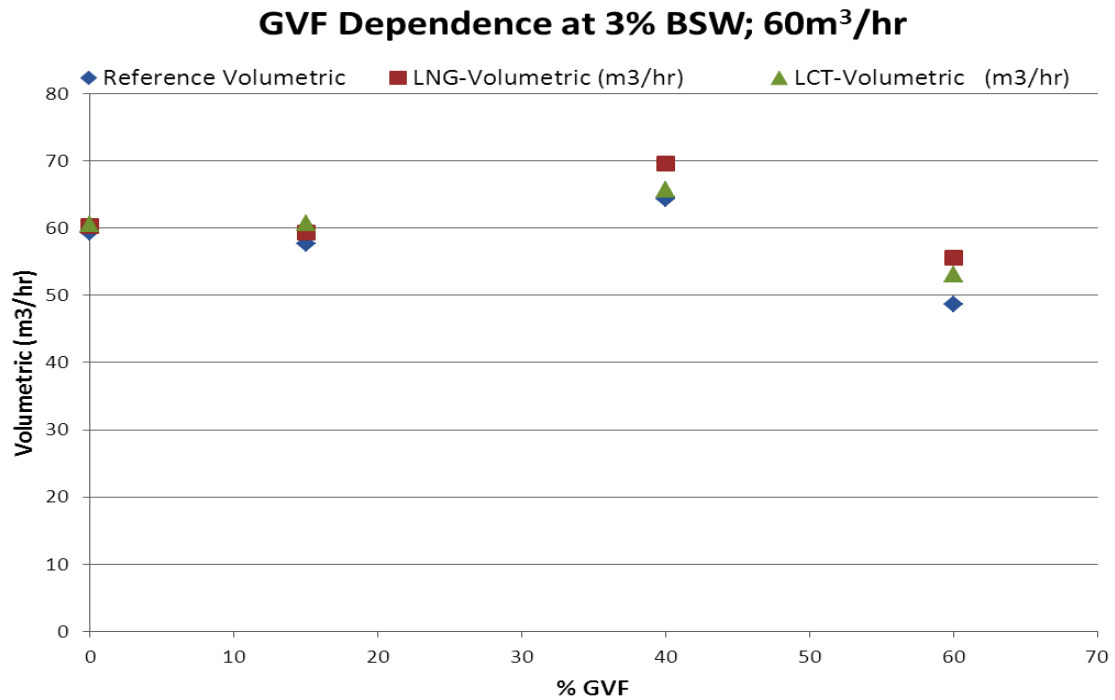


Figure 17a *The measurement of 2 USM at 15% GVF were still decent.*

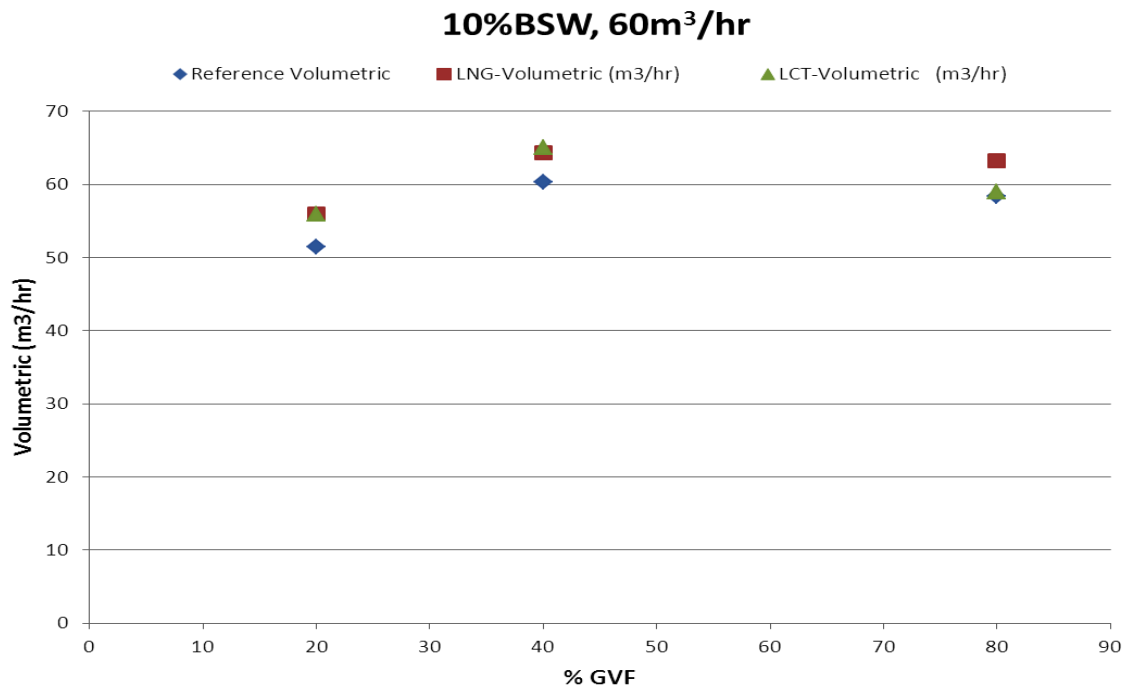


Figure 17b

