Final Scientific/Technical Report

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b. Award Number: DE-FE0031858
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d. PI Name: Qussai Marashdeh
   Title: CEO
   Email: marashdeh@tech4imaging.com
   Phone: 614-214-2655
e. Submitting Official: Same as PI
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   Tech4Imaging, LLC
   1910 Crown Park Ct.
   Columbus, OH 43235
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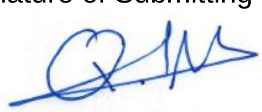

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1 What are the major goals of the project? (Summary)

1.1 Project Goal

The proposed innovation aims at extending the use of Multi-Dimensional Electrical Capacitance Volume Tomography (MD-ECVT) sensors for subsea oil and gas multiphase flow measurement to reduce subsea facility complexity, advance real time remote monitoring of well fluids, and enable greater tieback to the surface production facility. This technology is a low profile 3-phase flow meter capable of reporting the volumetric or mass flow rates of water, oil, and gas in real-time.

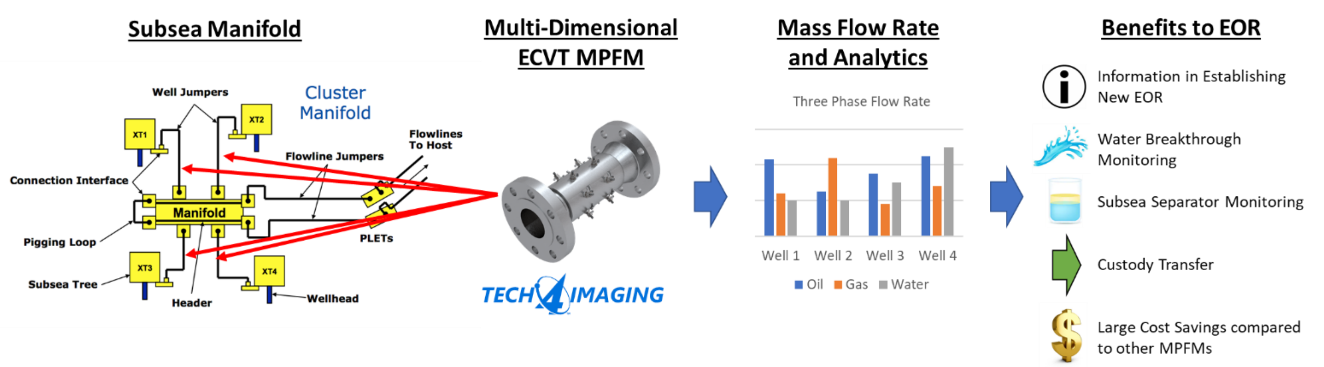


Figure 1: Value proposition of the multi-dimensional ECVT MPFM in EOR

1.2 Technology

This innovation is based on advanced multi-dimensional extensions of ECVT sensors that involve ECVT, Displacement Current Phase Tomography (DCPT), Maxwell-Wagner-Sillars polarization effect (MWS), and velocimetry which exploit the variation of electric properties between the oil, water, and gas coming out of the well. Capacitance sensors are embedded on the inside of a pipe spool and placed in-line with the subsea oil line piping on the extraction end of the well. The difference in dielectric, dielectric loss, surface polarization, and velocity of each phase are used in the multi-dimensional algorithm to measure the volume fraction, distribution, velocity, mass flow rate, and flow regime of the mixture moving through the pipe.

Prior to the award, early development had been completed on distinguishing three-phase mixtures in simulation and in static experiments as shown in Figure 2. The goal of the work done under this award is to advance this early development into dynamic applications in industrial environments.

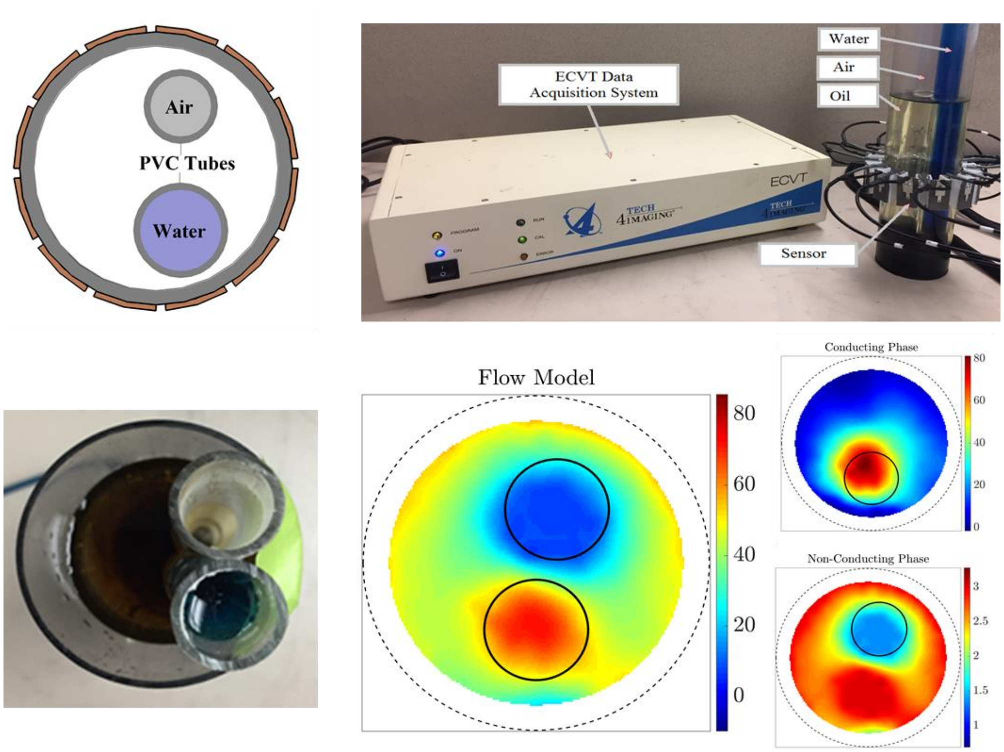


Figure 2: Static lab test of three phase mixture decomposition (oil, water, and air) using advanced ECVT

1.3 Objectives

1. Bring existing 3-Phase algorithm to flow loop testing
2. Develop algorithm for dealing with real world non-idealities such as sand, salt, and deposition.

3. Build subsea ready sensor package
4. Build subsea environment chamber and test unit in chamber
5. Certify for field use
6. Verify by third party separator on live oil well

2 What was accomplished under these goals?

2.1 Objective 1: Bring existing 3-Phase algorithm to flow loop testing

2.1.1 Build flow loop

The initial focus on this objective was to build a three phase flow loop for creating flow regimes similar to real world oil wells. The first stage of this project was focused on oil, water, and gas volume fraction changes to adapt and verify existing three phase decomposition algorithms into dynamic flow algorithms.

State of the art monitoring equipment has been chosen to provide the best possible verification methods for this new technology. Since no true three phase flow meter exists commercially for such an application, our design uses a two-phase Coriolis meter for measuring oil and water flow rates before gas injection. A separate single phase gas flow meter is used for gas prior to injection. The three phases are combined before the ECVT sensor and separated after. The gas is injected using a 125 PSI air compressor and oil and water each have dedicated single phase pumps.

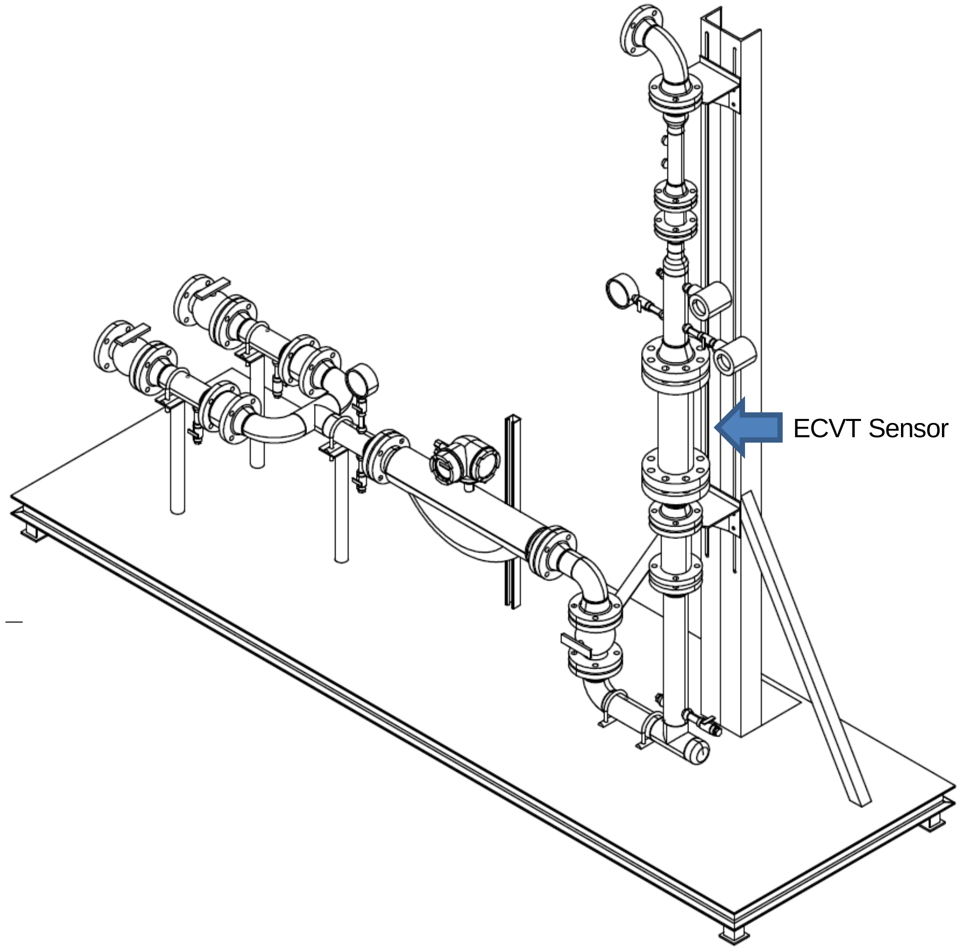


Figure 3: Multi-phase flow loop tower design by Accuflow

Tech4Imaging worked closely with Accuflow to develop an optimal design to fit in the required budget. Accuflow is a multiphase separator company with extensive experience in the oil industry and multiphase separation design. The multiphase flow loop design was completed as seen in Figure 3. The section shown above is designed to be connected to the liquid pumps and the separator to complete the system.

Tech4Imaging has been working for several years to develop in-house fabrication expertise and equipment to help streamline the prototyping and early fabrication process. Because of this effort we were able to reduce the cost of this unit by an estimated $15k-$20k. In house fabrication also ensured minimal issues and minimal cost/time for repairs or changes to the system.

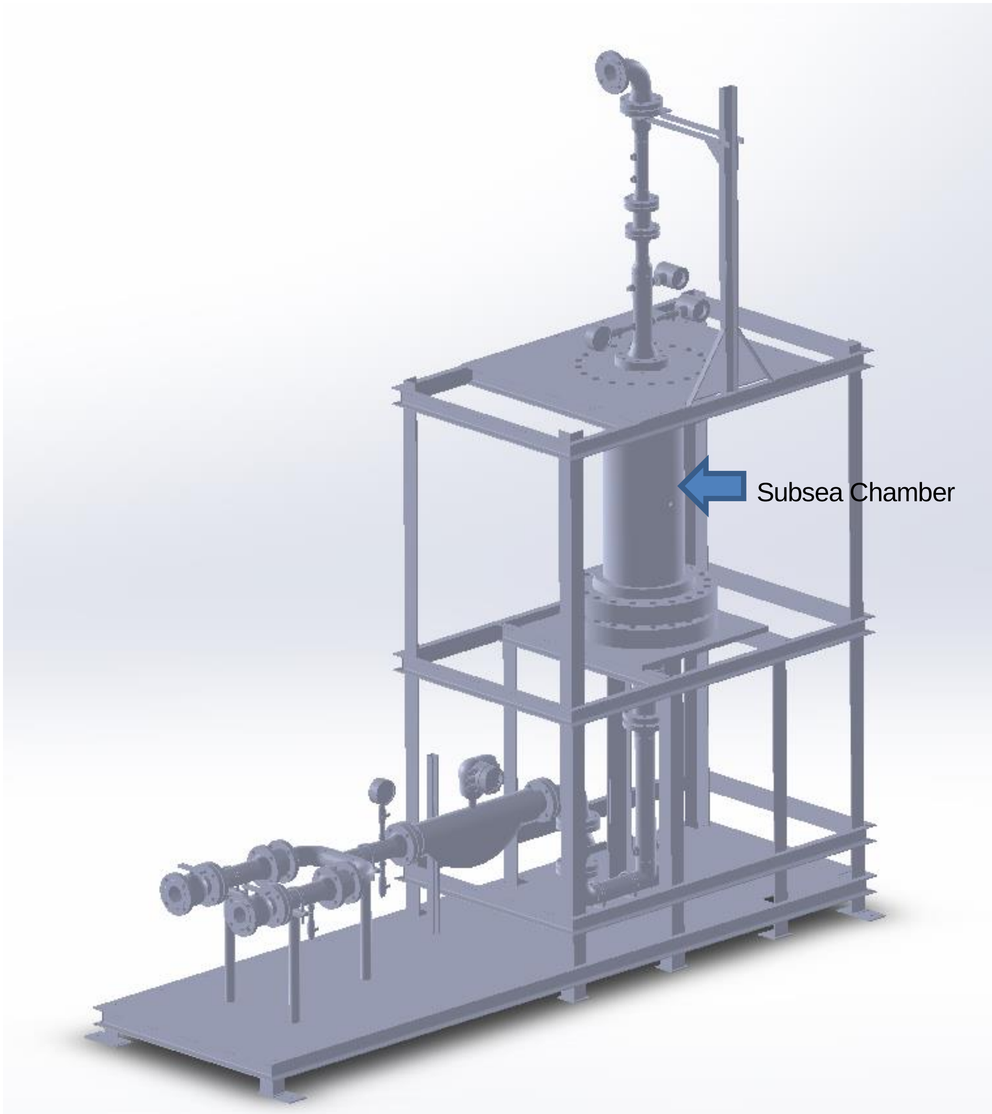


Figure 4: Flow loop model modified to accept the subsea environment chamber

Originally, the subsea environment chamber was going to be built as a separate unit from the flow loop and integrated in Phase II. We determined in order to save resources and time in the total project budget, we needed to design the subsea chamber and flow loop to be combined from the beginning. Because of this, we spent more time modifying Accuflow's flow loop design and the subsea chamber so that they could fit together. This proved to be a unique challenge due to the need for fluid to now flow through the center of the subsea chamber simultaneously while pressurizing it for subsea environment simulation. We finished the design work for the chamber to accommodate this need and have adapted the structural design for the flow loop to support the 1.5 ton subsea chamber in the vertical portion. The updated design can be seen in Figure 4.

We currently have built the flow loop as seen in Figure 5. The structure has been built to receive the subsea chamber. The sensor spool has been installed on the flow loop without an outer shell. This allows us to test many different sensor electrode configurations without the need to remove any part of the sensor spool or flow loop set up. This is one of the many advantages of the new sensor design which contains the pressure with a fiber wound plastic pipe rather than a metallic welded pipe.

The system has been pressure tested with gas up to 120 psi and examined for leaks using soapy water. All leaks were isolated and fixed. A controls system has been wired and programmed so that all of the instruments, pumps, and regulators can be run simultaneously. The system was run with water through both pumps to test for leaks and any flow problems. The system ran smoothly. L-HM46 Anti-Wear Hydraulic Oil was then added to the system and initial tests were run with a two phase system at low pressure to determine the ECVT performance without gas injection.

Figure 5: 3 Phase Flow Loop

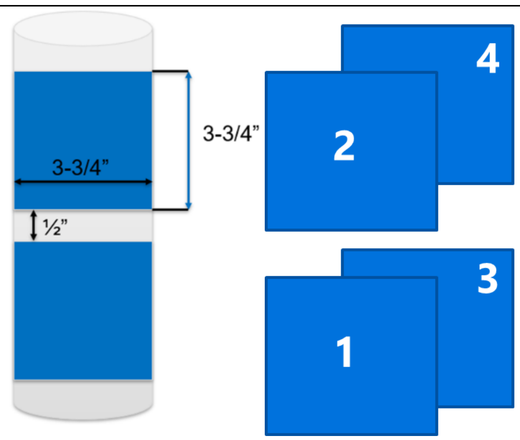
Finally, the entire three phase system was run at various gas volume fractions and watercuts. In general, the flow loop works very well and is able to reach a steady state flow within 5-10 minutes. However, after running the system for several hours, it can be difficult to reach very low (<5%) or very high (>95%) watercuts due to a lack of adequate residence time in the tank for complete separation. To accommodate this, the system must be allowed to rest periodically to let the fluids better separate.

