DEVELOPMENT OF A SELF-CALIBRATING MEMS PRESSURE SENSOR USING A LIQUID-TO-VAPOR PHASE CHANGE

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Mechanical Engineering

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August 2, 2021
Blacksburg, VA

Keywords: Self-calibrating, Phase Change, Two Phase, Pressure Sensor, MEMS

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ABSTRACT

A growing industry demand for smart pressure sensors that can be quickly calibrated to compensate for sensor drift, nonlinearity effects, and hysteresis without the need for expensive equipment has led to the development of a self-calibrating pressure sensor. Pressure sensor inaccuracies are often resolved with sensor calibration, which typically requires the use of laboratory equipment that can produce a known, standard pressure to actuate the sensor. The developed MEMS-based, self-calibrating pressure sensor is a piezoresistive-type sensor with a sensing element made from a silicon on insulator (SOI) wafer using deep reactive-ion etching to create a hollow reference cavity. Using a micro-heater to heat the small, air-filled reference cavity of the sensing element, a standard pressure is generated to actuate the sensor's pressure-sensitive membrane, creating a self-calibration effect. Previous work focused on modeling and improving the thermal performance of the sensor identified potential solutions to extend the sensor's calibration and operating range without increasing the micro-heater's power consumption. This report focuses on using a water liquid-to-vapor phase change inside the sensor's reference cavity to increase the sensor's effective range and response time without increasing power demands.

A combination of Ansys Fluent CFD modeling and benchtop experiments were used to guide the development of the two-phase, self-calibrating pressure sensor. A two-phase benchtop testing rig was built to demonstrate the anticipated effects of a liquid-to-vapor phase change in a closed domain and to provide experimental data to anchor CFD models. Due to the complexity of modeling a phase-change within a closed domain with Ansys Fluent R21.1, the CFD modeling was performed in two stages. First, the two-phase benchtop rig was modeled, and validated using benchtop test data to verify the Volume of Fluid multiphase model setup in Ansys Fluent. Then, a 2D Ansys Fluent model of the self-calibrating pressure sensor's reference cavity using the validated multiphase model was made, demonstrating the potential temperature, pressure, and density gradients inside the reference cavity at steady state. Using the guidance from the benchtop testing and CFD modeling, a prototype two-phase, self-calibrating pressure sensor was fabricated with a water volume fraction of at least 0.1 in the reference cavity. Testing the prototype two-phase sensor showed that the addition of a water liquid-to-vapor phase change inside the sensor's reference cavity can nearly triple the sensor's effective range of operation and self-calibration without increasing the power consumption of the cavity micro-heater.

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GENERAL AUDIENCE ABSTRACT

Highly sensitive pressure sensors are essential to many modern engineering applications. For a pressure sensor to be accurate and functional, it must be properly calibrated with a known, standard pressure range that overlaps with the sensor’s intended operating range. Mechanical wear, material aging, and thermal effects all reduce a pressure sensor’s accuracy over time, requiring recalibration which often involves expensive equipment and long downtimes. To eliminate the need for additional equipment and the removal of the pressure sensor from its use-site for calibration, the authors have developed a pressure sensor capable of self-calibration. The self-calibrating sensor uses a MEMS sensing element with an integrated micro-actuator in the form of a small heating element to create the standard pressure range necessary for calibration. Previous work focused on modeling the thermal performance of the sensor identified potential solutions to extend the sensor’s calibration and operating range without increasing the micro-heater’s power consumption. This report focuses on using a water liquid-to-vapor phase change inside the sensor’s reference cavity to increase the sensor’s effective range and response time without increasing power demands. To help guide the development of the two-phase, self-calibrating sensor, a benchtop testing rig and CFD model were used to examine the effects of heating a liquid inside of a closed domain. A 2D CFD model of the sensor’s reference cavity was also used to provide insight into the expected temperature and pressure gradients inside the sensing element after heating with the micro-actuator. Using the guidance from the CFD models, a prototype two-phase, self-calibrating pressure sensor was fabricated. Testing the prototype two-phase sensor showed that the addition of a water liquid-to-vapor phase change inside the sensor’s reference cavity can nearly triple the sensor’s effective range of operation and self-calibration without increasing the power consumption of the cavity micro-heater.

Acknowledgements

First, I would like to thank my advisor Dr. Wing Ng for his guidance and encouragement throughout this project. I would also like to thank Dr. Hang Ruan, Dr. Echo Kang, and Mr. Albrey de Clerck of NanoSonic Inc. for making this work possible though their technical expertise and support. I would also like to acknowledge my research team members Brennan Rausch, Shuo Mao, and Jason Stiefvater for their insight and contributions.

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DEVELOPMENT OF A SELF-CALIBRATING MEMS PRESSURE SENSOR USING A LIQUID-TO-VAPOR PHASE CHANGE

Nomenclature

P	Absolute pressure
T	Temperature
$\dot{m}$	Mass flow rate
a	Evaporation frequency
α	Phase volume fraction
ρ	Phase density
b	Condensation frequency

1. Introduction

Microelectromechanical systems (MEMS) based pressure sensors are prominent in a wide variety of engineering applications, such as biomedical and automotive [1]. One of the more common types of MEMS-based pressure sensors are piezoresistive pressure sensors, which use silicon-based piezoresistors arranged in a Wheatstone bridge configuration on a pressure-sensitive membrane. Once an external pressure is applied to the membrane, the flexure-induced stress on the piezoresistors causes a resistance change, which is transformed to a voltage change by the Wheatstone bridge. This voltage change is proportional to the applied pressure and can be directly converted to an exact pressure once properly calibrated. Pressure sensors are typically calibrated by relating the output of the sensor to a known range of input pressures, creating what is known as a calibration curve. The calibration process often requires expensive equipment and requires the sensor to be removed from the use-site, leading to costly periods of extended downtime. Even after proper calibration, mechanical wear from repeated use causes sensor inaccuracies such as hysteresis, nonlinearity, and signal drift [2]. To meet the growing industry needs for low-cost, rapid on-site sensor calibration, the authors have developed a smart pressure sensor capable of self-calibration, first presented in previous publications [3,4]. This presented work builds upon the development of the self-calibrating pressure sensor, focusing on recent efforts to extend the sensor's operating range.

For a sensor to be capable of self-calibration without an external input, it must create its own input reference signal. This can be achieved by coupling a pressure sensor with an actuator device that simulates an applied, known pressure. Common actuation types include mechanical, electrical, and thermal [5]. The technique of using an actuator paired with a sensor is an established method used in self-testing sensors [6], which use the actuator to check the functionality of the sensor but has not been widely adopted possibly due to technological complexities.

