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Advanced Sensors and Instrumentation

Development of Microwave Resonant Cavity Transducer for Flow Sensing in Advanced Reactor High Temperature Fluids

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

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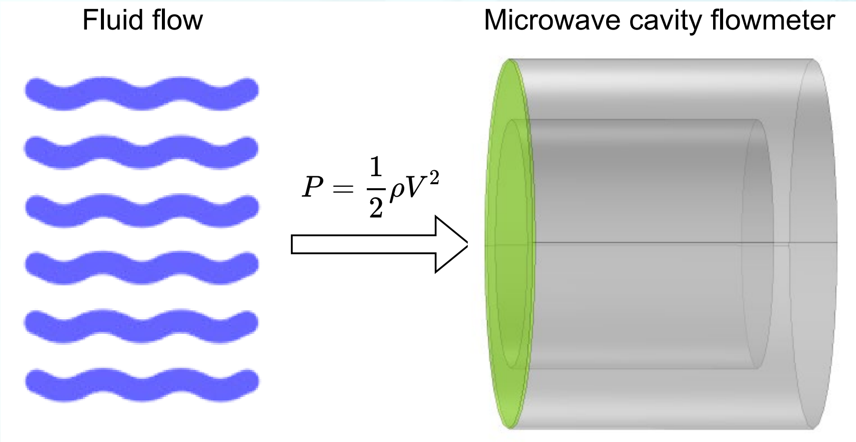
Project Overview

Develop multimodal immersion sensor of high temperature fluid

- Hollow metallic cylindrical microwave resonator with thin flexible membrane
  - Resilient to high temperature and radiation
  - Communication with sensor through hollow rigid metallic microwave waveguide
- Transduction through microscopic volume change that shifts resonant microwave frequency
  - Membrane deflection through dynamic fluid pressure – flow
  - Membrane deflection through static fluid pressure – level
  - Thermal expansion of cylinder – temperature

Applicable to sensing coolant fluid in sodium fast reactor (SFR) and molten salt cooled reactor (MSR)



Project Overview

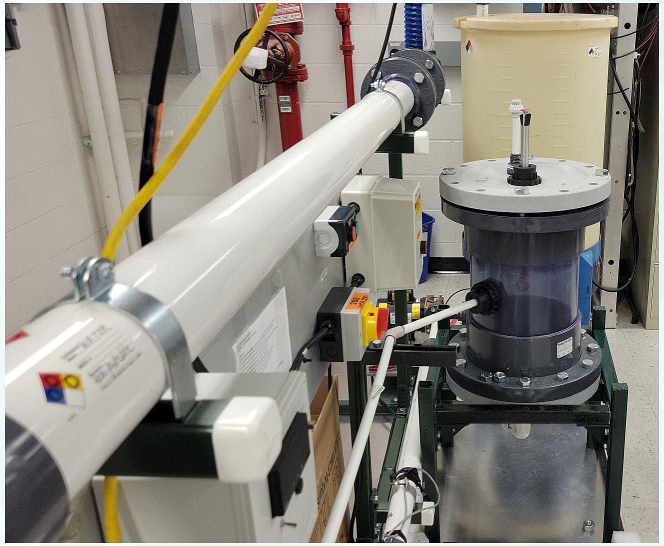
- **Project Schedule**

Y1

Sensor prototype design

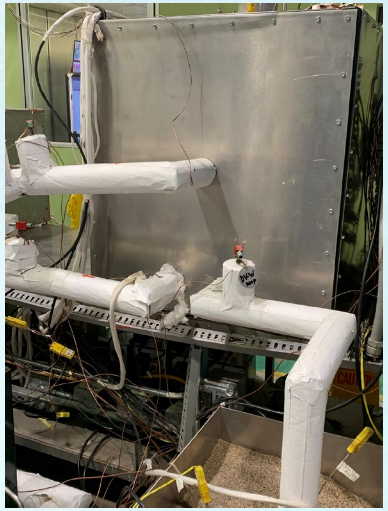
Y2

Flow sensing in water



Y3

Flow sensing in high temperature fluid



Completed

Project Overview

- **Participants**

Argonne National Laboratory	Illinois Institute of Technology	Kairos Power
Alexander Heifetz (PI)	Tianyang Fang	Anthonie Cilliers
Sasan Bakhtiari	Jafar Saniie	
Eugene Koehl		
Bill Lawrence		
HT Chien		

Technology Impact

	Ultrasonic	Electromagnetic	Anemometry	Microwave Resonant Cavity-Based
Sensing in which fluid	Liquid sodium & molten salt Based on detection of time of flight or Doppler frequency shift	Liquid sodium Take advantage of electrical conductivity of liquid sodium	Liquid sodium & molten salt Based on convective heat transfer by moving fluid	Liquid sodium & molten salt Transduction is based on fluid-structure interaction
Immersion or external	External Two transducers in pitch-and-catch or transmission mode require direct line of sight	Immersion or external Measure rate of conducting flux passing through coil cross-section	Immersion Involves measuring reference source cooling rate due to convective heat transfer	Immersion Can be made as small as type-K thermocouple
Deployment challenges	Crystal can degrade due to exposure to high temperature and radiation	Permanent magnet could be de-magnetized. Coil requires large size DC power supply	Relatively slow because of heat transfer	Hollow stainless steel structure resilient to high temperature and radiation

