The Effects of Water in Oil on the Performance of aFour Path Chordal Ultrasonic Flow Meter in a Horizontal Flow Line

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ABSTRACT

A series of flow tests were performed at the Ohio University multiphase test facility to evaluate the performance of a four path ultrasonic flow meter (UFM) in the presence of water in oil. The tests used a clear Perspex flow meter and piping, so that the flow behaviour could be observed and correlated with UFM performance.

Tests were initially carried out at a wide range of water-cut (water volume fraction), in order to verify meter operation. These tests showed that at higher velocities the water was fully dispersed and UFM operation appeared normal, although the true flow rate performance of the meter could not evaluated due the the lack of a suitable reference measurement. At lower velocities, water separated and formed a “river” along the pipe bottom. Under some circumstances the bottom acoustic paths could fail to operate due to refraction and dispersion effects when the ultrasound encounters the oil/water interface region.

Further tests were then carried out to attempt to quantify the UFM performance with water-cut in the range of 1% and 7%. For these tests, more of an attempt was made to quantify the uncertainty in flow rate measurement. At higher velocities, the combined oil and water volumetric flowrate measured by the UFM was within the experimental uncertainty of the test method. At lower flow rates, the performance of the flowmeter was degraded by water drop out affecting the lower path velocity measurement.

This paper describes the hydraulic behavior and gives advice on operational limits for good flow measurement in oil/water flows. The test data shows that the conditions in which good measurement can be obtained correspond well with the API[4] guidelines for good mixing in sampling applications.

1 INTRODUCTION

There has always been concern as to the effects of water in oil mixtures on the performance of Ultrasonic flowmeters (UFMs). Opinions have often been formed from circumstantial evidence, and seem to have been influenced by other factors such a gas in the fluid or the presence of particulate matter, rather than just the effects of water. To try and understand these effects and quantify the performance of a 4-path ultrasonic meter, Caldon designed a set of tests to be performed at the Ohio University Corrosion Research Center. Amongst other studies, Ohio University carries out testing on the effects of gas, water and oil mixtures on the corrosion of pipes and therefore seemed to be a good laboratory location for Caldon’s oil/water testing.

The tests were carried out in two stages, The second stage of testing built upon the better understanding gained from the previous first stage and the test method was substantially revised.

The series of tests were performed with two different viscosities (4 cP and 20 cP) and with “coarse” control of water content. These tests are more applicable to larger volumes of water content. In the second series of tests, a more direct flow comparison was performed and the water-cut was limited to between 1% to 7%.

The results give sufficient information to provide some basic precautions in how to use UFMs to measure fluids that consist of water in oil mixtures. To obtain a reasonable uncertainty of measurement of the combined volume the water and oil should be well mixed. When the flow becomes stratified, at lower velocities, then there is greater potential for meter performance to be degraded.

2 INITIAL TESTS INCLUDING HIGH WATER-CUT

The first series of tests were carried out using the following method:

The liquids were pumped from a single tank. Within the tank, the water and oil were separated by gravity, e.g., with oil on the top and water on the bottom. The oil was pumped out from the higher section of the tank and water from a lower section. The flow return was near the top of the tank. A picture of the facility is shown in Figure 1 below.

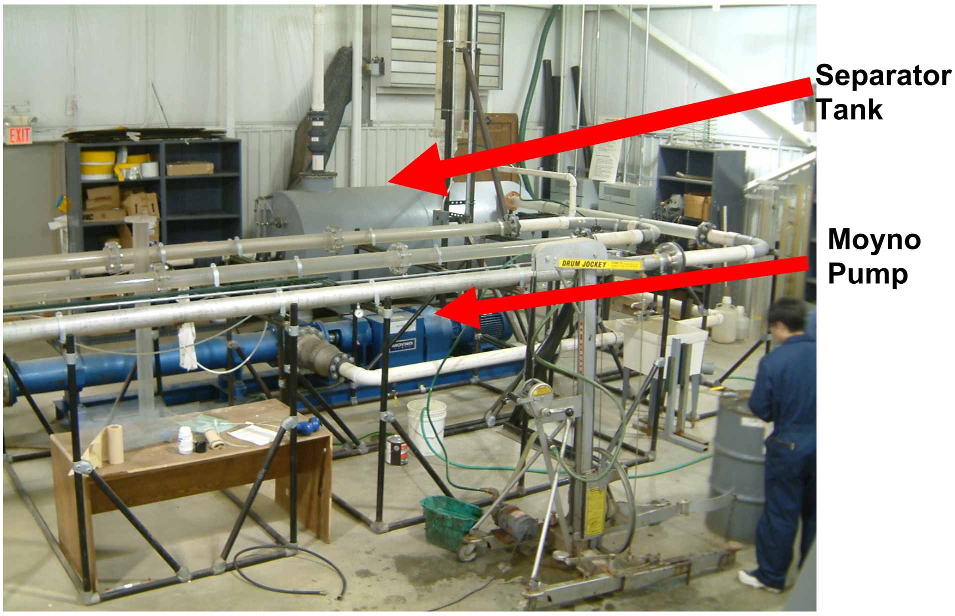


Figure 1: Flow/Separator Tank

The pumps used were semi-positive displacement type (Moyno), allowing the flow rate to be estimated by the RPM of the drive motor. It was intended that the water-cut would be controlled by varying the ratio of pump motor speeds. However, it was discovered early in the tests that the tank volume was too small to allow sufficient separation of the water and the oil before the liquid was drawn back in through the pumps. Therefore, the pump speed ratio was used to roughly set the water-cut. To measure the water-cut a diverter valve was used to by-pass the full flow stream into a settling tank. The water and oil volumes in the setlling tank were then measured off-line to determine water cut.

The test liquids used were water, LVT200 (~ 2.5 cS viscosity and 0.82-0.83 specific gravity) and Duopac 90 (viscosity 18.6cS, 0.851 specific gravity).

The ultrasonic flow meter was a 4-inch Caldon 4-path meter, the operation of which has been described before (e.g. see References 1 and 2). The meter used 1.6 MHz transducers and the body was made of Perspex. It was installed in a 4” Perspex flow line approximately 150 pipe diameters long. This test set up allowed for proper development and observation of the oil/water flow distribution. Photographs of the meter body and test line are shown below.