The self-calibrating pressure sensor developed by the authors uses thermopneumatic actuation to apply a precise pressure to the sensor's pressure-sensitive membrane for calibration [3]. The sensor has a sealed reference cavity filled with dry air, a micro-heating element, and a thermistor. When the heater is turned on, the air inside the cavity heats and expands, exerting a measurable pressure on the flexible membrane of the sensor. The cavity pressure measured by the sensor can be calculated from the measured cavity temperature using an equation of state, such as the ideal gas law or a real gas model. Previous modeling work by the authors has shown that the cavity thermistor temperature measurement provides an adequate approximation of the true volume-average temperature of the cavity, making it a suitable measurement to calculate the cavity pressure for self-calibration [4].

The sensing range of a pressure sensor is limited by the pressure range it is calibrated with [7]. For the self-calibrating pressure sensor, the calibration pressure range is limited by the pressure range the actuator can generate in the reference cavity. Two factors that affect the pressure inside the reference cavity are the maximum temperature the sensing element can survive and the heat transfer efficiency from the cavity heater to the air in the cavity [4]. The latter was the focus of the Ansys Transient Thermal modeling work in a previous publication by the authors that determined 95% of heat generated from the cavity heater was lost to conduction through the substrate [4]. Alternative substrate materials were modeled and investigated, showing that the heater-to-cavity heat transfer efficiency could be significantly improved by reducing the thermal diffusivity of the substrate material [4]. The largest improvements in heater efficiency were seen with a suspended-in-air heater design model, reducing the heater power consumption by 92% [4].

While improving the efficiency of the cavity heater reduces the heating time required to raise the cavity pressure, it has little impact on the maximum pressure that can be achieved inside the reference cavity, as that is limited by the temperature survivability of the sensing element. In the sensor's current configuration, the heater can only raise the pressure of the air inside the reference cavity by about 5 psi before the sensor's temperature limit is reached [4]. Previous work by the authors showed that changing the gas inside the reference cavity would not have a noticeable effect on the maximum cavity pressure

[4]. For a significant pressure increase without altering the temperature survivability of the sensor, a liquid-to-vapor phase change inside the reference cavity is needed. A fundamental understanding of thermodynamics would imply that an air-water mixture heated in a closed container would produce higher pressures than if the container were solely filled with air due to the evaporated vapor as the water is heated [8]. The presented work details the development of a self-calibrating pressure sensor with a reference cavity partially filled with liquid water to increase the calibration pressure range and thus the sensing range of the pressure sensor. Water was chosen for the cavity liquid due to its availability, low corrosivity, and predictable phase-change behavior [8,9].

Very few self-calibrating pressure sensors can be found in literature, let alone pressure sensors that operate with a liquid-to-vapor phase change. One self-calibrating pressure sensor found in literature is developed by Yameogo *et al*. for in-vivo biomedical applications [10]. This wireless, piezoresistive pressure sensor monitors intercranial pressure within the skull and uses electrostatic actuation to correct drift over extended periods of use (i.e., self-calibrate). An adjustable voltage is applied between two electrodes, causing the sensor membrane to deflect, acting as a reference pressure for self-calibration. Another self-calibrating pressure sensor found in literature was developed by MKS Instruments, Inc. [11]. Self-calibration is achieved using a multi-sensor system, with one pressure sensor and one reference sensor that both share a common sealed chamber. Electrostatic actuation can used to deflect the pressure-sensitive membrane of the reference sensor, which is used to correct drift caused by aging of the pressure sensor. This system can also be outfitted with a third sensor that measures the environmental pressure surrounding the system to compensate for drift caused by environmental effects. Using multiple sensors in a single unit to accomplish self-calibration can be cost ineffective and counterproductive, as the accuracy of self-calibration for the pressure sensor depends on the reference sensor and environmental sensor both remaining accurately calibrated.

Only one pressure sensor, besides that presented by the authors, has been found in literature that incorporates a liquid-to-vapor phase change within a sealed reference cavity. M. Huo *et al*. developed a self-testing piezoresistive-type MEMS pressure sensor with a sealed cavity below a pressure-sensitive membrane supporting four piezoresistors in a Wheatstone bridge configuration [12]. A heating resistor is used to actuate the membrane; however, heating the air-filled cavity does not generate a large enough pressure to adequately test the function of the pressure sensor. To achieve higher pressures during the self-testing procedure, a hole at the base of the sensor is used to add and later drain a liquid phase change material (PCM) to and from the cavity. Using water for the PCM, the self-testing output is up to 3% of the full-scale sensor output [12]. Unlike the presented sensor, this sensor does not measure the internal cavity temperature, therefore it is unable to self-calibrate.

Understanding the physics of a liquid-to-vapor phase change in a closed domain is crucial for the development of a two-phase, self-calibrating pressure sensor. For proper calibration, the equation of state relating the pressure of an air-water mixture in a sealed cavity must be defined as a function of the cavity temperature. Further considerations are necessary to determine whether the initial volume fraction of liquid water inside the cavity effects the pressure. To help guide the development of a prototype two-phase, self-calibrating pressure sensor, large-scale benchtop tests and CFD modeling were used to help determine the liquid fill level needed in the sensor cavity. The CFD modeling of the sensor cavity was also used to visualize the temperature and pressure gradients resulting from the water liquid-to-vapor phase-change. Finally, test results from the prototype two-phase, self-calibrating pressure sensor will be presented demonstrating the extended calibration range from the liquid-to-vapor phase change in the reference cavity.

2. Modeling and Development

2.1 Governing Physics

When heating multiple gases in a close container, Daltons law of partial pressures can be used to calculate the total pressure of the gas mixture. Dalton’s law of partial pressures states that the total pressure exerted on the walls of a container by a mixture of gases is equal to the summation of the partial pressures of each gas in the mixture [13]. Therefore, if the pressure sensor reference cavity is filled with both air and some liquid, such as water, the total pressure in the reference cavity will be the sum of the partial pressure of the air and the partial pressure of the vapor evaporated from the liquid, as expressed in the equation

$$P_T = P_a + P_v \tag{1}$$

where P_T is the absolute total pressure in the cavity and P_a and P_v are the absolute partial pressures of the air and vapor, respectively. In a closed container with a known volume and initial state, the partial pressure of air can be calculated using the ideal gas law. Assuming the volume of the reference cavity is constant and the system is closed, which is a fair assumption as the sensor cavity is shown to only vary by 3% at maximum operation [4], this simplified form of the ideal gas law can be used to calculate the partial pressure of air in the cavity,

$$P_{a,f} = \frac{P_{a,i} T_{a,f}}{T_{a,i}} \tag{2}$$

where $P_{a,f}$ is the final absolute partial pressure of the air in the cavity after heating, $P_{a,i}$ is the initial absolute partial pressure of the air in the cavity, assumed to be that of atmospheric pressure, $T_{a,f}$ is the final absolute temperature of the air in the cavity after heating, and $T_{a,i}$ is the initial absolute temperature of the air in the cavity before heating.

