ONGOING MONITORING OF STEAM QUALITY WITH MICROWAVE TECHNOLOGIES

CTD 2018-103

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2. EXECUTIVE SUMMARY

Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.

Steam is an essential part of SAGD, which involves producing steam, transporting the steam to wellheads and injecting the steam underground such that the heat transferred to the formation decreases the viscosity of the bitumen. Steam quality, measured by the percentage of steam that is vapor, provides an indication of the amount of liquid present. In once-through steam generators (OTSGs), maximizing steam quality enhances energy efficiency and reduces waste water. Steam assessment involves measuring temperature and pressure, then determining the internal energy via tables. However, the amount of liquid present must also be determined to properly assess steam quality. While numerous approaches to this assessment have been proposed, there remains a need for a continuous, fast and reliable measurement of steam quality that can be implemented at various locations from boiler to well-head.

We aim to develop a robust approach to steam quality monitoring using microwave sensing techniques. Specifically, our objective is to demonstrate the feasibility of monitoring steam quality to within 1%. To tackle this problem, we defined a series of 5 tasks.

In Task 1, an electromagnetics (EM) simulation tool was adapted to represent signals interacting with flow in pipes. This incorporated the EM properties, as well as the geometry of the two-phase flow. This geometry was informed by computational fluid dynamics simulations (Task 2), which provided insight into the variety of distributions of flow inside pipes. These simulation tools allow for understanding flow in pipes and definition of sensing requirements.

The development and feasibility assessment of sensing approaches using simulations was the third task. The key result related to this task is the identification of sensing approaches that characterize the liquid and gas phases in the pipe, as well as changes in these quantities.

Task 4 further developed the sensing methods, bridging the gap between simulation models and implementation. The key results are demonstration of implemented sensors with responses that match simulations, and exploration of practical issues via measurements and simulations.

Finally, an experimental flow facility was developed and used to test the sensing approaches in Task 5. The flow was characterized and approaches to perturbing the flow defined. The sensor responded to these perturbations as expected. Overall, the sensing approaches developed in this project demonstrate the potential to characterize steam quality to within 1%, as well as to track 1% changes in steam quality in near real-time.

Learnings: As anticipated, tracking a 1% change in steam quality is technically challenging due to multiple intersecting factors. With careful analysis and simulation, we characterized the impact of different factors and developed appropriate sensing strategies that encompass a range of two-phase flow scenarios. This was supported by a series of incrementally more complex experimental tests to verify sensor behavior and response.

Working with industrial partner Cenovus provided key practical perspectives on the project. This included feedback on assumptions and technical challenges with practical implementation of the sensing system, as well as discussions on additional application areas. This partnership was critical producing outcomes with relevance to industry, and hence greater potential for impact.

Project outcomes and benefits: Our results demonstrate the potential to accurately characterize steam quality with microwave techniques, as well as to detect 1% changes in this quantity. The techniques require further adaptation to realistic operating conditions, however the tools developed as part of this project form a strong foundation on which to further develop the technology. The multidisciplinary team formed to tackle this project is well positioned to take these next steps.

As this project involves early stage technology development, the technology has not been implemented in industry and does not have associated measurable impacts on GHG emissions. We have advanced the technology proposed in our original application through careful design, simulation and testing. We are now exploring next steps related to technology transfer. We have also contributed towards training of highly skilled personnel, as the project involved a research engineer, postdoctoral associate and PhD student. In addition to applying and developing their technical expertise, these researchers gained valuable skills through work on a multidisciplinary project with an industrial collaborator.

3. INTRODUCTION

Please provide a narrative introducing the project that includes the following:

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that was addressed along with the context and scope of the technical problem.

Sector introduction: Steam is an essential part of SAGD, which involves producing steam, transporting the steam to wellheads and injecting the steam underground such that the heat transferred to the formation decreases the viscosity of the bitumen. Steam quality, measured by the percentage of steam that is vapor, provides an indication of the amount of liquid present.

Once-Through Steam Generators (OTSG) are common in the oil-sands in-situ industry for steam generation. OTSGs can convert lower quality water to steam compared to a drum boiler. However, the solids present in the feed water may still be problematic as they accumulate on the inside surface of the steam pipe (fouling) and prevent proper heat transfer from the pipe to the water. To limit this effect, OTSGs operate at lower steam quality in order to have enough water in the liquid phase to limit the ability of the impurity to adhere to the pipe walls. The steam quality target may change between operations but an OTSG is typically set to run at around 80% steam quality. It is recognized that the operating target could be as high as 85% to even 90%. However, due to current measurement inaccuracies in the steam quality, the operators reduce the steam quality targets by about 2% as a safety margin. Maximizing steam quality enhances energy efficiency and reduces waste water. With reduced steam quality at the wellhead for injection, less heat is available for transfer, which requires increased steam to achieve heating targets.

Steam assessment involves measuring temperature and pressure, then determining the internal energy (enthalpy) via tables. Density is also a function of temperature and pressure, and heat transfer can be obtained if the flow rate is known. However, the amount of liquid present must also be determined to properly assess steam quality. Currently, the steam quality can be measured in a number of different ways. Conductivity can be measured at the inlet and outlet, including the outlet blow down or steam condensate. Based on the relationship between the conductivity and the total dissolved solids (TDS), the steam quality is inferred. This method is performed in the field and provides results quickly, however has limited accuracy. A lab-based TDS analysis can be performed by boiling the water and measuring the mass of the solids. This method is more accurate but requires more time. An inference method based on the inlet and outlet volumetric flow meters, as well as temperature and pressure, can also be applied. Accuracy is on the order of 2-3%.

Technology gap: The key issues for steam quality assessment are accuracy and measurement delay. Additional techniques have been proposed, including determining mass flow rate with ultrasound, measuring absorbed light from laser sources and finding concentration by fitting to models, and detecting changes based on the microwave-frequency properties of materials. However, there remains a need for continuous, fast and reliable measurement of steam quality that can be implemented at various locations from boiler to wellhead. Therefore, the goal of this project is to develop a steam quality sensing technique that is fast and has 1% accuracy.

We aim to develop a robust approach to steam quality monitoring using microwave sensing techniques. Previous studies have suggested correlation between the microwave frequency properties of steam and steam quality. For steam quality assessment, a two-phase flow is likely to exist in the pipe. The first stage of the project involves identifying flow patterns that are most likely to develop at locations where sensing systems may be deployed. The second stage of the project involves developing a platform for microwave-frequency simulations of the flow patterns, then applying this tool to develop sensing strategies. In the third phase of the project, candidate sensing strategies are tested experimentally with different flow patterns. Together, these phases of the project explore the feasibility of steam quality assessment with microwaves, providing specific sensing requirements, sensor designs, and evaluation.

4. PROJECT DESCRIPTION

Please provide a narrative describing the project that includes the following:

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that were used to measure the success of the project.

Technology Description: The overall objective of the project is to demonstrate the capability of a microwave sensing prototype to estimate the steam quality to within 1% in a realistic environment. Previously reported work indicates that the microwave-frequency properties of steam track the steam quality. However, for accurate steam quality assessment, both the liquid and vapour phases present in the pipe must be considered. The project includes a sequence of specific tasks designed to meet the goal of assessing steam quality to within 1%.

The objective of **Task 1** is to ***design a simulation environment for testing different microwave sensing strategies***. A professional-grade simulation tool is used to model the interaction of microwave-frequency fields with the two-phase flows. This requires the microwave-frequency properties of the vapor and liquid phases to be specified for the temperatures and pressures of interest. The flow patterns must also be implemented by including liquid at specific locations and with different depths and physical distributions. Finally, idealized microwave sensors must be included in order to introduce microwave-frequency signals into the simulation and record data for subsequent analysis. Testing with simplified scenarios also provides initial validation of the simulation approach. The deliverables for this task are a flexible tool for simulating the interaction between microwave-frequency signals and selected two-phase flows in a pipe, allowing for exploration of different scenarios through modifying parameters rather than rebuilding simulation environments.

Task 2 involves ***studying flow patterns and dynamics*** with the objective of defining the flow patterns at the OTSG outlet and the wellhead. By understanding which two-phase flow patterns are likely to develop, the sensing approach can be tailored to these configurations. The sensing approach is tested with both simulations and measurements. Measurements require design of an experimental system that supports appropriate two-phase flows. The deliverables for this task include the definition of flow patterns at the OTSG and wellhead, as well as design of the experimental system supporting appropriate two-phase flows.

Task 3 involves applying the simulation tool developed in Task 1 to ***study sensing approaches with the different flows*** identified in Task 2. By testing a variety of different sensing approaches with different flows, the microwave-frequency signals can be analyzed to determine which approach provides the feedback needed to accurately determine steam quality. The deliverables for this task are the design of the sensing approach, including sensor characterization.

The objective of **Task 4** is the ***physical design and implementation of microwave sensors***. While the simulations provide insight into the microwave frequency performance of the sensors, the mechanical performance is not analyzed. Therefore, appropriate materials must be selected and strategies for incorporating the sensor into the prototype system must be developed. In addition, the hardware required to excite the sensor and collect signals must be implemented. The deliverables for this task are a sensing system ready for deployment in the prototype.

Task 5 involves the ***development of a lab-based experimental system*** that supports the two-phase flows of interest and integrates the microwave sensing strategy. The two-phase flows identified in Task 2 are created using the experimental system designed as part of Task 2. The sensing system developed in Task 4 is implemented into the experimental system, and the measured results are compared to simulations

Updates to project objectives: This project has grown a new collaboration between Dr. Fear's team in Electrical Engineering and Professor Ron Hugo's team in Mechanical Engineering. Prof. Hugo is an expert in two-phase flows, and his team has previously developed experimental testing facilities to investigate a wide variety of flow scenarios. His team has also developed monitoring approaches, including optical tomography. This expertise allows for more sophisticated experimental testing than originally anticipated due to the resources available in Prof. Hugo's lab.

Performance metrics: The overall goal of the project is to develop a method of assessing steam quality to within 1%. This is evaluated by performing measurements with the final sensing strategies as steam quality is adjusted in 1% increments. To reach this final performance metric, we consider metrics related to each task.

In Task 1, performance is evaluated by the ability to adjust geometries and operating conditions in an EM simulation environment that is tailored to steam quality assessment in pipes. In Task 2, performance metrics are completion of analysis of two-phase flows in pipes via simulations, and development of a design for an experimental system that is expected to produce similar flow patterns. For Task 3, the developed sensing approaches are evaluated by demonstrating the ability to track changes in steam quality of 1% in simulations. In Task 4, the key performance metric is agreement between simulations and corresponding lab-based measurements collected with the implemented sensor. Finally, the performance metrics in Task 5 are characterization of the flow established in the experimental system, and evaluation of changes in measurements collected with the sensor with changes in experimental flow. The final metrics are the ability to change flow to represent a change of 1% in steam quality, and the ability to accurately characterize steam qualities with sensor measurements.

5. METHODOLOGY

Please provide a narrative describing the methodology, equipment and facilities used to execute and complete the project.

Task 1: Implementation of simulation environment for exploring interaction of microwave signals with two-phase flows

The sensor design is performed with EM simulation tools, specifically the 3D field simulator HFSS. This simulation tool is used to create models of the interaction between microwave signals and two-phase flow in the pipes. This requires the electrical properties of condensate (liquid phase) and steam (gas phase) to be specified for selected combinations of temperature, pressure and total dissolved solids (TDS). This also requires the geometry of the liquid and steam phases to be modeled. Implementing individual models for each condition of interest is time consuming, so the methodology developed for this task automates these steps via Python scripts.

Task 2: Defining two-phase flows present in OTSG and wellhead locations, as well as design of experimental testing

Flow patterns are investigated with computational fluid dynamics simulations. The scenarios investigated include a 12-inch diameter pipeline and a 3-inch diameter pipe section inside of a Once Through Steam Generator (OTSG) where water vapor (steam) is the primary phase and liquid water is the secondary phase. A horizontal experimental flow facility is adapted to experimentally reproduce the flow patterns expected as a result of the simulation models.

The flow is modelled using two widely used Computational Fluid Dynamics (CFD) software packages: ANSYS Fluent and OpenFOAM. These simulations are performed by assuming the liquid and vapor phases to be in thermodynamic equilibrium. The properties for both phases are taken at the temperature and pressure of expected during operation, as well as under the conditions expected in the lab. By varying parameters such as velocity and injection location, as well as adding features such as elbows, the flow patterns expected in realistic scenarios and lab-based tested are identified.

To experimentally validate the sensing strategies with different flow conditions, an experimental testbed is developed that allows different flows to be established. The Mechanical Engineering team has an experimental testing lab that is outfitted with several pumps, as well as air compressors and instrumentation. The flow system design is based on a reconfigurable system that was successfully developed for another project. The sensing system is incoroporated, along with additional measurement systems to depict the established flow and characterize the volumetric and mass flow rates, as well as temperature and pressure. By varying the operating conditions (flow rates for water and air), different flow regimes are established.

Task 3: Study different sensing approaches

This task utilizes the simulation environment developed in Task 1 and flow patterns determined in Task 2. Four different approaches to sensing differences in parameters that occur with changes in steam quality are incorporated into the simulation environment. A low-frequency capacitive approach was tested, however did not provide adequate results. Specifically, this method is sensitive to not only the amount of water but also the distribution. The goal of the sensing method is to provide consistent results related to the amount of liquid regardless of its distribution. An alternative method of gaining insight into the composition of material inside the pipe was also designed, however details are omitted (due to commercialization potential). The steam quality in the simulations is modified, and the corresponding response of the sensor is analyzed. It is also useful to detect the height of the liquid in the pipe, as well as its conductivity. To sense the liquid level, a custom ultrawideband antenna that incorporates high temperature ceramics is embedded in the pipe wall. The reflected signals are analyzed when the liquid level in the pipe is varied. Finally, a conductivity sensor for the liquid under test is developed because changes in conductivity of the liquid are expected with changes in steam quality.

Task 4: Design and implementation of microwave sensors

The sensors designed in Task 3 are implemented, tested and compared with simulations in this task. Comparison between simulations and measurements lends confidence to the simulation results that are obtained when modifying parameters. Validated simulation models are also extremely useful when designing modifications to the sensing strategies due to the confidence in predictions from these simulations.

Implementation of the sensors is performed by the Schulich School of Engineering machine shop, with some machining of materials outsourced to a local supplier. Simplified lab-based testing is performed in the Applied Electromagnetics Research Lab at the University of Calgary using vector network analyzers and impedance analyzers, as appropriate. The characteristics of the sensors are measured and results compared to simulations. A baseline case is tested first. Where discrepancies exist, differences between the simulated model and experimental implementation are explored to determine impact on performance. After the baseline behavior is validated, the sensors are tested with scenarios representing different steam qualities. This allows comparison of the responses of the sensors under varying conditions with simulated predictions.

Task 5: Development of a laboratory-based flow experimental system

The experimental system designed in Task 2 is implemented in this task, and a range of test scenarios are defined. Initial testing involves ensuring that no significant leaks are present. Next, the water and air flows are varied to create different flow patterns in the pipes. These flow patterns are easily observed because the pipes are acrylic.

Prior to testing with the sensor, the flow is characterized. For example, the lowest flow rate and smallest adjustment for the pump, as well as the stability of the pump and compressor performance over time, are characterized.

With the flow characterized, a test plan is developed. The completed testing includes the responsiveness of the sensing system to changes in flows.