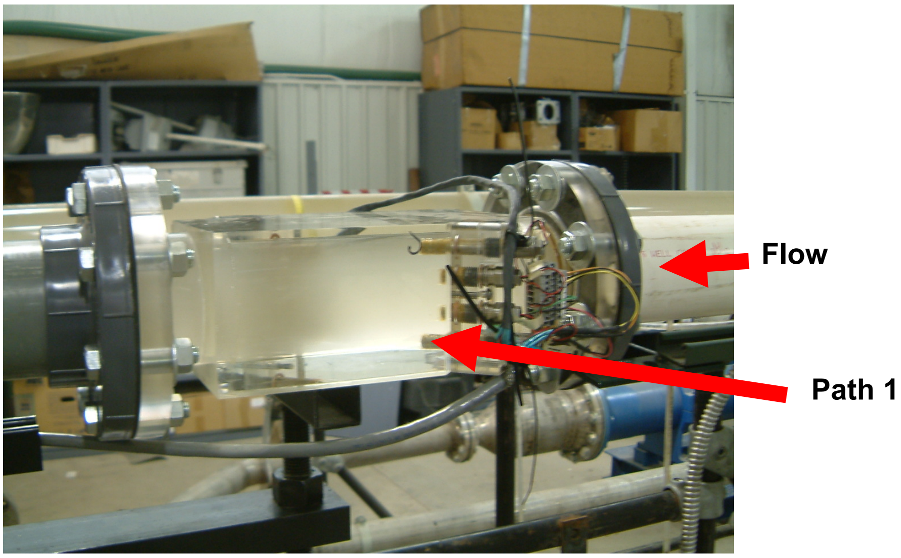


Figure 2 Test Meter

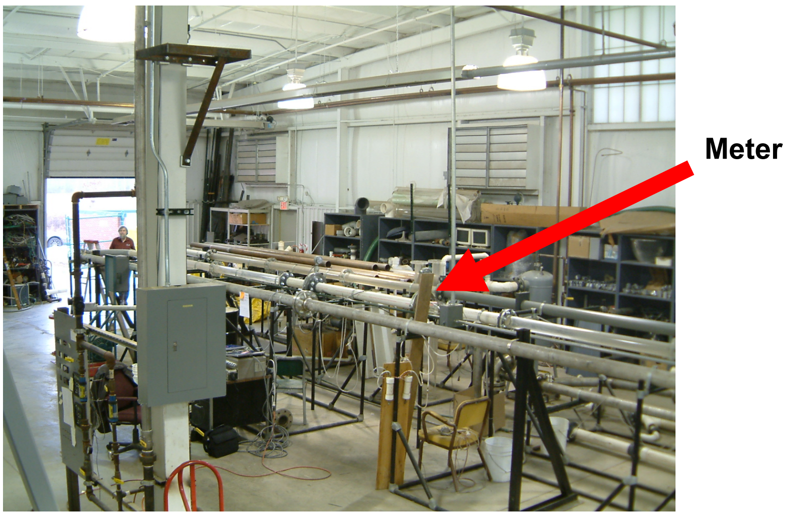


Figure 3 Meter Installation

2.1 Initial Test Results

During the tests diagnostic data was recorded to monitor features that define the UFM's quality of operation (e.g., gains, signal to noise ratio, standard deviation of the samples and velocity of sound).

In the case where no water was purposefylly added to the oil the diagnostic results indicated excellent performance. For example, the signal-to-noise ratio (SNR) was around 90 for all paths and flows. The flow velocity profile was also acceptably symetrical. In reality a pure oil test was not possible as there was always a background contamination level of water in oil. However, this did create the opportunity to carry out some tests with small quantities of water to see the effects.

A series of low velocity tests were performed where the presence of water was observed to vary in the bottom of the pipe from a small rivulet to almost a quarter fill. Under these conditions, with water still running separately from the oil, the transducers submerged below the water gave a good signal and those above the water line gave a good signal, but any on the oil/water interface gave a very poor signal.

The results of the intial series of tests can be summarised as follows:

- At velocities greater than 2.6 to 3.1 m/s, the meter worked at all water cut levels tested (0%-25% for 2cS, 0-75% for 18.6cS). At these velocities, the water droplets appear to be completely dispersed. There was some degradation of SNR and increase in gain, but not consequential with regard to meter operation.

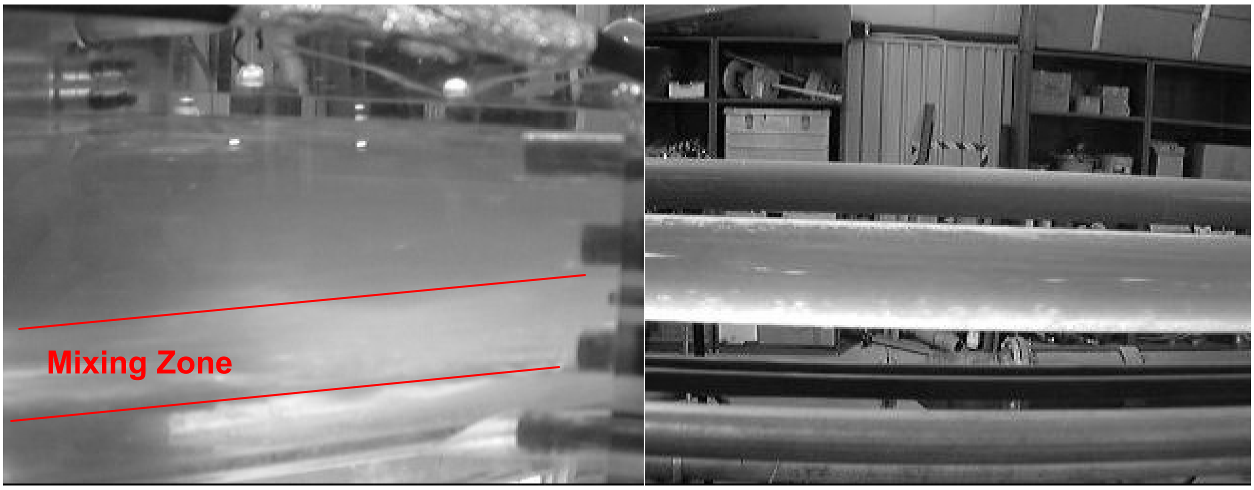
- For 2 cSt oil, at velocities less than 3.1 m/s, the water droplets began to drop out and a layer of water developed on the bottom of the pipe. By 1 m/s, the droplets had essentially dropped out and the water was running along the bottom of the pipe. At these velocities, there is a transition region at the water/oil interface. This transition region has surface "waves" (for lower velocities) or a combination of waves with large to small droplets breaking off waves (for higher velocities). The height/thickness of the transition region is a function of the velocity, relative densities, viscosity and water cut.
  - For acoustic paths below the water/oil transition region (depending on the water-cut and velocity), the acoustic paths work well – as if in pure water.
  - For acoustic paths above the water/oil transition region (again depending on the water-cut and velocity), the acoustic paths work well – as if in pure oil.
  - For acoustic paths within the water/oil transition region, the acoustic paths are degraded in performance or may have failed.