For closed systems containing both an air-water vapor mixture and liquid water, the partial pressure of the water vapor in the mixture is equal to the saturation pressure of water at the temperature of the air-water vapor mixture [14]. Antoine's equation is often used to approximate the vapor pressure of water as a function of temperature in the form of the piecewise function

$$P_v = 10^{8.07131-\frac{1730.63}{233.426+\mathrm{T}}}, 1℃ \leq T \leq 100℃ \tag{3}$$

$$P_v = 10^{8.14019-\frac{1810.94}{244.485+\mathrm{T}}},\ 100℃ \leq T \leq 374℃ \tag{4}$$

where P_v is the vapor pressure of water in mmHg and T is the temperature of the water in degrees Celsius [15]. Summing the equations for the partial pressures of the air and water vapor produces the equation for the theoretical total absolute pressure in the sealed reference cavity

$$P_T = \frac{P_{a,i}T_{a,f}}{T_{a,i}} + 10^{8.07131-\frac{1730.63}{233.426+\mathrm{T}}},\ 1℃ \leq T \leq 100℃ \tag{5}$$

$$P_T = \frac{P_{a,i}T_{a,f}}{T_{a,i}} + 10^{8.14019-\frac{1810.94}{244.485+\mathrm{T}}},\ 100℃ \leq T \leq 374℃ \tag{6}$$

where P_T is the total pressure in mmHg, which is purely a function of the initial temperature and pressure of the air and the temperature of the liquid water in the cavity.

Figure 1 below compares the pressure change, according to equations (5) and (6), inside a closed, rigid container initially at room temperature with both air and water and the pressure change inside an identical container filled with only air modeled as an ideal gas. The significant increase in pressure at high temperatures with the two-phase container compared to the single-phase container justifies developing a self-calibrating pressure sensor that incorporates a liquid-to-vapor phase change inside the reference cavity. With the single-phase sensor design, the average departure from room temperature in the reference cavity is limited to about 100℃, resulting in pressure rise of ~5 psi. Replicating that same temperature change in a reference cavity comprising of liquid water and air would result in a pressure increase of 18.5 psi, according to figure 1, potentially quadrupling the effective range of sensor's self-calibrating capabilities. To better visualize the potential temperature and pressure gradients in the cavity after a liquid-to-vapor phase change, a CFD model of the sensor cavity was developed and will be discussed in a later section.

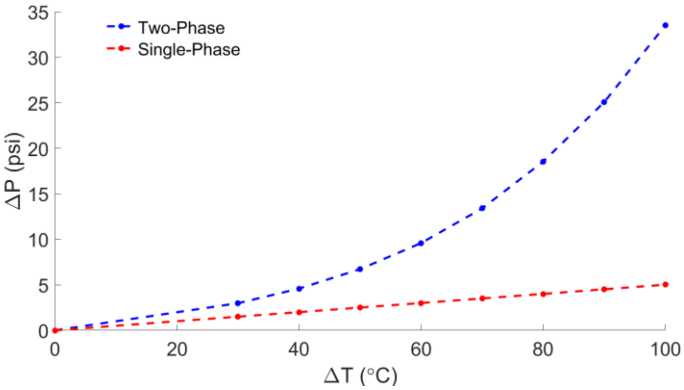

Figure 1. Pressure change as a function of the temperature change inside a rigid, closed container for single-phase (air only) and two-phase (water-air mixture) regimes.

2.2 Two-Phase Benchtop Rig

Before attempting to fabricate a two-phase, self-calibrating pressure sensor with a partially liquid-filled reference cavity, a benchtop testing rig was constructed to simulate the pressure rise resulting from a liquid-to-vapor phase change in a closed domain. The main motivation for using the two-phase benchtop rig to simulate a closed-domain phase change is to guide the CFD modeling approach for the self-calibrating pressure sensor's cavity. Modeling a liquid-to-vapor phase change in a closed domain using the software Ansys Fluent R21.1 is not trivial, and typically requires experimental data to validate the modeling approach and selected multiphase model [16,17]. Manufacturing and testing multiple new self-calibrating pressure sensors with various cavity liquids would be time consuming, making it difficult to get various useful datasets to validate the CFD modeling approach. By using the two-phase benchtop rig, multiple different cavity fluids at various fill-level percentages can quickly be tested while also collecting transient temperature and pressure data at multiple points within the rig to validate an accompanying CFD model for the benchtop rig.

The two-phase benchtop testing rig, shown in figure 2, consists of a 3" diameter, 1/8" thick clear polycarbonate (PC) tube secured between aluminum plates. Rubber O-rings between the aluminum base and lid interfaces with the PC tube, providing sealing and insulation. The lid of the testing rig is removable, allowing for easy access to the PC tube pressure vessel for changing out cavity liquids. The removable lid also acts as the mount and point of access for several sensors and hardware necessary for testing. Two thermocouples are mounted to the lid, one to measure the temperature of the liquid-phase and another to measure the temperature of the gas-phase in the pressure chamber. A pressure transducer is used to measure the real-time absolute pressure in the rig's chamber. To heat the PC two-phase pressure chamber, the entire rig is seated on a temperature controlled hot plate. One side of the rig was painted with black, high-emissivity paint to allow for external temperature measurements using an IR camera.

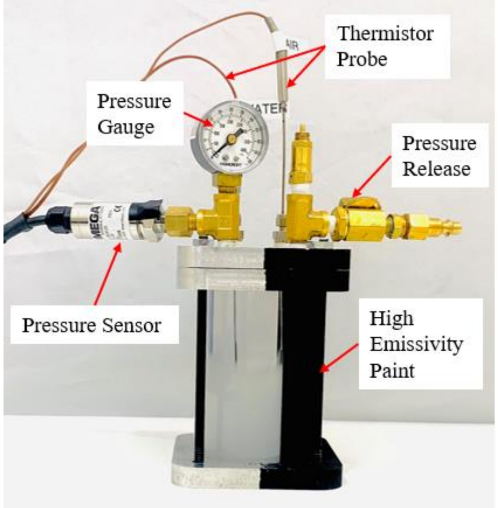

Figure 2. Annotated image of two-phase benchtop rig.

For modeling purposes, the geometry of the two-phase benchtop rig presented in figure 2 was simplified. All threaded interfaces were made smooth and hardware such as nuts, thermocouples, and pressure gauges/sensors were neglected. Furthermore, to reduce the computation time of the simulation, a quarter model of the rig with two symmetry planes was used. This can be done due to the symmetric nature of the simplified rig geometry. The fluid domain inside the PC tubing can be adjusted to accommodate different fluid types, fill ratios, and initial conditions.

CFD modeling and validation was performed in two stages. First, a steady-state Ansys Fluent solid-fluid coupled model of the benchtop rig with a single-phase (air) fluid domain was run to validate the model's general setup and boundary conditions using experimental data. By first validating the boundary conditions for the rig model using a single-phase in the PC tubing, a major source of potential error and uncertainty is eliminated for determining the correct Ansys multiphase model to simulate a liquid-to-vapor phase change in the two-phase Fluent model.