6. PROJECT RESULTS

Please provide a narrative describing the key results. If appropriate, use the project's milestones as sub-headings and include the following:

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

Task 1: Implementation of simulation environment for exploring interaction of microwave signals with two-phase flows

The EM simulations require both the electrical properties and geometry of the flow to be modeled in an automated fashion. The electrical properties of the liquid and gas phases are permittivity and conductivity. Permittivity is the ability of a material to store energy, while conductivity relates to the absorption of energy by the material (loss). The permittivity of the liquid phase is influenced by temperature and pressure, where temperature typically has a greater impact. Using data available in the literature, models are created to describe the changes in permittivity over frequency at different temperatures from 25 to 325^{o}C.

The conductivity of the liquid phase is strongly influenced by the total dissolved solids (TDS), as well as the temperature. As the steam quality increases, the TDS increase because the dissolved solids remain in the liquid phase while the water molecules move to the gas phase. Therefore, TDS will directly impact the conductivity of the condensate and it is necessary to obtain the conductivity as a function of TDS. As sodium and chloride comprise up to 90% of the TDS, a model available in the literature is applied to estimate the conductivity given the TDS. This model was confirmed via measurements. The conductivity of water with dissolved ions is dramatically impacted by temperature. It is widely accepted that conductivity increases by about 2% per degree temperature increase and this is incorporated into the model predicting conductivity.

For the gas phase, conductivity is negligible. The permittivity changes with pressure, and a model from the literature is implemented to represent these changes. A second scenario is considered, namely mist flow or small water droplets moving within the gas. The diameter of these droplets is expected to be less than 0.5mm, however it is not feasible to explicitly represent this physical dimension in simulation models. Alternatively, the equivalent electrical properties of the steam and droplets mixture is calculated using mixing laws previously reported in the literature. Two different approaches are considered, however experimental testing is required to determine which approach is the best fit for the scenarios of interest. With both approaches, small changes in permittivity are noted with changes in steam quality, implying that measurement approaches must be sensitive.

In addition to calculating the electrical properties of the liquid and gas phases, the two-phase flow must be physically located in the pipe. Based on preliminary fluid flow simulations, a stratified flow with very small water droplets moving within the steam is likely. Additionally, a difference in velocity between the mist and liquid phases is to be expected. The parameters of this flow are calculated with a set of functions that provide the velocity of both phases, the liquid height at the bottom of the pipe, and the amount of water droplets flowing in the steam. Figure 5 shows the different patterns that result from varying the wave speed and frequency of the liquid phase.

Therefore, a simulation model capable of representing the two-phase flows at different operating conditions has been developed. By creating models of the electrical properties of the liquid and vapor phases, as well as the dimensions of the flow pattern, a wide range of scenarios can be investigated by changing a few parameters in a script that populates information into simulations. Therefore, the results of this task meet the performance objectives. This simulation tool is used in Task 3, in which sensing strategies are tested with different flow scenarios. This is also a useful tool for future projects.

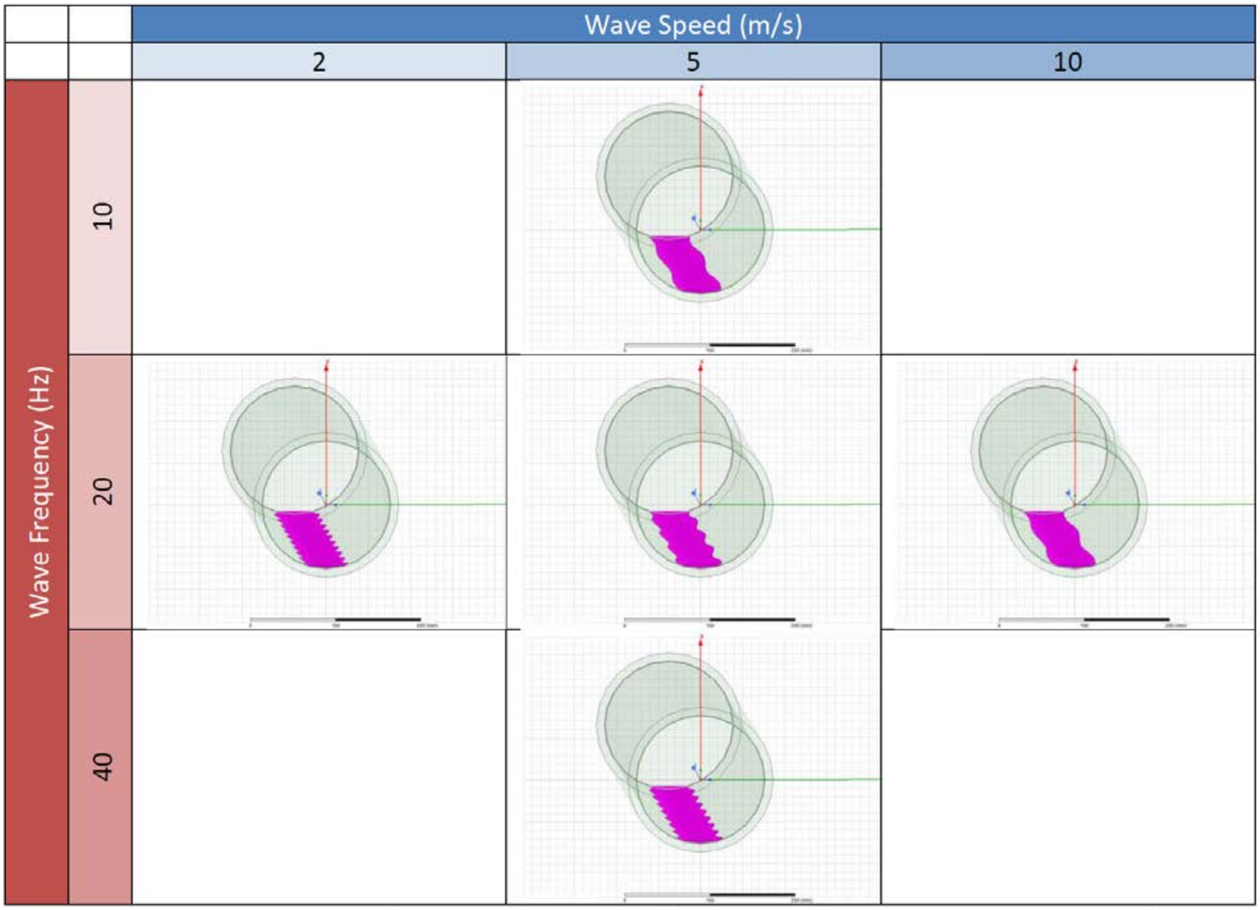


Figure 1 Flow patterns in pipes for different parameters of the wavy stratified flow.

Task 2: Defining two-phase flows present in OTSG and wellhead locations, as well as design of experimental testing

Simulations of 12” and 3” pipes are performed to investigate the flow patterns that are developed. As elbows are present in the OTSG, simulations are performed for 3” pipes that incorporate a range of elbows. Finally, the design of an experimental test facility is presented.

12” Pipe Simulations

A set of simulations is performed to predict the flow pattern in a 12-inch pipeline. Three steam qualities are considered: 80%, 90% and 96%. The pipe length simulated was 10 meters (32 diameters), long enough for the flow to become fully developed. Liquid water is injected at the pipe centerline through a 1.9-inch jet. Both ANSYS and OpenFoam simulation packages produced similar results, so only the ANSYS results are shown in Figure 2. For cases with lower steam quality (80%), a stratified liquid water layer forms at the bottom of the pipeline. For cases with higher steam quality (96%), liquid water remains close to the pipe centerline, possibly in the form of small droplets entrained by a continuous vapor phase. The axial location at which the liquid water reaches the pipe bottom is found to vary according to the steam quality, with lower steam qualities resulting in shorter axial distances.

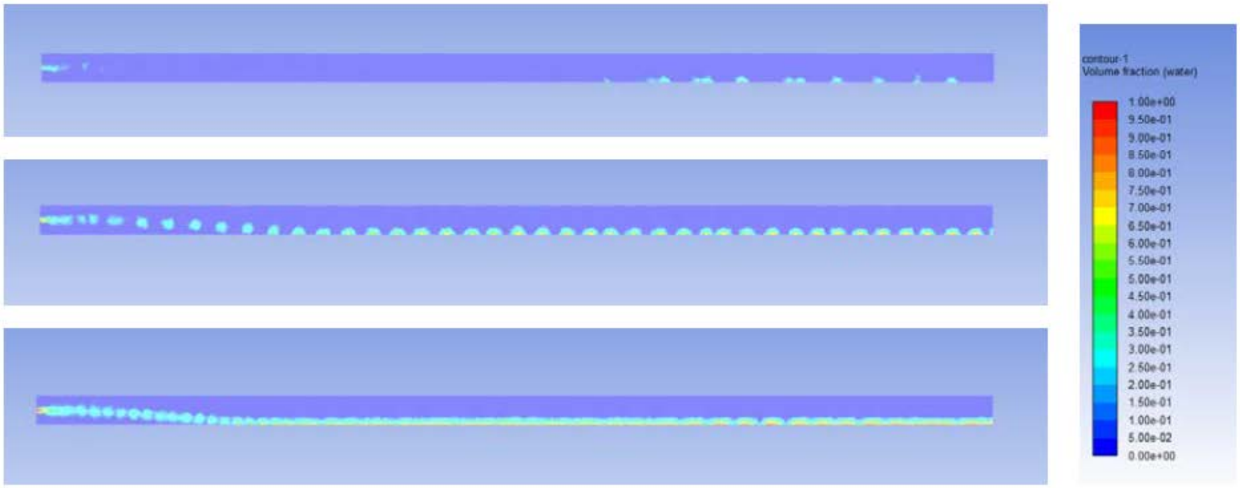


Figure 2 ANSYS Fluent - lateral view of 12 inch pipe with steam quality - 96% (top), 90% (middle), 80% (bottom).

3" pipe simulations

The OTSG plant has numerous 3-inch in diameter straight pipe sections, and the fluid flow in one of these sections is simulated. Two liquid water injection scenarios are examined: a 0.5-inch diameter jet that injects at the pipe centerline, and a 0.5-inch diameter jet that injects along the bottom of the pipe. The study objective is to determine the number of pipe diameters required for the flow to become fully developed.

The simulations with the 3-inch pipe show that the liquid water injection point influences flow development. Figure 9 shows the lateral view for the entire 10 m pipe length with superimposed cross-sectional views for the case of centerline injection. Non-intuitively, the liquid phase is found to move to the top of the pipe by the midpoint of the pipe length. This is believed to be caused by the centerline liquid jet breaking up into what appears to be large liquid slugs. These slugs are unstable and move in the azimuthal direction around the perimeter of the pipe. With downstream distance, the slugs start to move towards the bottom of the pipe cross section. For the bottom injection shown in Figure 10, although the liquid phase still displays a small amount of motion in the azimuthal direction, the angle to which the liquid phase moves up the pipe wall is greatly reduced from the case shown in Figure 9.

To further investigate the flow patterns due to varying flow rates and points of liquid phase injection, simulations are performed for a 3-inch diameter pipe section with a length of 10 meters (131 pipe diameters). These simulations are performed for a constant steam quality of 85%, however the injection velocity is 6.5 m/s or 8 m/s. The injection point is either at the middle or the bottom of the pipe. From Figure 11, we observe that the injection velocity of the liquid water phase plays a similar role to steam quality, with lower injection velocity resulting in a shorter axial distance before the liquid water phase reaches the bottom of the pipe. The liquid water phase is found to form a layer at the bottom of the pipe even when the liquid phase is injected at the pipe centerline.

For the experimental facility, injecting the liquid phase at the bottom of the pipe wall (6 o'clock position) will allow us to achieve fully developed flow in a shorter distance whereas centerline injection can assist in creating a mist-like pattern. Stratified flow is achieved after about 5 pipe diameters from the injection point when injecting at the bottom of the pipe section. When injecting at the pipe centerline, liquid water starts to form a layer after approximately 32 to 40 diameters, depending on injection velocity.

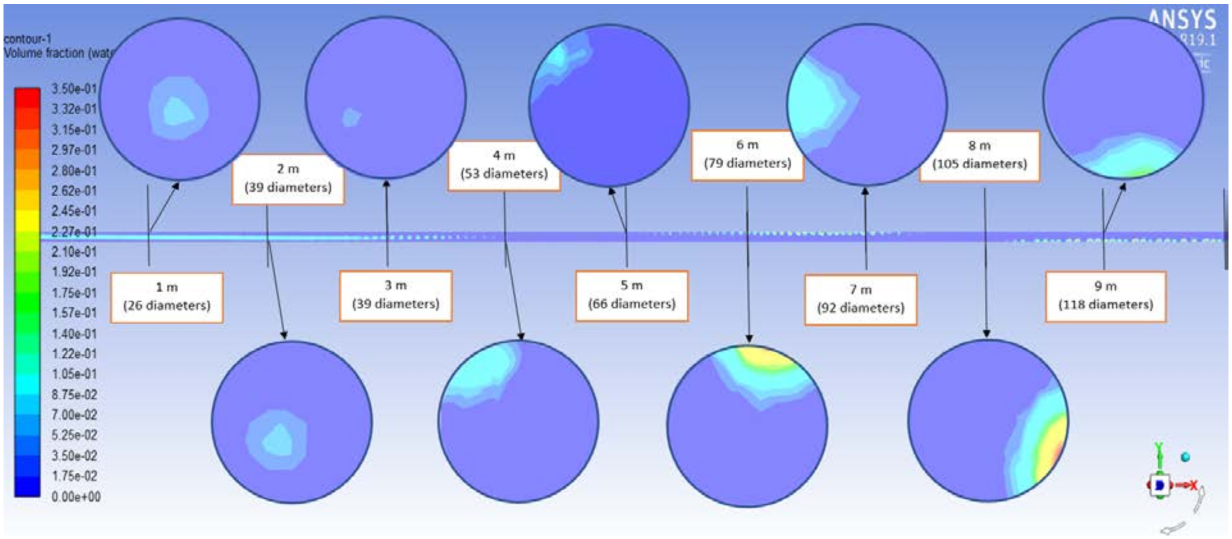


Figure 3 Spatial evolution of 3-inch diameter OTSG pipe section with water injection at pipe centerline

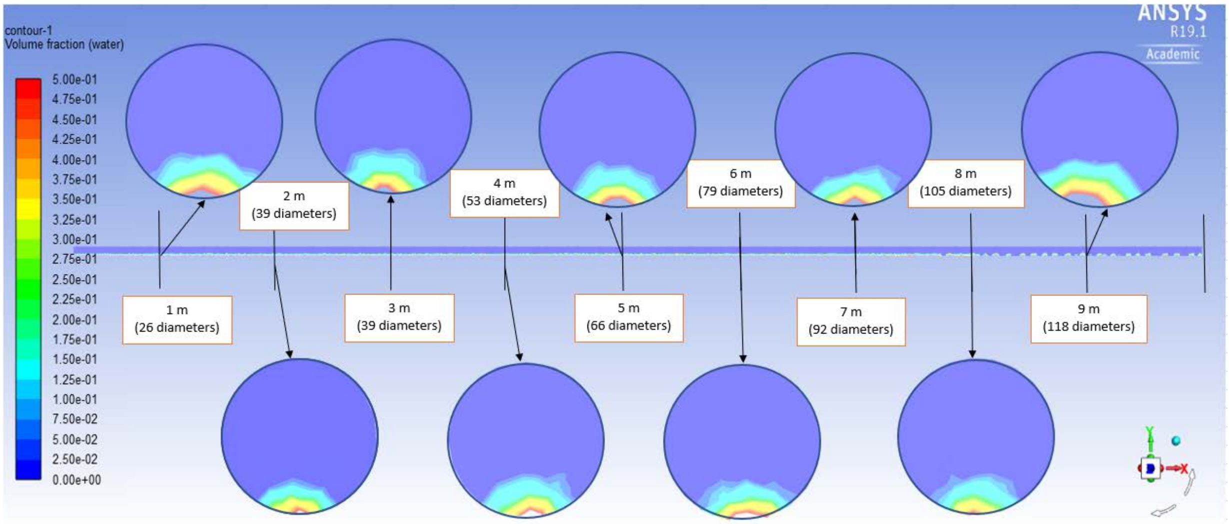


Figure 4 Spatial evolution of 3-inch diameter OTSG pipe section with water injection at pipe bottom