- For 18.6 cSt oil, water droplets began to drop out at velocities less than 2.6 m/s. Under these conditions, the observations discussed above are still valid. The intersection of the water/oil transition region with a transducer path adversely affects its performance. However, the transition layer was thinner and more defined than that of the 2 cSt oil. This localizes the effect of the transition layer to one path and the effect upon that path is not as great as with the 2 cSt oil. For example, during these tests, no path failed at any time.

- With 2 cSt oil, for water-cuts below 10%, the UFM operated without any apparent performance degradation (irrespective of the velocity). With 18.6 cSt oil, at a flow rate of 0.6 m/s and low water cuts, the transition region can interfere with the bottom path. Under this condition, increased gain, low SNR and rejects eventually cause the software to reject the path due to poor acoustic quality. The remaining three paths are unaffected. Obtaining low water-cut at low flow rates was very difficult with the configuration at Ohio University. This was due to the lowest pump speed for the water pump being too high for our purposes.

- At velocities ~ 1.5 m/s, the oil/water distribution is most noticeably in a transition region between stratified and well mixed flow, and this is the area where things are most difficult for the meter. With 2 cSt oil, and if the water-cut was high enough, the meter had 2 or even 3 acoustic paths in and out of failure. With 18.6cS oil, although multiple transducer paths were adversely affected, at no time did any path fail.

The next figures show a typical set of observations, taken at high velocity. The water-cut during the time of these observations was approximately 20%.



Meter Body **Upstream Pipe**

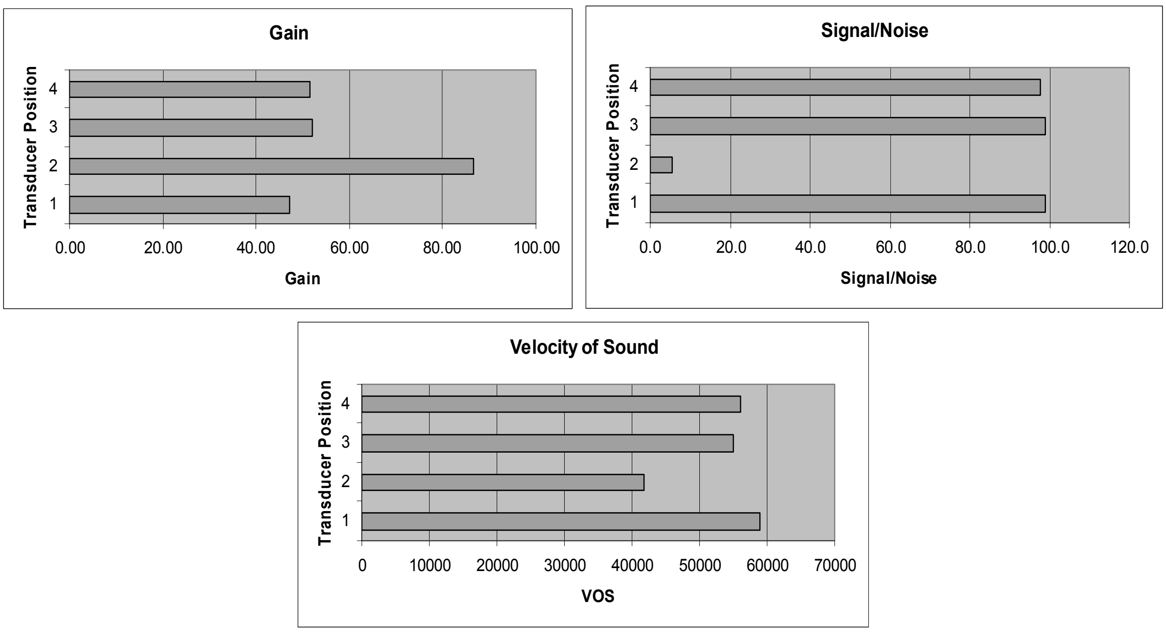


Figure 4 High Flow 20% Water Data

The mixing zone is a very turbulent shear layer of varying percentages of water and oil, with varying degrees of signal attenuation. The velocity of sound (VOS) for paths 3 and 4 (top paths) was a value of around 55,000 in/s (1,400 m/s) which is normal for the oil and around 59,000 in/s (1,500 m/s) for path 1 indicating water on the bottom. In between the value is invalid because of the poor signal quality, as shown by the plots of SNR and gain.

Figure 5 below shows the flow with a small volume of water at a velocity of below 1m/s. The graphs illustrate the effect of the stream on the gain and signal to Noise ratio, indicating that the interface between the water and the oil is impacting the bottom path.