For the single-phase rig Ansys model, air was treated as an ideal gas with initial pressure and temperature matching the conditions in the lab during testing (13.7 psi and 23℃). The temperature of the aluminum base in contact with the lab hot plate was fixed to 99℃, matching the surface temperature of the hot plate measured at steady state. To determine the correct convection boundary condition to apply to external surfaces of the rig model, the temperature at several points on the outside of the benchtop rig at steady state measured using an IR camera were compared to the Ansys model results. An example comparison of an IR image showing the temperature on the outside of the benchtop rig at steady state with a temperature contour plot showing the corresponding Ansys model results can be found in figure 3. Using this validation approach, the best agreeance between the model and the experimental data was had using a convection coefficient of 6 W/m^2-K and a freestream temperature of 23℃ for all exposed surfaces. This falls in line with typical convection coefficients for stagnant air at room temperature [17].

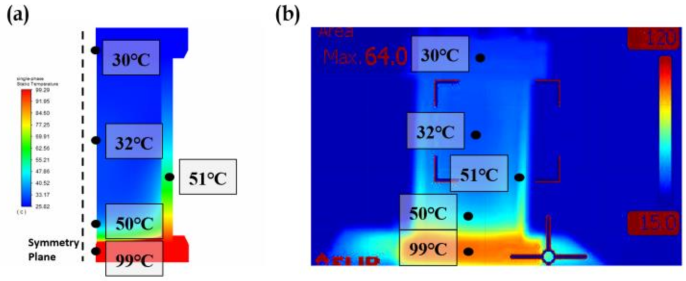

Figure 3. Temperature contour plots of the benchtop rig (a) Ansys Fluent model and (b) experimental data (IR image) for a single-phase (air).

After establishing the proper boundary conditions and model setup for the single-phase benchtop rig Ansys Fluent model, the fluid domain of the model was modified to contain 10% liquid water by volume and 90% air by volume at ambient conditions. With the addition of a liquid phase to the original Fluent model, a proper multiphase model needed to be selected to accurately simulate the water liquid-to-vapor phase change as the rig heated.

Again, the steady state temperature at several points on the outside of the benchtop rig measured using an IR camera were compared to the Ansys model results to validate the selected multiphase model. From this comparison, it was determined that a Volume of Fluid multiphase model using three Eulerian phases was appropriate. The Lee evaporation-condensation mass transfer mechanism was used to define the mass flow rate of liquid-to-vapor and vapor-to-liquid with the respective equations

$$\dot{m}_{l\rightarrow v} = a * \alpha_l \rho_l \frac{T - T_{sat}}{T_{sat}} \quad \text{for } T > T_{sat} \tag{7}$$

$$\dot{m}_{v\rightarrow l} = b * \alpha_v \rho_v \frac{T - T_{sat}}{T_{sat}} \quad \text{for } T < T_{sat} \tag{8}$$

where a and b are the user-defined evaporation and condensation frequencies, respectively. For the Lee evaporation-condensation mass transfer mechanism, a user defined function was used to set the saturation temperature as a function of pressure, in accordance with Antoine's equation. The validated evaporation frequency and condensation frequency were 0.01 Hz and 10 Hz, respectively. Using a condensation frequency three or more orders of magnitude greater than the evaporation frequency is common practice when modeling evaporation inside a closed domain with Ansys Fluent [17].

2.3 Sensor Cavity Two-Phase Modeling

Having validated the proper multiphase model to use in Ansys Fluent to simulate a liquid-to-vapor phase change in a closed domain, a simple steady state 2D Ansys Fluent model for the self-calibrating pressure sensor's reference cavity was developed. This model was created to further guide the design of the two-phase, self-calibrating pressure sensor prototype, helping determine the amount of water to add to the reference cavity during sensor fabrication and what the anticipated cavity pressure change is at different heater powers. Results from the simple 2D model will also provide valuable insight into the potential temperature and pressure gradients that may exist within the sensor cavity.

For this 2D Fluent model, the fluid domain dimensions match that of the rectangular side profile of the self-calibrating sensor's reference cavity, with a height to base length ratio of 0.145. To match the fill level ratio from the two-phase benchtop rig modeling and testing, the fluid domain in the cavity was originally divided into the two initial fluid states, room temperature air occupying the upper 90% of the cavity and room temperature liquid water occupying the bottom 10% of the cavity. This fill ratio can easily be changed for future modeling to determine the ideal cavity fill level for sensor fabrication. For simplicity, the temperatures at the boundary walls were fixed to match the expected temperatures inside the cavity at steady state when operating the cavity heating element at near maximum power, according to previous Ansys modeling work [4]. The heating element on the bottom wall of the cavity was simulated using a fixed wall temperature of 180°C. The remaining boundaries of the cavity were fixed with wall temperatures of 80°C and 60°C. A schematic showing the setup of the 2D cavity model can be seen below in figure 4.

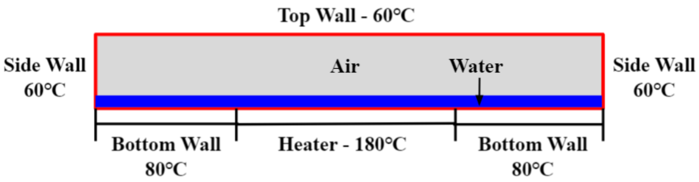

Figure 4. Initial and boundary condition for the 2D two-phase sensor cavity Ansys Fluent model.

Running the 2D sensor cavity model with the validated mass transfer mechanism from the two-phase benchtop rig Ansys Fluent model shows the potential temperature and pressure gradients inside the reference cavity at steady state. From the temperature contour plot in figure 5a, there is a large temperature gradient in the sensing element's cavity, similar to what was seen in the previous thermal modeling of the single-phase, self-calibrating pressure sensor [4]. Although there is a significant temperature gradient inside the cavity, figure 5b shows that the internal cavity pressure is a uniform 162 kPa absolute, or 9.8 psig, regardless of location. This is supported by the conservation of momentum for a gas at steady state [19]. At steady-state, the gas-vapor mixture is motionless, therefore there is no pressure gradient creating a net-force that acts on the gas [19]. As a result, there is a gas-vapor mixture density gradient inversely proportional to the temperature gradient [19].

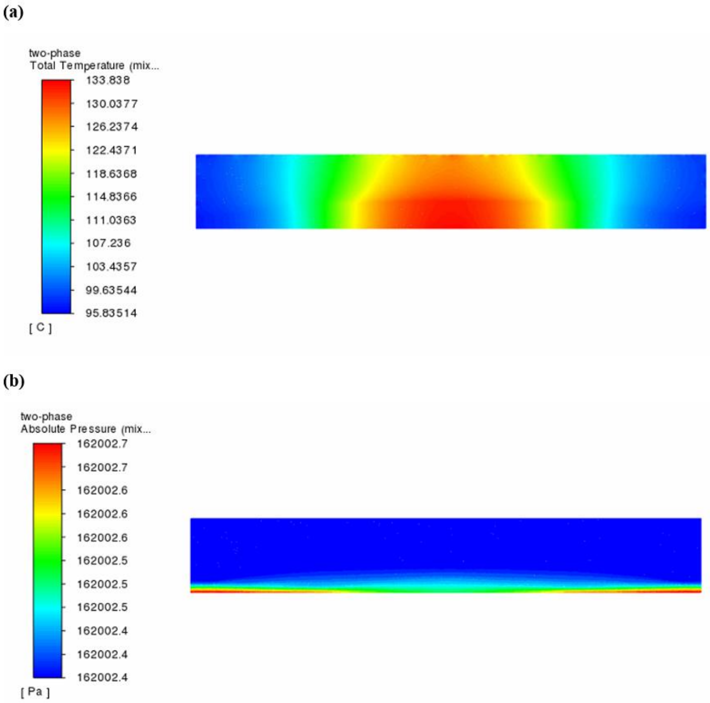

Figure 5. 2D sensor cavity Ansys Fluent steady state model results for (a) temperature and (b) absolute total pressure.