Several companies were contacted to see if they could provide solutions to speed up the oil/water separating time to improve the ability to test high and low volume fractions. recommendations included a distillation column, oil/water filter separators, heating the tank and alternate baffle designs. The various options were analyzed, and it was decided that modifying the baffle design had the highest likelihood of success with the lowest cost. Based on recommendations from Accuflow we created a PVC pipe system that splits the returning mixed flow into 4 streams pointed at the back wall of the tank. 2 of the streams enter at the air-oil interface and 2 at the water-oil interface. This starts the separation process earlier and lowers the velocity of the fluid entering the tank, allowing it to separate more quickly. In addition, because the flow is directed away from the outlet, the mixed fluid should have more time to separate before it is pulled back out of the tank. This has had a significant improvement over the previous design, which dumped the liquid back into the top of the tank directly, causing mixing in the already separated layers.

The addition of the PVC pipe system improved the overall performance of the system. Steady state flow is typically achieved within 3 minutes of running the system at any given water cut and the system separates much more quickly.

2.1.2 Sensor electrode design

Initial testing was done with a four plate sensor in a 2x2 configuration in which there are two electrodes directly across from each other with the pipe in the middle and two electrodes identically arranged directly beneath the top two as described in Figure 6. To protect the electrodes from room interference, a copper grounding shield was placed around the electrode plates. Tests were performed to ensure that the copper grounding was placed far enough away from the plates that it did not create excessive parasitic capacitance with the sensor plates, which could lower the SNR. The stabilized NEMA 4 DAS was utilized to collect the data to minimize drift due to temperature fluctuations in the electronics. This is the DAS that is being converted into a C1D1 certified DAS for field use in Phase II.



2x2 Parallel Plate Configuration

2x4 Cylindrical Plate Configuration (showing one half of a clam shell design)

Figure 6: Layout of electrode plates used for different sensor designs

After initial testing, we wanted to improve upon the sensor design to achieve more linear data for two and three phase flow as well as make the mechanical assembly easier to achieve in the final product. We thus adapted the sensor into a 2x4 electrode plates design which conforms to the circumference of the pipe section. From a mechanical perspective, this configuration is easier to assemble because it can be printed on a flexible PCB and wrapped in place compared with flat electrodes which would need a more sophisticated mounting system and may be more difficult to fit inside a cylindrical outer shell. From an electrical perspective, this electrode configuration provides more information (more plates) and is closer to the original simulations run for three phase mixtures. The clam shell design in Figure 6 shows a 3D printed version of the sensor that can easily be transferred to a flexible PCB design.

The 3D printed sensor design was identified as a possible source of drift due to the thermal expansion and contraction of the plastic. A new sensor design was investigated that would rigidly mount copper plates to the PEEK spool. This new design included the addition of a platinum RTD at the sensor plates to allow better thermal compensation of the sensor itself.

A new 2x4 cylindrical plate configuration sensor was rigidly mounted onto the PEEK as shown in Figure 7. In addition, an RTD for temperature measurement was attached to the PEEK. Cable shielding from the sensor to the DAS was improved so that all coax cables are shielded as they exit the sensor shell as shown in Figure 8 and the system ground was upgraded to reduce overall system noise. Results of the overall grounding and shielding changes are shown in Table 1.

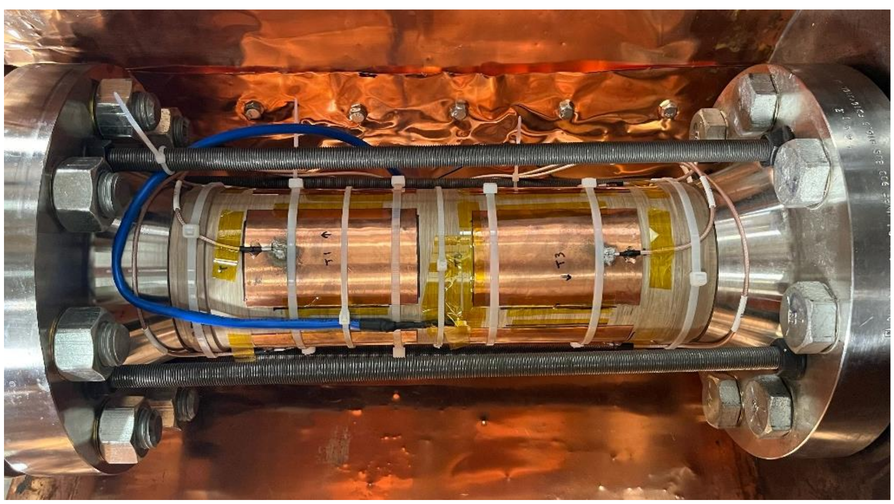


Figure 7: PEEK sensor with plates and RTD attached

Figure 8: Sensor cable shielding and ground braid

Table 1: Comparison of electronic noise before and after groudning the sensor

Standard deviation of Signal Magnitude	
Pre-Grounding	Standard deviation = 386.39
Added a system ground to the flow system	Standard Deviation = 231.79
Connected the sensor shield to the DAS	Standard Deviation = 221.56

2.1.3 Two phase flow tests

The flow loop, sensor, and DAS were used to conduct two-phase testing with oil and water. Two phase testing was done prior to three phase testing to establish a baseline performance on the simpler problem. Early tests showed low repeatability. Upon inspection of the problem, the DAS was determined to be the primary issue. Low thermal stability and coarse amplification steps limited the DAS's performance. This is because the DAS was borrowed from a lab imaging product developed at T4I and was never optimized for long term stability in industrial environments. Typically the DAS is calibrated at the time of use. Upon making this identification, the DAS was redesigned and streamlined for flow measurement. This made the design cheaper, leaner, and more stable than the lab grade imaging DAS. Details of this development are discussed in sections 2.2.6 and 2.2.7

Once the new DAS was built and tested, two phase flow loop testing was performed again with great improvement in repeatability. The flow loop was capable of stabilizing different flow rates from 0 to 100% watercut in oil/water flow at 4000 bbl/day. Two flow regimes were identified that created different sensor responses: oil continuous and water continuous. **Error! Reference source not found.** shows how the flow regimes affect the capacitance signal. In oil continuous, the capacitance signal increases very linearly as the watercut increases. This flows regime exists between 0% and 15% watercut. Between 15% and 30% watercut, there is a transition region in which the system may fluctuate between each flow regime. Between 30% and 100% watercut, the flow regime is water continuous. In the water continuous flow regime, the signal is highest at lower watercut and approaches a similar signal level as the 0% watercut point. This relationship is approximately 1/X.

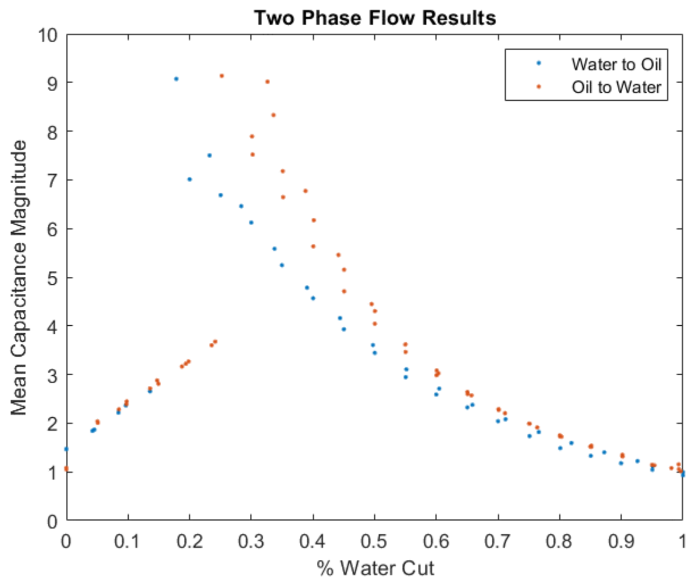


Figure 9: Capacitance Magnitude going oil to water or from water to oil.

When the phase of the capacitance signal is measured, there is an obvious delineation between the phase of oil continuous and water continuous flow regimes as shown in Figure 10. The phase of the oil continuous flow regime is negative and does not respond to a change in watercut. This is because there is no change in conductivity in the continuous medium. However, once the flow becomes water continuous, the phase becomes positive and is responsive to volume fraction with a 1/X relationship like the capacitance magnitude. This predictable change in phase makes it possible to know which relationship to apply to the capacitance magnitude for determining the watercut.

Another behavior that was observed in the capacitance data was a hysteresis that appeared when the system was incrementally stepped up in watercut from 0% to 100% compared to stepping in the opposite direction from 100% to 0%. The hysteresis was highly repeatable and affected the water continuous measurement primarily. It also affected the range of watercut in which the transition flow regime occurred. The 0% to 100% watercut case has a higher watercut at which the transition occurs. This is shown in **Error! Reference source not found.**. This phenomena is thought to be an effect of residual oil clinging to the pipe walls and changing the fluid behavior. In both cases, the oil continuous section retains the same linear correlation between watercut and capacitance magnitude and the water continuous section converges to a similar value at 100% watercut.

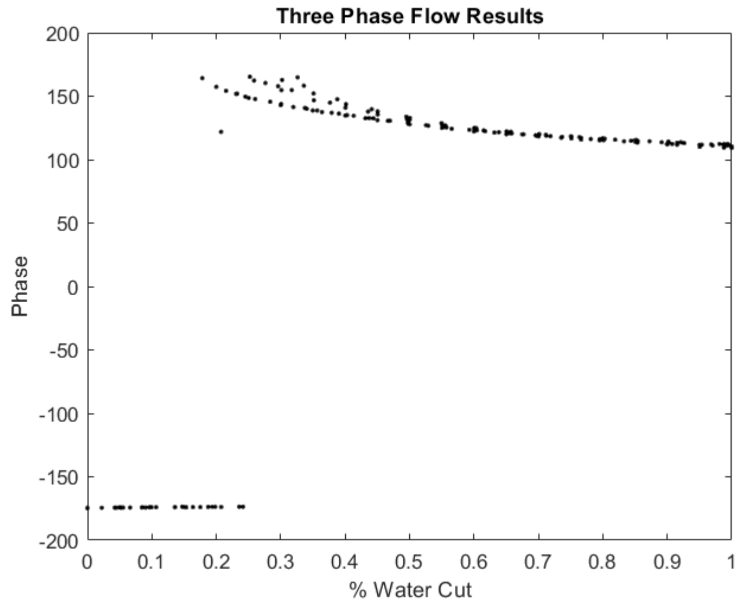


Figure 10: Phase response of a two phase flow across watercut

A fit was applied to the capacitance data based on **Error! Reference source not found.** after determining if the flow was water or oil continuous according to Figure 10. The resulting error in watercut when compared to the Coriolis is shown in Figure 11. The error is below 5% for watercut across all watercut when steps are taken from 100% to 0% watercut. However, the error is higher in the transition region when stepping from 0% to 100% watercut due to the hysteresis. Error is largely below 2% in the oil continuous region for both stepping directions.

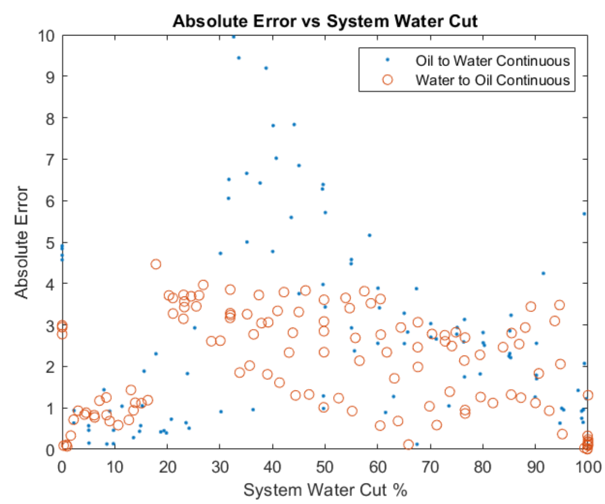


Figure 11. Absolute error when going from oil continuous to water continuous and water continuous to oil continuous

2.1.4 Three phase flow tests

Once a baseline performance of watercut measurement in two-phase flow was established, we introduced gas into the flow to create a three-phase flow. Gas was injected into the system using a 120 PSI air compressor and a flow controller. The injection occurred downstream of the Coriolis meter so that the Coriolis measurement was unaffected. The three-phase flow loop was capable of modulating the gas volume fraction (GVF) from 0% to 67% while also modulating the watercut from 0% to 100%. The 67% GVF limit was when the liquid was run at 4000 bbl/day. The same algorithm was used for three-phase flow as two-phase flow. A similar performance was achieved as shown in Figure 12 and Figure 13. This shows the robustness of the watercut measurement against the introduction of gas. This is a large improvement upon the gold standard in the industry – the Coriolis – because Coriolis is notorious for high errors once small amounts of gas are introduced.

The highest accuracy is still in the oil continuous flow regime and the lowest accuracy is in the transition region from oil continuous to water continuous. The transition watercuts are still very similar to two-phase and the hysteresis effect was still present.

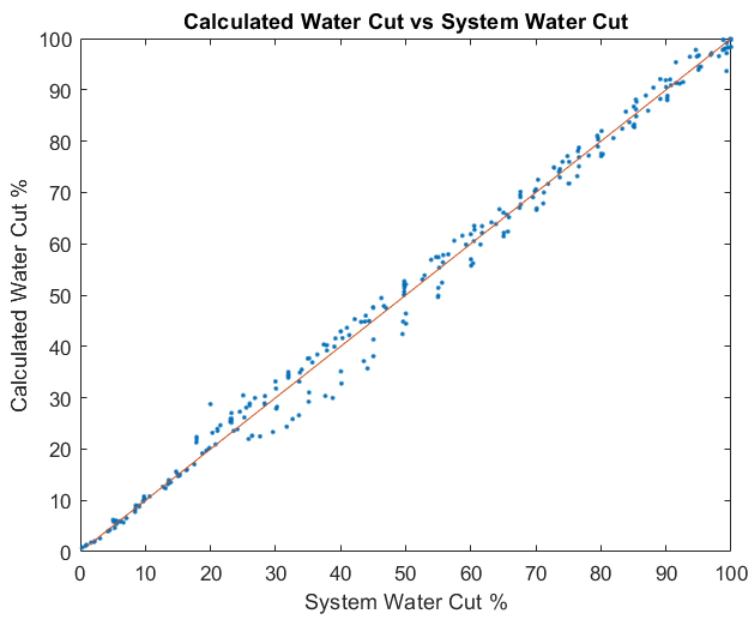


Figure 12: Calculated water cut vs. Actual System water cut

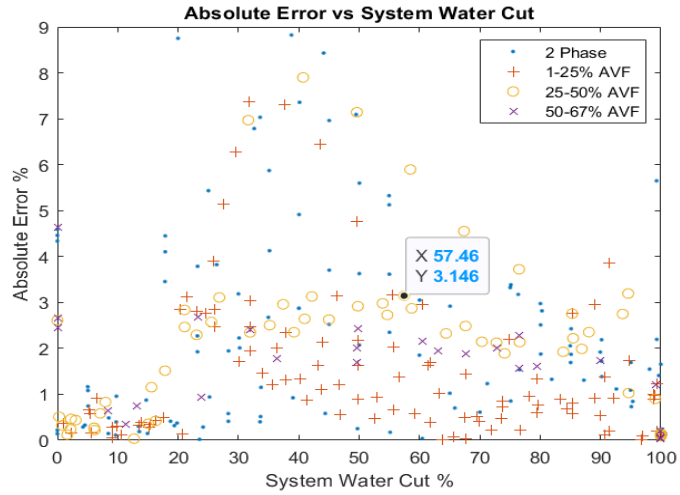


Figure 13: Absolute Error of the Water Cut measurement vs. System Water Cut at differing Air Volume Fractions

To give a visual depiction of the absolute error of the water cut in an Oil/Gas/Water mixture the ternary plot in Figure 14 was created. This plot shows the location of the transition region (yellow) in the three phase mixture, and demonstrates that gas volume fraction is not related to higher error up to 60% GVF at 4000 bbl/day.