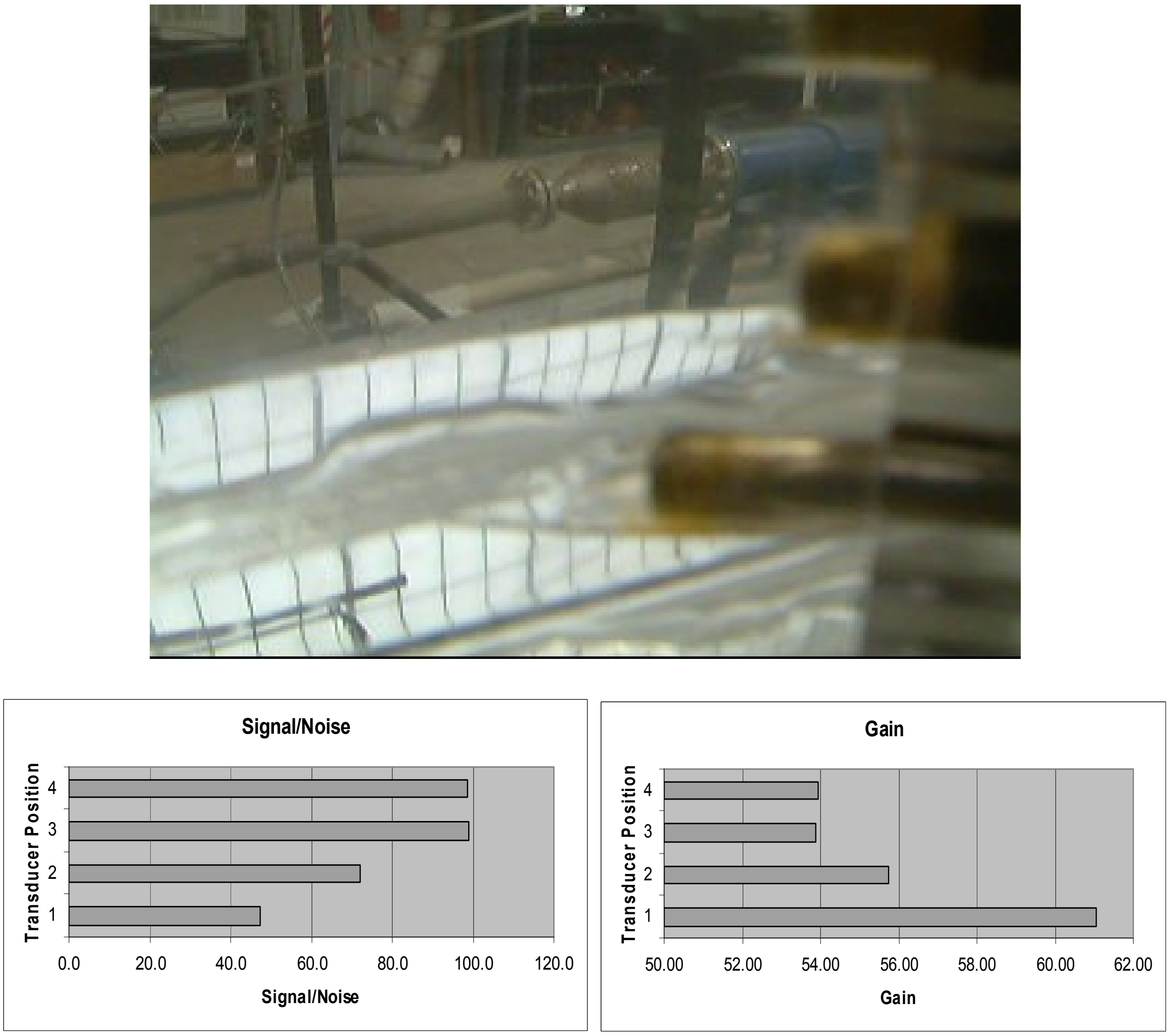


Figure 5 Data For Low Flow <1% Water

3 WATER IN OIL TESTS AT 1% - 7% WATER-CUT

Following the first series of tests a decision was made to perform more controlled tests over the 1 to 7% water-cut range. This test was felt to be more applicable to the majority of custody transfer applications. The test method was changed to give a more consistent volume of water to oil. Instead of using the pumps separately to mix the liquids, the tank was filled with the required volumes of oil and water, and the mixture was then pumped until it was fully mixed/dispersed. The reference measurement method was to use the pump RPM measurement as the method of calibration. The method utilized the output from the Moyno semi-positive displacement pump. A resolver was mounted on the pump shaft which produced a pulse train, which was used to gate the meter pulses.

This method was not able to give a good absolute measurement, but was very repeatable, to within 0.2%. Thus, the experiment used the calibration with 0% water in oil, at velocities above 1.5 m/s, as the baseline for all of the tests. The data is all referred to this datum. The criteria of higher velocity was used because of the fact that it was not possible to remove all traces of water from the system, and therefore the higher velocity data was considered to be more representative of the performance without water present.

The meter used for the tests was again the 4” Perspex LEFM 240C meter described earlier. The meter was installed with Path 1 on the bottom and Path 4 on the top. Water cuts tested were nominally 0% (Baseline), 1%, 3%, 5% and 7%. A check was made on the water-cut by taking a draw sample of the mixture into a long calibrated vertical tube, and allowing it to settle out. The proportion of water to oil could then be determined by comparison of the depths. The viscosity of the oil in these tests was 13 cSt and the specific gravity was 0.89.

3.1 Results

Before data was logged at any given water-cut, the test rig was run at a high flow rate for at least 30 minutes to ensure good mixing. The picture below shows a typical mixed flow at high flow rates, the “milky” appearance being caused by the water being well mixed through the oil in the form of many small droplets.

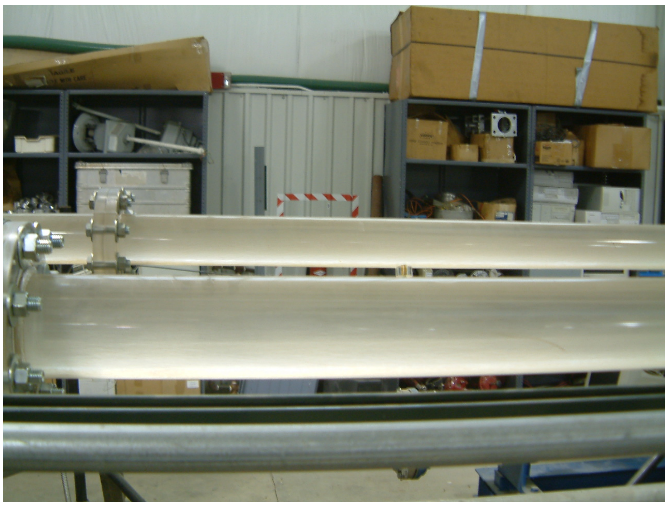


Figure 6 Mixed Flow Prior to Testing

The initial calibration of the meter is shown in Figure 7. It should be noted that the calibration at the low end is non-linear. This is explained later, when it was realized that there was still water in the line, and that it was gradually settling in the lower port, and therefore the calibration at the low end had some degradation.

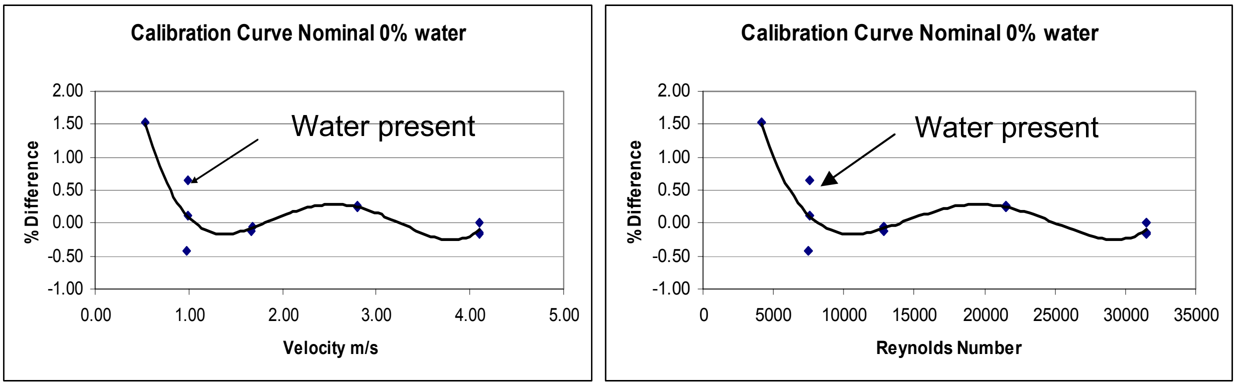


Figure 7 Initial Calibration

Tests were then carried out at water-cuts of 1, 3, 5 and 7%. The results, plotted as a percentage difference relative to the 0% water-cut baseline, are shown in Figure 8 below. During these tests, the meter was configured such that the results were computed using all four paths, even those whose path velocities would normally be rejected owing to poor signal diagnostics. Therefore the poor performance at low velocities is exaggerated owing to the inclusion of spurious velocity data from path 1.