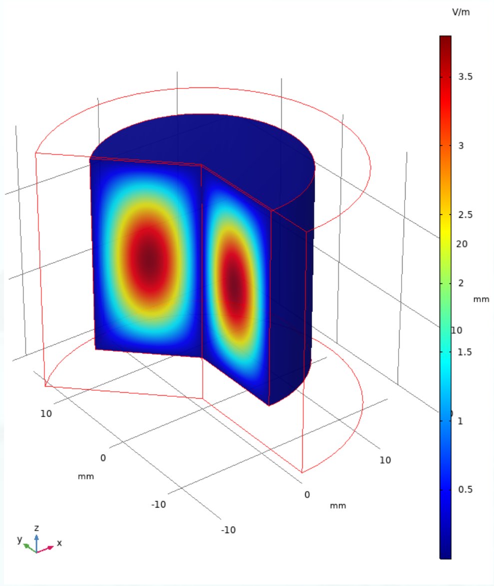
Results and Accomplishments

Developed analytic sensor model

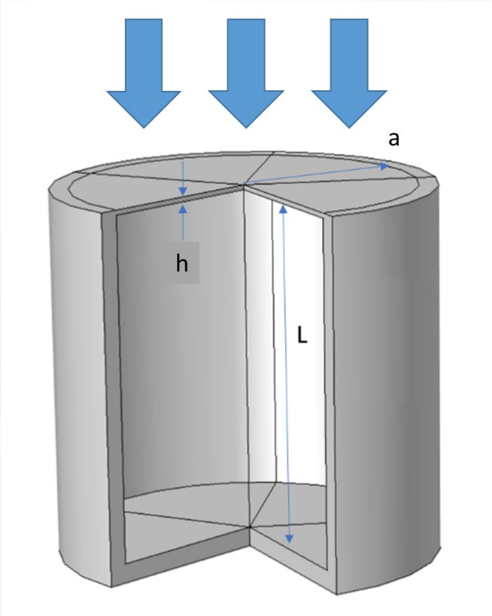
- Chose right circular cylinder design (L=2a) to achieve highest Q-factor
- Focused on low order TE_{011} mode

$$\Delta f_{011}^{TE} = f_{011}^{TE} \frac{\pi^2}{\left(2X'_{01}\right)^2 + \pi^2} \frac{\Delta L}{L}$$

$$\Delta L = \frac{1-\nu^2}{32E} \frac{a^4}{h^3} \rho V^2$$



TE_{011} mode f_{011} = 17.8GHz

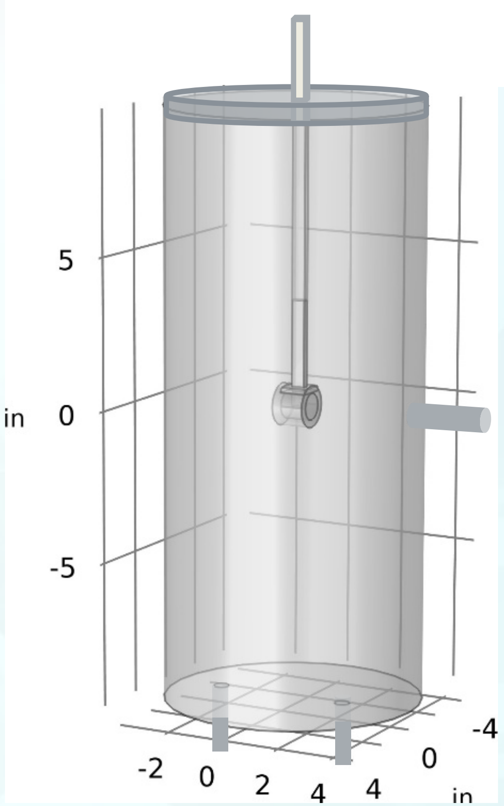


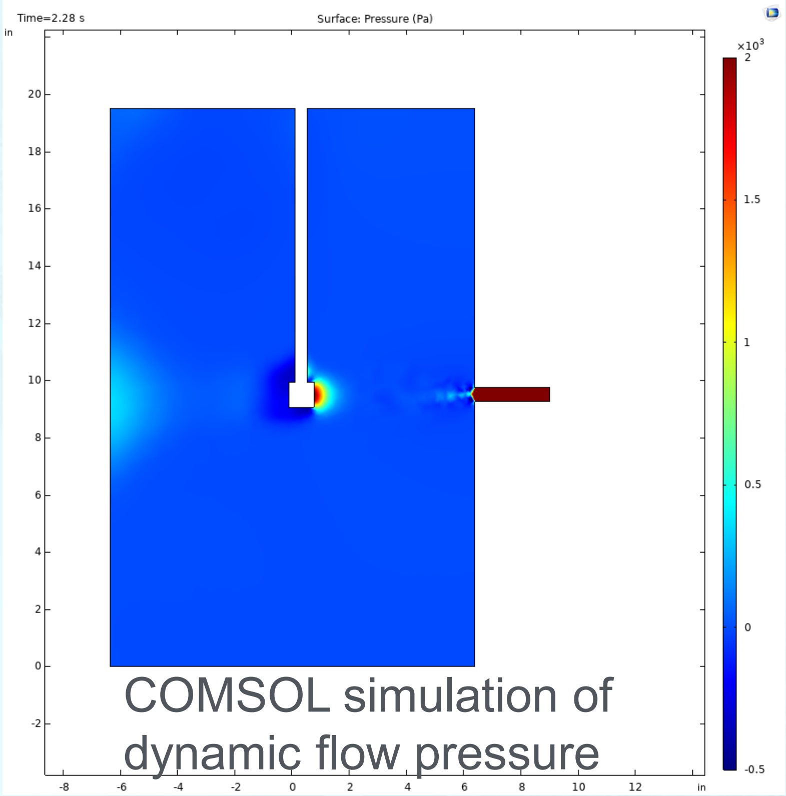
n,m,l = mode numbers
c = speed of light
X'_{01} = 3.832 (1st root of $J'_0(x)$)
L = length
a = radius
h = membrane thickness
ε_r = relative dielectric permittivity
μ_r = relative magnetic permeability
E = Young's modulus
ν = Poisson ratio
ρ = fluid density
v = fluid velocity