The results of the 2D cavity Ansys Fluent model further demonstrate the substantial reference cavity pressure increase expected using a water liquid-to-vapor phase change compared to heating a dry cavity with only air. Furthermore, the CFD modeling shows that the pressure in the cavity after heating is uniform, which was not realized from previous modeling work for the self-calibrating pressure sensor. With the guidance provided from the 2D cavity Ansys Fluent model and the two-phase benchtop testing rig, the first two-phase, self-calibrating pressure sensor prototype was developed.

3. Two-Phase Sensor Prototype

3.1 Development and Description

A prototype of the two-phase, self-calibrating pressure sensor, seen below in figure 6, was fabricated with a design similar to that used for the previous single-phase self-calibrating pressure sensor. The sensor prototype uses a novel flexible strip packaging, which allows the sensor to be mounted to contoured surfaces, such as aircraft nosecones or the exterior of underwater vehicles, while maintaining a low profile. On the far end of the flexible strip housing is the two-phase sensing element, which is housed underneath NanoSonic's protective HybridSil® coating.

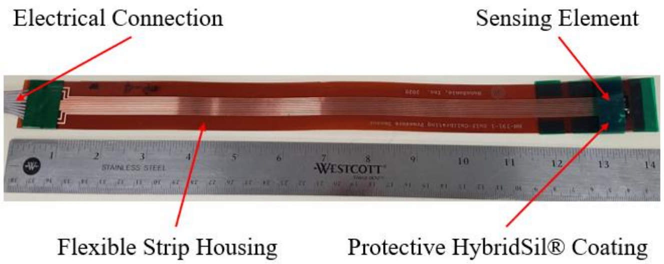

Figure 6. Photo of prototype two-phase, self-calibrating pressure sensor.

The self-calibrating pressure sensor's sensing element, shown in figure 7, has a 4 mm square base and a total height of 805 μm [4]. The buried oxide (BOX), device, and silicon base layers are fabricated from a silicon on insulator (SOI) wafer [4]. A hollow reference cavity was carved out of the silicon base layer using deep reactive-ion etching (DRIE). On the device layer, four piezoresistors are arranged in a Wheatstone bridge configuration. Before bonding the glass substrate layer to the SOI wafer to create the sealed reference cavity, both the cavity heater and thermistor are manufactured directly onto the substrate surface. With the heater enclosed with the thermistor in the sealed reference cavity, a controllable thermopneumatic actuator is formed, giving the sensor self-calibrating capabilities [4]. As the heater increases the temperature of the fluid in the reference cavity, the fluid expands, deforming the membrane and device layer. The surface thermistor mounted on the top surface of the sensing element monitors the temperature of the device layer.

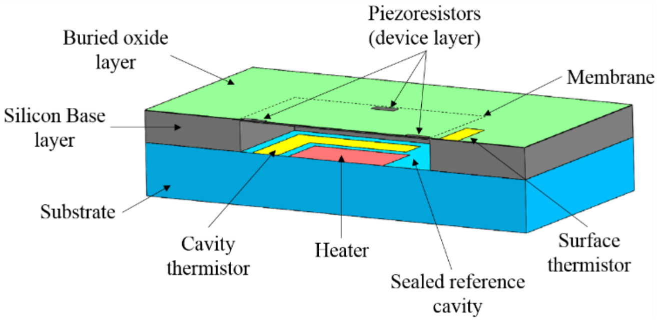

Figure 7. Cross-section view of the sensing element inside the self-calibrating pressure sensor [4].

To create a two-phase, self-calibrating pressure sensor, a small deposit of water was added to the sealed reference cavity of the sensing element shown in figure 7. The water was added to the cavity using a micropipette with a minimum volume of 0.1 μL. Based on the guidance provided from the two-phase benchtop testing and the 2D cavity Ansys Fluent model, the amount of water added was no less than 10% of the cavity's total volume. This was done to provide enough liquid water to prevent complete evaporation at the expected cavity temperatures. Maintaining a liquid water phase in the cavity at all times ensures the cavity pressure follows the relationship to temperature described earlier in equations (5) and (6).

3.2 Testing and Calibration Procedures

Before calibrating the prototype two-phase sensor, a shakedown test was performed to determine whether liquid water was successfully sealed in the reference cavity during sensor fabrication. This was done by turning on the sensor's cavity heater to about 90% maximum power (~0.45 W). If liquid water were present in the cavity, plotting the measured pressure and cavity temperature voltage signals would result in a nonlinear curve similar in shape to that seen previously in figure 1 for a two-phase closed system. To confirm the presence of a phase-change, the measured pressure change and cavity temperature change were normalized using the equation

$$\Delta X_n = \frac{\Delta X - \Delta X_{min}}{\Delta X_{max} - \Delta X_{min}} \tag{9}$$

where ΔX is either pressure change or cavity temperature change, and compared to the normalized theoretical pressure change according to equations (5) and (6) for the expected temperature range inside the sensor cavity. Plotting these two normalized curves in figure 8 shows two overlapping nonlinear curves, which proves the existence of a water liquid-to-vapor phase change in the sensor cavity.

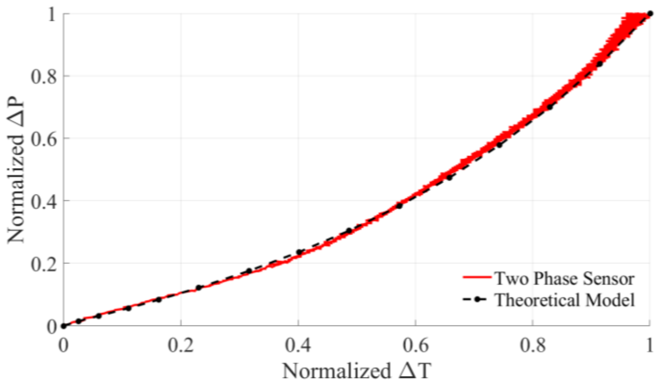

Figure 8. Normalized pressure and temperature change measurements for the prototype sensor compared to theoretical results.