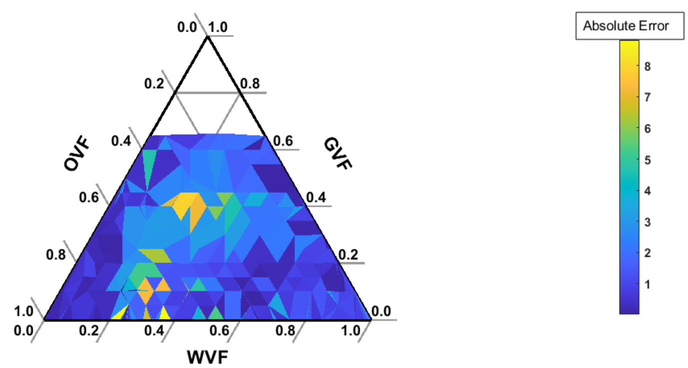


Figure 14: Ternary plot of the absolute error of watercut for each experimental data point on the three-phase flow loop running at 4000 bbl/day of liquid.

Installing the sensor and field verification testing at a Kern County Ca. oil well in cooperation with Accuflow was completed December 4th through December 8th 2023 and the details are presented in section 2.6.

During the Kern county test, we encountered gas volume fractions higher than our in house flow loop had reached (up to 99%). This difference revealed a discrepancy in our in house calibration and the field conditions. After testing at the Kern county test site, additional tests were run on the in-house flow system to try and achieve higher GVF. The liquid flow rate was reduced to 400 bbl/day to allow for higher GVF. A series of tests were conducted up to 95% gas volume fraction. To be able to achieve greater than 90% GVF, the liquid flow had to be decreased to a point where there was not good mixing. Good mixing is an assumed part of the current algorithm. A static mixer exists in the vertical flow pipe just before the ECVT sensor to assist in homogenizing the mixture. At low flow rate and low pressure, the assumption starts to break down and we see some higher error introduced. Figure 15 shows the results.

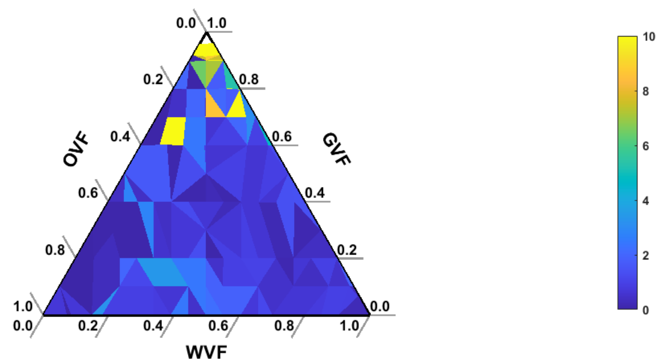


Figure 15: Ternary plot of three-phase flow loop watercut error at 400 bbl/day reaching 95% GVF

2.2 Objective 2: Develop algorithm for dealing with real world non-idealities such as sand, salt, and deposition.

2.2.1 Salinity

The Ohio State University was subcontracted to determine a method for dealing with high salinity concentrations which can reduce the effective capacitance signal. This research also focuses on developing a method to measure three phase flow accurately under variable salinity conditions. We developed a simulation that shows strong evidence for water dispersed flows that our algorithm can accurately report the three phase volume fraction of air, oil, and water in a mixture regardless of the salinity level. The simulation setup is shown in Figure 16.

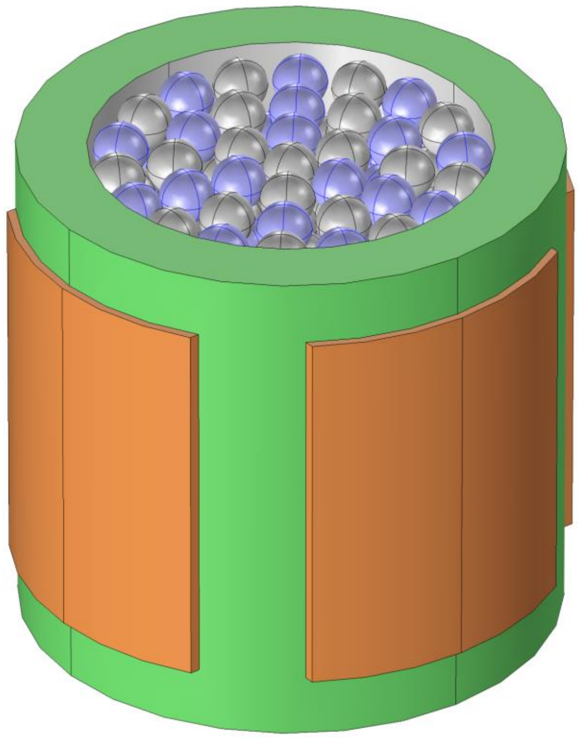


Figure 16: Simulation set up for three phase water dispersed salinity variation simulation. Green is dielectric pipe, copper is capacitance plates, blue is water droplets, grey is gas bubbles, background phase is oil.

The salinity was varied from tap water to saturation level of salinity with volume fraction of air and water ranging from 0 to 17% each dispersed in oil. As shown in Table 2, Table 3, and Table 4, the correlation between the calculations in simulation and the actual values are very tight across all salinities. This shows great indication that for water dispersed mixtures, the measurements will not be affected by salinity levels.

Work was completed focusing on simulations for varying salinity levels in water continuous flows, which is a more difficult challenge. An algorithm has been developed that will adjust the volume fraction calculation based on the input from an external salinity sensor or periodic sampling. This should allow for maintained instrument accuracy over the lifetime of wells.

Table 2: Three phase water dispersed volume fraction of water simulation results

<table>
<tr><th>Actual v Calculated</th><th>Error Plot</th></tr>
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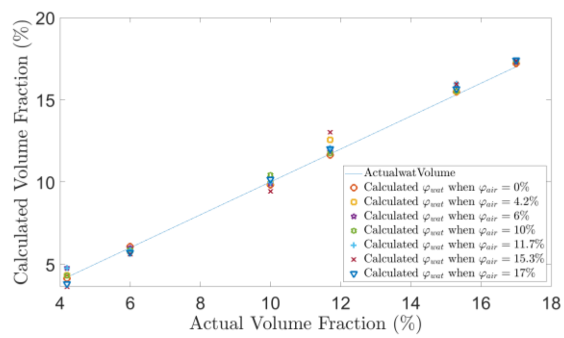
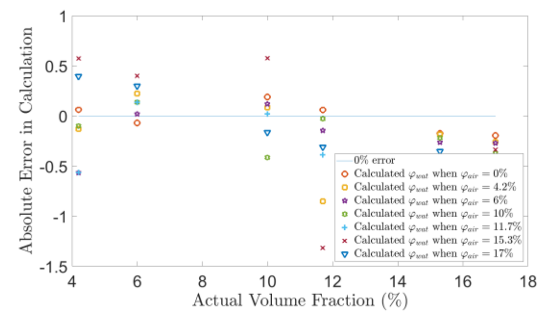
<tr><td>
</td><td>
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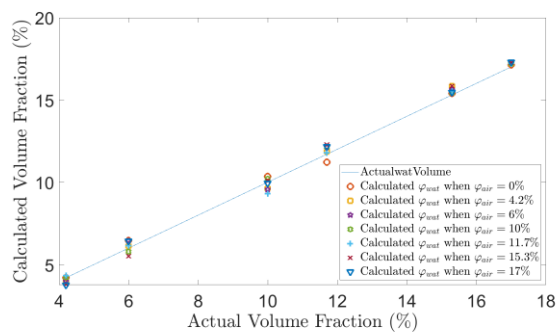
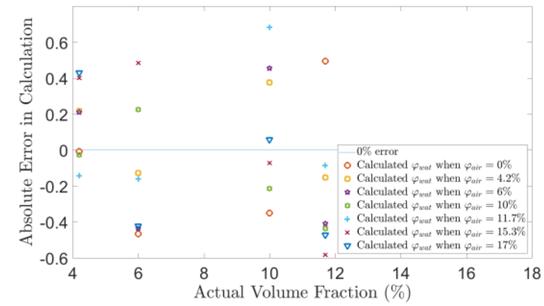
<tr><td>
</td><td>
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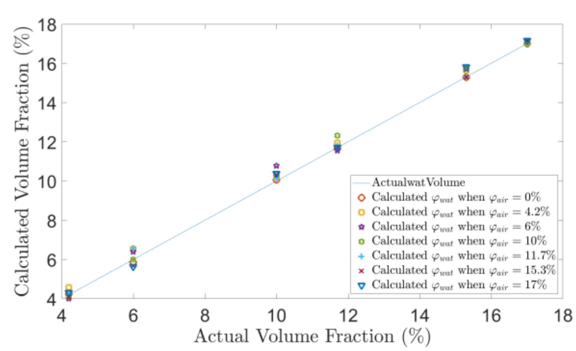
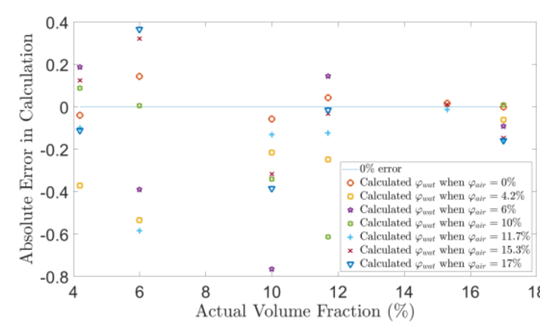
<tr><td>
</td><td>
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<tr><td>Three Phase Water Volume Fraction</td><td>Salinity 100 ppt</td></tr>
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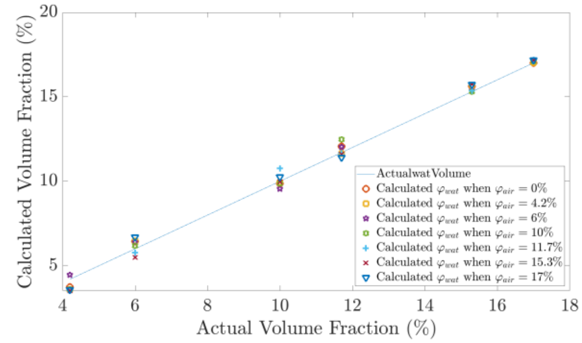
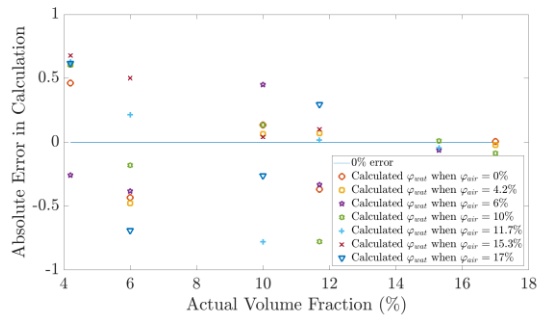
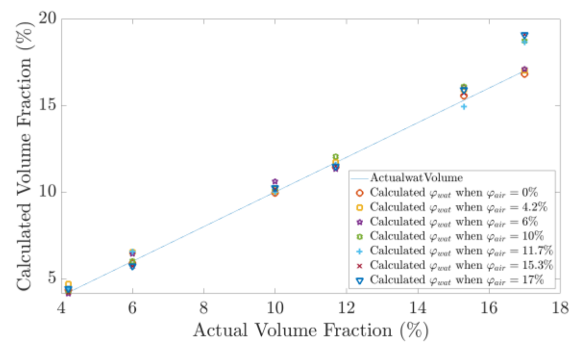




Three Phase Water Volume Fraction | **Salinity 250 ppt**



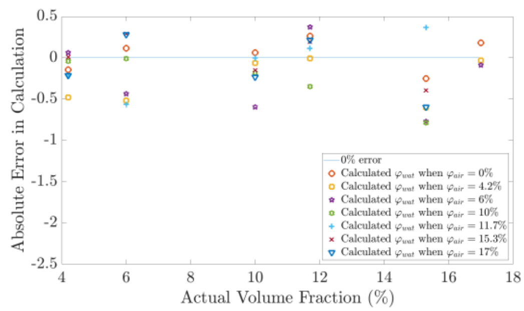
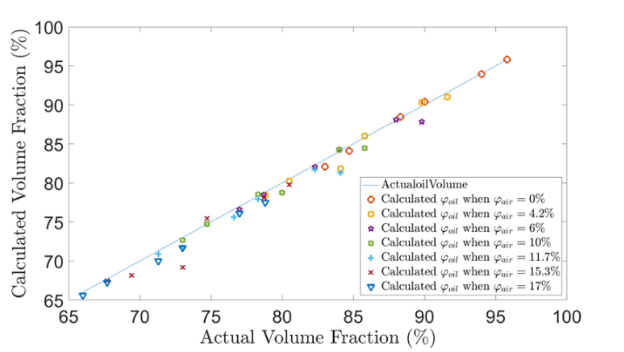
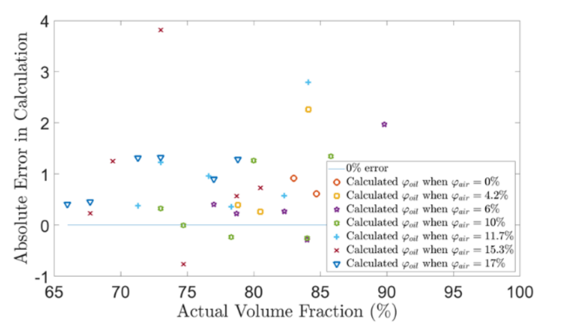


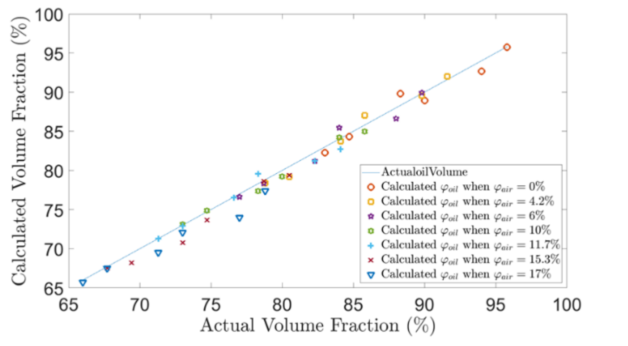
Table 3: Three phase water dispersed volume fraction of oil simulation results

Actual v Calculated	Error Plot
Three Phase Oil Volume Fraction	**Salinity 0.03 ppt**

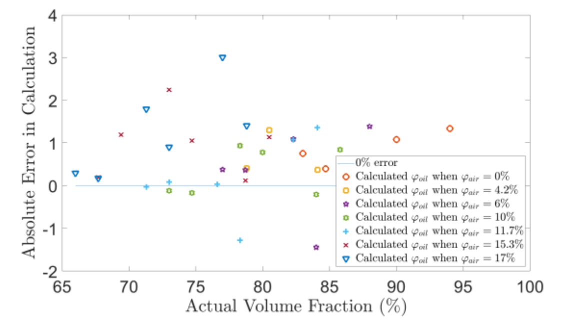




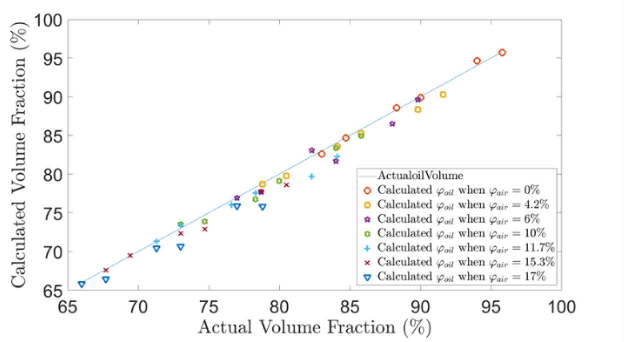
Three Phase Oil Volume Fraction | **Salinity 1 ppt**