Results and Accomplishments

Identified existing TAPS experimental setup for liquid sodium flow sensing test

- Impinging jet flow
- Insulated cylindrical tank 19.5in x 9.5in with ¼ in center feed line



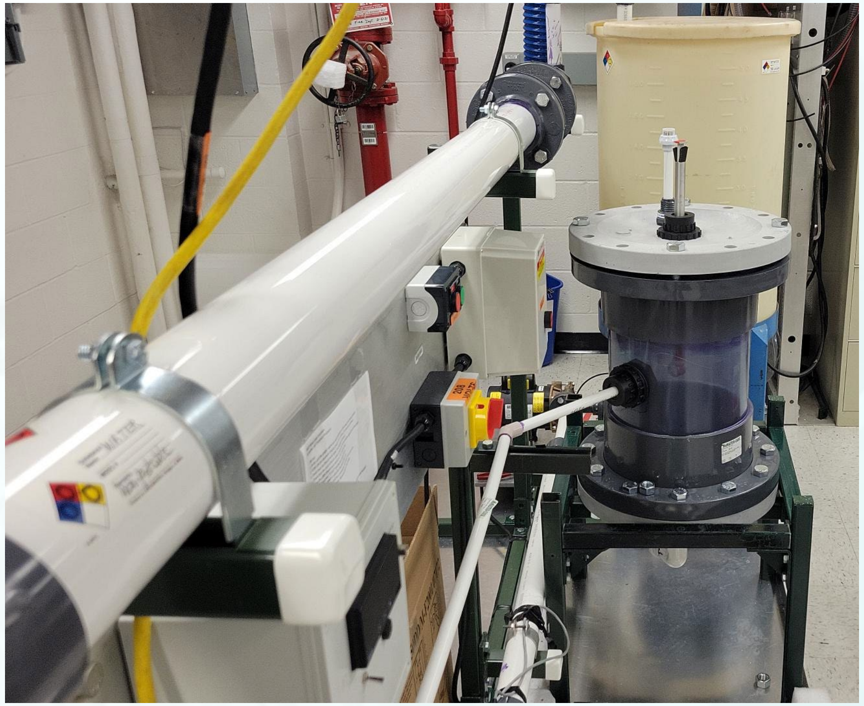


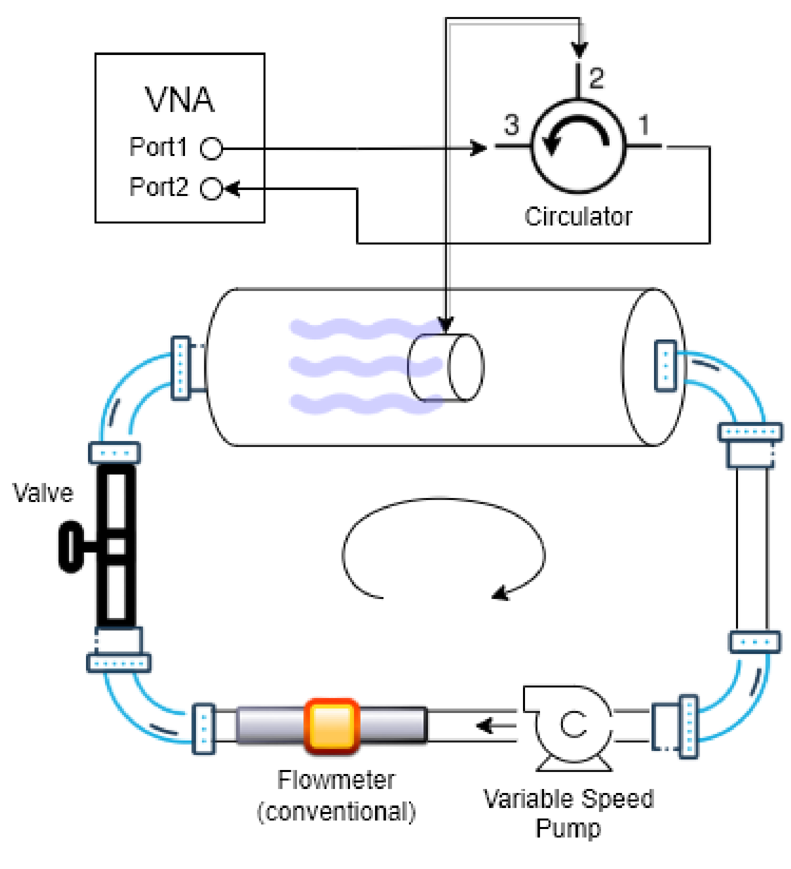
COMSOL simulation of dynamic flow pressure

