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ASI 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
November 4 – November 7, 2024

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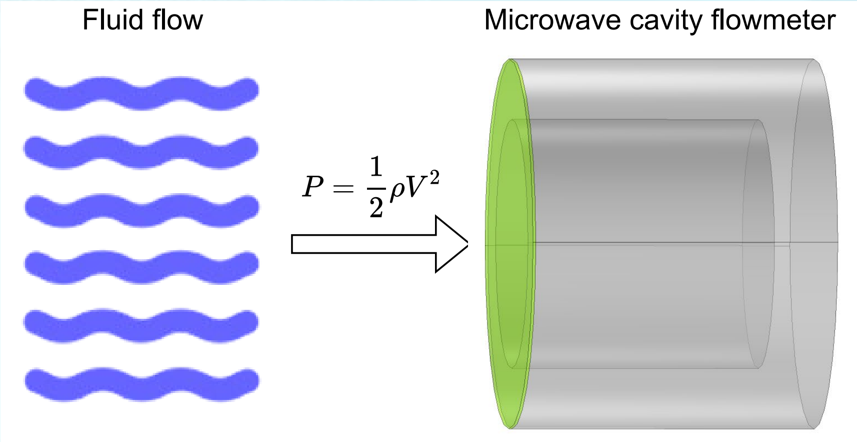
Project Overview

Objectives

- Develop high temperature and radiation-resilient multimodal sensor of coolant fluid
- Applicable to sodium fast reactor (SFR) and molten salt cooled reactor (MSR)

Sensor Description

- Hollow cylindrical microwave cavity resonator immersed in fluid
  - Sensor signal readout through hollow rigid metallic microwave waveguide
- Signal transduction through fluid structure interaction
  - Microscopic deflection of thin wall changes microwave resonant frequency
- Multimodal sensing
  - Dynamic fluid pressure – flow
  - Static fluid pressure – level
  - Thermal expansion – temperature