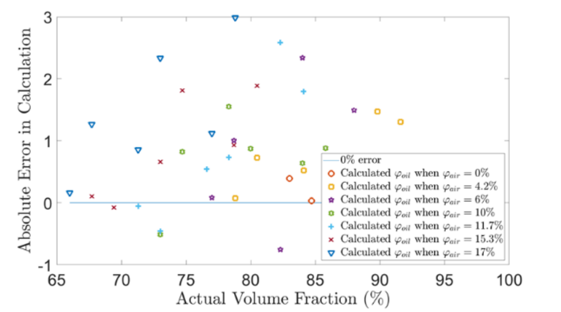
Three Phase Oil Volume Fraction



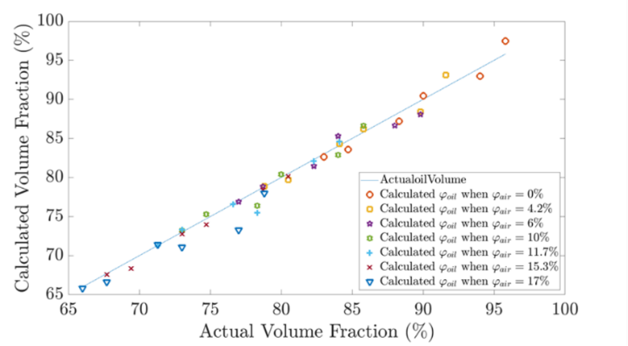
Salinity 33 ppt



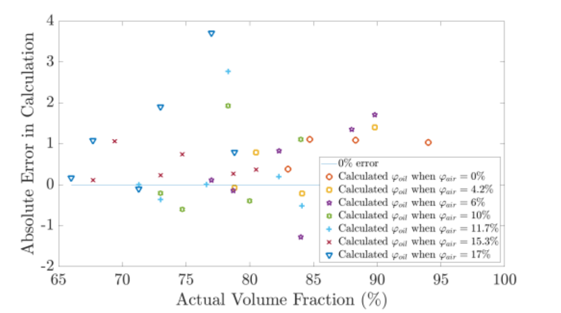
Three Phase Oil Volume Fraction



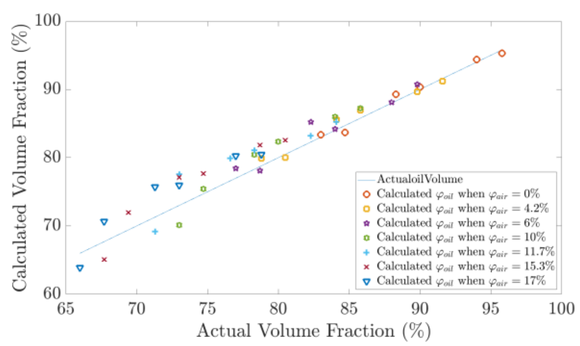
Salinity 100 ppt



Three Phase Oil Volume Fraction



Salinity 250 ppt



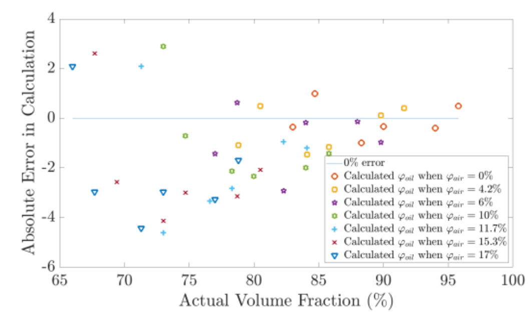
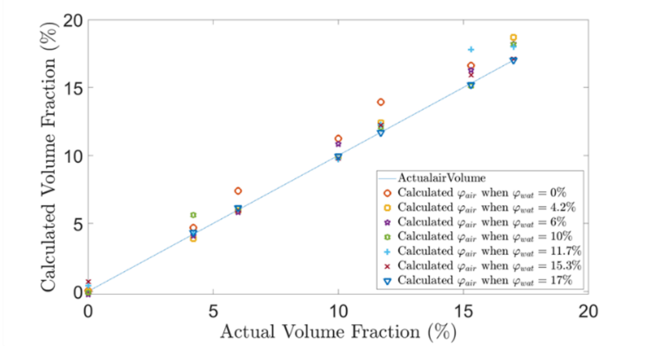
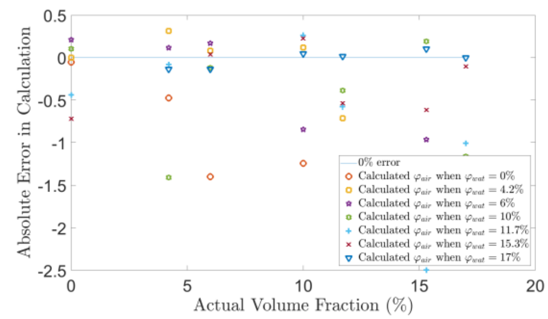


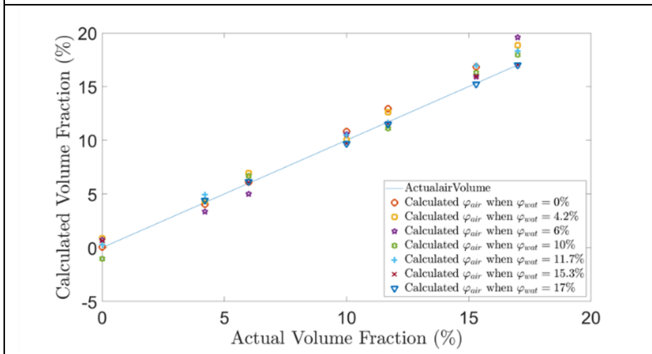
Table 4: Three phase water dispersed volume fraction of air simulation results

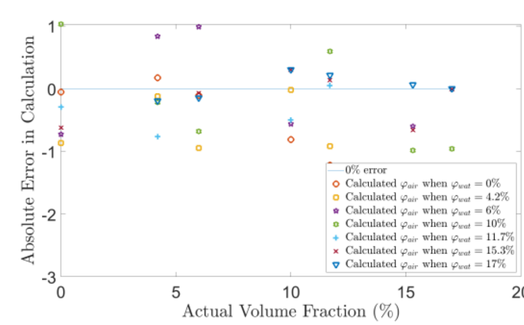
Actual v Calculated	Error Plot
Three Phase Air Volume Fraction	**Salinity 0.03 ppt**



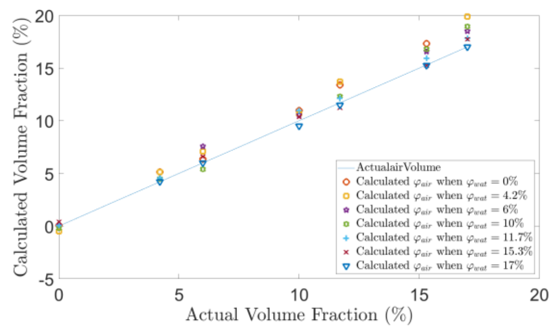


Three Phase Air Volume Fraction	**Salinity 1 ppt**

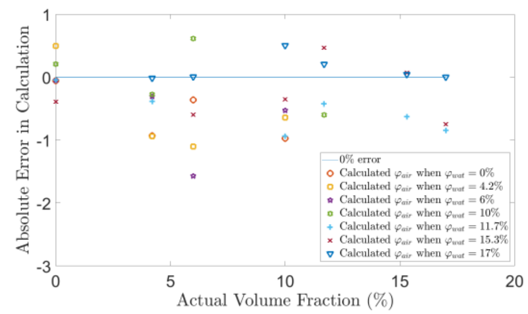




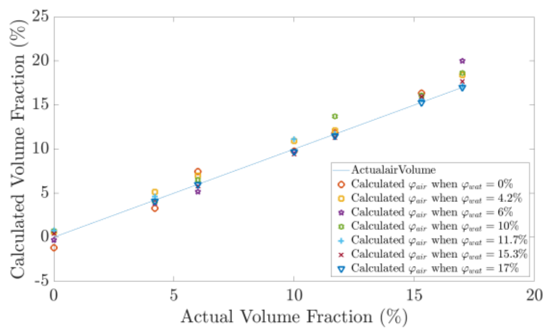
Three Phase Air Volume Fraction	**Salinity 33 ppt**



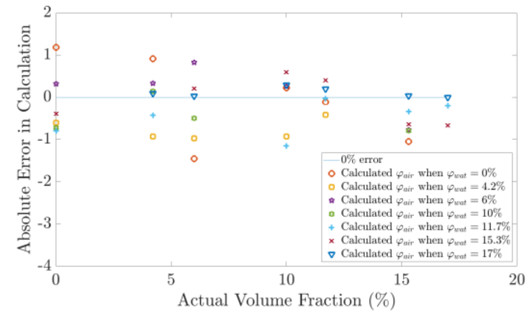
Three Phase Air Volume Fraction



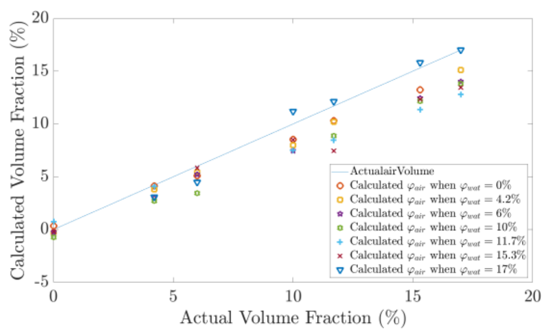
Salinity 100 ppt

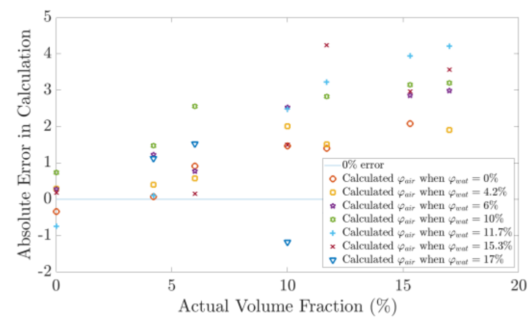


Three Phase Air Volume Fraction



Salinity 250 ppt





The next section shows results from experiment on temperature and salinity effects on the capacitance signal. Water salinity levels up to 300ppt were tested using an ECVT test fixture. The results of these tests confirm that water salinity will have an effect on the volume fraction calculation in the water continuous phase. An algorithm incorporating simulation and test data can be created with inputs of water cut and salinity to correct for all possible combinations.

A test fixture was constructed to measure the effect of various salinities and water temperatures on instrument output, seen in

Figure 17.The fixture is capable of being filled with different fluids at different temperatures and volume fractions. An external scale, conductivity sensor, dielectric constant sensor, heater and internal RTD are included to control for different temperatures, salinities and volumes of water. We will be taking measurements for various salinities at various temperatures in order to determine the effect of salinity on our sensor output. The dielectric constant of saline water is well studied, so this provides an opportunity to compare our instrument dielectric constant readings to literature, as well as build a model to compensate our output for various salinities.

In addition to the 2x4 plate configuration an extra row of 4 helical plates was added for fill and drain testing comparison between the 2 plate configurations. This new test sensor will be used for determining fluid temperature effects and water salinity effects on the measurements.

Figure 17 Improved Test Fixture

Testing was performed using the test fixture shown in

Figure 17 to determine the effects of varying salinity and temperature on the capacitance magnitude. The DAS used for testing did not have a temperature input for monitoring the sensor temperature. To accommodate this the DAS and the sensor were put into the thermal chamber together and a baseline run was completed to correct for temperature. The initial run with air as the medium is shown in **Error! Reference source not found.**.

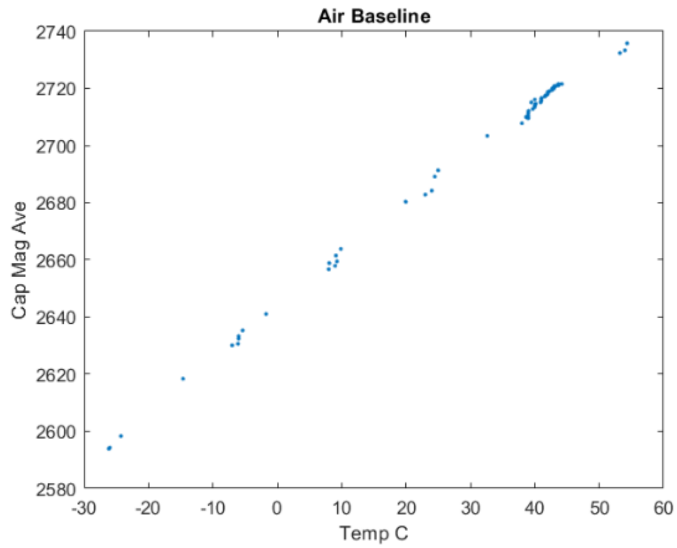


Figure 18. Baseline Air data with Thermal Chamber going from -30 to 50°C

The results from the air baseline were used to generate a temperature compensation algorithm. **Error! Reference source not found.** shows the results of applying the algorithm to the air dataset.

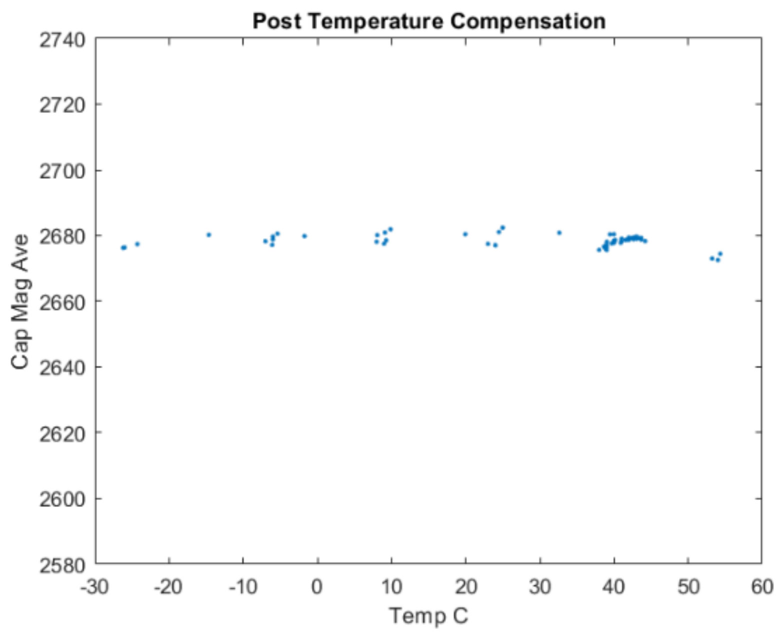


Figure 19. Baseline Air data with applied algorithm

To prevent evaporation of water during the thermal cycling a seal consisting of aluminum foil and a hose clamp was applied to the top opening of the test fixture during each test cycle. A variety of salinity concentrations were tested along with distilled water and are shown in **Error! Reference source not found.**.

Table 5. Salinity Concentrations

Date	Initial Weight (grams)	Added Salt Weight (grams)	Final Weight (grams)	Approx. Salinity (ppt)
10/26/2023	989.7	25	1012.6	25.26
10/27/2023	1009.9	25.1	1034.1	50.62
10/30/2023	1032.2	150.4	1181.8	202.6
10/31/2023	1180.3	100.1	1278.9	303.7
11/1/2023	1000	0	1000	0
11/2/2023	994.5	1.02	995.1	1.26 (measured)
11/3/2023	992.1	24	1015.3	24.2

Each test was started at room temperature and increased to 50°C with a 1.5 hour soak at 50°C. After this the chamber was run through a series of setpoints going from 50°C to 35°C to 20°C to 5°C to 20°C to 35°C and back to 50°C with a 1.5 hour soak at each temperature. The resultant capacitance magnitude for each test run is shown in Figure 20 **Error! Reference source not found.**. From this figure you can see the large shift from distilled water to 1 ppt saline water. Assuming that any ground water is going to contain some level of salts then the distilled water data can be excluded for the determination of a correction algorithm. **Error! Reference source not found.** Figure 21 shows a surface plot with the temperature in Degrees C on the X axis and Salinity on the Y axis in ppt with the Z axis being the capacitance magnitude.