Results and Accomplishments

Developed vessel integrated into water loop for preliminary flow sensing in impinging jet geometry

- Water vessel with the same geometrical parameters as liquid sodium vessel
- Pump rated up to 60gpm flow rare at ambient pressure
- Omega flowmeter installed for reference flow measurements

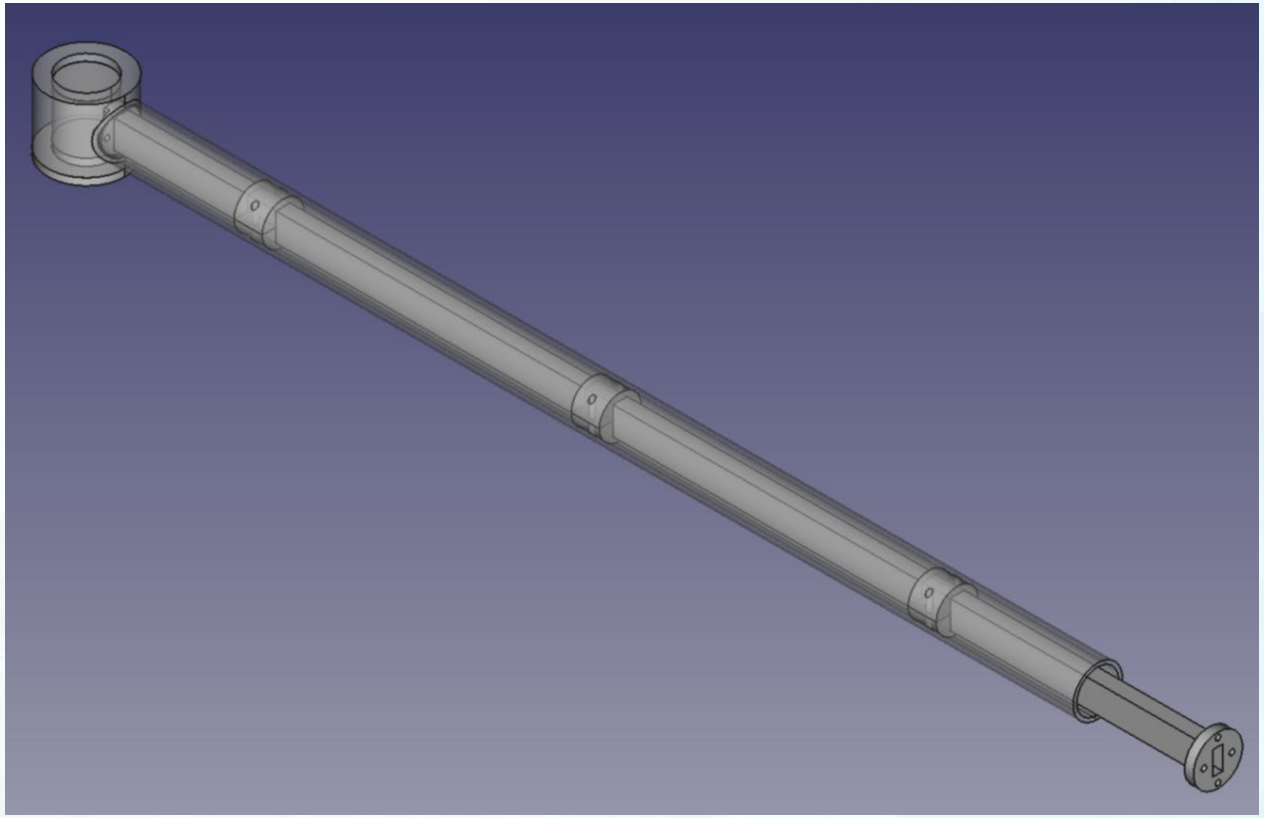




Results and Accomplishments

Designed probe assembly for liquid sodium flow test

- Stainless steel 316 welded structures
- Commercial brass WR-42 waveguide attached to cylindrical resonator and enclosed in SS316 tube



Results and Accomplishments

Designed microwave cavity sensor

- Internal dimensions L = a = 22.2mm
- Cavity excited through subwavelength hole with 2mm diameter
- Membrane thickness 8mil = 203μm
- Silver-plated interior surfaces to achieve high Q resonances