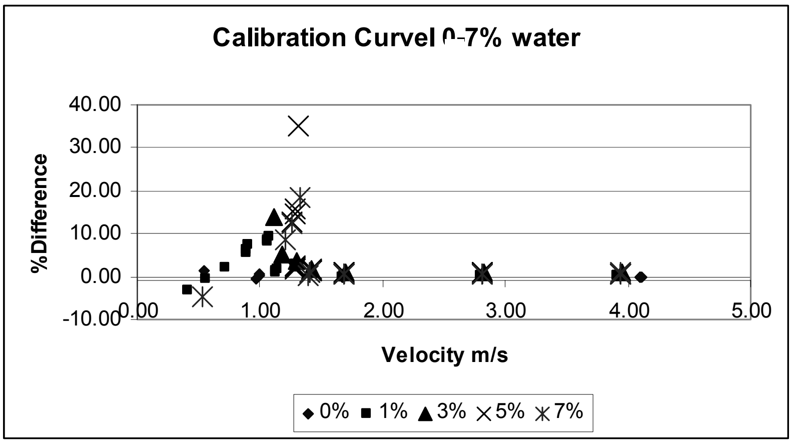


Figure 8 Calibration of the Meter with 1-7% Water content

A summary of recorded diagnostic data for individual paths is shown in Figures 9 - 12. In Figure 9 the data is a conglomeration of water-cuts and therefore variations with water-cut can not be distinguished.

Figure 9 shows that the signal to noise ratio for paths 1 and 2 (in the lower part of the pipe) are reduced by the presence of water at velocities of less than approximately 1.3 m/s.

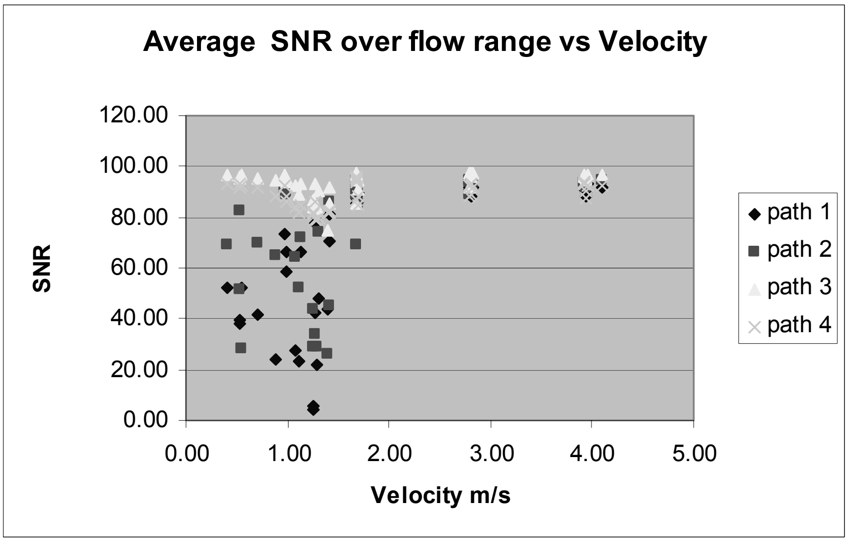


Figure 9 Signal to Noise Ratio Data for all Water-Cuts

Figure 10 shows an increase in average gain over all paths as the water-cut increases. Again the effects are most pronounced at velocities below 1.3 m/s velocity,

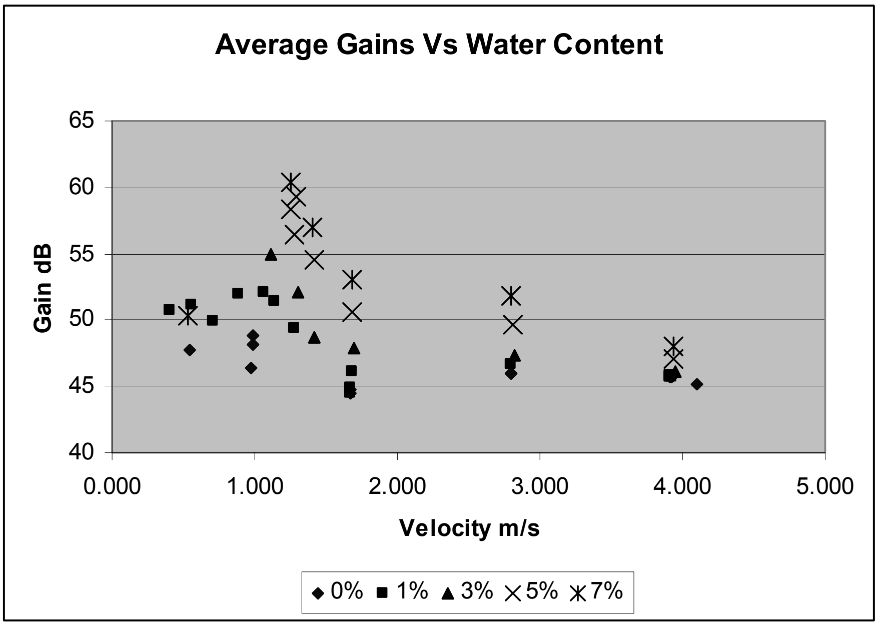


Figure 10 Average Gain Data for all Water-Cuts

Figure 11 shows the flatness ratio (i.e. the ratio of the velocities measured on the outside paths divided by the velocities measured on the inside paths) vs velocity and water-cut. It can be seen that this ratio is constant at velocities above 1.3 m/s.