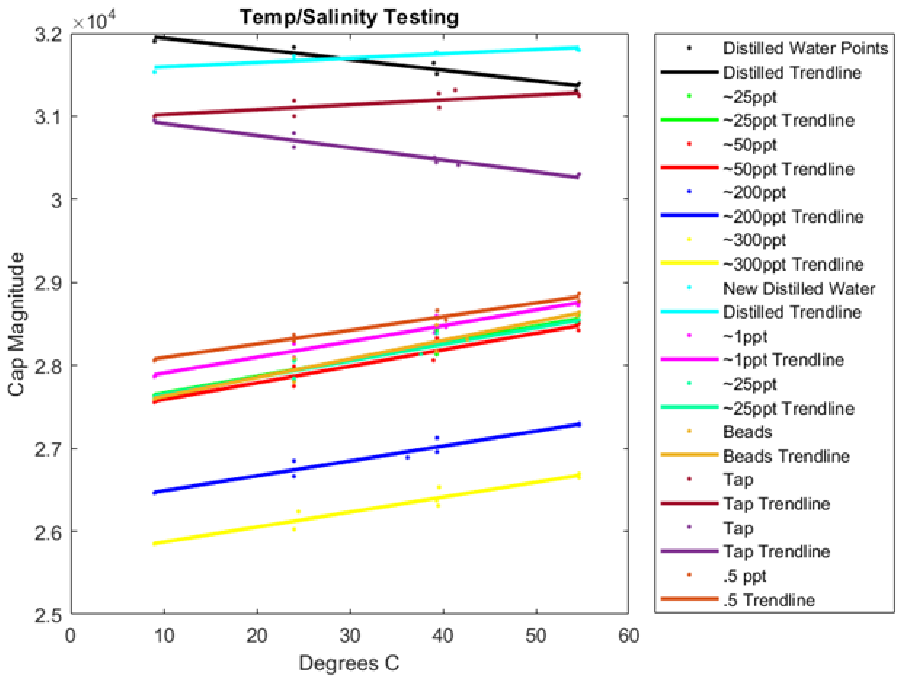


Figure 20: Capacitance Magnitude vs. Temperature at Varying salinities

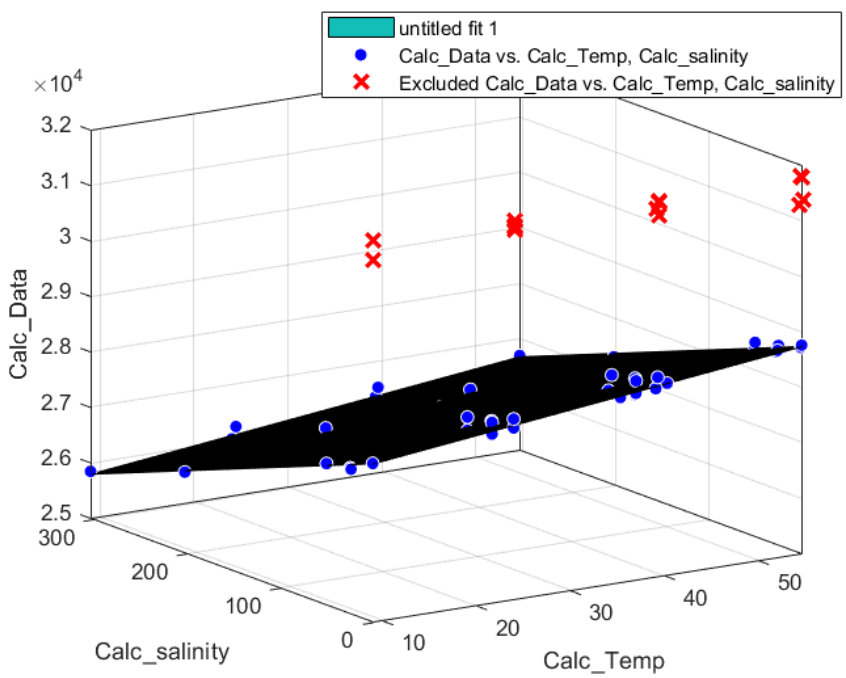


Figure 21: Salinity and Temperature Correction Curve Fit

2.2.2 Oil Quality Change

One likely scenario in the field is that we will encounter different qualities or types of oil. The main difference between all these oils (other than impurities) is the oil density. To determine how this might affect our measurement, we performed a test using oils of four different densities by simply filling the sensing region of an ECVT sensor with each oil. As shown in Figure 22, the oil density is directly related to the signal amplitude from the ECVT sensor. More work must be done to determine how to account for this in our measurements. The trend for fossil fuel oils is similar to that found in Figure 27.

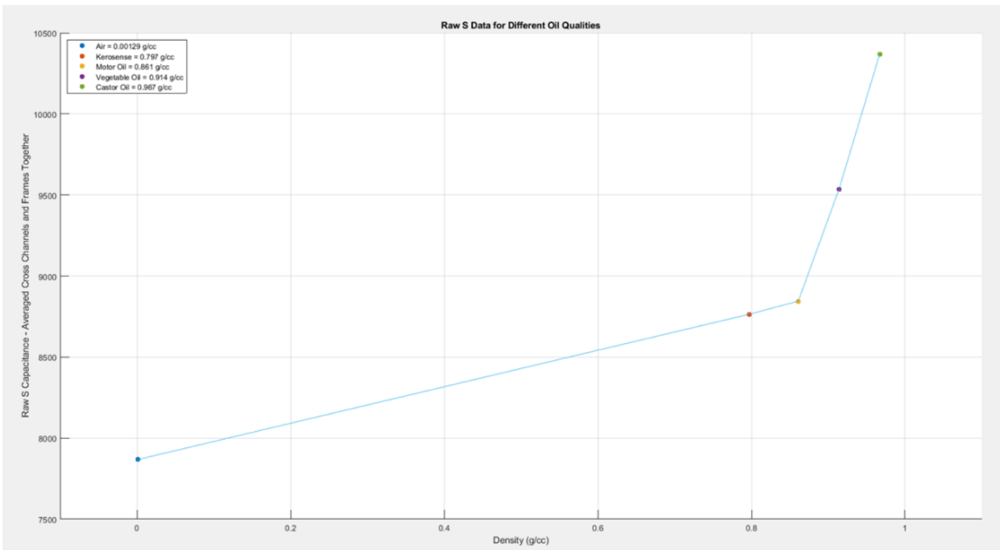


Figure 22: Density of oil compared to capacitance signal amplitude from ECVT sensor

2.2.3 Oil Scaling

A known phenomenon in oil pipes is the hydrocarbon scaling on pipes caused by cold temperatures and high pressures. This scaling is likely to close the effective cross section of the pipe and throw off the ECVT readings if unaccounted for. We started to investigate how this would affect our signal and how it might be mitigated. A 12 plate single layer ECT sensor was used to generate images from jars filled with oil which had different thicknesses of wax along the edge as shown in Figure 23 and Figure 24. The results indicate that the difference can be seen in reconstructing the image of the sensing domain. It may be possible to use a velocimetry measurement in dynamic tests to indicate where the oil is moving and the wax is stationary. We can then adjust the effective cross section being used in the global mass flow measurement accordingly.

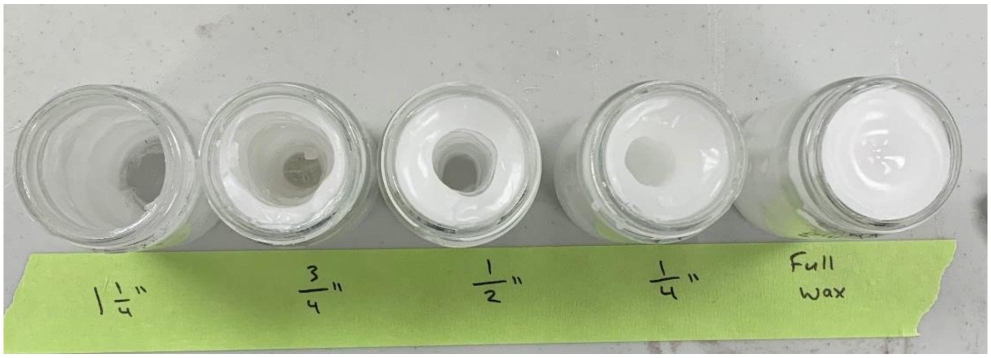


Figure 23: Wax scaling thicknesses

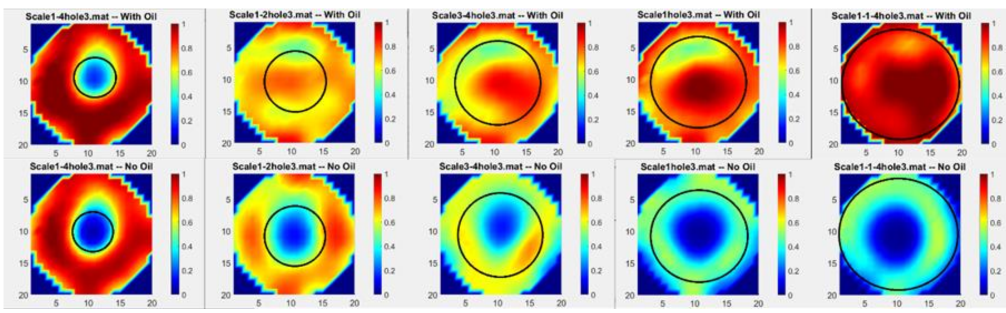


Figure 24: Image reconstruction of the wax filled jars from left to right columns showing ¼" hole, ½" hole, ¾" hole, 1" hole, and 1 ¼" hole in the wax. The top row represents the hole filled with vegetable oil and the bottom row represents the wax without oil.

2.2.4 Solids Content

Before introducing solids into a two or three phase flow, thus creating a complex four phase flow, we designed and built, in house, a gas-solid flow loop to study the response of the ECVT sensor to solids passing through the sensing region. The flow loop consists of a 3" diameter pneumatic section in which the solids are conveyed by vacuum from the bottom hopper into the top hopper and a gravity drop section in which the solids fall from the top hopper directly into the bottom hopper. The flow loop took many iterations to properly get the solids to settle out of the pneumatic portion of the loop and into the top hopper, but we were eventually successful. Designing and building the flow loop in house saved upwards of $60,000 for the project compared to outside quotes. The final working loop can be seen in Figure 25.

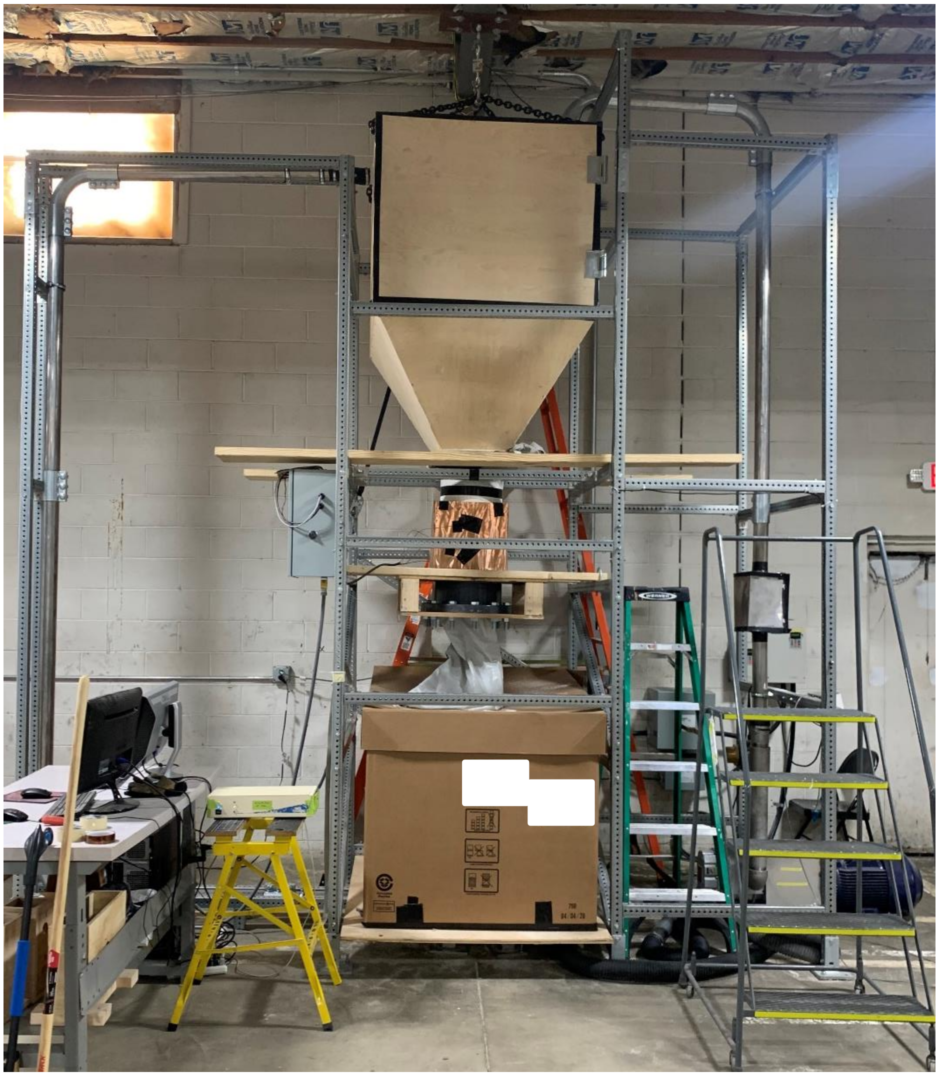


Figure 25: Gas-solid flow loop for studying ECVT mass flow measurement of solids content.

We filled the test loop with a polymer solid and set up an ECVT sensor in the gravity drop portion. The top hopper was suspended from a digital weigh scale to measure real-time loss in weight measurement as the solids flowed from the top hopper to the bottom hopper. This set up was instrumental in determining the optimal plate geometry and configuration for the ECVT sensor. We tested various numbers of plates and geometries which produced varying sensitivities to different regions of the flow. For instance, one geometry might over emphasize the signal from the edge of the sensing region compared to the center, thus making different flow regimes produce different mass flow measurements. To mitigate this variation, we developed a sensor designed to produce homogeneous electric field through the entire flow region. The results of one of the tests with this sensor configuration can be seen in Figure 26. The accuracy is within 0.5% relative error of total mass flow and the system closely tracks the weigh-scale through time.

The results from this test influenced our design for the two and three phase tests and will be considered when moving to combine solids into the three-phase flow.

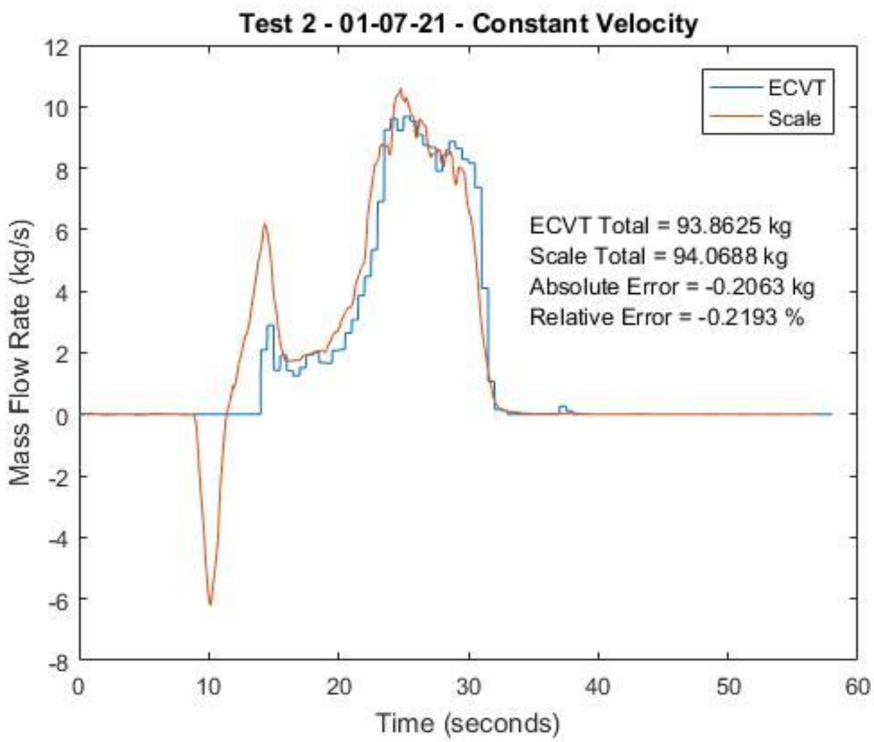


Figure 26: Mass flow results of ECVT for gas-solid flow compared to a loss-in-weight scale measurement.