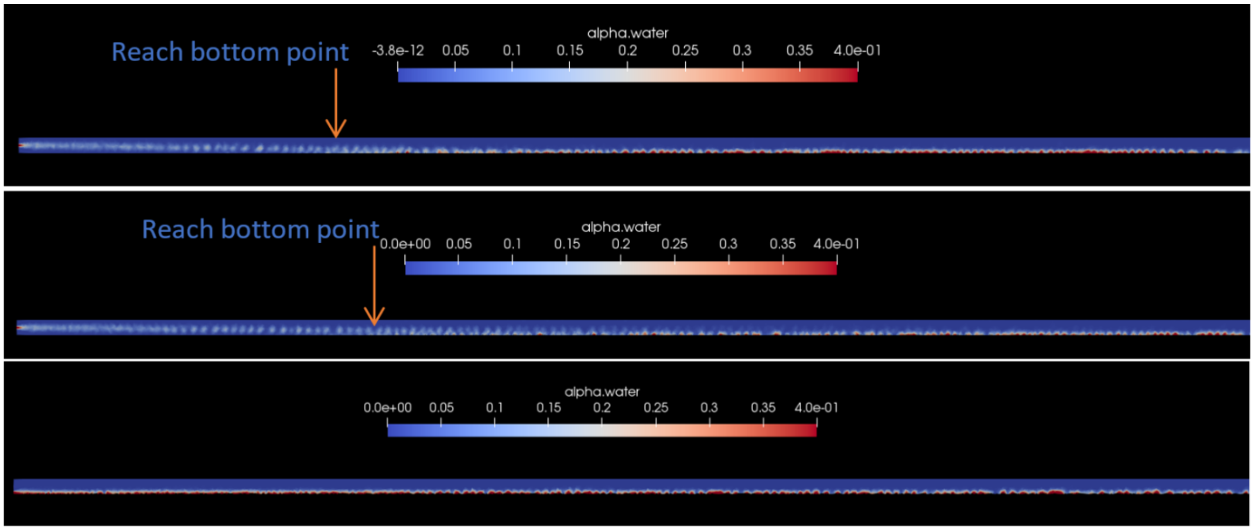


Figure 5 Lateral view of 3-inch OTSG pipe section with injection at the middle of the pipe (upper and middle) and the bottom of the pipe (lower). The injection velocity was 6.5 m/s (upper and bottom) and 8 m/s (middle).

One elbow

Simulations of both 3” and 12” pipes containing a single elbow are performed at 85% steam quality. An example simulation result (Figure 6) show that the elbow disrupts the flow, however it is re-established at a sufficient distance away from the elbow.

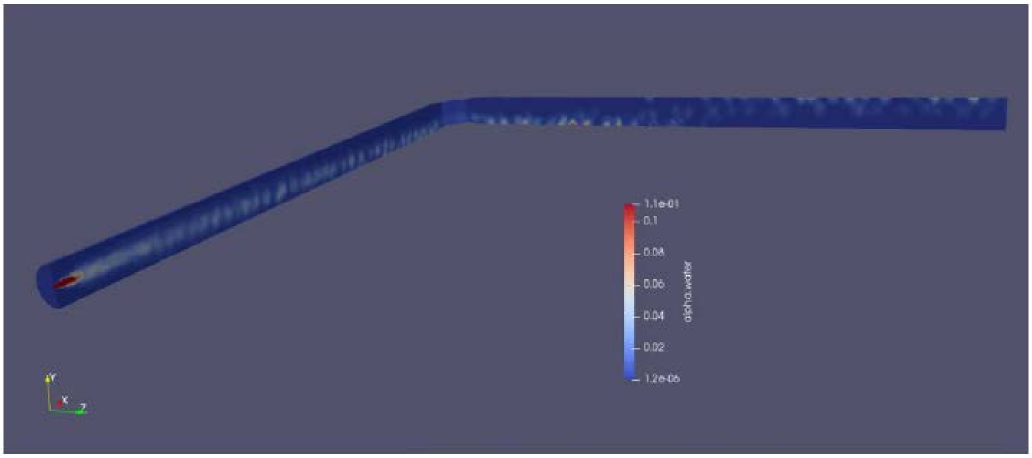


Figure 6 Simulations of 12” pipe with elbow performed with OpenFoam.

Two elbows

As the OTSG contains sections of pipe connected to elbows, further analysis of this scenario is performed with 3” pipe sections. The simulated scenario is shown in Figure 7 for a horizontal configuration and a configuration inclined at 15°. Table 1 summarizes the different configurations simulated with ANSYS Fluent; the steam quality for all scenarios is fixed at 85%. When comparing simulations performed at 20^{o}C and 300^{o}C for a selected inclination, differences are noted.

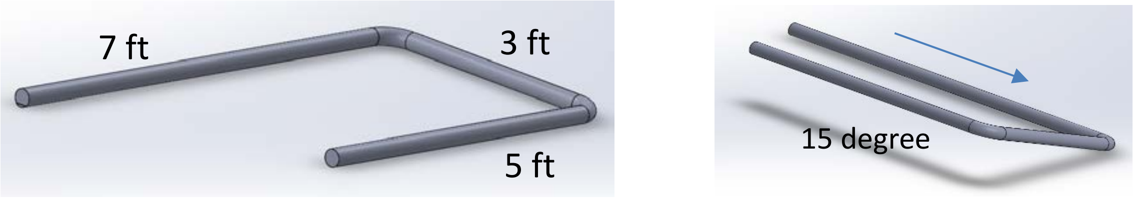


Figure 7 Pipe with two elbows (a) horizontal and (b) inclined at 15^{o}.

Table 1 Two elbow configurations simulated

Inclination	**Temperature**
Horizontal	20^{o}C
Horizontal	300^{o}C
15^{o}	20^{o}C
15^{o}	300^{o}C
30^{o}	20^{o}C
30^{o}	300^{o}C
45^{o}	20^{o}C
45^{o}	300^{o}C

For the horizontal case, a concentration of water in the region between the elbows is noted at the lower temperature (Figure 8). This concentration moves from the upper to lower part of the pipe. The flow in the outlet pipe exhibits spatial variation. Although it is located along the lower surface of the pipe, it is concentrated at certain locations. At the high temperature (Figure 9), a concentration is noted near the elbows with a slight accumulation at the top of the pipe. The flow is fairly stable in the outlet pipe.

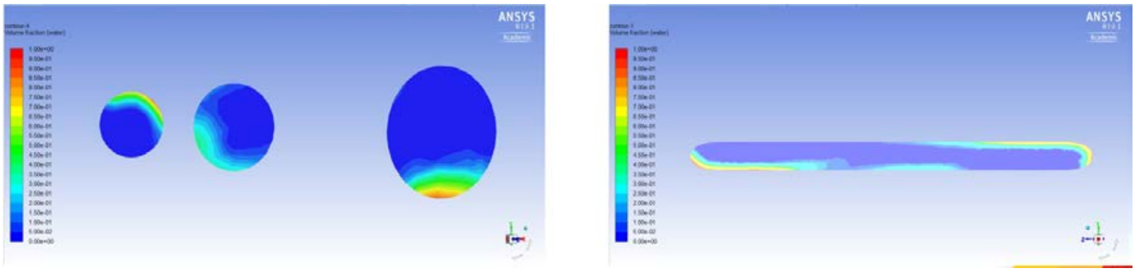


Figure 8 Cross sectional and lateral view of flow pattern between two elbows for horizontal pipe at 20°C

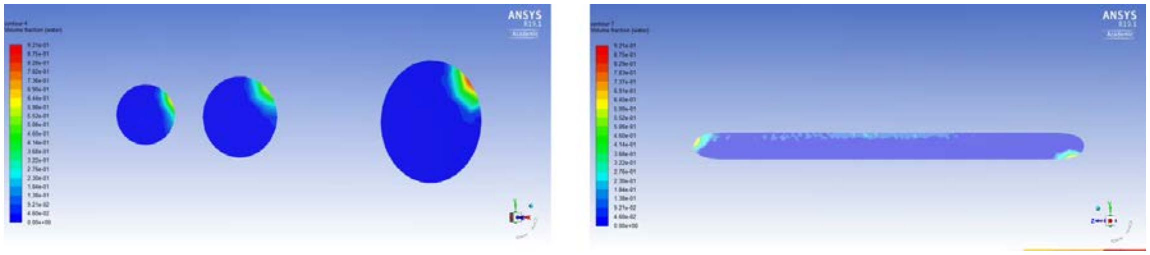


Figure 9 Cross-sectional and lateral view of flow pattern between two elbows for horizontal pipe at 300 °C

With an inclination of 15°, slugs are noted between the elbows at the low temperature (Figure 10). The flow in the outlet pipe is fairly stable, but does exhibit variations with time and location. At higher temperature (Figure 11), slight concentrations are noted in the upper and lower parts of the pipe between the elbow, but no slugs are present in the outlet pipe.

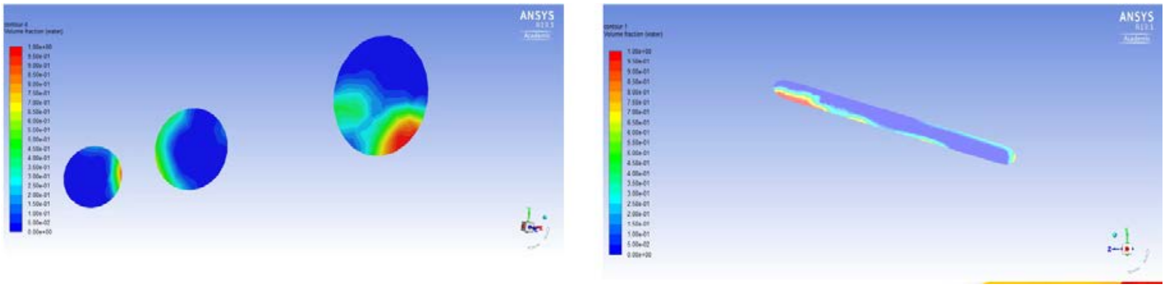


Figure 10 Cross sectional and lateral view of the flow pattern between two elbows for 15 ° inclined pipe at 20 °C

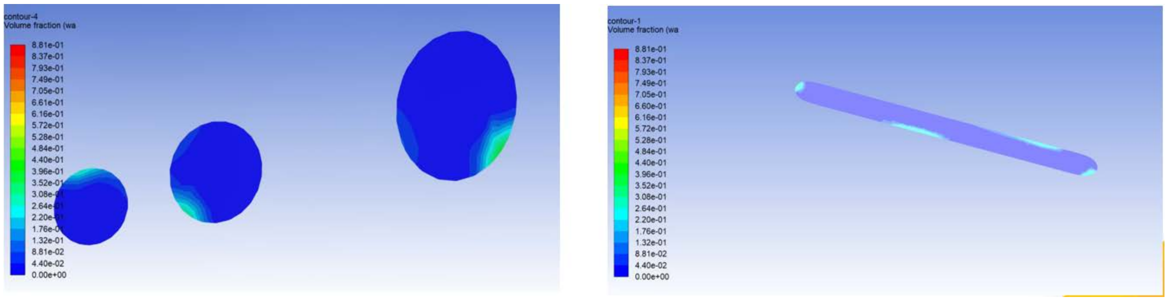


Figure 11 Cross-sectional and lateral view of flow pattern between two elbows for the 15 ° inclined pipe at 300 °C

Comparing different inclination angles, the slug that develops in the pipe between the elbows is at different locations. Specifically, the slug is further from the elbow on the outlet side with lower inclination angles. A similar trend is noted for the slight accumulation observed at higher temperatures.

As the OTSG operates at high temperatures and includes elbows, these results imply that sensing method must be robust to the location of condensate phase. The outlet pipe appears to exhibit stable flow within several pipe diameters, so sensing in relatively close proximity to elbows may not be problematic.

Design of the Experimental Facility

A horizontal multiphase flow facility will be adapted for this study (Figure 12). Liquid water will represent the liquid phase of steam, and air will represent the vapor phase. Pipe sections used in the flow facility are interchangeable from 1 to 3 inches, and this investigation will use the largest (3 inch) pipe diameter. Pipe sections are supported by two metal frames, as shown in Figure 13. The largest length of pipe possible is approximately 32 ft (10 m).

We plan to integrate cameras and an optical tomography system into the experimental facility in order to provide an independent measure of flow patterns. Three cameras are supported by a mobile frame (see Figure 14). The visualization pipe section is cast acrylic and surrounded by a hexagonal acrylic view box that corrects for optical distortions. For tomography, the cameras need to be placed around half of the acrylic pipe and separated from each other at a fixed angle (60 degrees for 3 cameras). The incorporation of the camera system into the experimental facility provides, at a minimum, the ability to collect 2D images that provide a top-down view of the flow in the pipe. This information can be used to estimate the amount of water present. The reconstruction of the flow via tomography techniques uses a volumetric imaging algorithm developed in MATLAB and ImageJ. The possibility of both mist and stratified flow patterns at the same time may bring new challenges to the volumetric reconstruction of the flow.

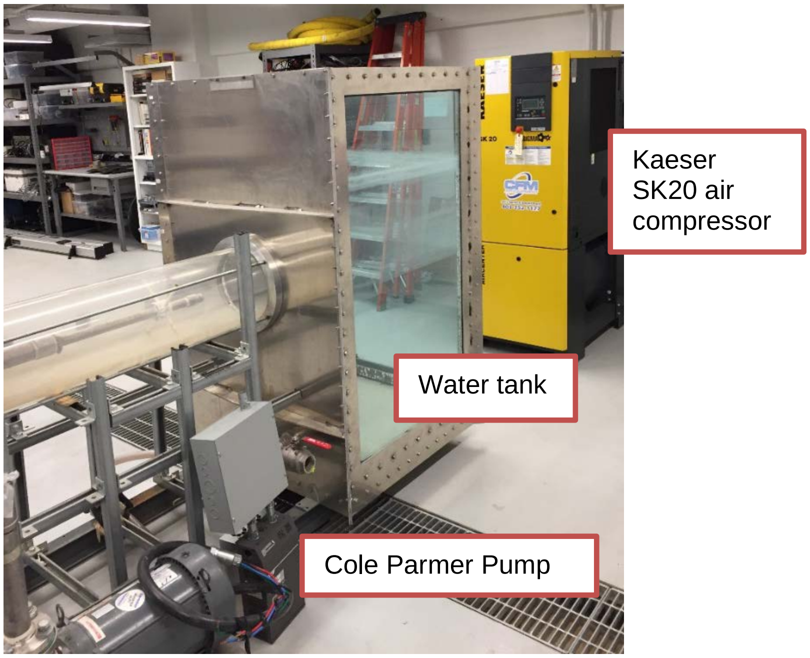


Figure 12 Multiphase flow facility at the Mechanical Engineering Department at the University of Calgary. The flow of liquid phase water is provided by a Seepex BN 17-6L pump that delivers water flow ranging from 5-50 GPM. Air flow is provided with a Kaesar SK 20 air compressor that operates at 125 psig and provides 88.3 cfm of air at operating pressure.