Aluminum prototype

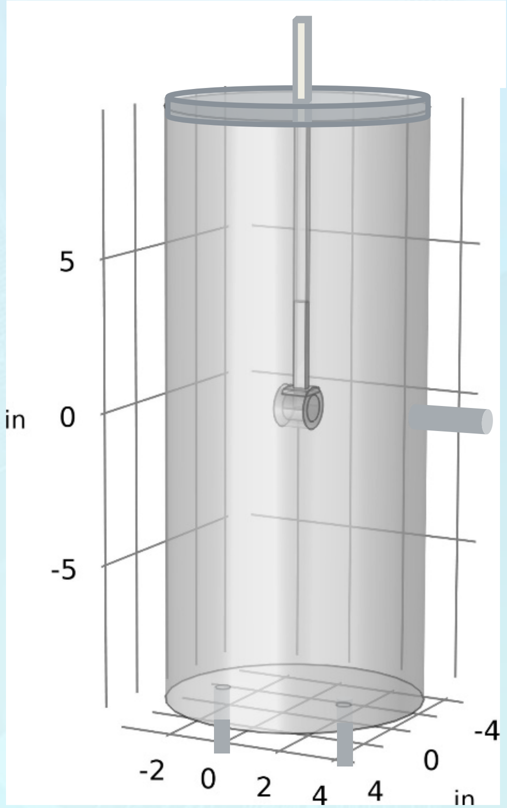
SS316 transducer

Results and Accomplishments

Flow sensing in liquid sodium vessel in impinging jet geometry

- TAPS (Thermoacoustic Power Sensing) vessel
- Temperature up to 350^{o}C, ambient pressure

Transducer Waveguide

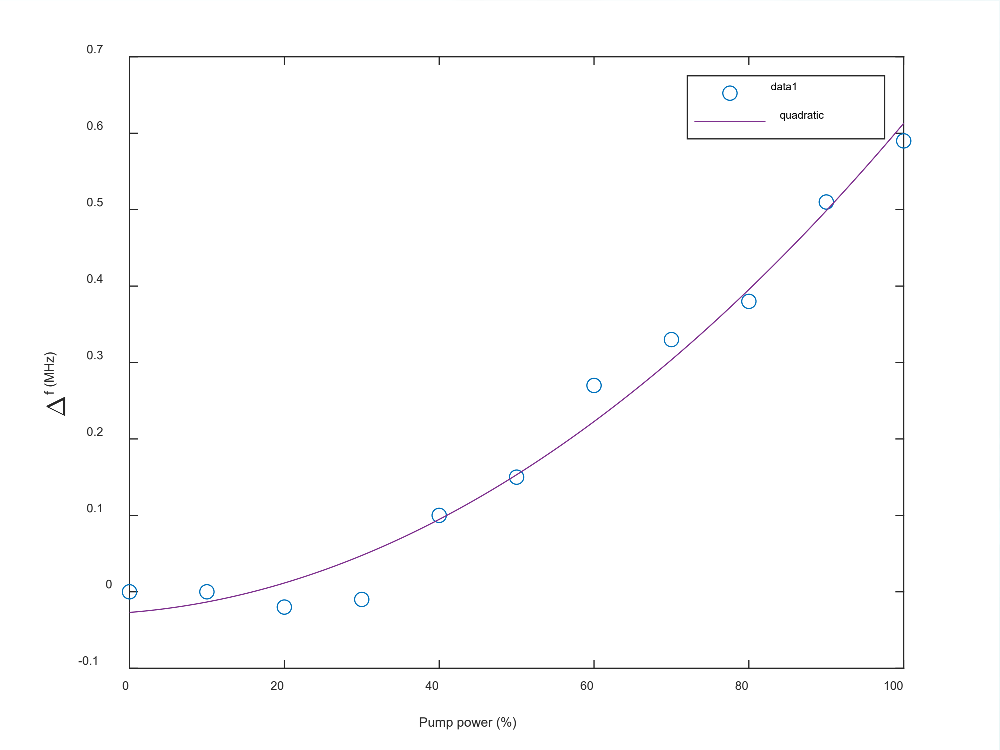


Results and Accomplishments

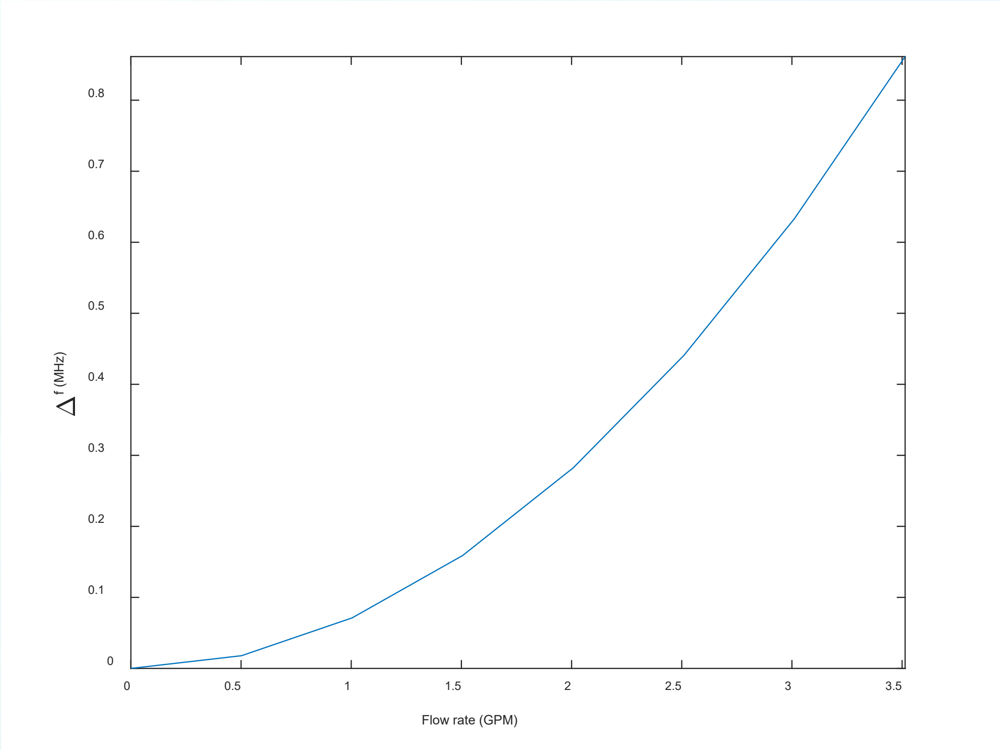
Measurement of flow in liquid sodium at 343°C