2.2.5 Testing additional variables on the flow loop

Scale and wax deposition on the walls can be simulated by adding inserts on the inside of the pipe in the sensing region and running the same two and three phase tests with different thicknesses of inserts. While the effect of scale build up was tested in a bench test (see section 2.2.3), the effects were never tested on the large scale three-phase flow loop. This is recommended for future development.

The cost of filling, disposing, and cleaning the flow loop after testing with salinity was much higher than first anticipated and became prohibitive especially after COVID 19 and recent inflation. A new method of testing in dynamic flow is recommended to be developed for future testing. For this current development, we relied on static testing, simulation, and field testing.

Oil quality may not need to be tested on the flow loop because the main factor that would change signal based on different oil types is the oil density. The oil density changes linearly with the dielectric constant of the oil as seen in Figure 27. Thus, if the dielectric constant is increasing, our capacitance signal would increase because there is more oil in the sensing region.

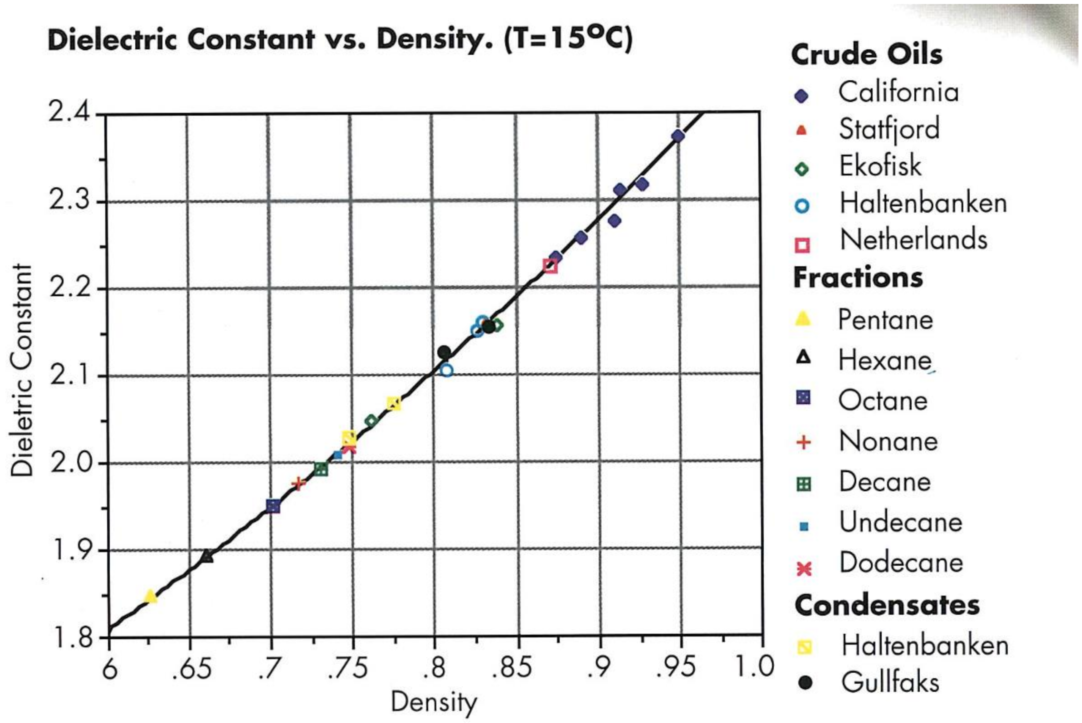


Figure 27: Oil density and dielectric constant (received from Accuflow)

With the help of Accuflow, we have surveyed the available cases to us for the amount of solids content that could be present in the flow in the field. In many cases, a solids filter is required up line of industrial equipment and instrumentation to reduce wear. We estimate for non-fracking situations that the amount of solids in the line would be 650-1000 mg/L. This is substantially insignificant when compared to the quantities of oil, water, and gas we are measuring. Thus dealing with solids in the line can be accomplished by requiring a solids filter upstream of the three-phase flow meter to remove the amount of solids below the sensitivity level.

2.2.6 DAS Thermal Stability

Early in 2022 it was determined that the thermal stability of the electronics needed to be improved. A change in operating temperature such as the room temperature could cause a drift in the data as much as +-8% over an interval of 50°C. With this range of temperature swing being highly likely in the field, we sought to improve the drift qualities of our electronics. We have concluded these upgrades which included a combination of hardware component changes, PCB reworks, heat sink additions, and live temperature compensations based on temperature sensors implanted in the hardware. We recently achieved a milestone in which the drift was restrained to +-0.5% over the same temperature range.

Full implementation of temperature compensation will require a temperature vs signal drift curve for both the DAS and the sensor. After many rounds of testing and controlling for variables like RF noise and humidity changes, the procedure for collecting the temperature curves has been standardized for both the DAS and the Sensor. Efforts have been completed to automate this process to allow it to run without an operator and to automatically implant the curve coefficients in the sensor firmware during the factory calibration stage. Figure 28 shows the uncompensated DAS drift in solid lines for each channel and compensated DAS drift in dashed lines for each channel. Implementation of this example algorithm reduced the drift error by up to 5% of full scale, significantly improving accuracy. Signal temperature drift during flow loop testing was identified as a source of error during initial testing and the implementation of the temperature compensation algorithm is a critical milestone before we resumed flow loop testing and algorithm verification.

Platinum RTD's have been selected as a temperature sensor that can be mounted alongside the capacitance plate in the ECVT sensor. This will allow us to temperature compensate the electronics along with the sensor. We have spent considerable time optimizing the acquisition circuitry to read these RTD's in real time so we can correct the capacitance measurement. Initial data collection with a sensor with a prototype RTD is underway to characterize the performance and effect of temperature.

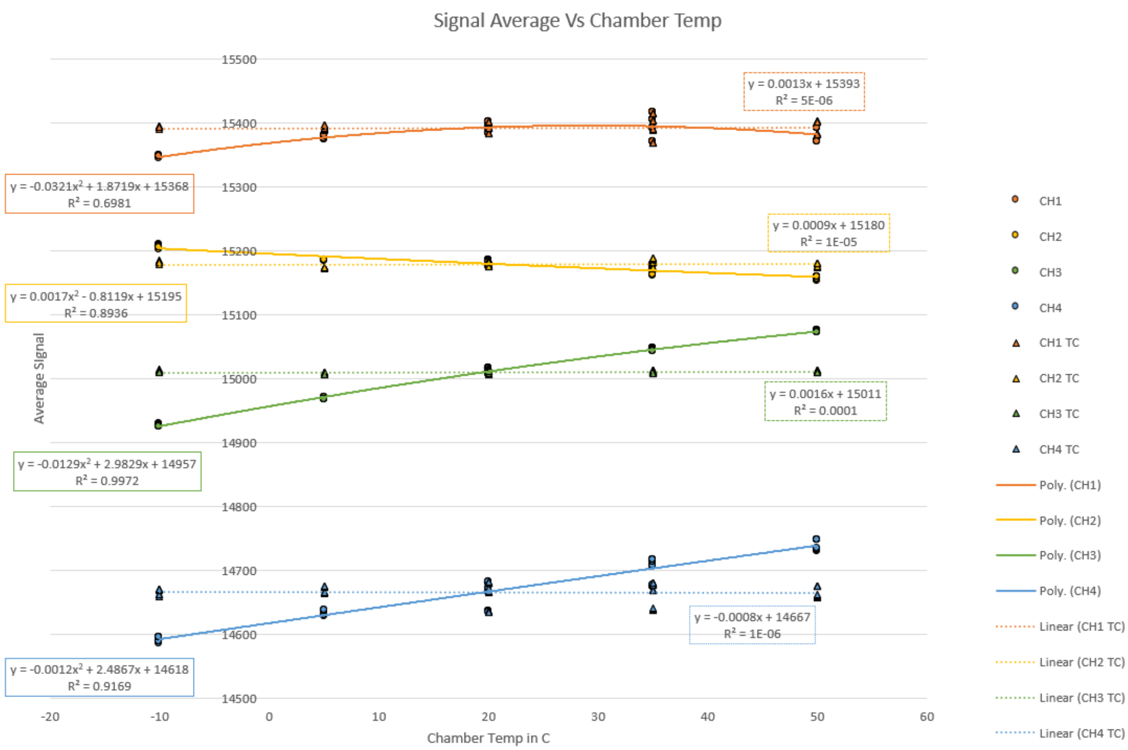


Figure 28: Temperature Compensation

2.2.7 Electronics Upgrades

We have been working on designing new circuitry that is more sensitive and repeatable, allowing us to improve volume fraction calculation and sense smaller increments of change. This involved the selection and testing of new higher accuracy electronic components as well as the design of new circuit boards. We recently completed testing the impact of our design changes and confirmed that the new design has an increased dynamic range, a larger signal to noise ratio, and a higher data collection framerate than the previous design. The test data for a comparison with low dielectric plastic material is presented below in Table 4. Based on these testing results we have ordered the new design to be manufactured and implemented. We have received the updated circuitry for these boards and have built the improved sensors that have been used to collect flow loop data.

Table 6: Das 4 to Das 7 Improvements

	Dynamic Range	SNR	Framerate
Das 4	1,660 pts	22.46 dB	678 fps
Das 7	3,819.5 pts	36.65 dB	21,739 fps

Another factor that affects the accuracy of both the sensors and electronics is moisture ingress. To this end, we tested with a variety of conformal coating materials and epoxies to prevent signal drift due to changes in ambient humidity or exposure to water. After testing several types we have selected Humiseal 1A33 as a conformal coating for the PCBs. It has good coverage and drying times compared to the others tested. It also has ultraviolet fluorescing particles so complete coverage can be verified before instrument assembly.

To complete the conformal coating testing we had to install a fume hood and vent system in our warehouse facility. This system is now operational and allows us to use a wider variety of materials and coatings in the future.

In some cases, a cheaper NEMA 4 chassis can be used for that DAS instead of the stringent requirements of the C1D1 chassis. This DAS configuration is shown in Figure 29 and is convenient for testing in the lab or in the field where the device can be placed in a safe location.

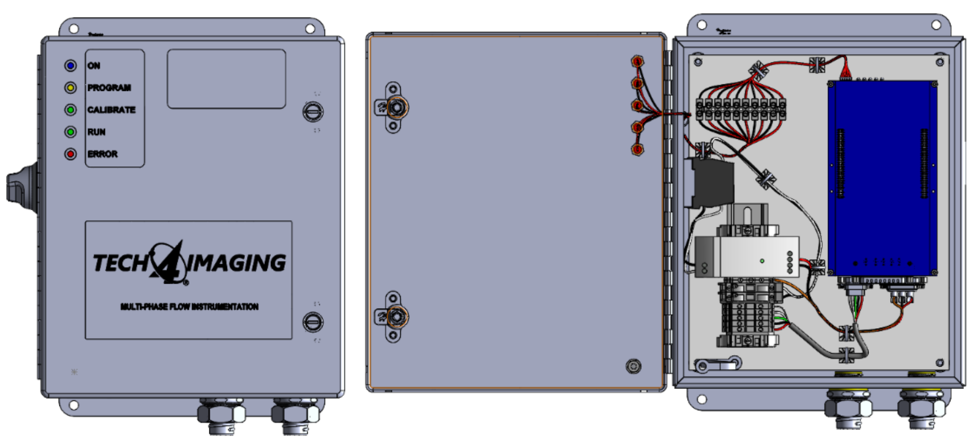


Figure 29: Updated NEMA DAS

2.3 Objective 3: Build subsea ready sensor package

The subsea ready sensor has been designed from the inside out, starting with the extreme conditions existing on the inside of the oil pipe. Our design requires a replacement of the pipe section where a non-conductive component allows our electric fields to penetrate the flow. As seen in the prototype in Figure 30, a fiber wound composite section is sealed between two stainless steel flanges.

Figure 30: High pressure sensor without subsea shell

The inner bore of the section is entirely smooth. This prototype is rated for up to 1,500 PSI and has been tested up to 2,200 PSI but can be adapted easily for pressures above 5,000 PSI. The electrode sensors will be placed around the composite section and secured in place. A design has been developed on how to house the electrodes from the subsea environment and achieve required oil field certification. We have used all threaded connections rather than welds because we discovered through discussion with oil and gas experts that welds are difficult to pass certification. An exploded view of the sensor assembly is shown in Figure 31 and the full assembled view is shown in Figure 32. This design is for 5,000 feet below sea level. The modifications have been fabricated and assembled as seen in Figure 33. The system was pressurized from inside the cavity to 110 PSI using compressed air to check for leaks using soapy water. No leaks were found. The system is was then installed in the subsea chamber for external pressure testing.

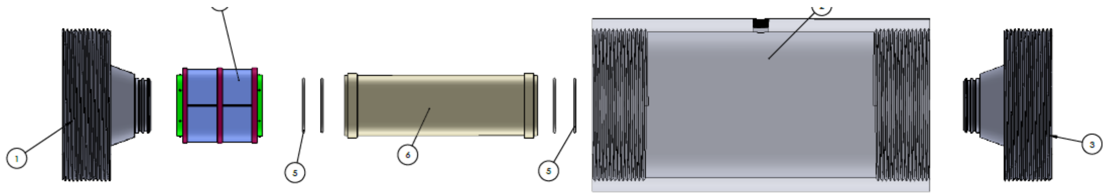


Figure 31: Exploded view of sensor assembly with outer shell

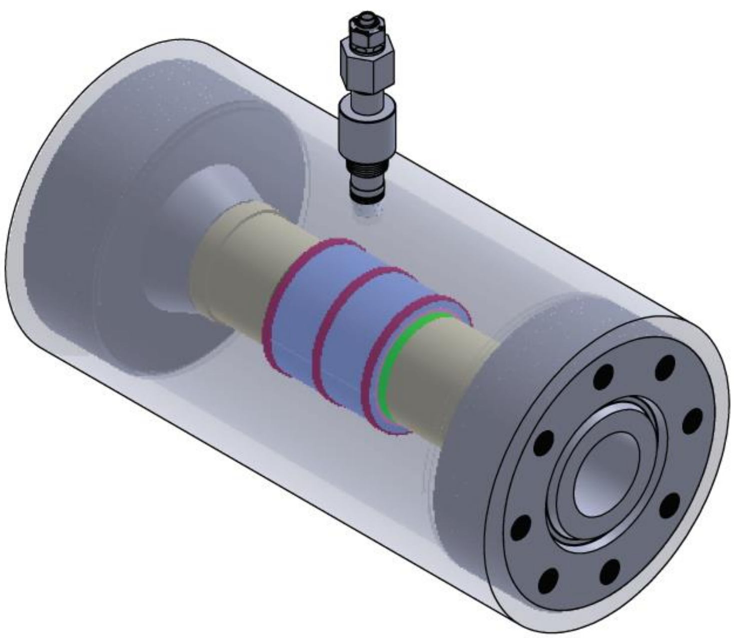


Figure 32: Sensor spool with subsea pressure shell, PCB sensor, and cable port

Figure 33: Assembled Subsea Sensor

Figure 34: Internally Pressurized Subsea Sensor Spool

2.4 Objective 4: Build subsea environment chamber and test unit in chamber

To prove that the system can survive the subsea environment, we have designed a subsea test chamber to produce the required pressures to simulate subsea conditions on the outside of the sensor. The chamber is a simple design in which the sensor spool is placed inside of a large spool piece that is then pressurized. The system has been designed to be integrated into the flow loop. Due to cost constraints, the outer spool piece was fabricated out of mild steel rather than stainless steel and coated in a marine grade coating to protect against salt and oxidation. The chamber has been fabricated, received, and assembled shown in Figure 36.

Due to the tight tolerance requirements, several iterations on some of the components had to be fabricated before it finally fit together correctly. Everything currently fits together except for the cable port alignment, but this was not required for this test because we did not have any working electrodes inside the sensor package yet. We simply plugged the cable ports and continued with pressure testing. The system withstood three cycles of hydrostatic pressure up to 3,000 PSI without noticeable pressure drop over 10 minutes. Thus, the sensor package for subsea deployment has been proven to withstand 3,000 PSI external pressure loading for working at depths down to 5,000 feet below sea level (~2,300 PSI).