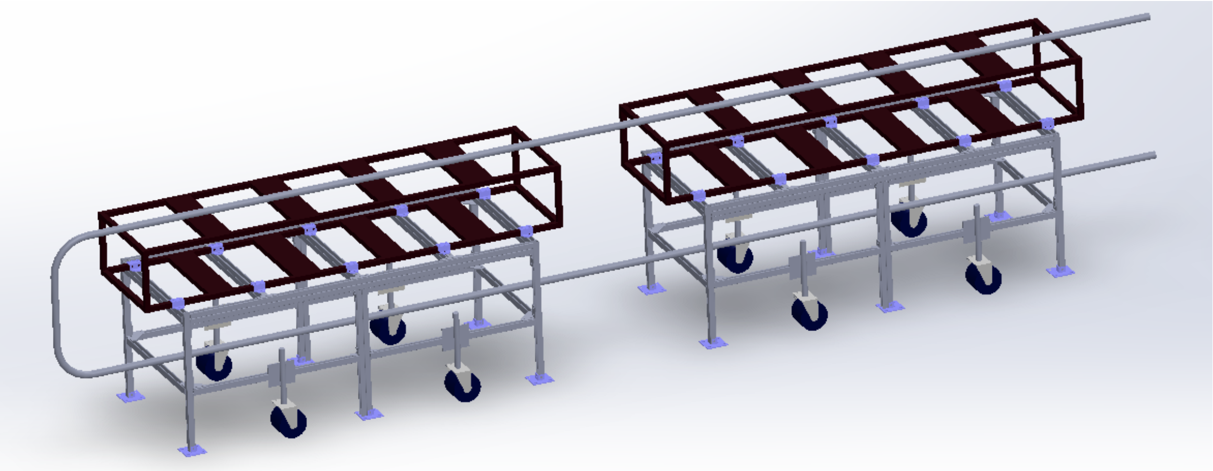


Figure 13 Pipe frame with a maximum length of 32 ft (10 m)

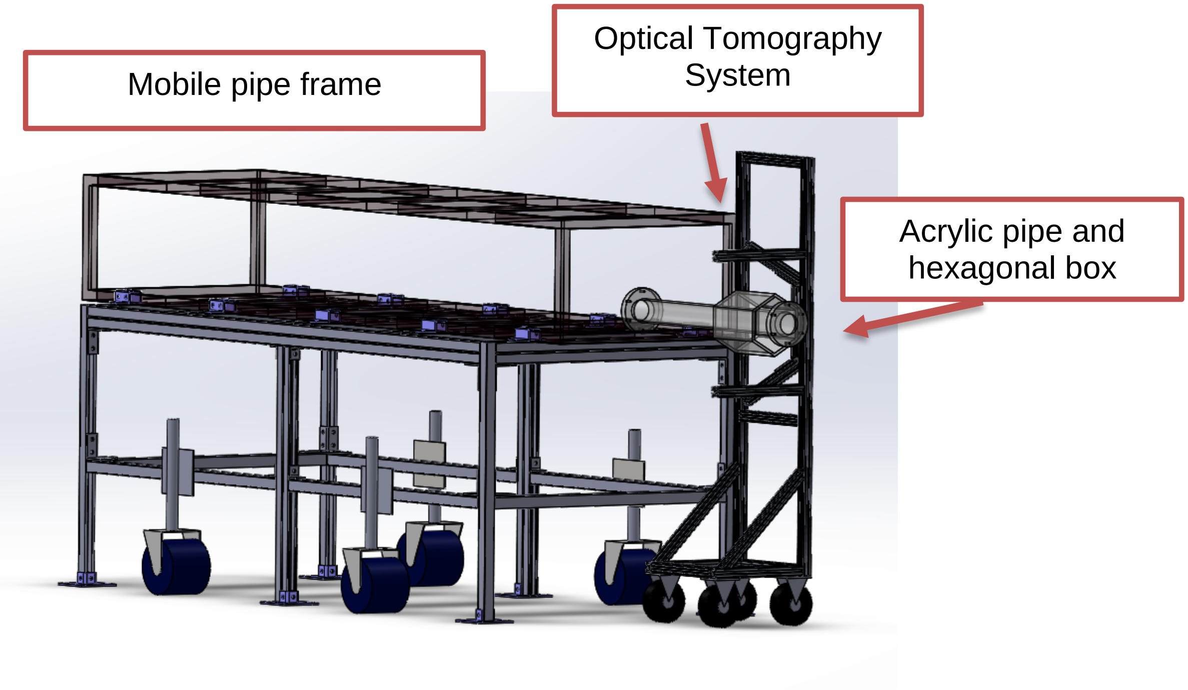


Figure 14 Pipe frame and optical tomography frame

The performance metrics for Task 2 include investigation of a range of scenarios related to 2-phase flow, as well as design of an experimental test facility expected to support flows of interest. The simulations described in this section are developed in consultation with our industrial partner, and allow for exploring flows with different temperatures, velocities, and pipe geometries. This exploration feeds into the design requirements for the sensing system. The experimental test facility has been designed to support two-phase flows (water and air). The simulations also suggest that the water should be injected at the bottom of the pipe for stratified flow developing within ~5 pipe diameters or the centre of the pipe for mist flow. Finally, simulations suggest placing the sensor before any elbows are present, as well as providing an independent method to characterize flow (e.g. optical tomography).

Task 3: Study different sensing approaches

The sensing approaches are explored from the simplest to the most complex. Simulations are used to examine the response of proposed sensor designs under different conditions.

Capacitive sensing

The simplest approach to sensing is a low-frequency capacitance measurement. This involves embedding electrodes on either side of the pipe. The capacitance is expected to change when different amounts of liquid are present between the electrodes. However, the capacitance was found to change when the distribution (shape) and volume of liquid changed, so alternative approaches were pursued.

Microwave sensors

The next technique explored is a microwave field reflection measurement (FRM). A FRM result depends on the material inside the pipe. The goal is to have FRM results that are functions of the materials inside the pipe. This is shown in the figure below that illustrates the response of one design as steam quality is adjusted. We note that several designs are explored via simulation, however the details of these designs are not elaborated due to potential for technology transfer and commercialization.

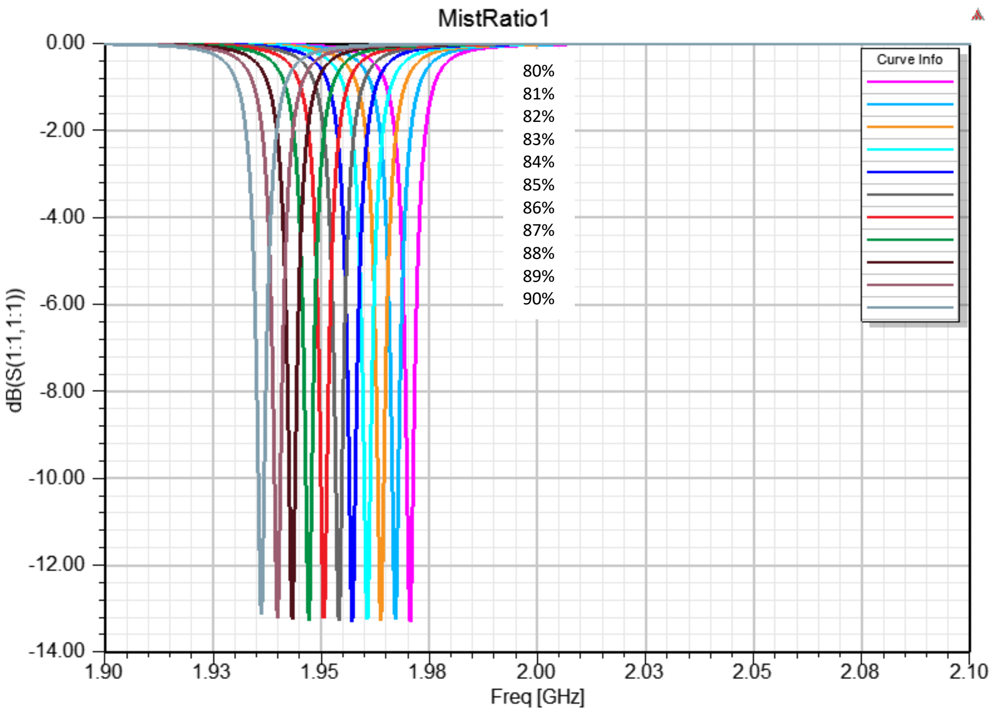


Figure 15 Reflected signal from FRM changes with change in steam quality.

Phase reflection

To find the height of the liquid level in the pipe, a reflection-based approach is examined. This approach consists of embedding an antenna in the pipe wall, then analyzing the phase of the reflected signal. The antenna may potentially be used to feed the FRM, providing two approaches to sensing in combination. Although this approach was promising in initial feasibility studies, further investigation demonstrated that this approach is not feasible due to the high conductivity of the liquid layer (due to TDS).

Conductivity measurement

The final approach to sensing involves measuring the conductivity of the liquid phase with a sensor embedded in the pipe. Figure 16 demonstrates that the conductivity estimates obtained via simulation of this sensor design are accurate to within 1%.

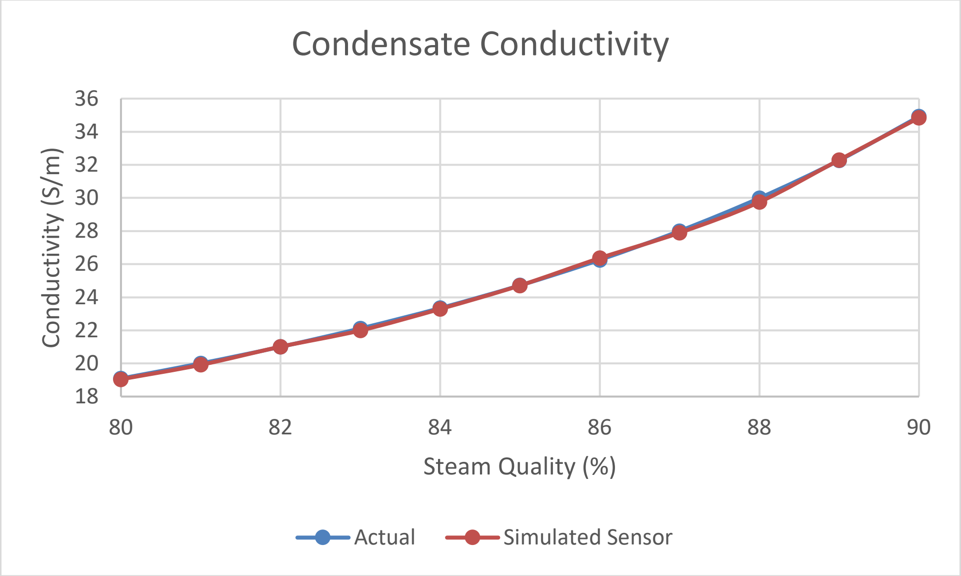


Figure 16 Conductivity extracted via simulations of the sensor in Figure 32 is in good agreement with the known value over a range of practical steam qualities.

In terms of performance metrics, Task 3 aimed to design sensors capable of characterizing steam quality with accuracy of 1%. FRM designs are shown to be capable of this. A second sensing approach to provide a measure of conductivity is also proposed.

Task 4: Design and implementation of microwave sensors

A key challenge is translating simulations of sensor designs into practice. In Task 4, the FRM designs and conductivity sensor are implemented. Measured results are compared with simulations in order to verify behaviour.

FRM testing

Several designs are implemented and tested. Tests and results for two FRM designs are presented, although the details of these designs are omitted due to technology transfer potential.

The first tests are performed with an empty device. Figure 17 shows the measured and simulated impedance magnitude over frequency. First, we observe that measured responses are just below 2.87 GHz while the simulated response is at 2.877 GHz. This discrepancy is fairly minimal and is most likely the result of dimensional mismatch between the model and physical FRM. We observe, however, a great difference in magnitude. The impedance magnitude is typically ~2000 Ω when the FRM is measured. High impedance values have not been observed in simulations despite refinement attempts. Overall, the correlation between simulated and measured results is satisfactory other than the impedance magnitude at response.

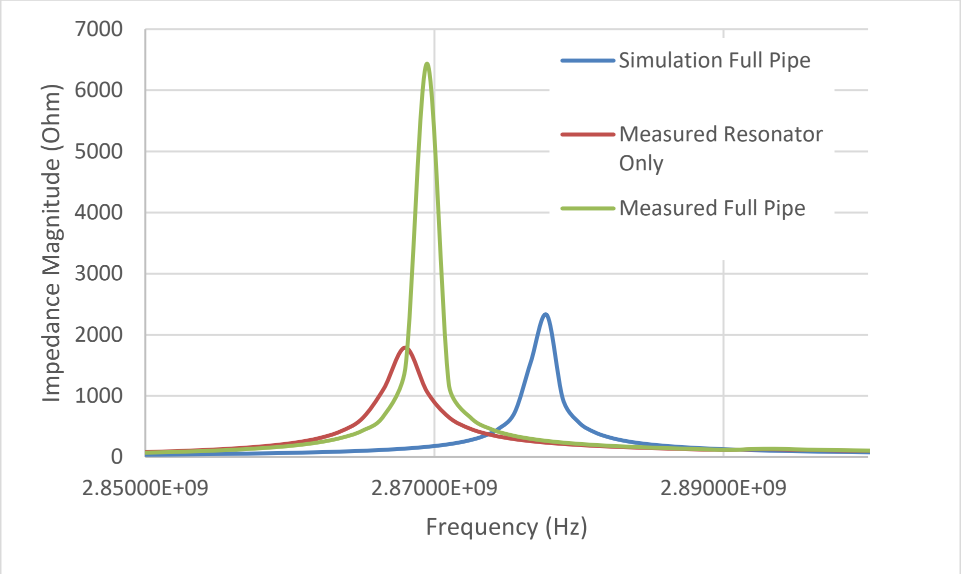


Figure 17 Impedance response of the empty FRM. Measurements are collected with the FRM only and with additional pipes connected to the FRM.

The second set of tests involves measuring the response of the FRM with and without steam. As steam has slightly higher permittivity than air, the response frequency is expected to slightly decrease. The experimental setup is shown in Figure 18. A beaker of water is heated by a hot plate, and the FRM and two pieces of pipe are placed on top. The steam starts to form and travel through the pipe and FRM structure. First, the steam passes through the entire system until it heats up and the measured response becomes stable. Due to expansion of aluminum, the response frequency is expected to decrease. Therefore, it is important to ensure that the temperature is similar between the measurements with and without steam. Using a thermocouple, the temperature on the surface to the FRM is measured. The temperature can fluctuate enough to modify the response of the FRM in a very short time. Therefore, all measurements were taken when the FRM temperature was at 52.8 °C. To stop the steam, a simple aluminum plate is placed on top of the beaker.

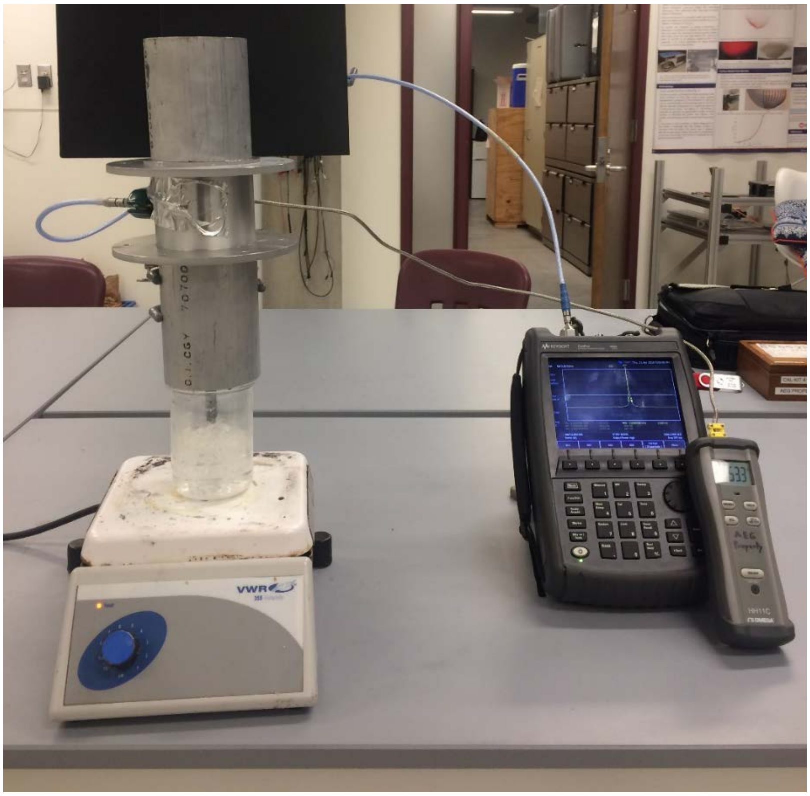


Figure 18 Setup for measuring steam going through the FRM.