After confirming the presence of liquid water in the sensor cavity, the sensor was pressure calibrated at room temperature. The two-phase sensor was placed in a sealed chamber connected to a pressure control handpump and then placed inside a temperature-controlled environmental chamber set to 20°C. The heating element in the cavity was kept turned off for the entirety of the pressure calibration to ensure the measured pressure was true to the pressure applied by the handpump.

Using the handpump, the pressure in the sealed chamber was varied from -10 psi to 10 psi in 2 psi increments, providing the data necessary to create a linear fit equation to convert the sensor pressure voltage signal to a pressure (psi). Since the measured signal from an external applied pressure is equal and opposite to that from an internal cavity pressure of the same magnitude, this calibration curve can be used to determine the pressure inside the sensor cavity. Now the exact pressure resulting from the liquid-to-vapor phase change inside the reference cavity can be determined.

4. Results

4.1 Sensor Performance

To highlight the extended range of self-calibration in the two-phase self-calibrating pressure sensor, the cavity heater was turned on to 90% of its maximum power (~0.45 W) and held until the cavity temperature reached steady state. Plotting the resulting cavity pressure as a function of time in figure 9 shows that just 3 seconds after turning on the heating element the cavity pressure in the prototype two-phase sensor has increased by 3 psi, matching the pressure change in the single-phase, self-calibrating sensor at similar heater power levels [4]. That pressure change is tripled to 9 psi after just 2 minutes, effectively tripling the effective range of self-calibration of the sensor. The gauge pressure in the sensor cavity also appears to reach 9.5 psi at steady state, closely matching the results from the 2D cavity Ansys Fluent model (9.8 psig).

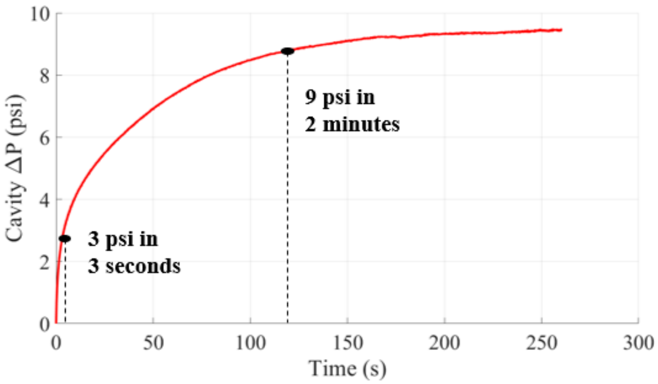

Figure 9. Measured cavity pressure after powering on the cavity heater.

The improved performance of the self-calibrating pressure sensor can be even further realized by plotting the measured cavity pressure change for the two-phase sensor as a function of the cavity temperature and comparing it to the same curve for the single-phase sensor, as done in figure 10. Taking advantage of the higher pressures associated with a liquid-to-vapor phase change, the two-phase pressure sensor provides a faster response time and self-calibration range than the single-phase sensor, all while decreasing the sensor's power demand.

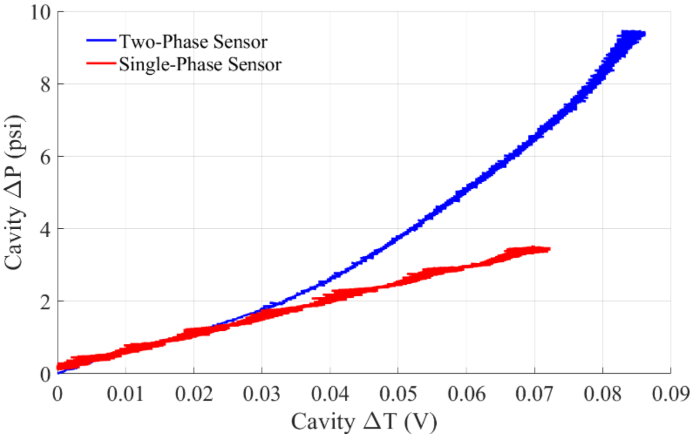

Figure 10. Comparison of the measured cavity pressure vs. the cavity temperature change for the two-phase sensor and the single-phase sensor.

Not only is the performance of the self-calibrating pressure sensor significantly improved by the addition of a liquid-to-vapor phase change, but the two-phase sensor prototype also has notable advantages over other available phase-change based pressure sensors. Unlike the presented two-phase self-calibrating sensor, the self-testing pressure sensor based on a phase-change developed by M. Huo *et al.* is unable to resolve hysteresis and drift (i.e. self-calibrate) due to the lack of an internal cavity temperature measurement [12]. The outdated silicon wafer MEMS fabrication techniques used limit the resolution of the self-testing sensor to 0.06 mV/psi, while the resolution of the present two-phase self-calibrating sensor fabricated using SOI wafer technology with deep reactive-ion etching (DRIE) is almost 80 times greater at 4.7 mV/psi [12,20,21]. Furthermore, the two-phase, self-calibrating pressure sensor uses a fixed volume of liquid in the reference, which allows for repeatable testing and self-calibration. The cavity of the self-testing pressure sensor must be entirely drained before use and refilled again for functionality checks, creating a potential repeatability concern.

4.2 Sensor Cavity Liquid Loss

Initial tests of the prototype two-phase, self-calibrating pressure sensor indicated a form a liquid water loss or consumption inside the sensor cavity. The measured cavity pressure and temperature from one of these tests can be found below in figure 11. As the sensor's reference cavity was heated and the internal pressure began to build, a sudden drop in pressure occurred around 7.5 psig even though the cavity temperature continued to rise. The probable cause for this loss of pressure is a leak forming in the sensor cavity due to the high pressure brought on by the liquid-to-vapor phase change. Leakage was not an issue with the previous single-phase sensor design, as cavity pressures never exceeded 5 psig.

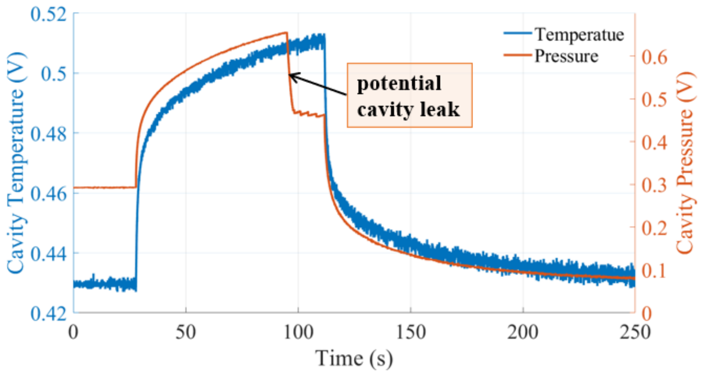

Figure 11. Measured cavity pressure and temperature change indicating a potential leak.