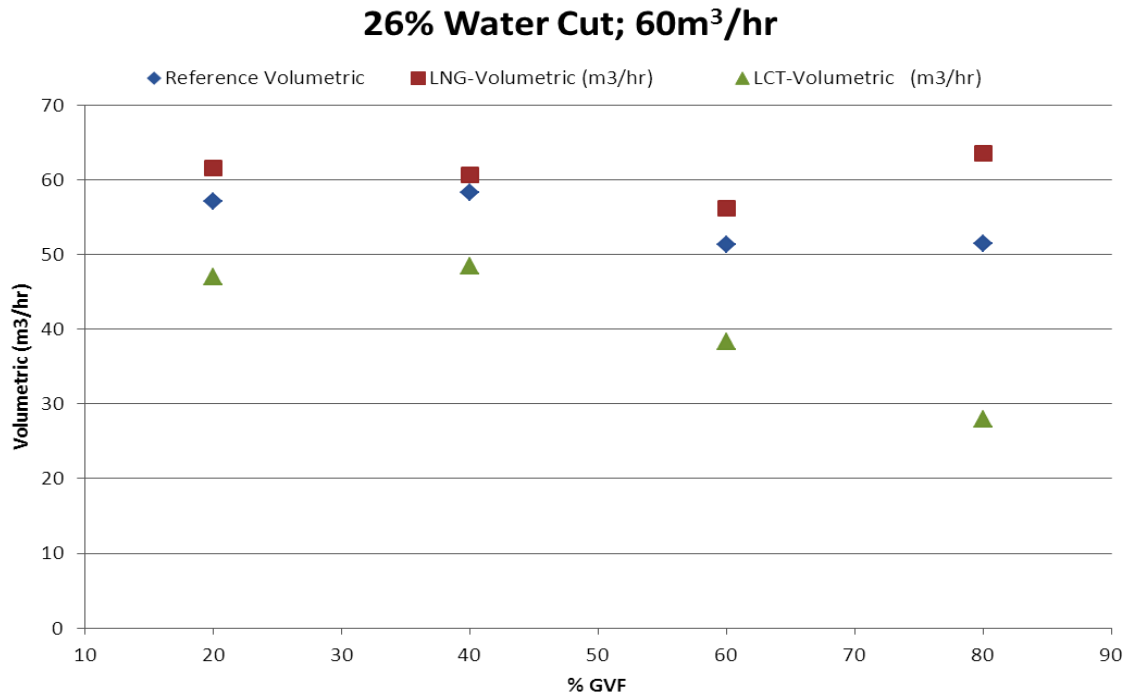


Figure 17c

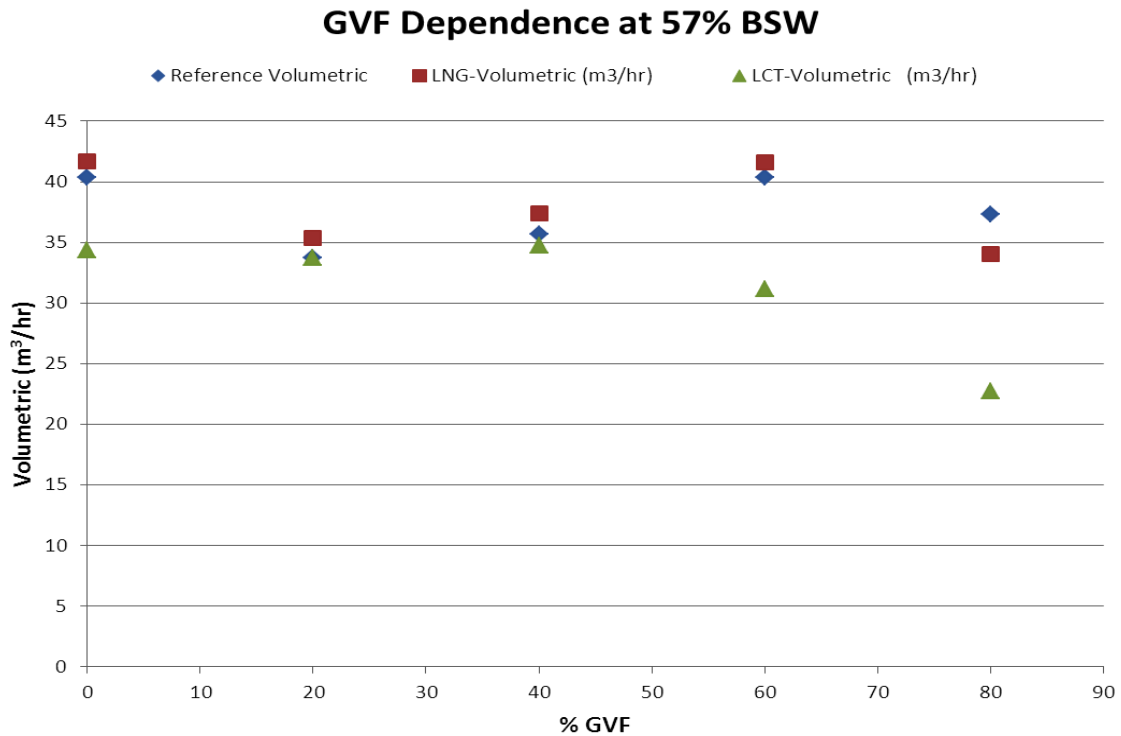


Figure 17d The impact of high GVF to the LNT meter did not appear to be more than the impact of high BSW.