Figure 39 shows the measured results for steam and no steam in the FRM. First, quite high impedances (between 10 000 to 20 000 ohm) are measured. These values are higher than previously measured. This may be related to the condensation that is naturally building up in the pipe. However, this does not dampen the response, so this test setup performs adequately. The frequency of response sits at 2.858GHz and 2.859GHz with and without the steam, respectively. This is a difference of only 1MHz instead of the 10MHz expected based on a relative permittivity of dry steam of 1.006. The 1MHz shifts equals to a steam permittivity of 1.0007, which is about 10 times smaller. The reason for such a small shift in response frequency may be because the steam does not occupy the entire space.

Based on these results, an improved experimental system would be beneficial. First, the FRM should be kept at a constant temperature of 100°C. Second, another way of generating steam should be used that ensure sufficient capacity. Lastly, the pipe system should be sealed. However, these results do demonstrate the reliable detection of steam using the FRM.

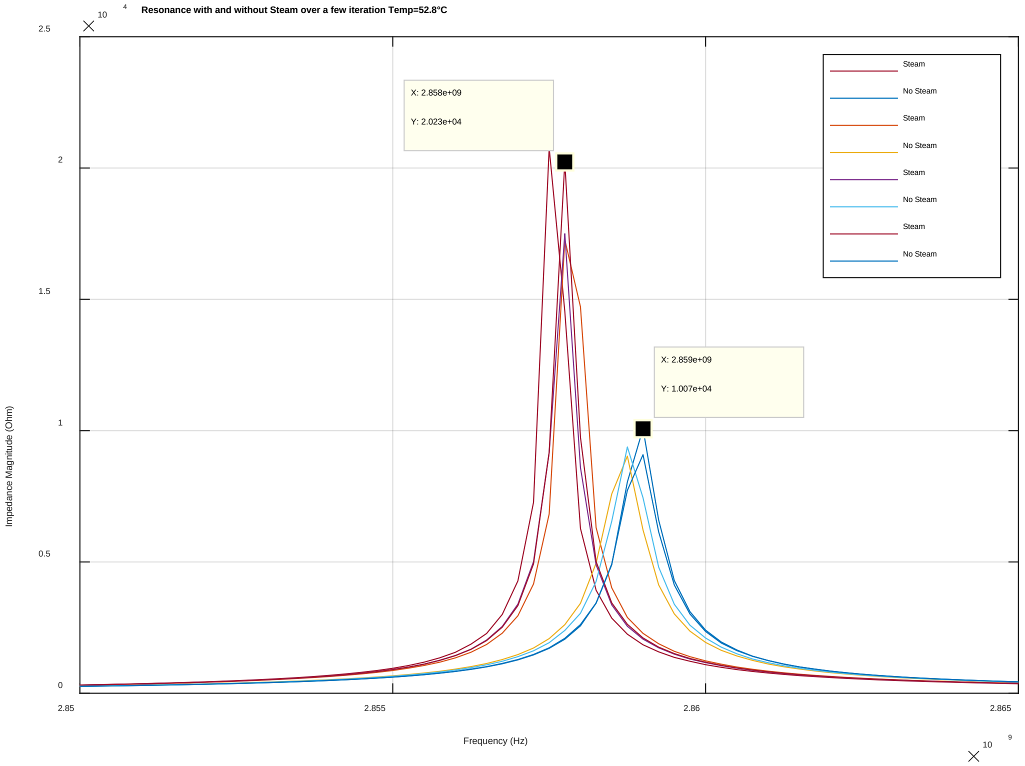


Figure 19 Measured impedance magnitude with and without steam

The third set of tests mimics a stratified flow with different steam qualities. This consists of placing a specific amount of tap water in the FRM corresponding to a specific steam quality. This design is not particularly well suited to measuring amounts of liquid due to its nonlinear behaviour. However, the goal of this experiment is to validate the simulation. A small amount of liquid is added to the pipe to simulate specific steam qualities (Table 2). For each steam quality, the response of the FRM is measured.

Figure 20 shows the impedance response measured for each steam quality. The magnitude is about 300 ohms for the highest quality (smallest amount of water), demonstrating the dampening effect that liquid water has on the response compared to the empty FRM case. As expected, the impedance decreases as the steam quality decreases (amount of water increases) until the 86% mark after which the impedance increases again with a shift of the response to slightly higher frequencies. For a steam quality of 80%, the impedance magnitude is similar to the 90% case with only a small frequency shift. The same trend is observed in simulations.

Due to its surface tension, the water surface is curved during the experiment, while a flat water surface is simulated. The liquid height in simulation is scaled by a factor of 1.15 which was found iteratively to best match the measured data (Figure 21). Further improvement in the simulation model could be implemented to account for the surface curvature observed in measurement, or soap could be added to the water in experiments to reduce its surface tension. Nevertheless, this comparison between simulations and measurements demonstrates that simulation can effectively calculate the frequency response behaviour of a cylindrical FRM with a stratified flow representing different steam qualities.

Table 2 Steam quality and corresponding amount of liquid water.

Qs (%)	H_L(mm)	Volume (ml)
90	2.46	3.58
89	2.64	3.98
88	2.81	4.37
87	2.99	4.79
86	3.17	5.22
85	3.34	5.65
84	3.51	6.08
83	3.69	6.55
82	3.86	7.00
81	4.03	7.47
80	4.21	7.97

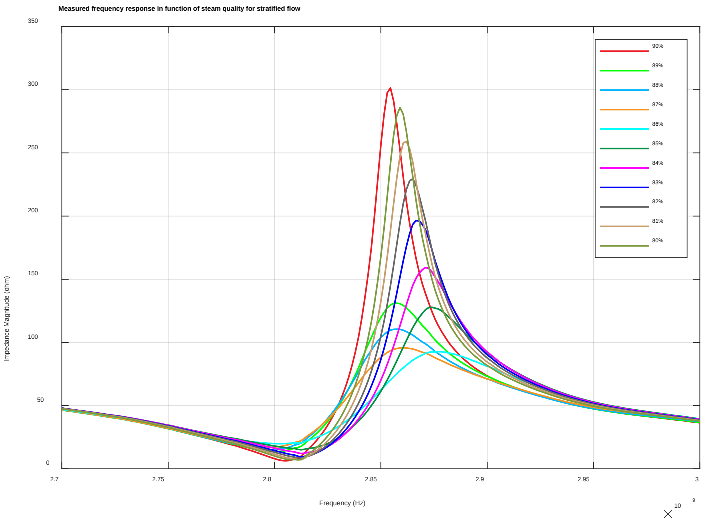


Figure 20 Measured impedance response for different steam quality

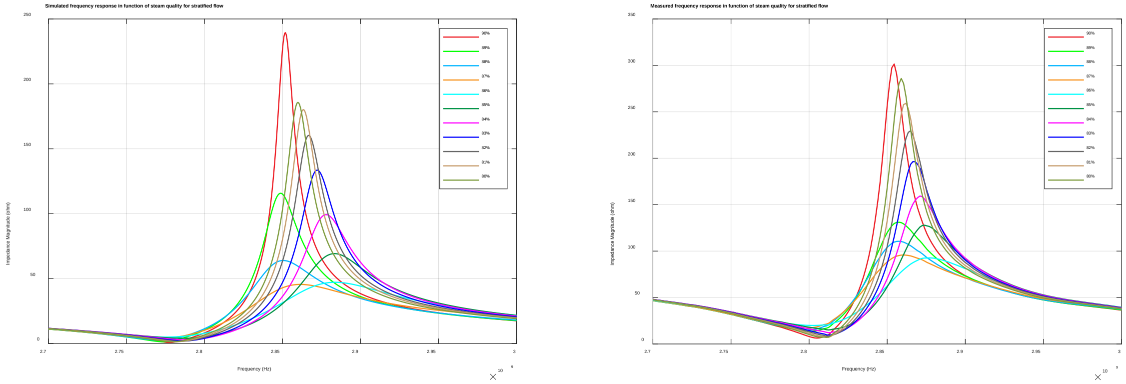


Figure 21 Left: Simulated frequency responses over different steam qualities. Liquid height is scaled by a factor 1.15 to account for curvature of the water. Right: Measured frequency response.

In summary, the first FRM prototype is measured under multiple scenarios and compared with theoretical knowledge and corresponding simulations. It is found that the measured response over the frequency range of interest is in agreement with simulations, allowing for prediction of behavior via changes to simulation models. When steam flows through the FRM structure, the resonant frequency shifts to lower frequencies, as expected. Water accumulation within the FRM structure is found to be problematic. Finally, testing the FRM with small amounts of liquid water shows that the measured frequency response trend matches with simulations.

For a second FRM design, excellent agreement between simulations and measurements is achieved. A similar set of tests is performed to verify the FRM response to scenarios representing various steam qualities. This allows parameters to be extracted from the response curve that relate to the steam quality. The plot below shows that the parameter associated with the FRM response tracks steam quality.

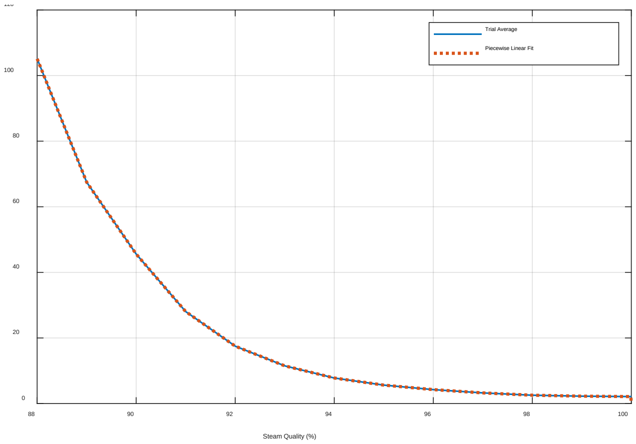


Figure 22 FRM parameter vs steam quality averaged of the 3 trials with a piecewise linear curve fitted to it.

Tests were also performed with two different measurement instruments. Figure 23 shows these results, indicating that error of less than 1% is obtained over the majority of the range of steam qualities. Unexpected variation is observed below 90% steam quality. To investigate the lack of accuracy at lower steam qualities, the measured signals are analyzed in more detail. Because of the different measurement equipment, there are changes in the FRM response and it is challenging to measure the parameter. Alternative features may be useful to explore. In addition, these observations demonstrate the necessity of stable measurement devices or electronics.

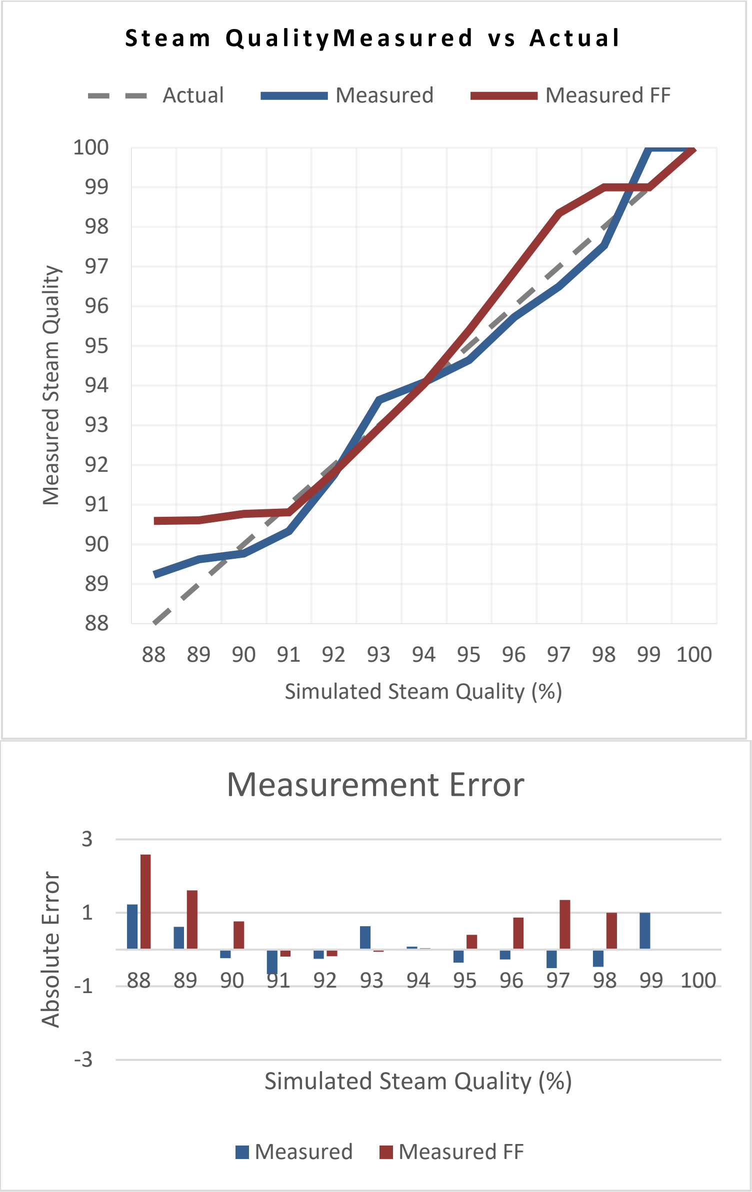


Figure 23 Validation of the steam quality measurement. Measured FF refers to a measurement instrument that results in differences in the response curve.

To test with low flows, a setup was developed consisting of a peristaltic pump with flow controlled by voltage of a lab power supply. The setup is shown in Figure 24. Knowledge of flow only cannot provide steam quality information as the flow speed is unknown. Therefore, a microwave reflection is also used to measure the liquid height in the pipe. This is implemented by using a previously developed reflection-based sensor. This technique was found to work well in static conditions. With a dynamic flow, the shape of the water layer is disturbed by the inclusion of this sensor. Therefore, there are limits to the accuracy of this approach.

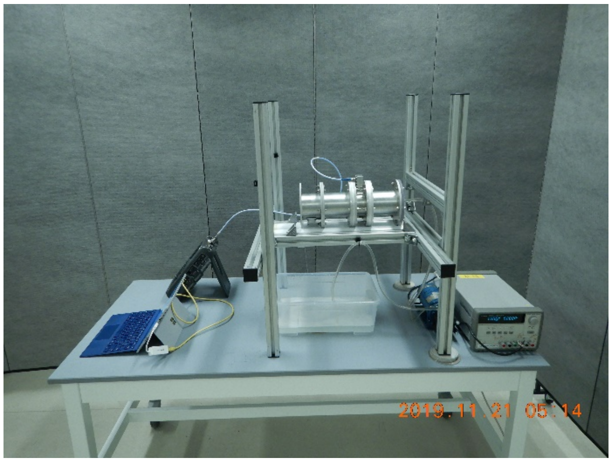


Figure 24 View of the test setup for dynamic flow.