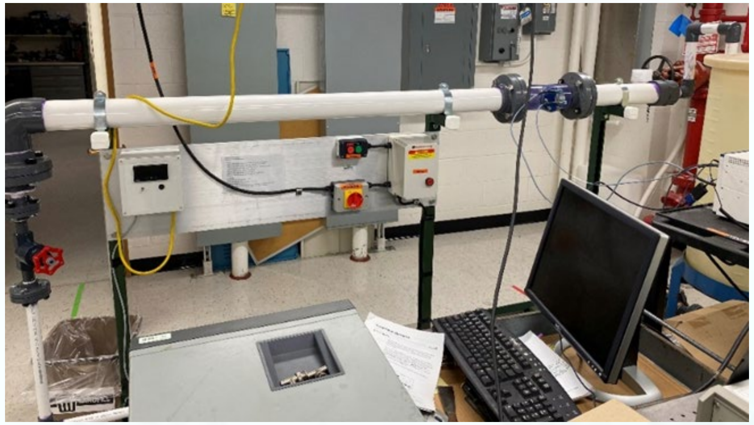


Project Overview

- **Project Schedule**

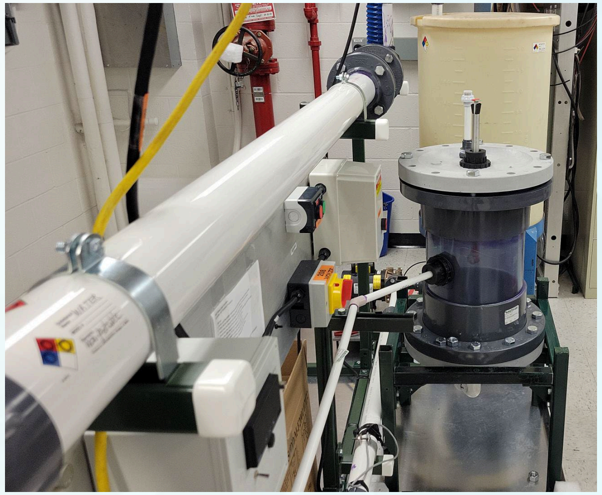
Y1

Sensor prototype design



Y2

Flow sensing in water



Y3

Flow sensing in high temperature fluid

Project Overview

- **Participants**

Argonne National Laboratory

Alexander Heifetz (PI)
Sasan Bakhtiari
Eugene Koehl
Bill Lawrence
HT Chien

Illinois Institute of Technology

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Kairos Power

Anthonie Cilliers

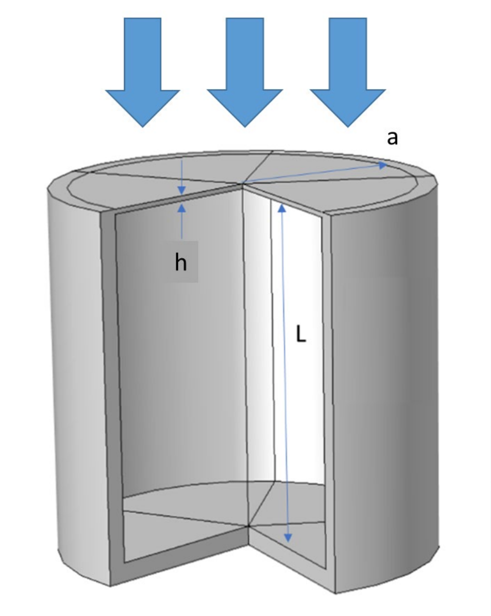
Technology Impact

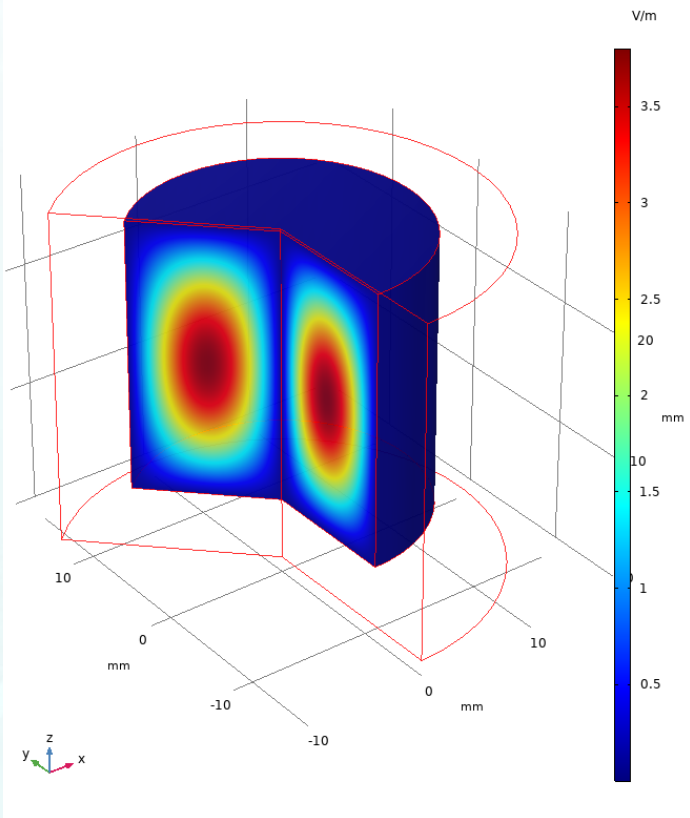
	Ultrasonic	Electromagnetic	Anemometry	Microwave Resonant Cavity-Based
Fluid type	Liquid sodium & molten salt Based on detection of time of flight (TOF) or Doppler frequency shift	Liquid sodium Take advantage of electrical conductivity of liquid sodium	Liquid sodium & molten salt Based on convective heat transfer	Liquid sodium & molten salt Transduction is based on fluid-structure interaction
Sensor deployment	External TOF two pairs of transducers transmit along and against flow. Doppler backscattering with single transducer	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
Challenges	TOF transducers, require direct line of sight, Doppler needs scatterers in fluid, crystal can degrade	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 continuum electromechanics sensor performance model