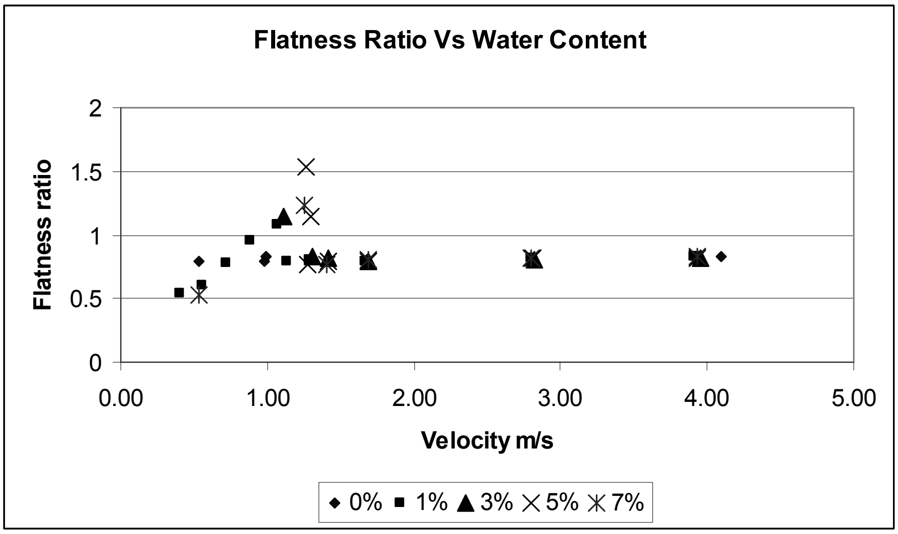


Figure 11 Flatness Ratio vs Water-Cut

Figure 12 shows the variance of the velocity measurements (i.e. the scatter) vs velocity and water-cut. It can be seen that the varience is low at velocities above 1.3 m/s and sometimes very high at lower velocities with water present.

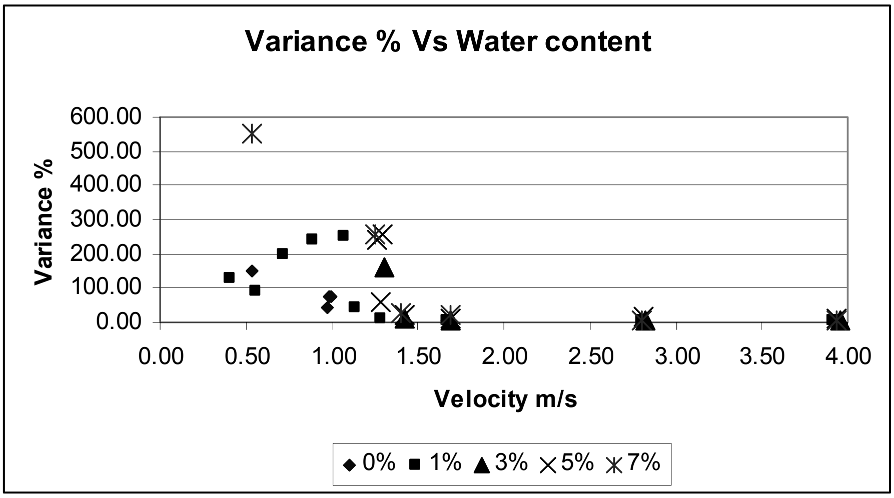


Figure 12 Variance vs Water-Cut

3.2 Discussion of Results for 1-7% Water

3.2.1 Performance at Velocities Greater than 1.3 m/s

Above a velocity of approximately 1.3 m/s (corresponding to a Reynolds number of around 10,000) the meter performed within the uncertainty of the calibration system at all water-cuts tested (i.e. up to 7%). Under these conditions there was no observable change in the meter's performance. As shown in Figures 9 – 12, the flatness ratio, gains, variance and SNR all remain relatively constant in this regime. These observations are also supported by examining the velocity profile measured by the meter. At velocities greater than 1.3 m/s, there is no change in measured velocity profile with water-cut, as shown in Figure 13.

These observations can be related to the distributon of the water in oil. Above a velocity of 1.3 m/s visually the water appears to be well distributed throughout the oil, as shown in Figure 14.

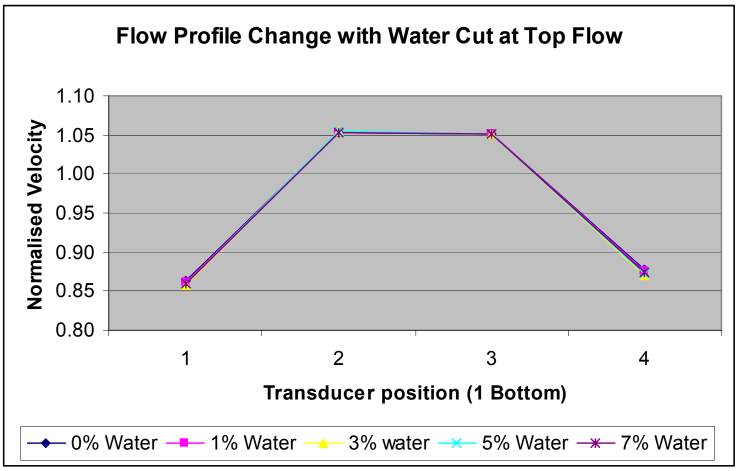


Figure 13 Change in Measured Profile with Water-Cut (velocity > 1.3 m/s)

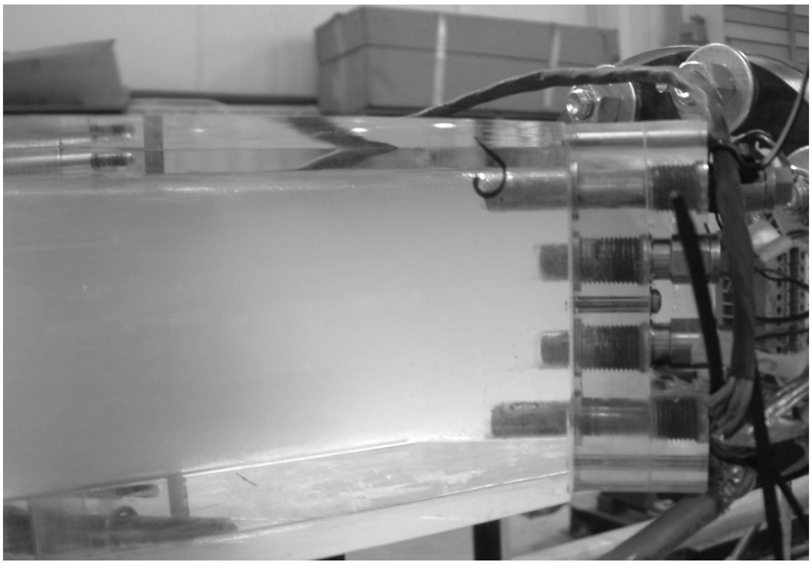


Figure 14 A Photograph Taken at 5% Water-Cut at Highest flow

3.2.2 Performance at Velocities Less than 1.2 m/s

Below 1.3 m/s (Reynolds number of 10,000) the presence of water begins to dramatically change the meter performance. The calibration now begins to open out and become non-repeatable. At this point the velocity measurement on the bottom path becomes inaccurate as shown in Figure 15.