Figure 25 shows the measured steam quality over 3 iterations. The fourth curve (reflection based) is the result given by the reflection measurement described above. In general, there is a good match between the two methods for voltages above 8V (96% Qs). However, the discrepancy increases for lower flow rates. This is due to water build up on the system, preventing the measurement of higher steam quality values. The pipe used for the reflection measurement is not exactly the same diameter and impacted the flow behaviour. While it is acknowledged that the reflection-based measurement is not ideal, the correlation observed for a significant part of the flowrate shows strong evidence of accuracy of the steam quality measurement. Also, the steam quality decreases linearly with the increase in pump voltage. This is expected as the flow increases linearly with pump voltage. Based on all these results, we infer that the steam quality is measured accurately in the flow regime.

Finally, the measurement stability with time and response time are investigated. Figure 26 shows that the measurements are stable over time. The step-like changes at higher steam quality are due to low sensitivity of the FRM parameter at high steam quality value. The largest change is observed at 14V with change of +/- 0.5%. This is still quite reasonable given that it corresponds to a liquid height change of +/- 0.1mm. Figure 27 shows that the sensing method quickly tracks changes in flow (steam quality), suggesting the potential for real-time monitoring. The response time is limited by the communication between the measurement device and computer controlling data acquisition (~300 ms).

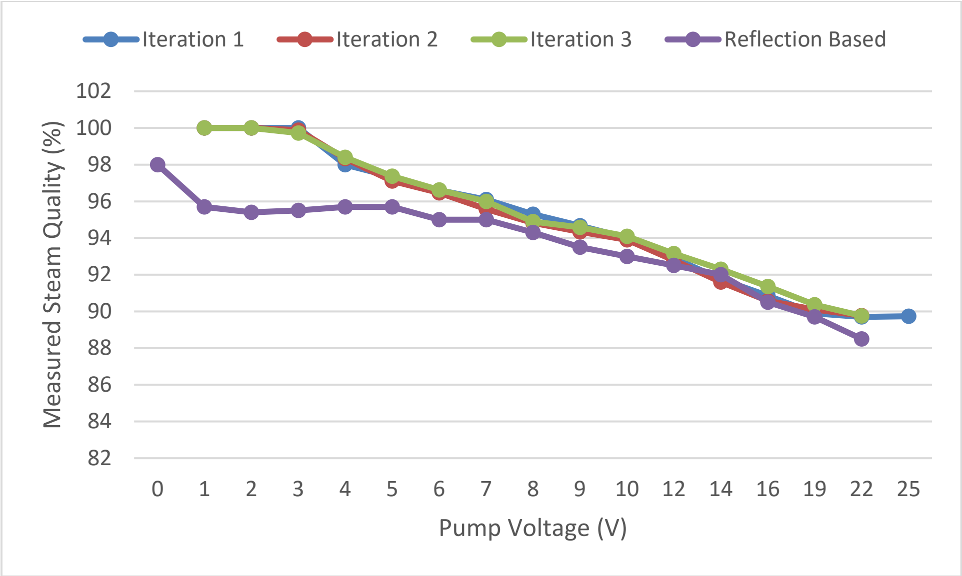


Figure 25 Measurement of steam quality as a function of pump voltage using the FRM and the reflection-based technique.

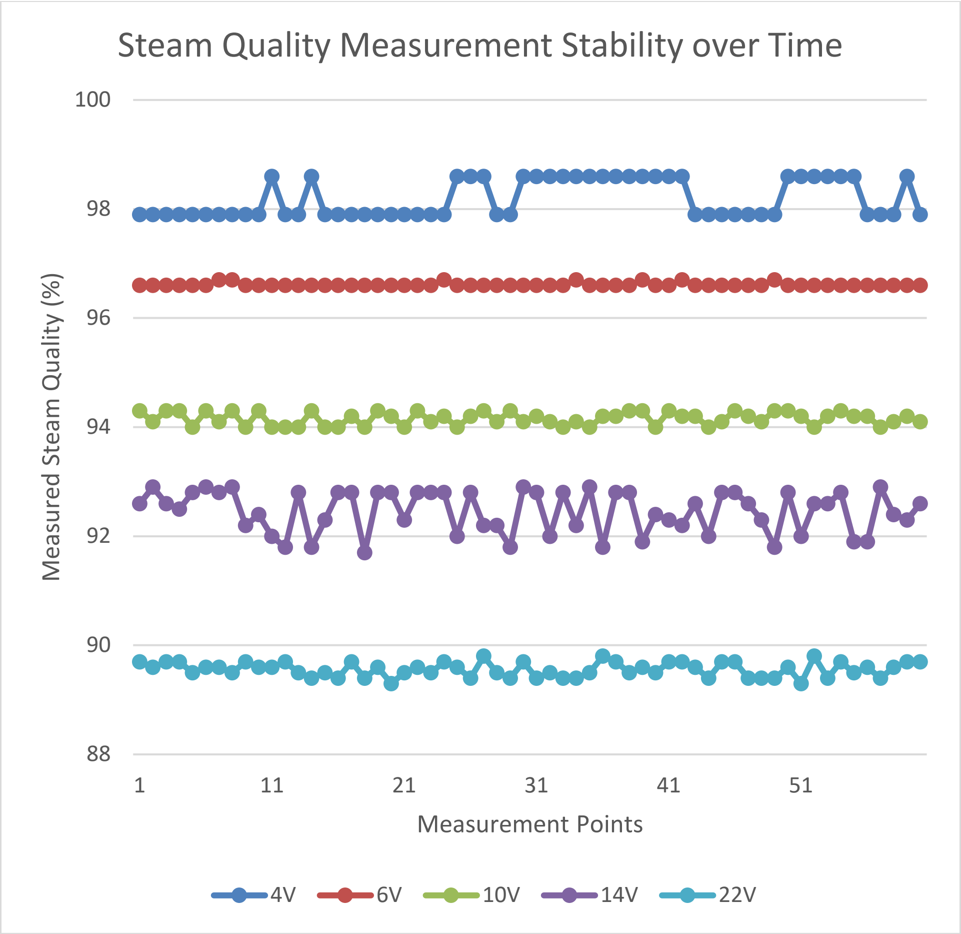


Figure 26 Measured Steam Quality over 60 points during a 90 seconds time span.

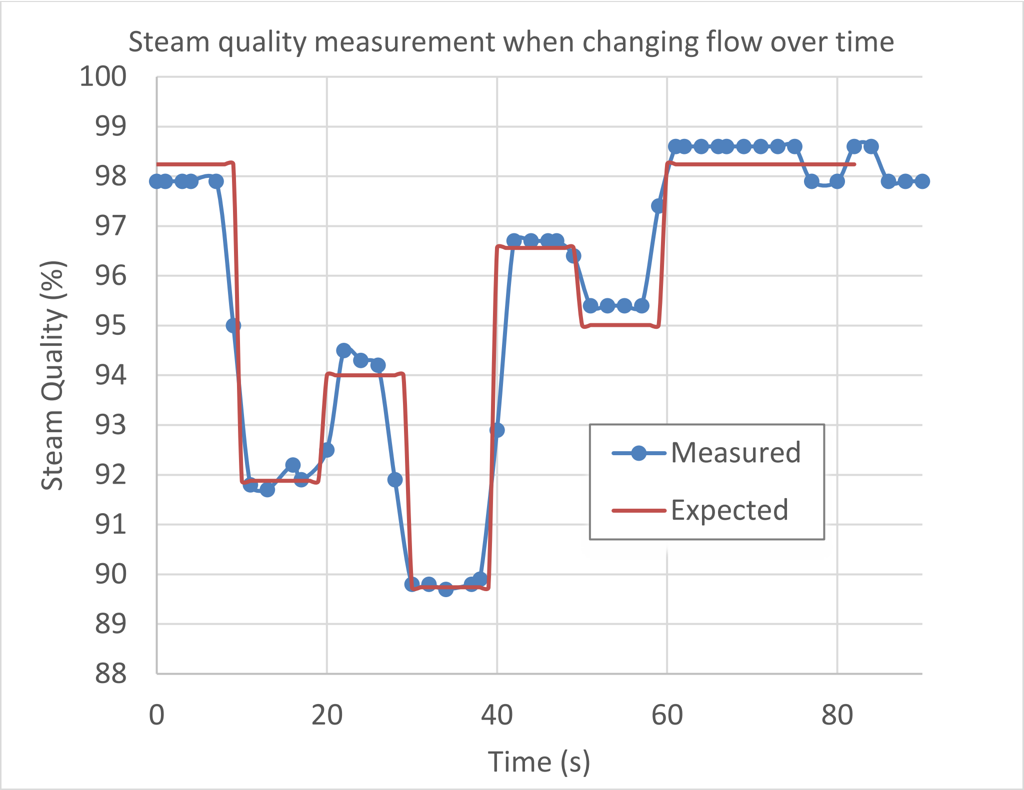


Figure 27 Measured vs expected steam quality when modified dynamically over time.

All of the above testing has been performed at room temperature and without appropriate water conductivity variation. An OTSG will operate at 315°C and 10MPa, while the conductivity of the condensate will change as a function of the feedwater conductivity and steam quality. In this section, the response of the FRM is studied at realistic operating conditions using simulations. Figure 28 shows the FRM parameter as a function of steam quality. One observes a linear relationship over the entire tested range from 80% to 97%. The change is about 3% per 1% in steam quality, which can be easily measured. For comparison, the calibration curve used for the room temperature test shows the same change of 3% per percent steam quality between 93 and 95%, and we observed excellent accuracy.

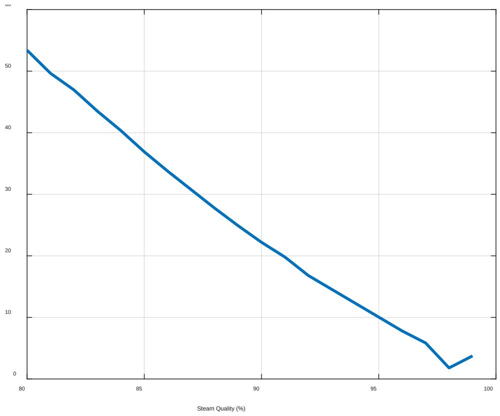


Figure 28 Calibration curve for the FRM at 315°C and 10 MPa, based on simulated data.

In summary, testing with the second FRM design in a range of scenarios demonstrated the ability to detect changes in steam quality of 1%. Additional testing demonstrated consistent results with time and the ability to track changes in steam quality. Sensor performance is also anticipated to be robust to expected OTSG operating conditions.

Conductivity probe

As the water is evaporated, its conductivity increases with steam quality. Figure 73 shows the conductivity change with steam quality at 315°C and 10 MPa. Analysis indicates that the conductivity probe should be able to measure conductivity between 15 to about 60 S/m with an accuracy of 2.5% to ensure correct measurement of steam quality.

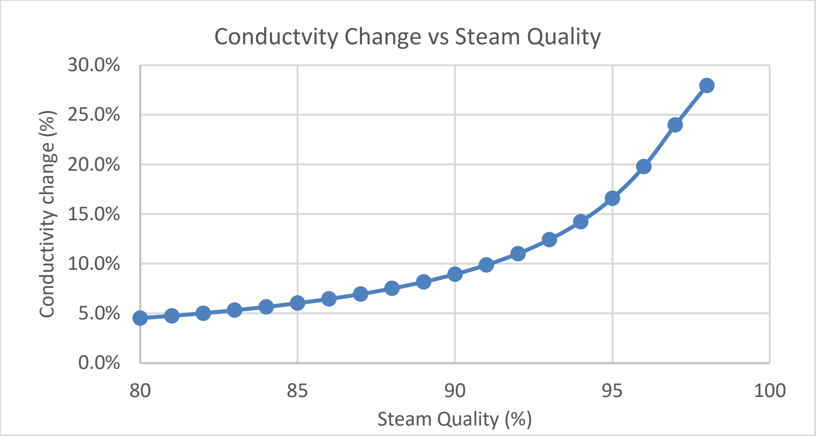


Figure 29 Conductivity and conductivity variation in function of steam quality at 315°C and 10 MPa.

An impedance analyzer is used to measure the probe response from which the liquid conductivity is deduced. This is performed at 1MHz frequency as this frequency is high enough to avoid electrode polarization issues and low enough to avoid parasitic problems. The probe is calibrated using two liquids with conductivity of 0.14 and 1.29 S/m. Then measurement of water with different salt concentrations is performed and compared with tabulated data in Figure 30. Measured error is approximately 10% for lower salt concentrations but reduces considerably above 3% concentration (5 S/m). Between 80 and 90% steam quality at 315°C, the conductivity increases by about 5 to 9% for each percent of steam quality increases. Therefore, a maximum error of 2 to 3% is an appropriate benchmark for conductivity measurement.

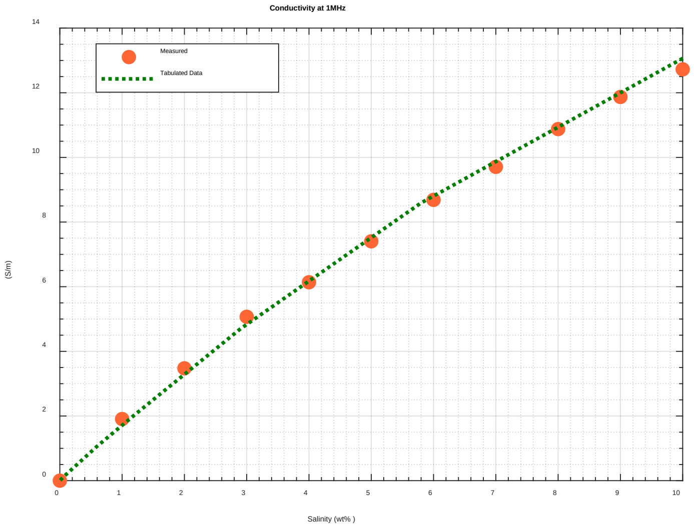


Figure 30 Comparison between the measured and tabulated conductivity based on the salinity of water. Tabulated data are from Galama A.H., Hoog N.A., Yntema D.R., "Method for determining ion exchange membrane resistance for electrodialysis systems", Desalination, Volume 380, 15 February 2016, Pages 1-11

Task 4 Summary: The key metrics for this component of the project are demonstrating agreement between simulations and measurements of the implemented sensors. This was successfully achieved with a FRM design and conductivity probe. Simulations and measurements of multiple scenarios provided insight into the capabilities and limitations of these approaches. One FRM design is very promising and can fulfill the requirement of assessing steam quality at +/- 1% accuracy. The only limitation is that it requires the liquid and steam velocity to be the same as it only measures how much space is occupied by the water. Alternatively, if the steam velocity is known along with the mass flow rate at the inlet, the condensate velocity and hence the steam quality can be calculated.

Task 5: Development of a laboratory-based flow experimental system

Figure 31 and Figure 32 show the experimental system. A user interface is developed to control the pump and measurement settings, as well as to display the measurements collected by various sensors. This includes air pressure and temperature, as well as volumetric flow rate for air and water. To investigate the flow established in the system, the pump is adjusted and water flow rate recorded. The average flow rate vs. input voltage is shown in Figure 33. The lowest average flow rate attained is about 0.165 L/s (3 Hz). The smallest increment to the pump is 0.01 V (~ 0.1 Hz increment), which corresponds to an average flow rate increase of 0.003 L/s . Similarly, the flow rate of air is investigated and results indicate that from 13 L/s to 21 L/s provides the most stable operation

Steam quality is varied by fixing the air flow rate and adjusting water flow rate. By adjusting the supply and bypass valves, the average water flow rate can be reduced from 0.165 L/s to 0.001 L/s. At an air flow rate of 13 L/s and a water flow rate of 0.001 L/s, the system can simulate a steam quality of 98%

Figure 31 Pipe frame and section with FRM and optical tomography system.