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





Electric field distribution in TE_{011} mode

Results and Accomplishments

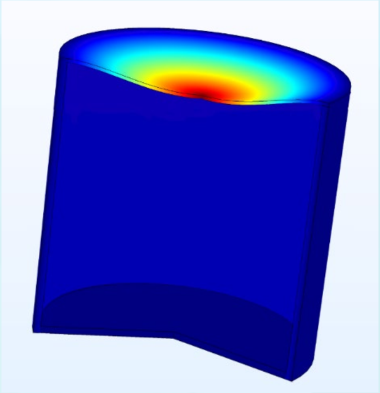
Developed continuum electromechanics sensor performance model

- Wall displacement calculated with mechanical model of radially constrained thin circular plate under uniform load

$$w(r) = w_0\left(1 - \frac{r^2}{a^2}\right)^2$$

Maximum displacement $w_0 = \frac{qa^4}{64D}$, where material flexural rigidity $D = \frac{Eh^3}{12(1-\nu^2)}$

E = Young's modulus
ν = Poisson ratio
L = length
a = radius
h = membrane thickness
q = fluid pressure



- Frequency shift calculated with microwave cavity perturbation theory

$$\frac{f - f_0}{f_0} = \frac{\Delta W_m - \Delta W_e}{W_m + W_e}$$

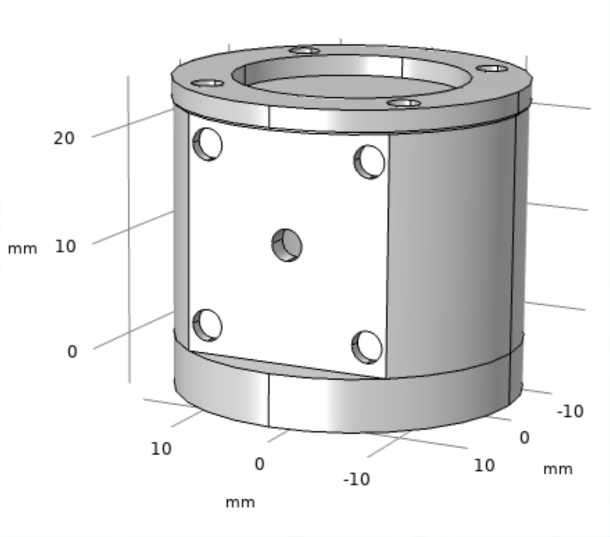
Energy in total volume V: $W_m + W_e = \int_{r=0}^{a}\int_{z=0}^{L}\int_{\phi=0}^{2\pi}(\mu|H|^2 + \epsilon|E|^2)d\phi dz dr$

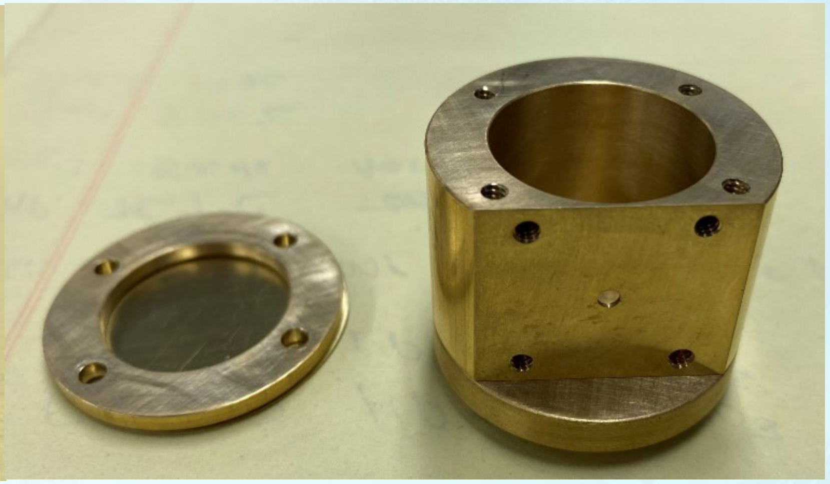
Energy in perturbed volume *ΔV*: $\Delta W_m - \Delta W_e = \int_{r=0}^{a}\int_{z=0}^{w(r)}\int_{\phi=0}^{2\pi}(\mu|H|^2 - \epsilon|E|^2)d\phi dz dr$

Results and Accomplishments

Designed and fabricated Brass 360 microwave cavity transducer prototype for initial testing in water