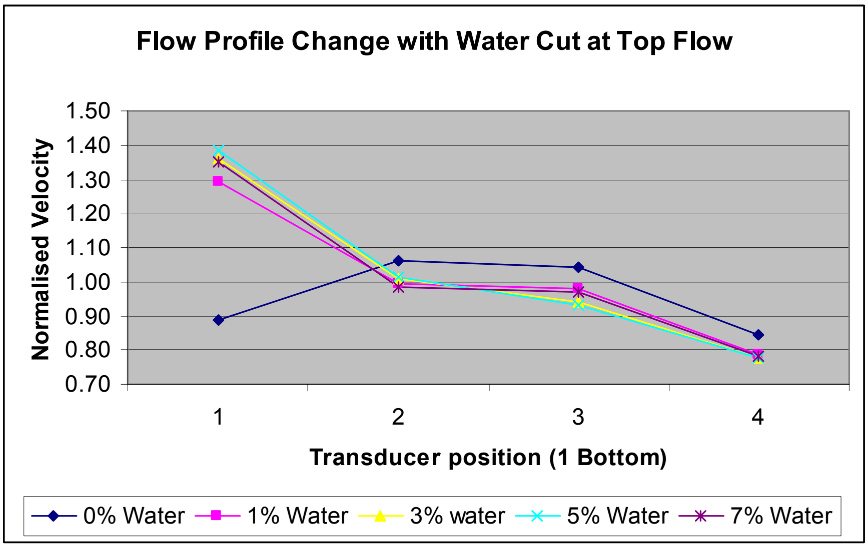


Figure 15 Measured Flow Profile Variation with Water Cut at ~ 1 m/s Velocity

When the data was examined what was disconcerting was the fact that the magnitude of the effect at this velocity did not seem to be dependent on the water-cut. The velocity on path 1 was also very unstable in these conditions and changed with time in the presence of water, as shown in Figure 16. The only notable difference between the behaviour at 1% and 7% water-cut was the time after change of flow it took for the effect to reach a maximum.

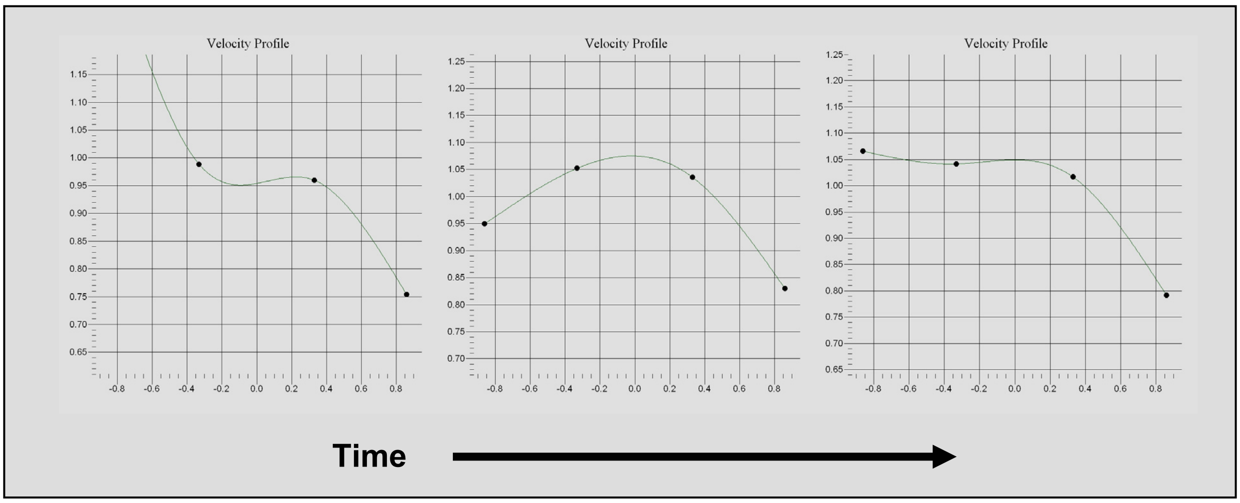


Figure 16 Changes in Measured Velocities with Time at 1% Water-Cut

At a velocity of about 1 m/s there was not an obvious rivulet of water at the bottom of the pipe, particularly at the lower water cuts. This could be observed at lower flows, with globules of water tracking along the bottom of the pipe rather than a continous stream at the lower water-cuts. On examination, the real cause of the problem at these conditions appears to be the formation of a ‘glob’ of water in the bottom transducer ports. This was observed clearly during the tests as shown in the Photograph in Figure 17.