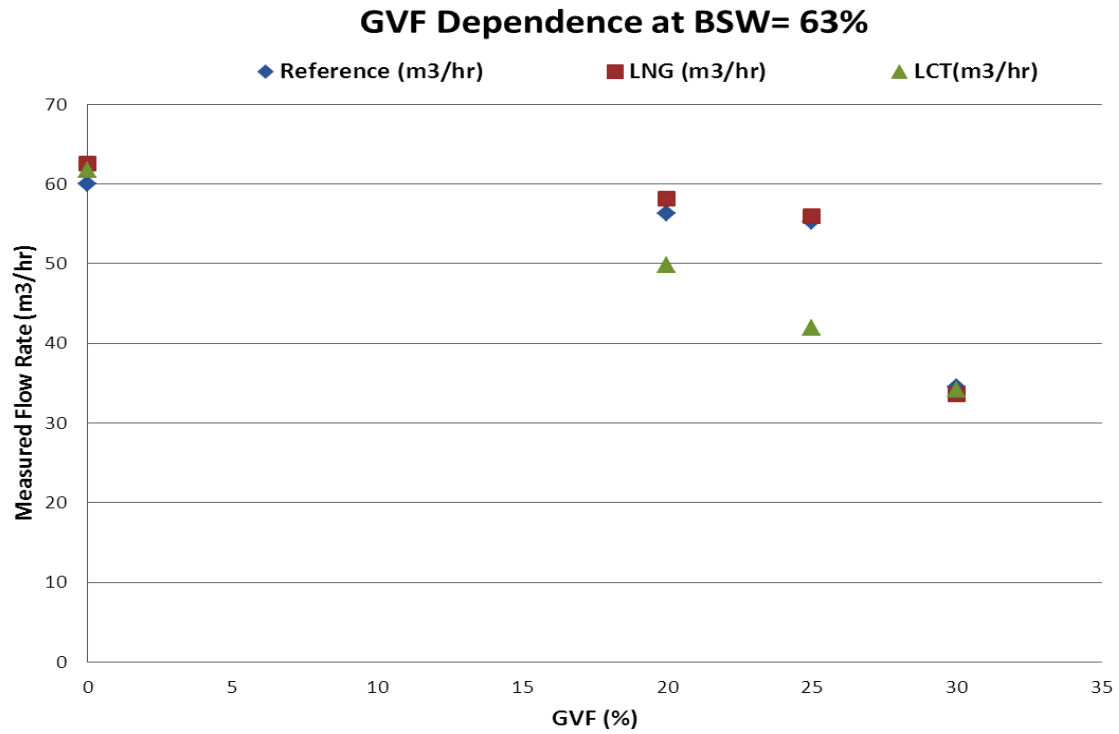


Figure 17e

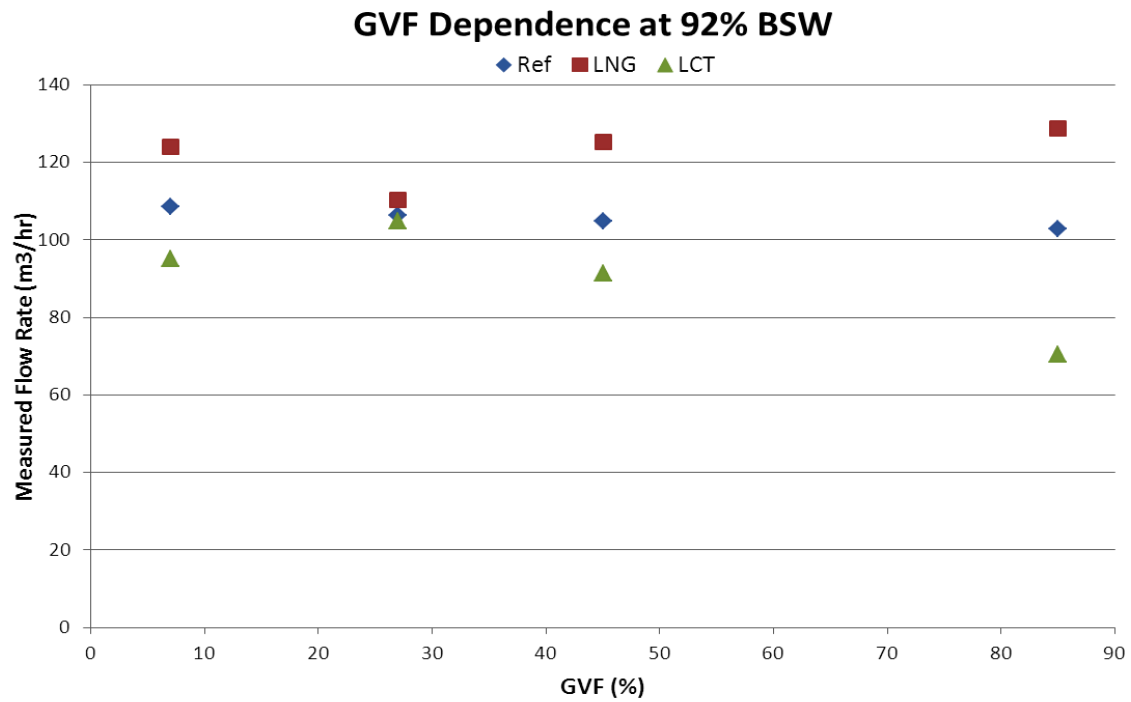


Figure 17f

6 SUMMARIES AND OUTLOOK

Based on the results of these studies, we have found that the Sentinel fiscal meter is capable of meeting Petrobras' objective to measure single phase liquid for custody transfer purposes and also provide process meter accuracy when water contamination occurs.

Given the observation that the lower paths of the LNG meter continued working at all tested conditions even in the presence of high percentage of GVF, it is possible that further study of the multi-path USM will enhance its performance in measuring 3-Phase flow. A specialized multi-phase flow diagnostic interface is also highly desired.

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7 REFERENCES

- [1] Alboudwarej, H., Felix, J., Badry, R. et al., Highlighting heavy oil, oilfield review, Schlumberger, Summer 2006.
- [2] Brown, J. G., Cousins, T., Augenstein, D. R., and Estrada, H. 27th International North Sea Flow Measurement Workshop, 2009.
- [3] Hogendoorn, J., Tawackolian K., van Brakel, P., van Klooster, J. and Drenthen, J. 27th International North Sea Flow Measurement Workshop, 2009.
- [4] Brown, J. G., Augenstein, D., Estrada, H., Laird, C. and Cousins, T., 28th International North Sea Flow Measurement Workshop, 2010.
- [5] Shirley Ao and Peter Espina. The American Flow Workshop, Houston, April, 2010
- [6] Ross, Amy and Stobie, Gordon, 28th International North Sea Flow Measurement Workshop, 2010.