- Cavity excited through 2mm diameter subwavelength hole
- L = 2a = 22.2mm matched for WR-42 waveguide flange
- Membrane thickness 8mil = 203μm
- f_{011} = 17.8GHz

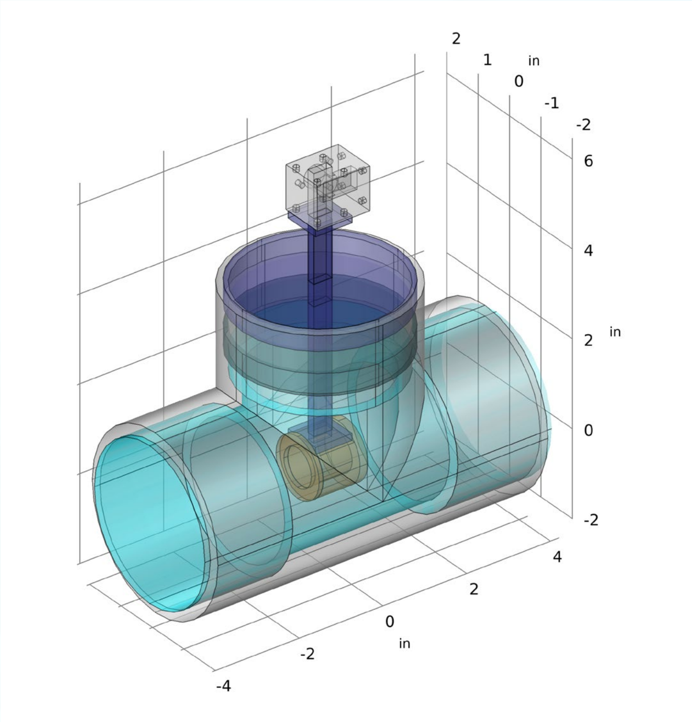


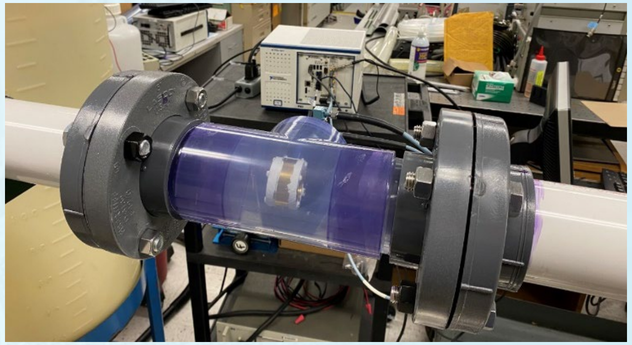


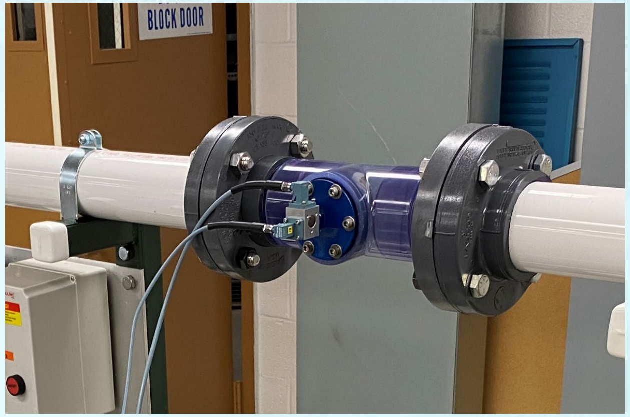
Results and Accomplishments

Designed and fabricated Brass microwave cavity transducer prototype for initial testing in water

- Cylindrical cavity coupled with WR-42 bulkhead waveguide
- Transducer installed in Tee section
- Signal readout with microwave circulator