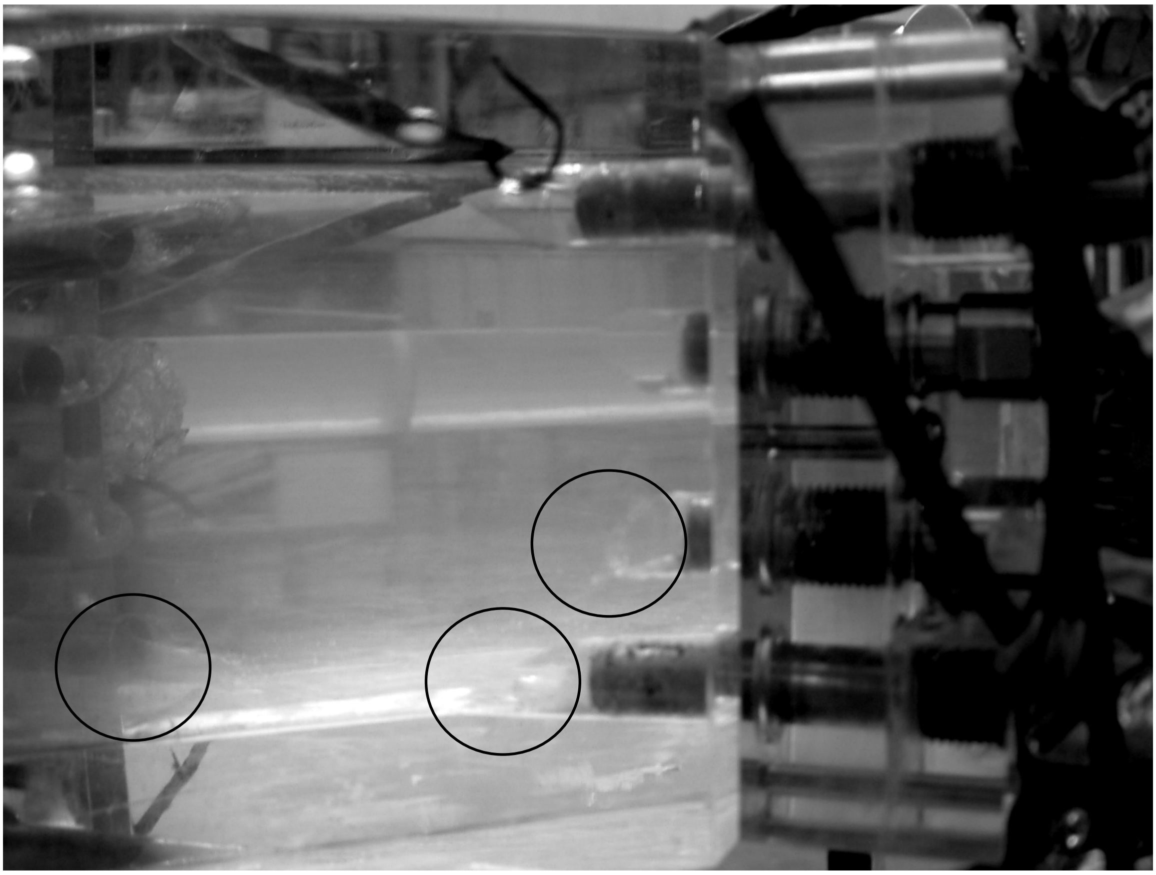


Figure 17 Formation of Water ‘Globs’ in the Lower Transducer Ports

It can be observed from the figure above that there are small formations of water in the second from bottom path. However, this did not appear to affect the velocity measurement on that path, even though a lower signal to noise ratio was observed.

The ‘glob’ of water that formed in the lower transducer ports could be observed to change in size with time. At the lower flows there was not sufficient velocity, or turbulence, to provide a vortex action to completely remove the glob of water. However, its size is added to and reduced by the action of the flow. The glob is essentially stationary except at the boundary, where it wobbles like a piece of jelly, occasionally shedding pieces of itself. The disconcerting feature of this effect is the fact that it does not appear to matter how much water is present, it will ultimately build up to a similar level in the lowest transducer ports.

At lower velocities of around 0.5 m/s there was indication that the effect of the ‘glob’ was mitigated and the velocity profile returned to a more parabolic shape, indicating a sensible velocity measurement on the bottom path.

As can be seen from the SNR, gain and variance plots, the ultrasonic signals on the bottom path are dramatically affected at these low flows. The shape of the 'glob' of water refracts the ultrasound, causing deflecton of the 'beam' and distorting the waveform of the received signal. With the shape of the glob shifting with time then the way that the signal is affected changes with time also, resulting poor repeatability as well as inaccuracy.

What is unclear is if the onset of this effect of is a function of velocity or Reynolds number, or perhaps some other parameters. The changes in performance and the appreence of the 'globs' all occur close to the transition from laminar to turbulent flow. This leaves the following questions unanswered;

- If the flow was turbulent would it remove the 'glob'?
- Will viscosity, density and surface tension differences significantly alter these effects?

These questions can only be answered by further tests.

4 CONCLUSIONS

The use of clear piping has provided additional insight into UFM operation when operating under conditions of water mixed with oil. Three flow regimes of water and oil mixtures have been observed. These are fully mixed flow, stratified (separated) flow and transitional flow. Based on observations and measurements in these regimes, the following conclusions can be made:

Fully Mixed Flow

At velocities greater than 3 m/s, independent of the oil viscosity and water-cut, the water is well dispersed through the oil. Under these conditions, the UFM may see some acoustic degradation (dependent on the water-cut), but the degradation is not consequential with regard to the UFM flow measurement operation. When calibrated, the meter performance does not change by more than the uncertainty of the test method.

Transitional Flow

At velocities less than 3 m/s and greater than 1.3 m/s, the water begins to drop out and a layer of water develops on the bottom of the pipe. At these velocities, there is a transition region at the water/oil interface. This transition region has surface "waves" (for lower velocities) or a combination of waves with large to small droplets breaking off waves (for higher velocities). The height/thickness of the transition region is a function of the velocity, relative densities, viscosity and water cut.

- For acoustic paths below the water/oil transition region (depending on the water-cut and velocity), the acoustic paths work well – as if in pure water.
- For acoustic paths above the water/oil transition region (again depending on the water-cut and velocity), the acoustic paths work well – as if in pure oil.
- For acoustic paths within the water/oil transition region, the acoustic paths are degraded in performance or may have failed.

The velocity at which good mixing is observed to occur corresponds closely to API's mixing requirements for product sampling.

Stratified (Separated) Flow

Below 1.3 m/s, the droplets have essentially dropped out and the water runs along the bottom of the pipe. For lower watercuts, below 5%, the water travels along the pipe bottom, but does not interfere with the bottom path (at least for the design of the meter tested). However, by some mechanism (such as the coalescence of droplets that traveling along the pipe wall) water can accumulate in the bottom transducer ports. to forming a 'glob'. This glob changes shape and size with time, but will not clear itself at low velocities. This glob degrades the acoustic signal (due to refraction), such that eventually the flow meter rejects that path's data from the flow calculation.

At higher water-cuts, the water stream can cover the bottom path. The bottom path may still be rejected from the flow calculation depending upon the character of the 'waves' of water. However, eventually the water will cover the bottom path such that its acoustics are acceptable. However, the next path from the bottom may then start to go through conditions similar to those that affected the bottom path.

Water-Cut Measurement

Although not presented here, the test data also shows that the measured sound velocity can reasonably be used to estimate water-cut, where the water cut is determined by a linear combination of the oil sound velocity and water velocity.

5 REFERENCES

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2. T. Cousins & J. Thorogood (2004) "Small Volume Proving of Ultrasonic Flow Meters" *S E Asia Hydrocarbon Flow Measurement Workshop, Singapore*, March 2004

3. T. Cousins, H. Estrada & D. Augenstein (2004) "Installation Effects and Diagnostic Interpretation Using the Caldon Ultrasonic Meter" *North Sea Flow Measurement Workshop*, St Andrews, Scotland, October 2004

4. API Chapter 8 "Sampling"