- No commercial reference flow meter
- COMSOL simulations provide interpretation of measurements

Experimental measurements



COMSOL computer simulations



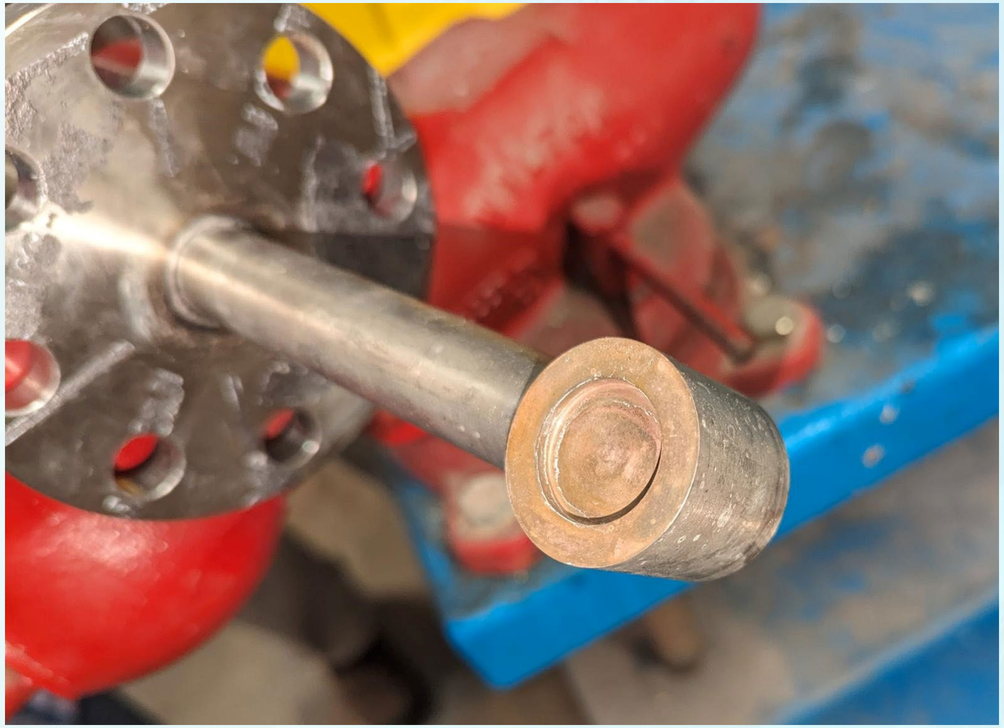
Results and Accomplishments

Transducer remained in liquid sodium for 70 days

- No structural damage observed
- Re-tested in water loop after removal from liquid sodium