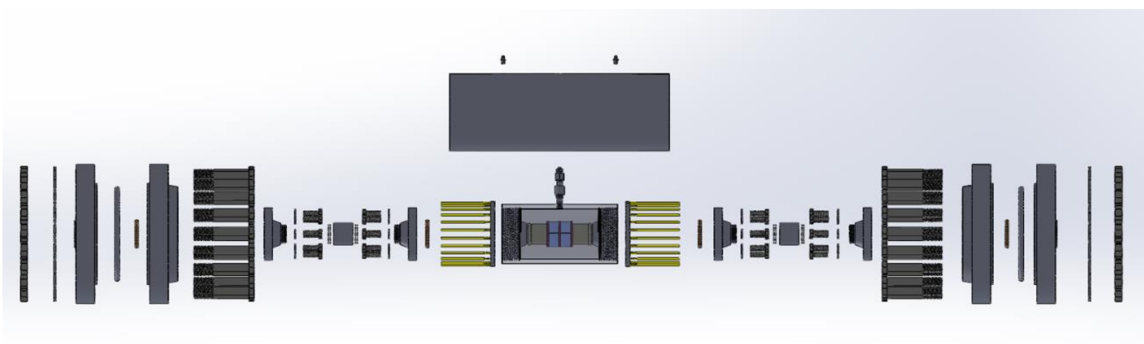


Figure 35: Subsea environment chamber exploded view with sensor inside.

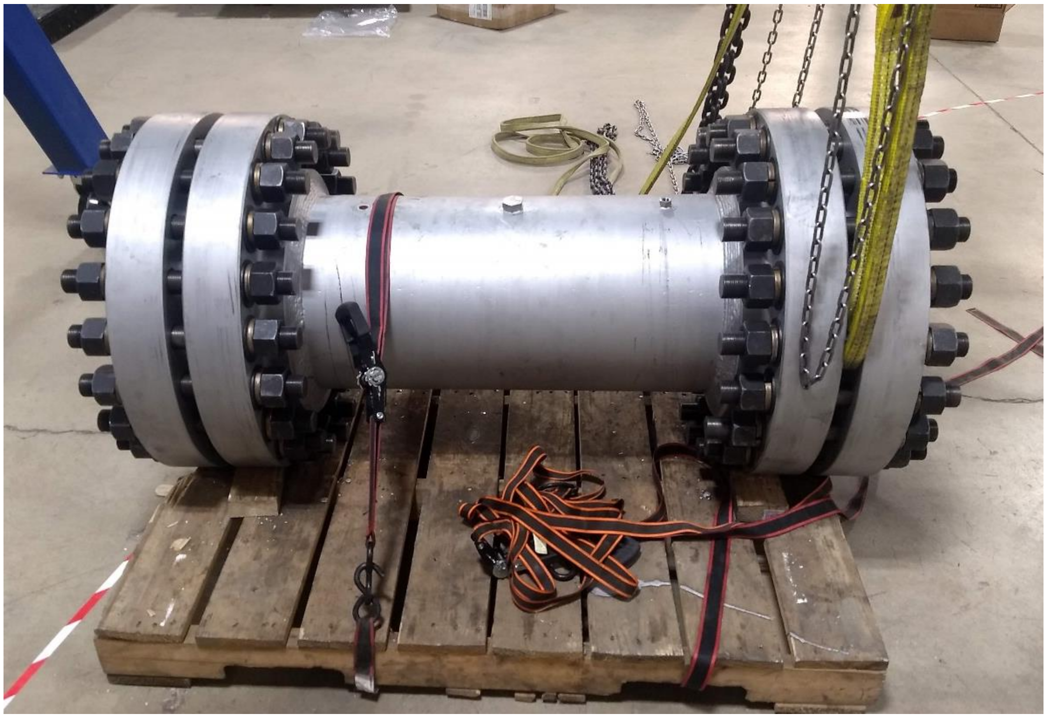


Figure 36: Subsea Chamber Assembly

2.5 Objective 5: Certify for field use

We currently have the certification standards required for field use so that we can implement them in our design and be ready to pass inspection at a later stage.

We have performed in house testing to ensure that the electronics will pass general electrical safety and environmental certification. Electromagnetic Compatibility (EMC) testing and general environmental testing have been performed including mechanical shock, vibration, temperature swings, and humidity. The equipment has passed all standard tests so far.

We have started a focus on implementing the stable DAS into a C1D1 rated enclosure. The mechanical layout can be seen in Figure 37, Figure 38, and Figure 39.

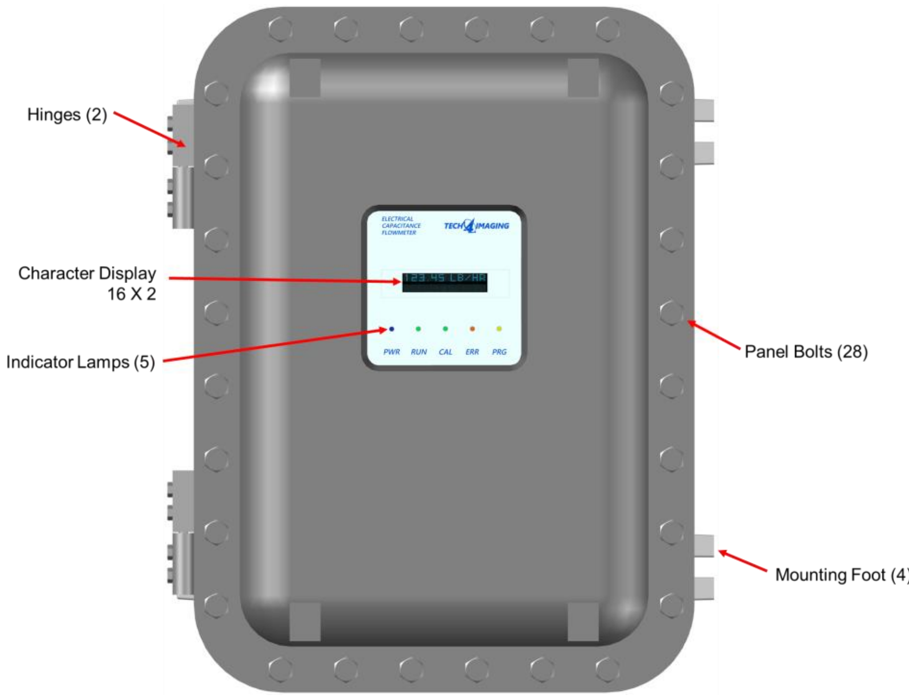


Figure 37: C1D1 DAS Enclosure (Front)

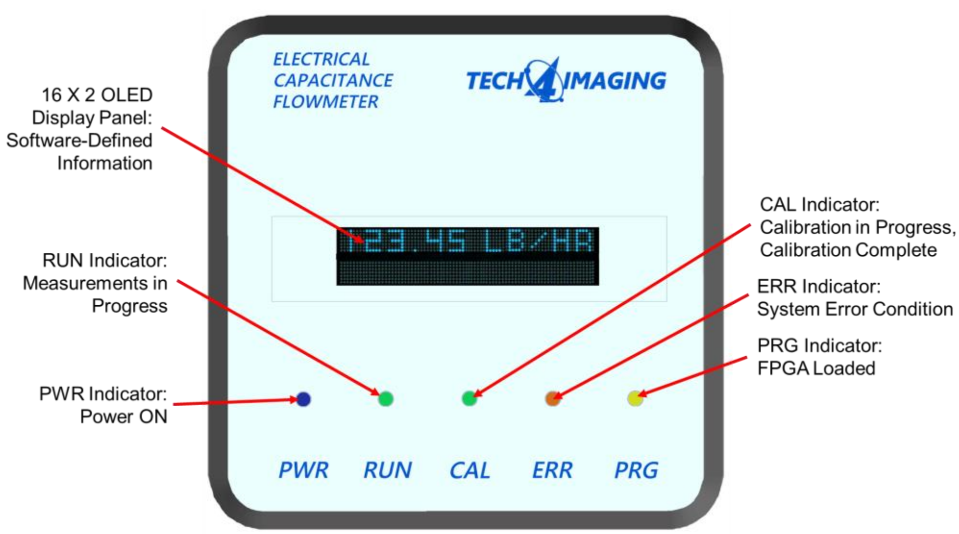


Figure 38: C1D1 DAS Enclosure (Display)

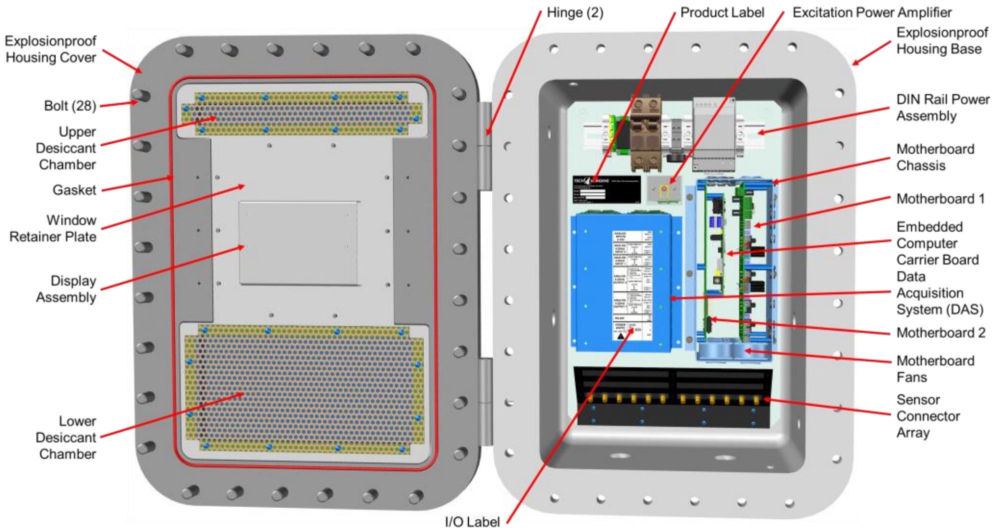


Figure 39: C1D1 Enclosure (Inside)

The enclosure and sensor designs have been sent to Intertek, a world renown standards and testing company. The design has been reviewed for North American certification for basic electrical safety, electromagnetic compatibility, and hazardous locations. We have had several discussions with the company. We have also had discussions with Accuflow, our testing partner. It was recommended that the safety requirements for testing be fulfilled by potting the cables coming from the sensor to the DAS and placing the DAS outside the C1D1 zone (10 feet away from the sensor and separator trailer) for the field test. This design was certified by the testing partner for safety in the approved test case. The flow meter was successfully commissioned to field testing for operation on a live oil/gas well.

2.6 Objective 6: Verify by third party separator on live oil well

A commitment was obtained from Accuflow to help us to get onto a live operating onshore well to test our measurements against their phase separator outputs in real world conditions. This test was completed at the final stage of Phase II of the project. They had currently witnessed a live test on our flow loops and were excited about the results.

The sensor and DAS were shipped to the test site. Prior to the sensor being installed into the Accuflow separator skid it was equipped with a hazardous location electric sealing fitting at the sensor shell. Then 10 feet of conduit was attached to bring the cables out to a non-classified zone for connection to the DAS and laptop.

Testing was performed on a single live oil well. The oil well was located in a remote area of Kern County California shown in Figure 40. The particular oil well was a gas lift well with gas volume fractions exceeding 95% and liquid volumes averaging about 100 bbl/day. Accuflow was able to modify an existing separator to accept the Tech4Imaging sensor into the three-phase section prior to any media separation. Figure 41 shows the separator skid on site with the sensor installed in the three-phase section. This skid utilized a gas/liquid separator and measured the liquid flow rate with a Coriolis flow meter and the gas flow rate with a single phase gas flow meter before recombing all three phases. Our flow meter was installed prior to the separator.

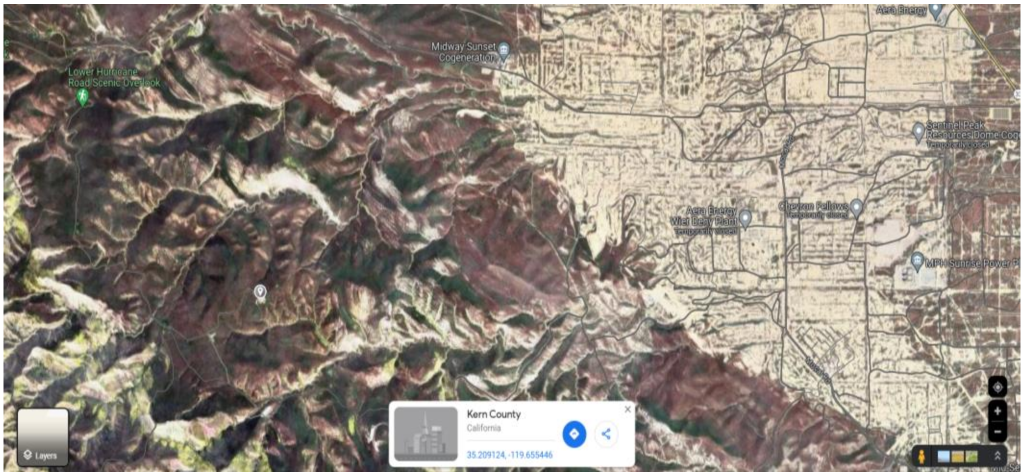


Figure 40. Oil Well Site location in Kern County California

Figure 41. Accuflow Separator Skid with Tech4Imaging Sensor

Given the remoteness of the selected site there was no 120VAC power available. The Accuflow test skid has a solar panel for powering all 24VDC equipment on the skid including the Tech4Imaging Sensor and DAS. The laptop used for data collection from the DAS had to be powered by a separate battery pack. This allowed for about 7 hours of data collection each day. The first day and a half of site testing was spent getting the Accuflow system connected up to the oil well along with verification and calibration of all readings. The next 2.5 days were spent collecting data from the system. The last day of testing was spent varying a by-pass valve on the separator skid to collect data with different volumetric flow rates for future determination of the capability to calculate flow velocity using the Tech4Imaging sensor.

The datasets from the 2.5 days of testing were analyzed with the Tech4Imaging created algorithm and plotted with the system water cut measurement from the Accuflow separator skid. These results are shown in Figure 42.

The resulting water cut calculation is off by about 30% of full scale. We believe this is due to a large variation in the operating conditions in this particular well compared to what was performed in our calibration flow loop in the lab. The GVFs were never encountered in the lab. Once we returned to the lab, we adapted the flow loop to allow GVF up to 95% as shown in section 2.1.4. However, there is still variation between our lab tests and the field tests. The factors driving this error have yet to be concluded, but, by comparing the capacitance measurement to the gas flow rate, there seems to be a correlation. This means that in the field, the capacitance measurement is sensitive to the gas flow rate, even though that is not the case in the lab. This comparison shown in Figure 43 shows dips in the capacitance magnitude that correspond to the spikes in the gas flow rate. For future field testing, we plan to install a sight glass to have visual inspection capabilities. This will better assist us in determining the difference between the lab and field cases. Once this difference is identified, the calibration process can be adapted appropriately.

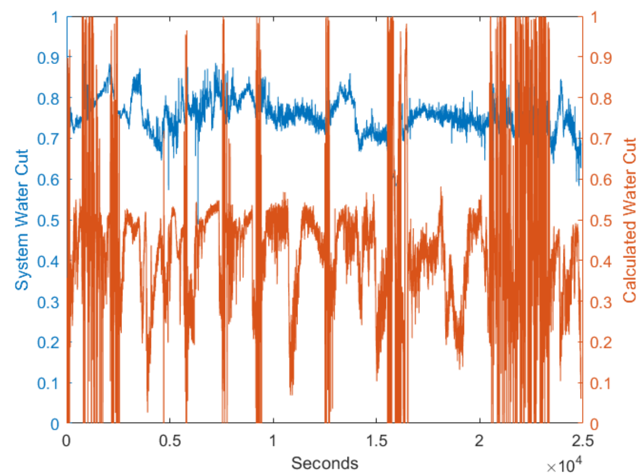


Figure 42. Calculated Water Cut and System Water Cut

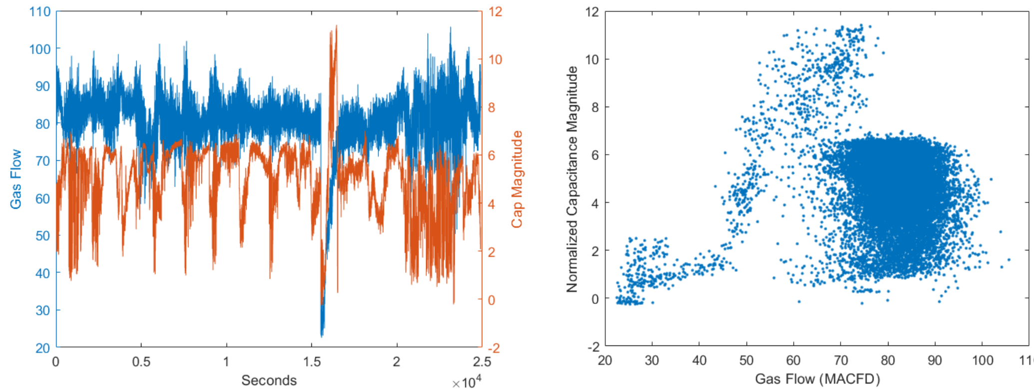


Figure 43. Gas Flow Rate against the Normalized Capacitance over time (left). Correlation of gas flow and normalized capacitance magnitude showing a positive relationship below 60 MACFD (right).