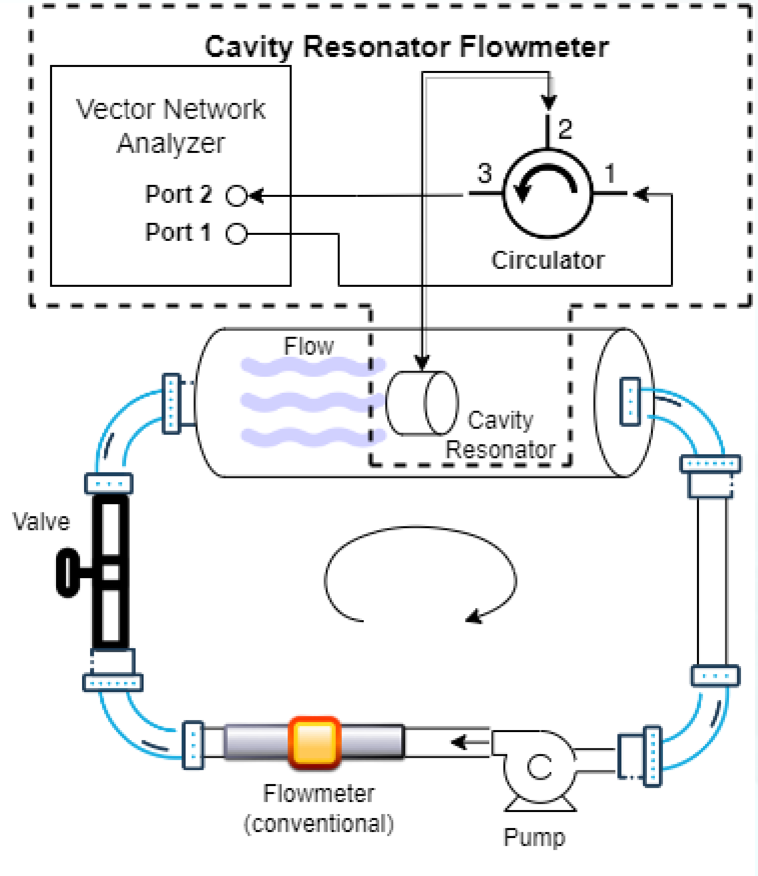


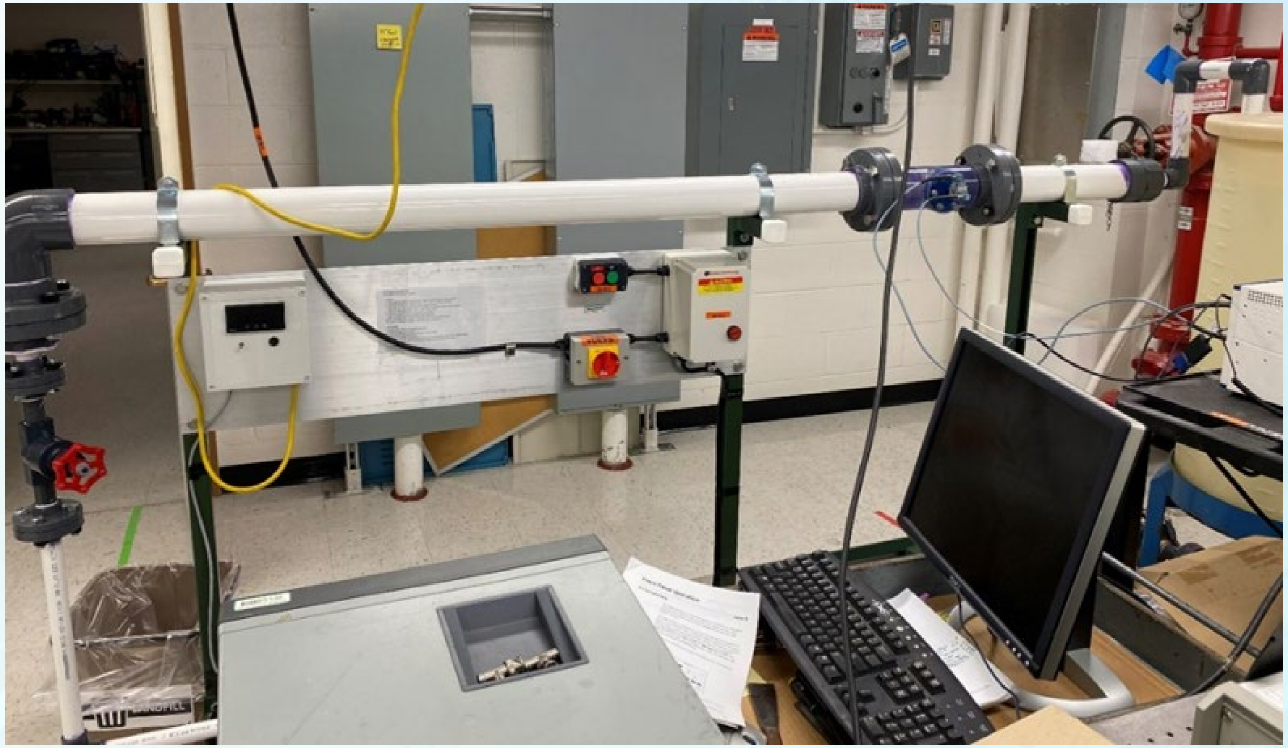


Results and Accomplishments

Developed water flow loop for proof-of-principle flow sensing

- Pump rated up to 60gpm flow rate at ambient pressure
- Omega flowmeter installed for reference flow measurements