Piezoresistive pressure sensor cavity leakage is well-documented [1] and can occur when the cavity pressure is high enough to damage the bond between the silicon base later and the substrate, causing a leak to form. Cavity leakage can be prevented in future iterations of the self-calibrating pressure sensor by increasing the bonding strength between the silicon base layer and the substrate. A hydrophobic coating can also be used inside the reference cavity to prevent chemical reactions between water and silicon at high temperatures and pressures that may consume water inside the cavity. More work is necessary to determine whether the reaction between water and silicon has a significant effect on the water level inside the reference cavity.

5. Conclusions and Future Work

Partially filling the reference cavity of a piezoresistive self-calibrating pressure sensor with liquid water can significantly improve its effective range of operation. By using a combination of physical modeling, large-scale benchtop testing, and CFD modeling, a prototype two-phase, self-calibrating pressure sensor was successfully designed and fabricated. The prototype two-phase, self-calibrating sensor's reference cavity was filled with no less than 10% liquid water by total volume, as guided from the 2D Ansys Fluent modeling of the sensor cavity. Testing of the two-phase sensor at 90% heater power resulted in a total cavity pressure change of 9.5 psi, tripling the cavity pressure change of the single-phase, self-calibrating pressure sensor at similar cavity heater powers. The two-phase, self-calibrating pressure sensor was also demonstrated to be advantageous over other available phase-change based piezoresistive pressure sensors, as the presented sensor is nearly 80 times more sensitive than the self-testing sensor developed by M. Huo *et al* [12]. The present sensor can also compensate for hysteresis and drift in real-time due to the internal cavity thermistor temperature measurement, a capability not available in other similar pressure sensors [4,10-12].

To further support the development of the self-calibrating pressure sensor with an extended range of operation, work has begun to investigate alternative cavity liquids that will provide higher pressures without increasing heater power demands. The first three liquid alternatives for water considered were ethanol, isopropyl alcohol, and acetone. These liquids were chosen due to their lower saturation temperatures at atmospheric pressure than water, resulting in higher vapor pressures at a given temperature [22]. Modifying equations (5) and (6) for each new liquid and plotting the pressure as a function of temperature in figure 12 shows that all three alternative liquids provide higher cavity pressures than water, especially at higher temperatures.

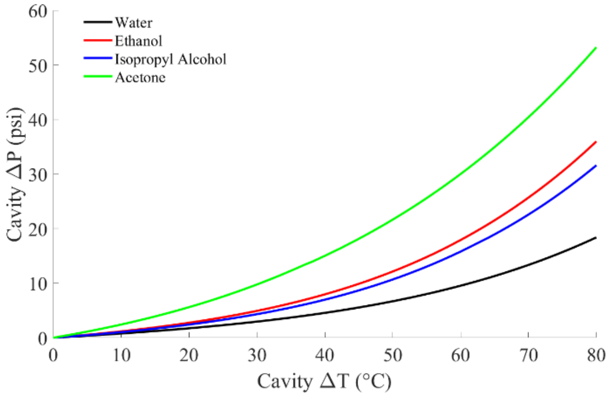

Figure 12. Theoretical pressure change vs temperature change for multiple different liquids.

Further research must be done to determine whether the corrosive properties of acetone, isopropyl alcohol, and ethanol may erode the sensing element, causing leaks to form in the sensor's reference cavity. The two-phase benchtop testing rig will be used with each of the proposed cavity liquids and samples of the silicon-based sensing element to help determine which may be detrimental to the sensor. New prototype self-calibrating pressure sensors will then be fabricated using the liquids that will not damage the sensing element. Future improvements to the self-calibrating pressure sensor's performance can also be made by eliminating any potential leakage in the reference cavity and increasing the temperature and pressure survivability of the sensing element. A high fidelity, transient 3D Ansys Fluent solid-fluid model of the two-phase pressure sensor that includes the geometries for the sensing element and strip sensor packaging will be developed to better understand the transient phase-change dynamics within the sensor cavity and the induced stress on the sensor's pressure-sensitive membrane.

Acknowledgements

This material is based upon work in part supported by the Air Force under contract FA864920C0335, and NASA under contract 80NSSC20C0036. We particularly acknowledge Dr. Brett Pokines and Mr. Andrew Bracey for their many insights and useful discussions of this work.

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Appendix A. Benchtop Rig Ansys Fluent Model Boundary Conditions

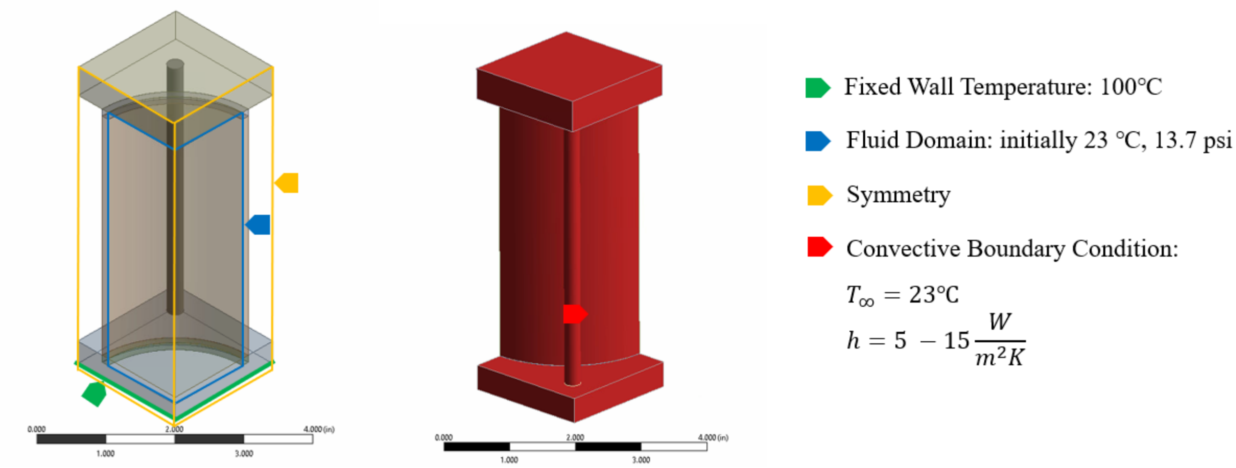

Figure A. Boundary conditions and setup for benchtop testing rig Ansys Fluent model. The fluid domain can be modified to support various combinations and volumes of different fluids.

Appendix B. Benchtop Rig Testing Results

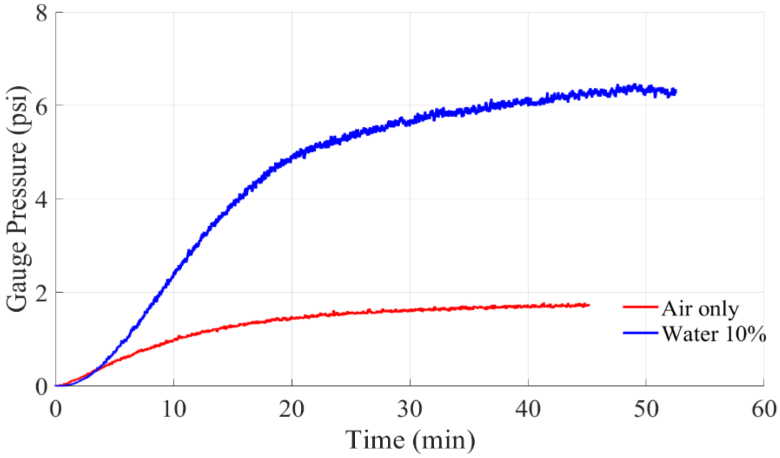

Figure B. Plot showing the benchtop testing rig pressure-time data, with the lab hot plate set to 100°C, for the cases of no water (only air) in the rig chamber and 10% water by total volume in the rig chamber. The presence of a small amount of water more than triples the chamber pressure at steady state.