Before

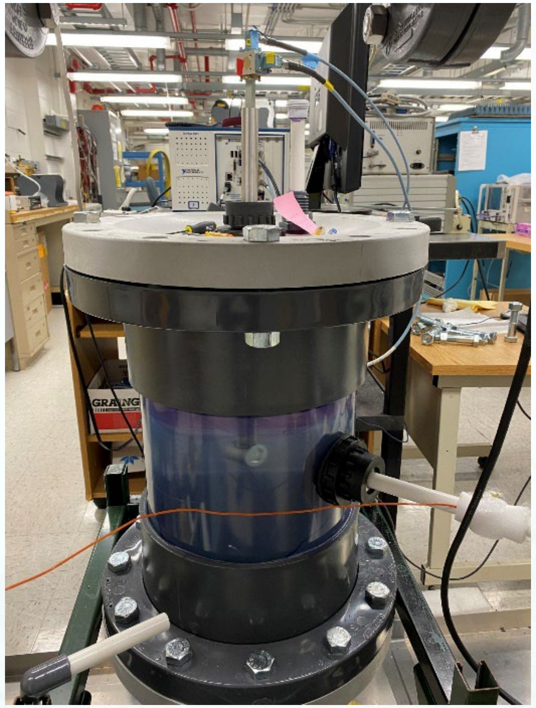
After

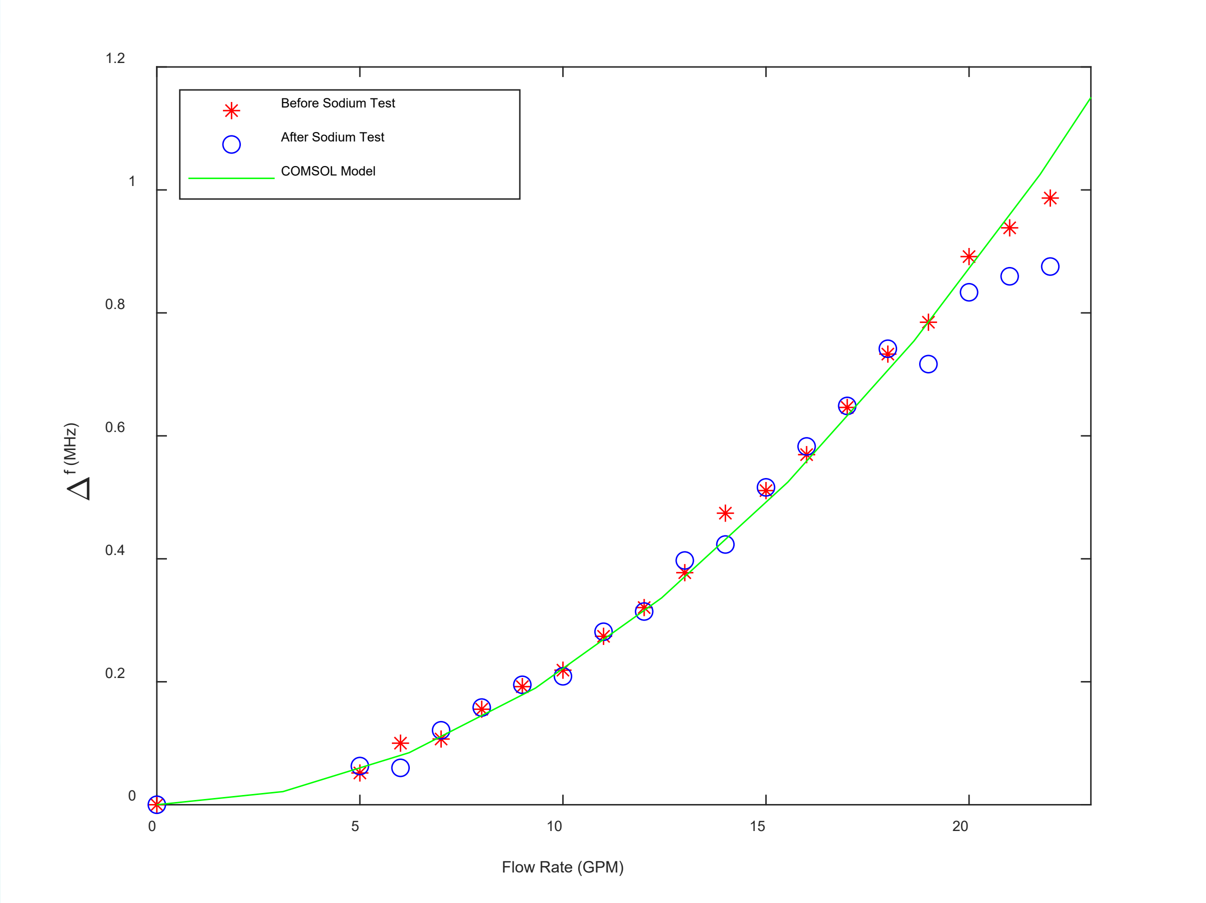


Results and Accomplishments

Transducer tested in water before and after liquid sodium test

- Re-tested in water loop after removal from liquid sodium
- Similar performance in water as prior to deployment in sodium





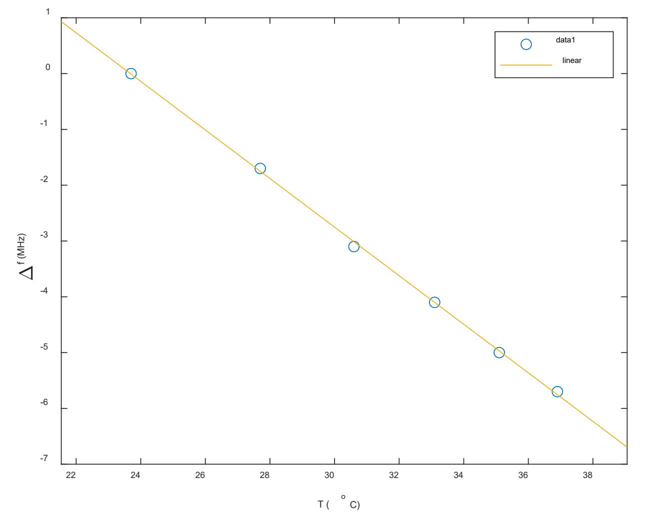
Results and Accomplishments

Developed Sensor Thermal Drift Compensation Procedure

- Thermal expansion of resonator changes resonant frequency
- Obtained linear fit for temperature-dependent frequency shift