Our testing partner was very interested in our results and offered to keep our flow meter prototype onsite for continued testing. The prototype remains onsite as we plan for future testing and development. However, this testing will be performed beyond the budget and schedule of this project and will require additional funding.

2.7 Conclusion

The initial stages of the project involved developing and constructing a flow system that could produce and quantify a three-phase mixture of oil, water and gas while simultaneously varying the flow rate and back pressure. This was performed successfully with the partnership of Accuflow. The flow system was also designed to allow for the installation of the subsea environmental chamber to allow testing of the design at high pressures. Flow rates of up to 4000 bbl/day of liquid, watercut from 0% to 100% and GVF from 0% to 95% were achieved on the flow loop.

A prototype sensor was designed and installed on the flow loop for measuring watercut in a three-phase system. Data was produced showing error as small as 2% in certain flow regimes and a maximum error of 10% at low flow rates in three phase flow in the 20-60% watercut domain. This method was valid with GVF from 0% to 95%. A hysteresis was seen depending on whether the test stepped from low to high watercut or high to low watercut. It is recommended that a method should be developed to deal with the hysteresis effect on the watercut measurement to improve accuracy. It is possible that accuracy could be improved from 10% to 4% across all watercut and GVF if successful.

A DAS was developed to meet the specific needs of the flow meter for thermal stability, frame rate, and signal to noise ratio. This included developing a temperature correction algorithm and test procedure. This allows the DAS to correct its measurements based on the temperature of the environment it is installed in. Humiseal 1A33 conformal coating was added to the manufacturing process to prevent moisture ingress on the PCBs. The DAS enclosure was also updated to include NEMA 4 and C1D1 (NEMA 7) configurations for field operation. The device was certified for use in the C1D1 rated area by the test site provider.

Testing was performed to investigate the effects of oil density on the capacitance measurements. Normalization with respect to one density of oil will show higher/lower signal level depending on the change in density which will correlate to a higher/lower mass flow rate accordingly. Thus, there is no need for correction for this parameter.

Testing was performed to investigate the effect of scaling on the pipe walls. Test results show indistinguishable signal between liquid oil and wax build up in a static state. It is recommended to conduct velocity profiles to distinguish the difference between moving and non-moving phases in the pipe. This information can be used to correct the flow rate for changing cross sectional area due to wax deposition. This methodology needs further investigation.

A fourth phase of solids content in the mixture was discussed. It was determined that in most cases in the field, solid filters are in place to reduce the solids content below detectable concentrations.

A test apparatus for investigating the effects of temperature and water salinity on the capacitance measurement was built to generate a salinity/temperature compensation algorithm for salinities up to 300 ppt and temperatures up to 50°C. Further testing with oil continuous states and dynamic states is recommended.

A subsea environmental chamber was successfully designed, built, and used to pressure test the subsea sensor design, validating the instrument for use down to 5,000 feet below sea level. The chamber was also designed to integrate into the three-phase flow loop.

The complex problems introduced by electronics instability, flow loop design/operation, flow regime variability, and COVID 19 prevented the advancement of the watercut algorithm into a three-phase mass flow rate algorithm within the time and budget of the project. The success of the watercut algorithm in the lab shows promise for deconstructing a three-phase flow into its components, which is step 1 of a three-phase mass flow rate algorithm. The response of the signal in the field shows promise for measuring accurately once the differences between the field test and the flow loop are identified. Our ability to correct for temperature and salinity show additional robustness for future field testing. However, velocity and density information for the three-phase flow was inspected thoroughly enough to report on at this time. These are the remaining elements for reporting mass flow rate and should be developed as part of a future project. In the meantime, a watercut meter that can deliver watercut in the presence of gas has received feedback from industry as a viable product by itself. Accuflow expects to purchase the device in bulk to service its customers once it is proven to work as well in the field as it does in the lab. This successful outcome shows a prototype that is close to commercialization with a confirmed market ready to purchase.

3 What opportunities for training and professional development has the project provided?

Many opportunities for training and professional development have been made during this project including attendance of virtual conferences, visiting oil fields to learn about industry and what is required for our product, conducting research at The Ohio State University and at Tech4Imaging, and learning about advanced manufacturing such as composite PEEK pipe winding, CNC machining, welding, and flow loop construction. Significant training and professional development relevant to this project include:

1- Supporting a postdoctoral researcher at The Ohio State University throughout the duration of the project.

2- Involving interns at different stages of the project.

3- Supporting development of Tech4Imging engineers on hands on testing and training relevant equipment certification and requirements for Oil & Gas well operation.

4- Summitting a paper for presentation in an international conference for multiphase flow.

5- Developing a draft journal paper for submission following the conference presentation.

4 How have the results been disseminated to communities of interest?

We have submitted a research paper to IEEE Sensors Journal for publication to share our results on salinity simulation and experimentation. The title of the paper is *Water Volume Fraction Calculation in Multiphase Flows Using Electrical Capacitance Tomography Sensors*.

We have performed multiple live online session with our commercial partner to show performance results.

5 Table Of Milestones & Schedule

			Year 1				Year 2				Year 3				Year 4			
		Tasks	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Milestone	Phase I																	
	1.0	Project Management and Planning	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	1.1	Data Management Plan	■															
	1.2	Technology Maturation Plan	■															
	2.0	Develop test matrices and tests	■															
	2.1	Design low pressure three phase flow test for task 4.0	■															
	2.2	Determine specifications for subsea operation	■															
	2.3	Design high pressure three phase flow test for Task 7.0 based on specifications of Task 2.2	■															
	2.4	Design subsea environment test based on specifications of Task 2.2	■															
	2.5	Design third party tests for Task 10.0 based on test designed in Task 2.3	■															
*	3.0	Sensor design and build for low pressure three phase flow test	■	■														
	4.0	Low pressure three phase flow loop testing		■	■													
*	5.0	Design and build high pressure flow loop at Tech4Imaging facility	■	■														
*	5.1	Design and build subsea environment chamber	■	■														
*	6.0	Design and build sensor for high pressure flow loop and subsea operation	■	■														
	7.0	Run high pressure tests on Tech4Imaging's flow loop to replicate results of the low pressure flow loop tests			■	■												
+	7.1	Run static subsea environment chamber test			■	■												
	8.0	Algorithm development for three phase mass and volumetric flow rates	■	■	■	■												
	9.0	Data acquisition system electronics design, fabrication, and testing	■	■	■	■												
+	10.0	High-pressure third-party testing verification of water cut readings				■												
	11.0	Lab tests for variability in salinity, oil quality, solids content, and hydrocarbon scaling	■	■	■	■												
Milestone	Phase II																	
	12.0	Develop and refine test matrices and tests for Phase II					■	■	■									
	12.1	Design low pressure three phase flow test incorporating salinity, oil quality, and solids content variables					■	■	■									
	12.2	Design high pressure three phase flow tests incorporating subsea environment					■	■	■									
	12.3	Improve DAS signal resolution and repeatability							■	■	■	■	■	■				
*	13.0	Test variables such as salinity, oil quality, and solids content on Tech4Imaging flow loop												■	■			
	13.1	Algorithm development for investigated variables														■	■	
	14.0	Integrate complete system																■
	14.1	Incorporate subsea chamber into high pressure flow loop																■
*	14.2	Test integrated flow measurement system on subsea flow loop																■
+	15.0	Certify data acquisition system for Class 1 Division 1 operating environment														■		
*	16.0	Develop test plan for final field test and obtain required paper work/certifications															■	■
		Go/No Go Point																
		National Environmental Policy Act (NEPA) approval of the Phase II site and field activities (Task 16.1)																
		Submittal of all deliverables for the work completed up to Subtask 16.0																
		Submittal of a Go/No-Go Report that includes, at a minimum, the following																
		1) Providing details showing that the developed data acquisition system has passed the certification according to Task 16.0 before moving forward.																
		2) a complete field test plan developed per but not limited to Task 16.0;																
		3) a technical briefing on the final design, field test plan activities and a discussion on whether or not the final design would lead to any technical and/or cost changes																
+	16.1	Test final system implementation on an active field well alongside a three-phase separator for validation																■
+	17.0	Develop data sheet based on all testing and verification done during Phase I and Phase II																■
	18.0	The Recipient will submit data to NETL-EDX																■

Figure 44: Milestones and Schedule

Tasks	SubTasks	Description	% Complete	Completion Date
13.0		Test variables such as salinity, oil quality, and solids content on Tech4Imaging flow loop	100	10/30/2023
13.1		Algorithm development for investigated variables	100	9/13/2023
14.0		Integrate complete system	100	10/1/2023
	14.1	Incorporate subsea chamber into high pressure flow loop	100	11/30/2023
	14.2	Test integrated flow measurement system on subsea flow loop	100	11/30/2023
15.0		Certify data acquisition system for Class 1 Division 1 operating environment	100	
16.0		Develop test plan for final field test and obtain required paper work/certifications	100	9/30/2023
		Go/No Go Point		
		National Environmental Policy Act (NEPA) approval of the Phase II site and field activities (Task 16.1)	100	5/30/2023
		Submittal of all deliverables for the work completed up to Subtask 16.0		
		Submittal of a Go/No-Go Report that includes, at a minimum, the following	100	11/30/2023
		1) Providing details showing that the developed data acquisition system has passed the certification according to Task 16.0 before moving forward.		
		2) a complete field test plan developed per but not limited to Task 16.0;		
		3) a technical briefing on the final design, field test plan activities and a discussion on whether or not the final design would lead to any technical and/or cost changes		
	16.1	Test final system implementation on an active field well alongside a three-phase separator for validation	100	12/8/2023
17.0		Develop data sheet based on all testing and verification done during Phase I and Phase II	100	1/11/2024
18.0		The Recipient will submit data to NETL-EDX	100	1/31/2024

Figure 45: Task Tracking Table

6 Products

The following products have been produced.

- Three phase flow loop
- Subsea chamber
- ECVT Sensor for subsea application
- Data Acquisition System
- Salinity test set up
- Research paper, *Water Volume Fraction Calculation in Multiphase Flows Using Electrical Capacitance Tomography Sensors*.

7 Participants and other collaborating organizations

We worked closely with The Ohio State University on research regarding the effects of salinity on measurement of the volume fraction of water using ECVT. We sponsored one post-doctoral at the university and the funding from this project has resulted in one research paper being submitted to IEEE Sensors Journal for publication.

We also worked closely with Accuflow to design and build the three-phase flow loop a Tech4Imaging's facility. Accuflow was instrumental in designing the flow loop, finding vendors, and specifying required equipment. Accuflow observed and commented on the testing. Accuflow provided the field test site to conduct measurements on a gas-lift oil well and assisted in installation of our unit. They also provided the separator skid for validation measurements.

8 Impact

The impacts of the development project were wide and many. The technical development lead to a better understanding of many aspects of capacitance interactions with two and three phase flows including salinity, volume fraction, mixing, and temperature. An algorithm was developed and proven on a lab flow loop that provides watercut measurement in a three phase flow regardless of GVF. This progress has opened up field testing with a commercial partner that is interested in seeing the prototype mature into a commercial product. Once funding can be secured, further field testing can be conducted.

This field testing lead to the training of engineers in field safety and data collection. Flow loop design and field testing led to the development of a strong partnership between Tech4Imaging and Accuflow to support further testing and development.

One journal paper on multi-phase flow measurement was published and at least one more is planned for publication. Funding was used to support a post-doctoral researcher at OSU which led to the first publication.

Funding was used to support and train multiple engineers and technicians at Tech4Imaging throughout the course of the project.

Advancement of the technology could help future enhanced oil recovery in a number of ways including understanding when to convert to co-production as a thermal energy resource, balancing injection, understanding when breakthrough has occurred, and allocating costs from different wellheads by monitoring production on each independently.

Development of the flow loop allows Tech4Imaging to contract testing services to outside entities that may want to study flow behaviors in various ways. This creates a new resource available to the scientific and commercial community.

9 Changes/problems

Task 14.1 was to incorporate the subsea chamber into the high pressure flow loop. While the chamber was modified to be incorporated into the flow loop as required by the task, the chamber was never fully installed in the flow loop. A schedule change was made to send the sensor to field testing prior to integration of the pressure chamber in the flow loop due to the availability of the field test site. The sensor was scheduled to be shipped back for integration into the subsea chamber on the flow loop after field testing. However, the field testing company, Accuflow, was so enthused with the sensor that they offered to keep it on site for further testing. We assessed the risks and opportunity of further field testing versus testing the system with the subsea chamber on the flow loop. Because the sensor survived the pressure chamber tests off of the flow loop and had already gone through extensive flow loop testing, the added knowledge of a combined test was much less valuable than the extended field test opportunity which is hard to come by.

10 Special Reporting Requirements

Nothing to Report

11 Budgetary Information

Nothing to Report (nothing has been specified by the contracting officer)

12 Project Outcomes

The project has resulted in multiple outcomes including a journal paper submitted, design documents, simulation results, reports, flow loop fabrication, sensor fabrication, DAS development, subsea pressure testing, salinity testing, and watercut algorithm/data in both lab and field testing. The major outcomes are listed below.

- Sensor design documents and fabrication, testing and reports
- Flow loop design documents and fabrication, testing and reports
- Subsea chamber design documents and fabrication, testing and reports
- Data acquisition system design documents and fabrication, testing and reports
- Salinity and water volume fraction simulation results, testing and reports
- Research paper, *Water Volume Fraction Calculation in Multiphase Flows Using Electrical Capacitance Tomography Sensors*

13 Data Sheet

The following data sheet was developed to use as technical marketing material for companies interested in purchasing a product or investing in further development/testing.

Flow Meter Specifications

Water Cut Accuracy			
Gas Volume Fraction	0-67% GVF	67-95% GVF	95-100% GVF
0-30% Water Cut	+/- 5% of Full Scale	No Data	No Data
30-60% Water Cut	+/- 10% of Full Scale	No Data	No Data
60-100% Water Cut	+/- 5% of Full Scale	No Data	+/- 30% of Full Scale

Data Acquisition System Specifications

Data Acquisition System Options:		
Environmental Protection Rating:	NEMA 7 Equivalent	NEMA 4 Equivalent
Product Dimensions		
Height / Width / Depth (IN):	22.25 / 16.25 / 8.75	14.195 / 11.428 / 8.29
Mounting		
Method:	Wall Mount Flange	Wall Mount Flange
Dimensions: Height / Width / Ø (IN)	14.125 / 16 / .5	12.77 / 8 / .312
Fasteners Included?	No	No
Properties		
Material:	Cast Aluminum	Steel
Finish:	Aluminum	Powder Coat
Estimated Weight (lbs):	93	15
Color:	Silver	Gray
Power		
Input::	24VDC, 120VAC, or 230VAC	24VDC, 120VAC, or 230VAC
AC Frequency:	45 to 65 Hz	45 to 65 Hz
Consumption:	< 15 W	<15 W
Connection:	Terminal Block	Terminal Block
Power Cable Included?:	No	No
Conduit Hole Provided:	1" FNPT	3/4" Knockout
Operations		
Output Method:	RS-422 / 4-20 mA	RS-422 / 4-20 mA
Connection:	Terminal Block	Terminal Block
Output Cable Included?:	No	No
Conduit Hole Provided:	1" FNPT	3/4" Knockout
Operating Temperature:	[-30C to +60C]	[-30C to +60C]
Data Output:	% Water Cut	% Water Cut