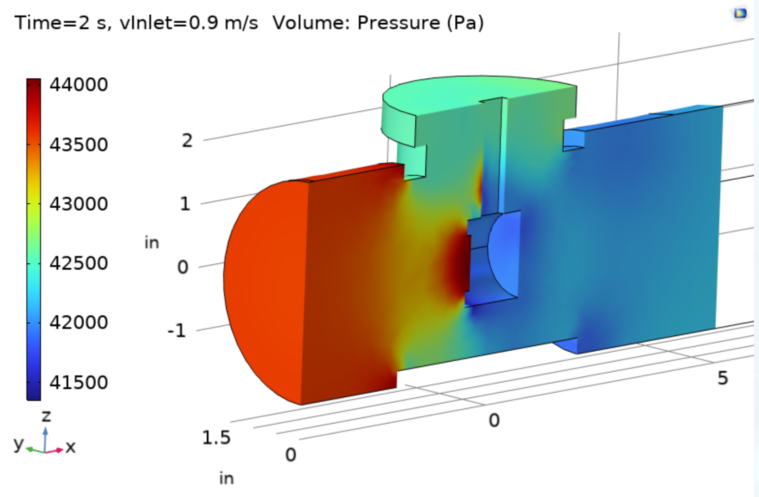




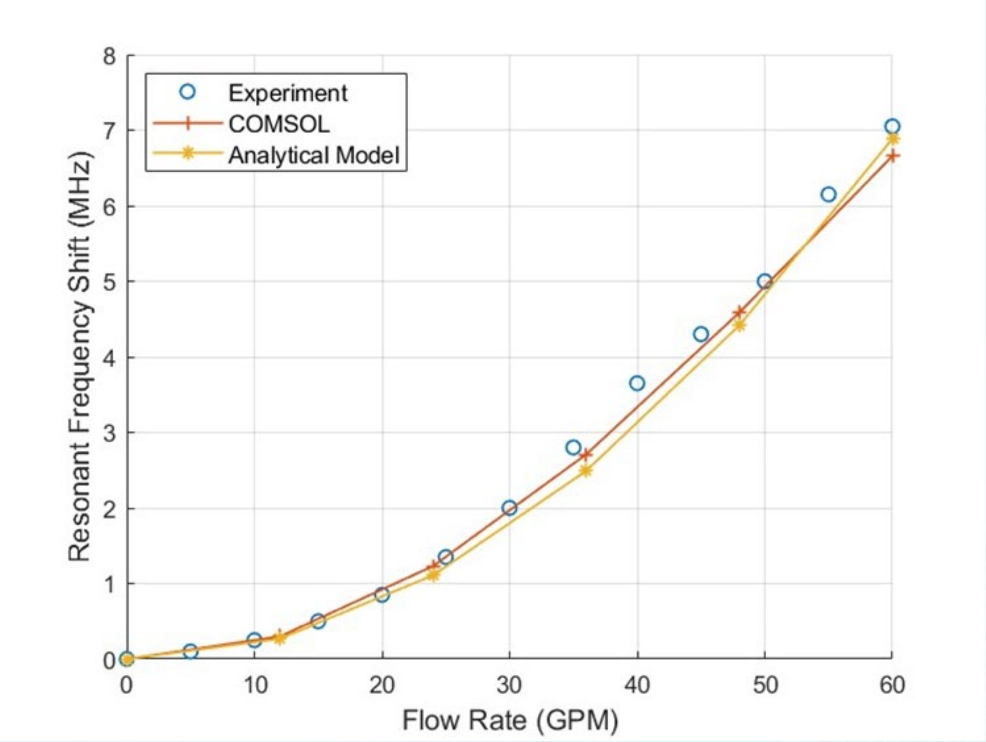
Results and Accomplishments

Proof-of-principle flow sensing in water loop

- Increased water flow rate at 5gpm increments
- Measured transducer microwave frequency with vector network analyzer (VNA)
- Calculated frequency shift for TE_{011} mode with resonant frequency f_{011} = 17.8GHz