Appendix C. Sensor Cavity CFD Results – Density Gradient

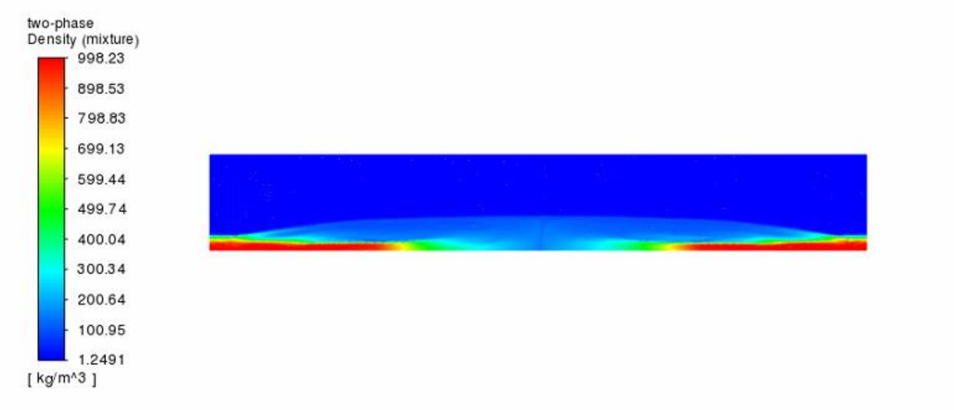

Figure C. 2D sensor cavity Fluent model results showing the density gradient inside the sensor cavity at steady state. The density gradient is inversely proportional to the temperature gradient at steady state.

Appendix D. Sensor Calibration and Testing Setup

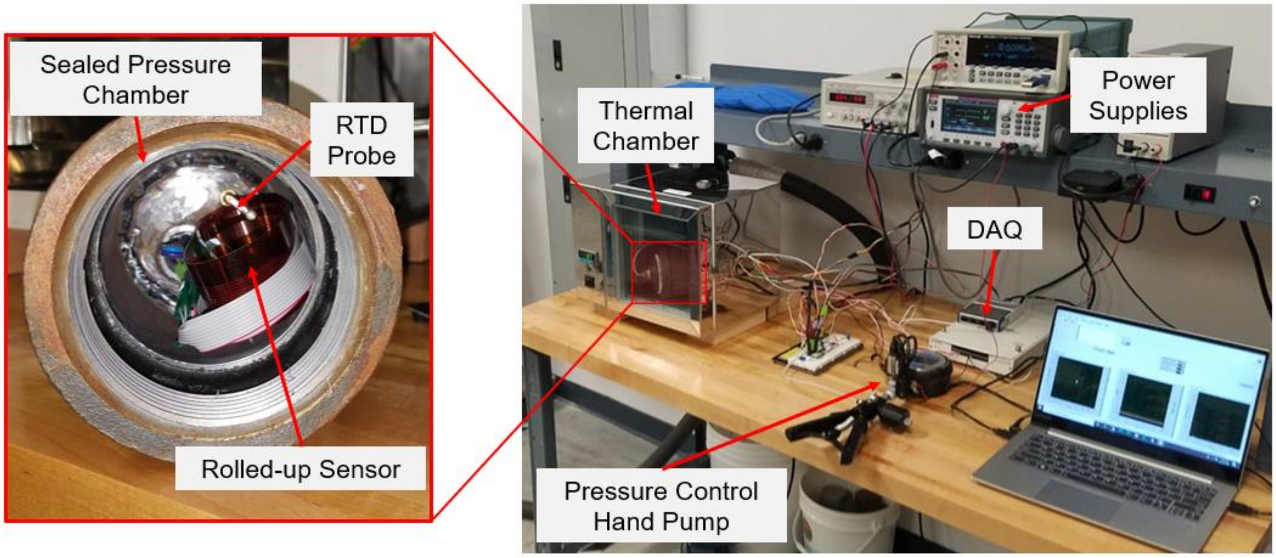

Figure D1. Testing setup for investigating functionality of prototype two-phase, self-calibrating pressure sensor. The sealed pressure chamber and the pressure control hand pump were used to generate standard pressures for sensor calibration. A thermal chamber was used to keep a consistent environmental temperature while calibrating the sensor.

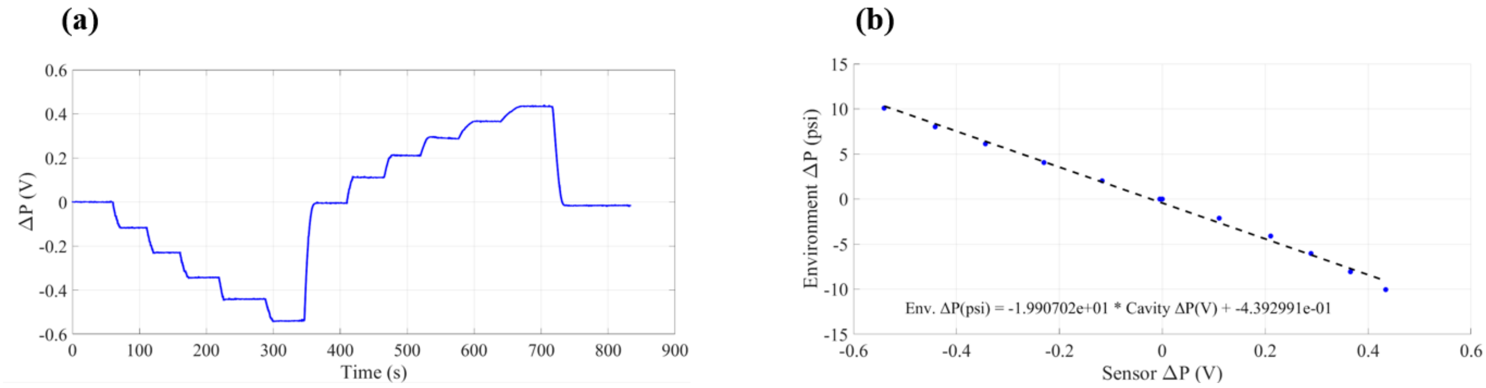

Figure D2. Plots showing (a) the applied standard pressure steps for calibrating the two-phase, self-calibrating pressure sensor and (b) the resulting pressure calibration curve and equation.