Figure 32 Pumps and reservoir tank.

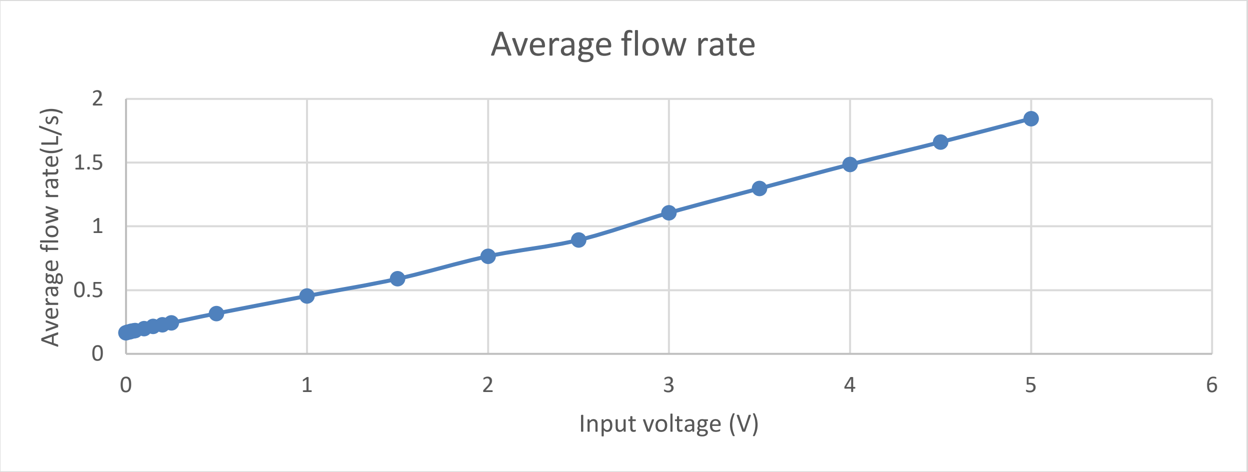


Figure 33 The average flow rate vs. applied voltage for the Seepex pump.

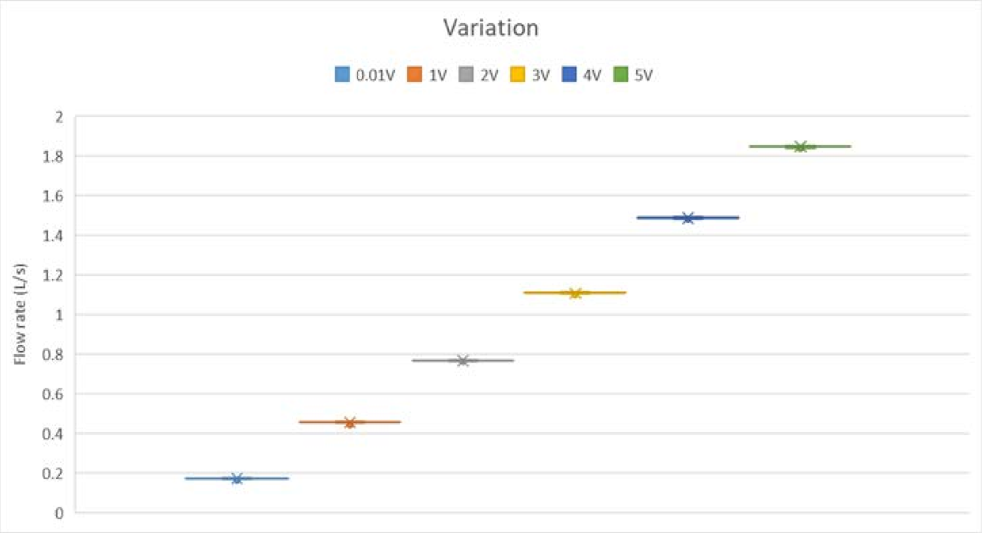


Figure 34 The variation in the flow rate of the Seepex pump at various operation points.

To quantify the amount of water in the FRM, a series of images are captured of the water film at the entrance and exit (see Figure 35). Two acrylic boxes filled with water are included to correct for optical distortion. Since some droplets could be observed attached to the wall of the pipe, it was decided that a bottom picture of the film could achieve a better measurement.

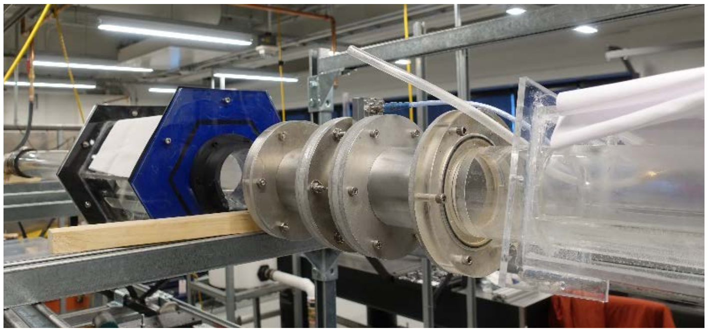


Figure 35 Experimental setup, two acrylic boxes and the FRM in place.

During the experiment, it was observed that the water film was changing quite rapidly and a small amount of water accumulation was present in the transition from the FRM to the acrylic pipe. Due to this rapid variation in the width of the film, the images could not be matched in time with the FRM's reading but instead provide a range of the amount of water in the pipe during the experiment. An example of the images obtained is shown in Figure 88.

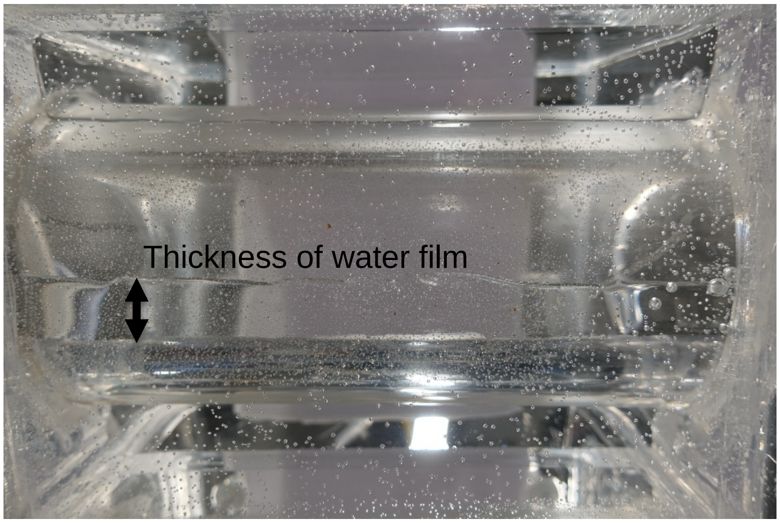
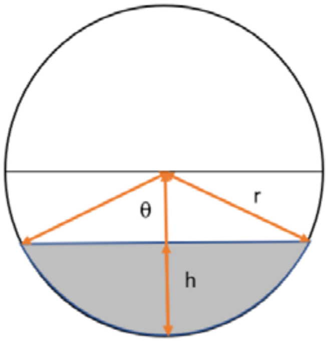


Figure 36 Sample image of the acrylic pipe (bottom up) demonstrating extent of water film in acrylic pipe.

The measurements of the film thickness are obtained by analyzing the edge of the film with software tool ImageJ. Several thicknesses are taken per picture and the average value is used to calculate the height of the water inside the pipe. Figure 89 shows the technique used to calculate the height of the water.



$$h = r - \sqrt{r^2 - \frac{1}{4}L^2}$$

$$\theta = acos\left(\frac{r-h}{r}\right)$$

$$A_{water} = 2\theta r^2 - \frac{1}{2}r^2 sin(2\theta)$$

Figure 37 Calculation of height of film. In the equations, h is the height of the film, r is the internal radius of the pipe, θ is the angle from the vertical to the radius at the edge of the water film in radians, and L is the arc length. A_{water} is the cross-sectional area of the water in the pipe.

The steam qualities are estimated with the densities of water and steam (680 kg/m^3 and 58.9 kg/m^3), and assuming flow at the same velocity. In several test cases, the range of the measured steam qualities was from 96% (water thickness of 0.744 in) to 99% (water thickness of 0.489 in).

Finally, the FRM is included in the system and the flow rate adjusted to represent different steam qualities. The steam quality measured over time is shown in Figure 90. The changes in steam quality are sensed by the FRM. Further work is required to correlate an independent measure of steam quality with the quantity obtained from the FRM. While the images provide an estimate of range, the accumulation of water impacts accuracy. A technique that measures the amount of water inside the FRM is required. However, the results in Figure 90 show that the response changes with time and the steam qualities are in the expected range.

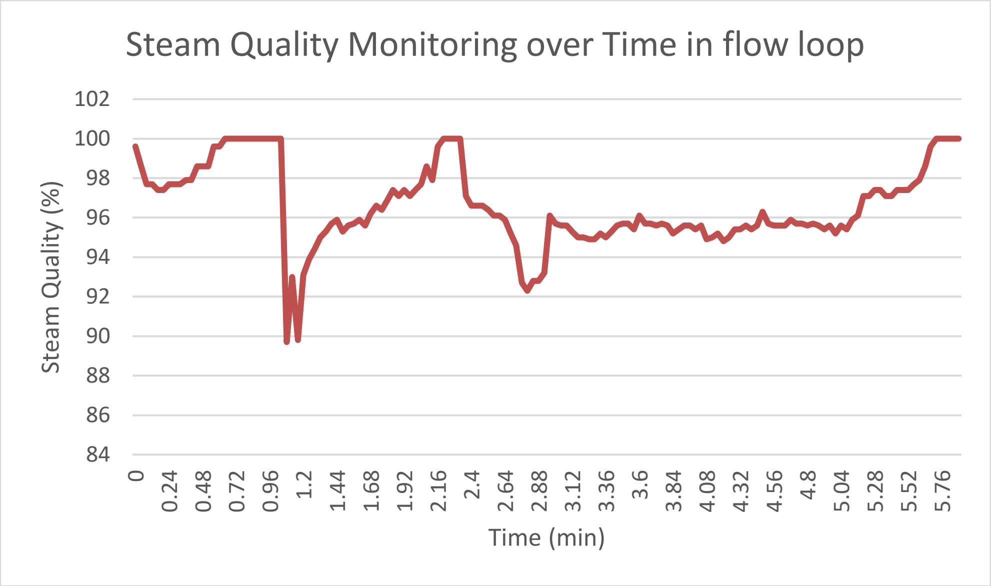


Figure 38 Steam quality estimated from FRM when incorporated into flow loop.

Summary: The key performance metrics for this final task are characterization of the flow established in the experimental system, and evaluation of changes in measurements collected with the sensor with changes in experimental flow. The flow in the experimental system is characterized, and changes in sensor measurements are detected when the flow is changed. Very low flow conditions are established in the experimental system, which was challenging given that these systems are not typically designed for such applications. Future work include improved methods to characterize the flow inside the FRM.

7. KEY LEARNINGS

Please provide a narrative that discusses the key learnings from the project.

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes.

As anticipated, tracking a 1% change in steam quality is technically challenging due to multiple intersecting factors. For example, the water may be present as droplets in mist or as a stratified layer. With careful analysis and simulation, we gained insight into the impact of different factors and developed appropriate sensing strategies that encompass a range of two-phase flow scenarios. This relied on an initial investment in effective multidisciplinary communication, continuous iterations between our electrical and mechanical teams, effective translation between simulations and measurements, and participation of our industrial partner.

The multidisciplinary approach that our collaborative team developed was critical to project success. The electrical engineers on the team were interested in testing the ability of microwave frequency approaches to tracking steam quality. This was based on a few papers in the literature reporting that microwave frequency properties of steam varied with steam quality. However, most of these reports involved measuring steam in simplified scenarios (e.g. constant flow and uniform distribution throughout sensing volume). To develop an approach that has the potential to work in real-world situations, we needed to understand the possible flow regimes in pipes with diameters and configurations (e.g. elbows and inclines) that would be found in OTSG operations. As analyzing this type of flow requires mechanical engineering expertise, our team expanded. Initially, the project moved forward with electrical and mechanical phases in parallel. Developing the microwave simulation environment involved incorporating models based on the literature, while the initial mechanical simulations involved identifying operating conditions to represent and appropriate simulation parameters. Defining both simulation approaches required us to spend time understanding the problem from the perspective of the other discipline, which involved extensive discussions. We believe that a key to successful multidisciplinary work is the initial investment in developing a common frame of reference for viewing the problems, which involves learning to effectively speak the language of the other disciplines.

Transitioning from the first phase of the project, the information from the electrical and mechanical simulations was integrated. Specifically, we applied findings from computational fluid dynamics simulations to inform sensor design, as this provided comprehensive insight into sensing requirements. For example, we defined cases of interest based on the mechanical simulations, such as flow with only steam (gas) and stratified flows with liquids in different locations. Our sensing approaches had to handle this range of different cases. We continued to test different configurations (e.g. one and two elbow, inclines) and applied our sensing approaches to the resulting flows. This extensive characterization and simulations of multiple scenarios also allowed us to develop multiple measures to estimate steam quality, including features of the resonator response and an additional conductivity sensor. The success of this second phase of the project built on the investment in multidisciplinary communication and was characterized by ongoing iterations between the mechanical and electrical teams.

The sensors developed in simulation were tested with a series of incrementally more complex experimental tests to verify behavior. We have previously developed expertise in matching simulations to measurements, and this project confirmed the power of these approaches. Specifically, we implemented candidate designs as early as possible and compared simulated and measured results for the simplest test cases. Simulation models were updated and modifications to prototypes were implemented to obtain agreement. Next, test cases with increased complexity were measured (e.g. empty resonator, steam, layer of water) and responses compared to simulations to ensure that expected trends are observed. This allowed for confident prediction of more complex cases with simulation models.

By obtaining a close match between simulations and measurements, the suite of tools developed for this project was validated. The resulting confidence in the results when testing more complex scenarios is critical to the further, efficient development of this project because the simulations provide data at reduced cost compared to experiments.

Finally, working with industrial partner Cenovus provided key practical perspectives on the project. This initially included feedback on operating conditions for the mechanical simulations, as well as reasonable assumptions to incorporate into the simulation models and defining industrially relevant targets for steam quality sensing. Discussing practical implementation of the sensing system informed the design of the sensors (e.g. build up on conductivity sensor). Our team also had many discussions on additional application areas, generating ideas for future work. This partnership was critical to producing outcomes with relevance to industry, and hence greater potential for impact.

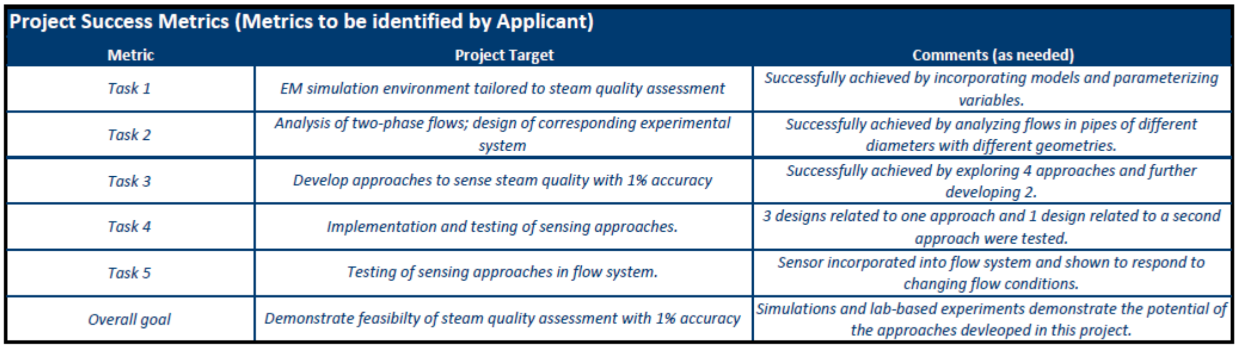
8. OUTCOMES AND IMPACTS

Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate and provide a description relative to the key Metrics selected at the project outset.