  - Calculated corresponding microwave frequency shift with COMSOL
  - Calculated corresponding frequency shift with microwave cavity perturbation theory



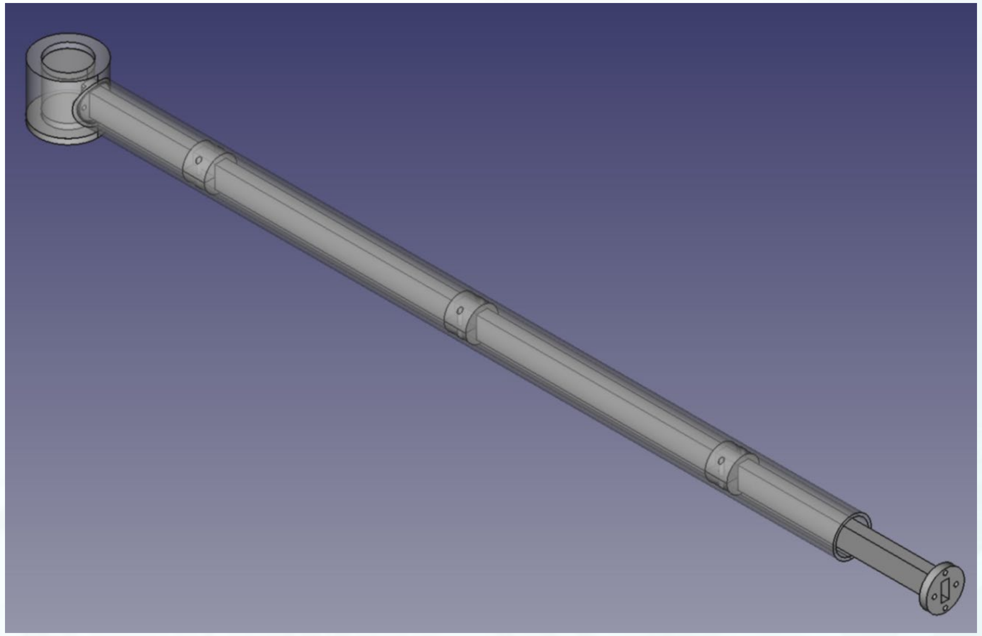
Calculated pressure distribution with COMSOL



Results and Accomplishments

Designed probe assembly for liquid sodium flow test in TAPS vessel

- 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 for high temperature operation