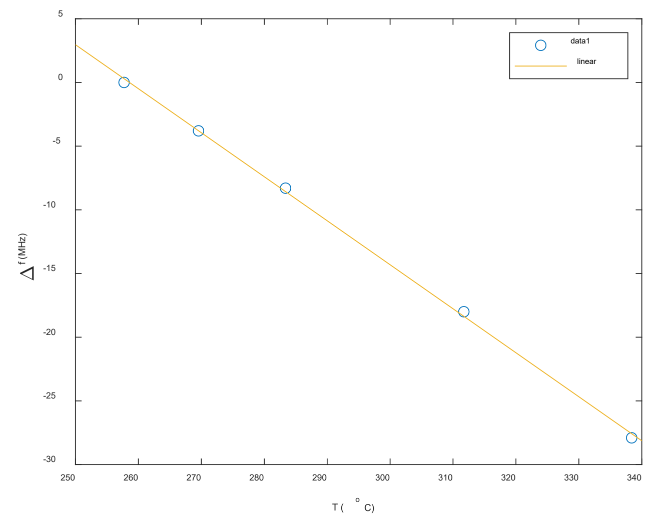
$$\Delta f_{011}^{TE} = f_{011}^{TE}\left(-\frac{\Delta L}{L}\right) \quad \text{where} \quad \frac{\Delta L}{L} = \alpha \Delta T$$

Water



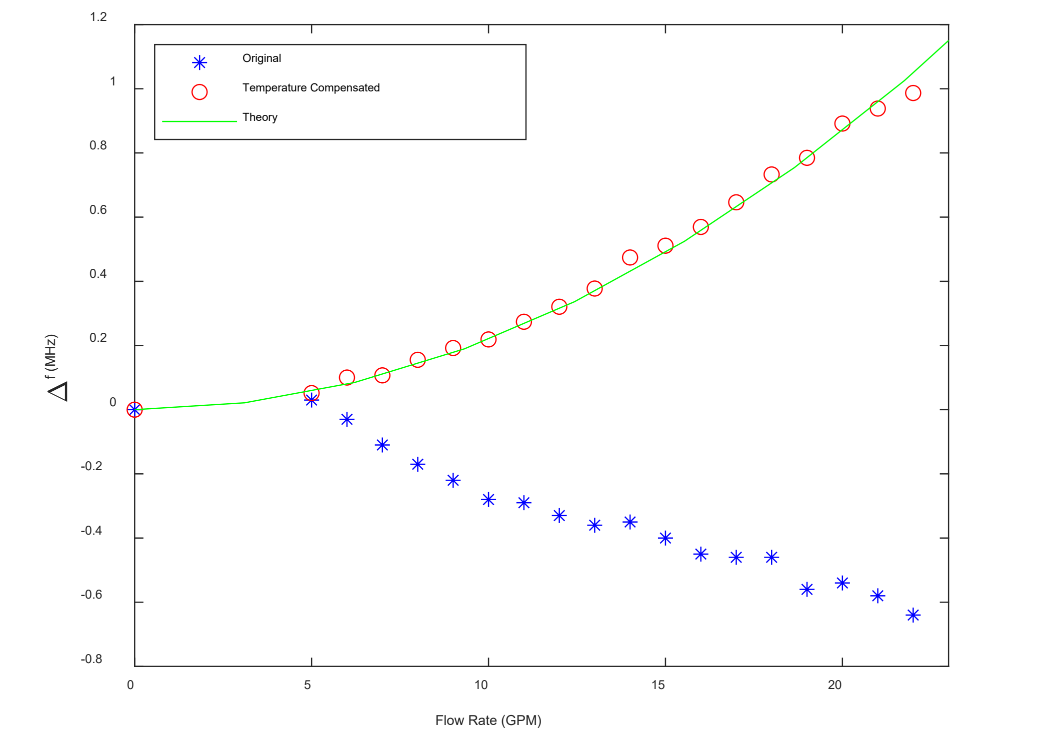
R^2=0.974

Sodium



R^2=0.955

Temperature compensation in water test



Concluding Remarks

- **Publications**
  - T. Fang, J. Saniie, S. Bakhtiari, A. Heifetz, "Optimization of Microwave Resonant Cavity Flowmeter Design for High Temperature Fluid Sensing Applications," IEEE International Conference on Electro Information Technology (EIT2023). **Second Place Award**
  - A. Heifetz, V. Ankel, D. Shribak, S. Bakhtiari, A. Cilliers, "Microwave Resonant Cavity-Based Flow Sensor for Advanced Reactor High Temperature Fluids, *Proceedings 12th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2021),* 232–238 (2021).
  - A. Heifetz, S. Bakhtiari, E.R. Koehl, T. Fang, J. Saniie, A. Cilliers, "Microwave Resonant Cavity Transducer for Fluid Flow Sensing," *Bulletin of the American Physical Society* (2022).
  - T. Fang, J. Saniie, S. Bakhtiari, A. Heifetz, "Frequency Shift Baseline Removal for Improved Measurement using Microwave Cavity Resonator," Proceedings of *2022 International Conference on Electro-Information Technology* (*EIT*), 436-439.

- **Patents**
  - A. Heifetz and S. Bakhtiari, "Microwave Resonant Cavity Transducer for High Temperature Fluid Flow Sensing," IN-20-146, Argonne National Laboratory (2020).

Concluding Remarks

Summary of accomplishments in FY23

- Designed and fabricated stainless steel sensor prototype for high temperature fluid environment
- Demonstrate flow sensing in liquid sodium vessel at 343^{o}C
- Demonstrated sensor resilience to high temperature environment after 70 days of testing in liquid sodium

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Thank You