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* template. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* template. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** Provide a list of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

Project outcomes and impacts: This project explored the feasibility of a radio frequency based approach to inline, real-time steam quality monitoring. We defined 5 specific tasks to accomplish our overall goal of demonstrating the feasibility of steam-quality assessment to within 1% accuracy. By developing electrical and mechanical simulation environments (Tasks 1 and 2), we created tools to allow for analysis of a range of scenarios and sensing approaches (Task 3). Multiple approaches were tested and the most promising techniques explored more comprehensively. 4 candidate designs were implemented and tested in a series of simplified scenarios, demonstrating agreement between simulations and measurements (Task 4). Finally, the sensing approaches were integrated into a flow system and tested in this complex environment (Task 5). Overall, our results demonstrate the potential to accurately characterize steam quality with this technique, as well as to detect 1% changes in near real-time. The technique does required adapting to realistic operating conditions, however the results of this project form a strong foundation on which to further develop the technology. Our multidisciplinary team is well positioned to take these next steps.

Table 3 Project-specific metrics



Project Success Metrics (Metrics to be identified by Applicant)

Metric	Project Target	Comments (as needed)
Task 1	*EM simulation environment tailored to steam quality assessment*	*Successfully achieved by incorporating models and parameterizing variables.*
Task 2	*Analysis of two-phase flows; design of corresponding experimental system*	*Successfully achieved by analyzing flows in pipes of different diameters with different geometries.*
Task 3	*Develop approaches to sense steam quality with 1% accuracy*	*Successfully achieved by exploring 4 approaches and further developing 2.*
Task 4	*Implementation and testing of sensing approaches.*	*3 designs related to one approach and 1 design related to a second approach were tested.*
Task 5	*Testing of sensing approaches in flow system.*	*Sensor incorporated into flow system and shown to respond to changing flow conditions.*
Overall goal	*Demonstrate feasibilty of steam quality assessment with 1% accuracy*	*Simulations and lab-based experiments demonstrate the potential of the approaches devleoped in this project.*

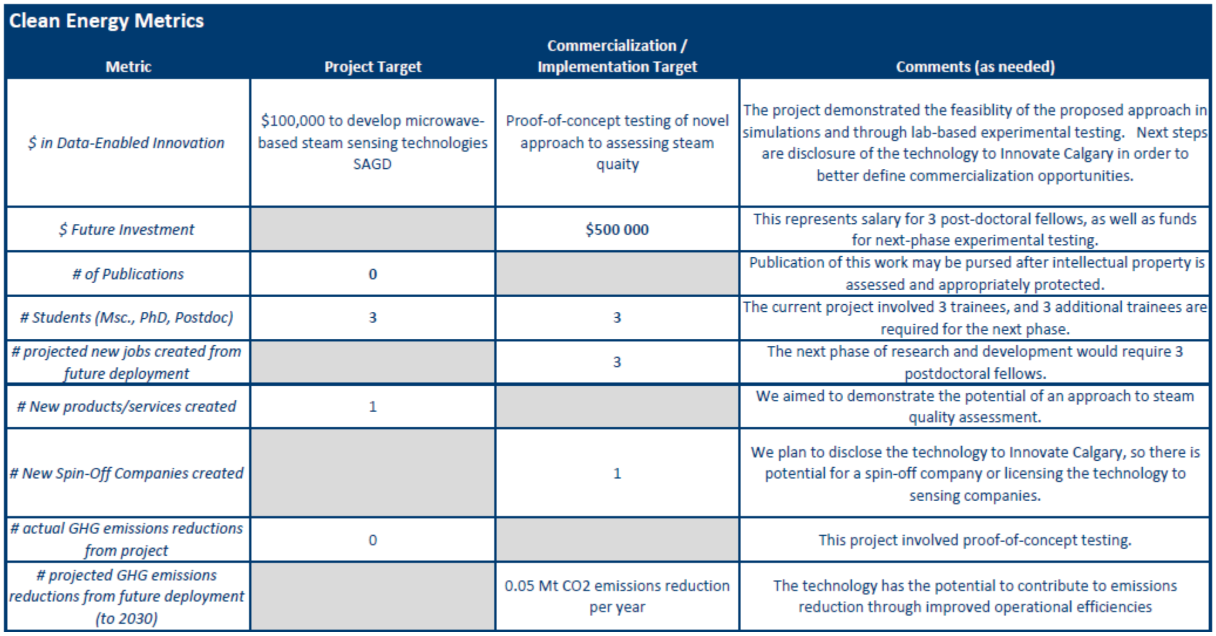
Clean Energy Metrics: This project involves early stage technology development, and investment in this project allowed progression from a preliminary experimental test of a single sensor in a pipe to the development of detailed understanding of two-phase flow in pipes and sensing requirements, as well as implementation of 4 sensing approaches and test results collected in a range of scenarios. To complete the next stage of testing, we anticipate requiring 3 post-doctoral fellows: one in mechanical engineering to lead development of test facilities at higher temperature and pressure, one in electrical engineering to further refine the sensors, and a second electrical engineer to focus on electronics and practical implementation. The cost of supporting these trainees for 2 years and implementation of the test facilities and sensors is estimated to be $500 000.

The project contributed towards training of highly skilled personnel, as the project involved a research engineer, postdoctoral associate and PhD student. In addition to applying and developing their technical expertise, these researchers gained valuable skills through work on a multidisciplinary project with an industrial collaborator. The 3 trainees required for the next stage of the project are expected to have similar experiences, with an additional entrepreneurial training component as the project moves into a commercialization phase.

The promising results obtained during the project will form the basis of a technology disclosure to Innovate Calgary to begin evaluation of the commercial potential of the technology. The project is expected to transition into a spin-off company after 2 years of U of C research, creating jobs for the 3 post-doctoral fellows.

To date, the technology has not been implemented in industry and does not have associated measurable impacts on GHG emissions. We describe our projections for future GHG reduction with a fully developed technology in place in the next section, and provide a summary in the table below.

Table 4 – Clean Energy Metrics



Clean Energy Metrics

Metric	Project Target	Commercialization / Implementation Target	Comments (as needed)
$ in Data-Enabled Innovation	$100,000 to develop microwave-based steam sensing technologies SAGD	Proof-of-concept testing of novel approach to assessing steam quaity	The project demonstrated the feasiblity of the proposed approach in simulations and through lab-based experimental testing. Next steps are disclosure of the technology to Innovate Calgary in order to better define commercialization opportunities.
$ Future Investment		**$500 000**	This represents salary for 3 post-doctoral fellows, as well as funds for next-phase experimental testing.
# of Publications	**0**		Publication of this work may be pursed after intellectual property is assessed and appropriately protected.
# Students (Msc., PhD, Postdoc)	**3**	**3**	The current project involved 3 trainees, and 3 additional trainees are required for the next phase.
# projected new jobs created from future deployment		3	The next phase of research and development would require 3 postdoctoral fellows.
# New products/services created	1		We aimed to demonstrate the potential of an approach to steam quality assessment.
# New Spin-Off Companies created		1	We plan to disclose the technology to Innovate Calgary, so there is potential for a spin-off company or licensing the technology to sensing companies.
# actual GHG emissions reductions from project	0		This project involved proof-of-concept testing.
# projected GHG emissions reductions from future deployment (to 2030)		0.05 Mt CO2 emissions reduction per year	The technology has the potential to contribute to emissions reduction through improved operational efficiencies

Program specific metrics: This project has grown a new collaboration between the University of Calgary researchers and Cenovus. We plan to continue this relationship, and next steps include a seminar at Cenovus to describe the project and results.

We have advanced the technology proposed in our original application through careful design, simulation and testing. We have moved this technology from TRL 2 to TRL 4-5 through this project.

Table 5 – Program-specific metrics

Program Specific Metrics

Metric	Project Target	Commercialization / Implementation Target	Comments (as needed)
# of End Users participating	1	1	Plan to continue the relationship with Cenovus as the sensing technologies advance towards commericialization.

Project outputs: Our collaboration has been featured in Schulich School of Engineering outreach (https://schulich.ucalgary.ca/news/shared-vision, https://schulich.ucalgary.ca/about/strategic-plan/global-research-impact). We also plan to explore technology transfer and commercialization, as well as a seminar with a hands-on demo at Cenovus. If appropriate from an IP-protection perspective, the project methods and results have the potential to generate conference presentations and/or a short journal papers on sensor design and proof-of-concept studies. This project also lead to increased support for a research engineer, postdoctoral fellow and PhD student.

9. BENEFITS

Please provide a narrative outlining the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, ecosystem, etc.) compared to the industry benchmark. Discuss both benefits and impacts and any trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the Province. Discuss the research infrastructure used or developed to complete the project.

Economic: This feasibility study of a microwave sensing approach to measuring steam quality is anticipated to be the first phase of a longer-term project. The immediate benefits of this initial feasibility study are job creation for trainees, as well as the training opportunities afforded by working on a multidisciplinary project with an industrial collaborator. This feasibility study has generated the data and design required for a larger-scale, multi-year project aimed at testing and further developing the technology in more realistic, industrial settings.

Environmental: As the technology has not been implemented in industry, the following discussion is an analysis of future potential for the technology. On average, SAGD requires 2.6 barrels of steam to produce one barrel of oil. The current industry operating targets typically range from 80-82% steam quality with demonstration projects showing much higher steam qualities are possible. Higher quality steam at the well-head is more effective at transferring heat to decrease viscosity of bitumen. By incorporating monitoring technologies at the generator, critical locations in the plant and at well-heads, steam quality can be tracked through the plant and approaches to improving steam quality optimized. This optimization has an impact on GHG emissions.

For example, the ability to increase the steam quality within the OTSGs may allow for a reduction in GHG emissions by eliminating the cooling and recycling of the blowdown within the facility. An accurate and ongoing approach to steam quality monitoring may also result in fewer OTSG trips and restarts. Based on the enthalpy of the steam, we calculated the natural gas consumption of an OTSG at different steam qualities. These calculations show that, for an increase of 1% in steam quality, we anticipate a decrease of about 0.15% in natural gas consumption. This decrease is mostly due to the reduction of water blow down. For GHG emission reduction, based on current emissions from in-situ production of 30Mt CO2 per year, we anticipate a net emissions decrease of 0.05 Mt CO2 per year with an increase in steam quality of 1% when this technology is implemented in a field operation.

In addition to the GHG emissions reductions outlined above, the reliable estimation of steam quality could provide Cenovus with the ability to better estimate dry out conditions in the pipes, maximize steam production, and reduce unnecessary downtime.

The path to implementation in the field includes a next stage of research and development to test the sensing approach in more realistic environments (higher temperatures, pressures). This is anticipated to be a 2-year project for three postdoctoral fellows, two in electrical engineering and one in mechanical engineering. The results obtained through this next phase would position the trainees to pursue commercialization of the technology. Participation in programs such as Creative Destruction Labs would accelerate these efforts, corresponding to an additional year to ensure that intellectual property is protected, the customer base identified, and manufacturing approaches identified. The impact of this further work is anticipated to be a spin-off company, along with training opportunities spanning technical development and entrepreneurship.

Social: This project has generated increased interest in entrepreneurship and technology translation in our research team. We plan to discuss further with Innovate Calgary in order to effectively define the roadmap for further development of this technology. The project has helped to de-risk the technology for further commercialization and development. . This project also demonstrates how technology can be used to understand and potentially optimize processes, with the ultimate aim of reducing GHG emissions. This contributes towards the continued aims to grow an ecosystem supporting development of technologies aimed at enhancing energy efficiency, both at the University of Calgary and in the province of Alberta.

Building innovation capacity: This project involved a PhD student, postdoctoral associate and research engineer. The PhD student and PDF are mechanical engineers and contributed expertise in two-phase flow, while the research engineer is an electrical engineer with expertise in sensor design. A key part of the success of the project was learning to appreciate the technical issues in these different disciplines, as this was a new collaborative project between Dr. Fear and Hugo's teams. The experimental testing facilities and simulation frameworks that were developed as part of this project are anticipated to support a range of future projects.

10. RECOMMENDATIONS AND NEXT STEPS

Please provide a narrative outlining the next steps and recommendations for further advancement of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken in the coming years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

We plan a disclosure to Innovate Calgary related to the sensing technology. One potential path is licensing to a vendor developing related technology, and this is likely the shortest path to market.

We have outlined specific technical next-steps are outlined for the sensing options implemented in this project. For each of these sensors, more realistic testing environments (higher temperature and pressure) are required to refine the technology. We have also identified the ability to visualize the flow inside of or in close proximity to the sensor as important, which likely involves finalizing the optical tomography approach or adding imaging sensors to the system.

In addition to disclosing the technology, our collaborative team is exploring funding applications to new programs to support further research and development.

11. KNOWLEDGE DISSEMINATION

Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry, government or other end users. In addition to standard approaches (e.g., publications and conferences) please also list novel methods of engagement or collaboration to enhance dissemination.

We plan for a disclosure to Innovate Calgary, as well as a seminar at Cenovus with a hands-on demonstration. This would allow us to collect additional feedback from our industrial partner. We are also considering consider conference and/or journal publications once the IP protection path is determined. As outlined above, this project has been featured by the Schulich School of Engineering as part of the launch of the strategic plan.

12. CONCLUSIONS

Please provide a narrative outlining the project conclusions.

- Ensure this summarizes the project objectives, key components, results, learnings, outcomes, benefits and next steps.

This project aimed to develop a method for steam quality assessment using microwave technologies. Specifically, an accuracy of 1% for measuring steam quality and the ability to track changes of 1% were targets. Achieving this outcome involved 5 key tasks. A toolkit was developed that included microwave-frequency and computational fluid dynamics simulations for representing flow in pipes. By customizing and automating models of flow in pipes, an understanding of the possible flow patterns and effective strategies for sensing was developed. Specific designs of sensors were investigated in more detail, and the resulting best candidates were implemented and tested in a range of increasingly complex scenarios. The resulting sensor designs met the project objectives.

As anticipated, tracking a 1% change in steam quality is technically challenging due to multiple intersecting factors. With careful analysis and simulation, we characterized the impact of different factors and developed appropriate sensing strategies. A multidisciplinary team was critical for this work. Our industrial partner Cenovus provided key practical perspectives on the project. This included feedback on assumptions and technical challenges with practical implementation of the sensing system, as well as discussions on additional application areas. This partnership was critical producing outcomes with relevance to industry, and hence greater potential for impact.

As this project involves early stage technology development, the technology has not been implemented in industry and does not have associated measurable impacts on GHG emissions. We have advanced the technology proposed in our original application through careful design, simulation and testing. Next steps include exploring the potential for technology transfer and commercialization. We have also contributed towards training of highly skilled personnel, as the project involved a research engineer, postdoctoral associate and PhD student. In addition to applying and developing their technical expertise, these researchers gained valuable skills through work on a multidisciplinary project with an industrial collaborator.

Our results demonstrate the potential to accurately characterize steam quality with microwave techniques, as well as to detect 1% changes in this quantity. These techniques require further adaptation to realistic operating conditions, however the tools developed as part of this project form a strong foundation on which to further develop the technology. The multidisciplinary team formed to tackle this project is well positioned to take these next steps.