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

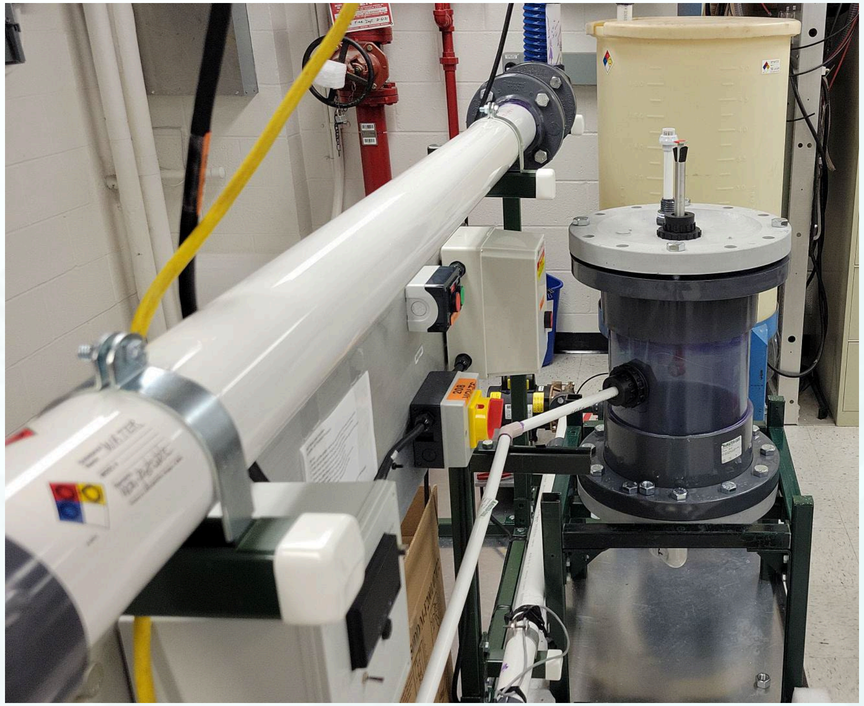
Aluminum prototype

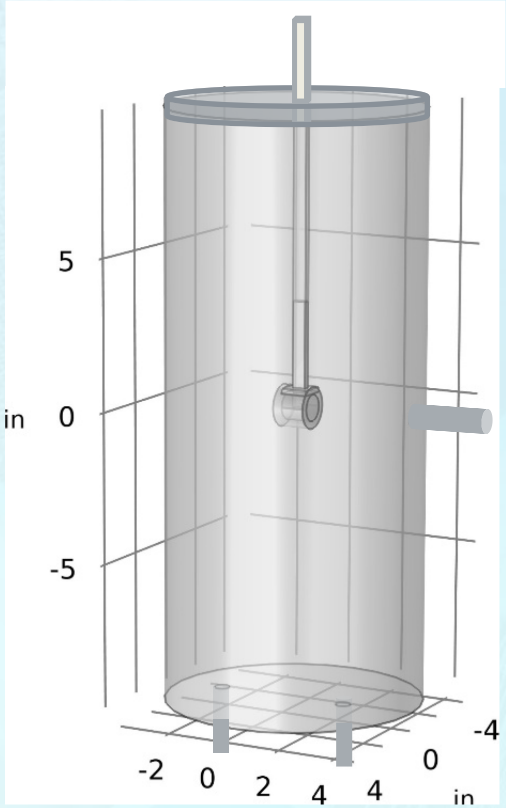
SS316 transducer

Results and Accomplishments

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

- Water vessel 19.5in x 9.5in with ¼ in center feed line 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

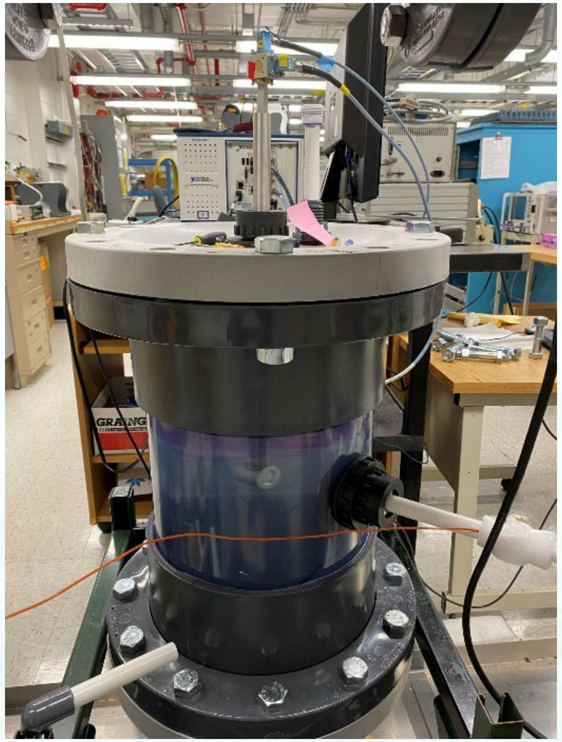


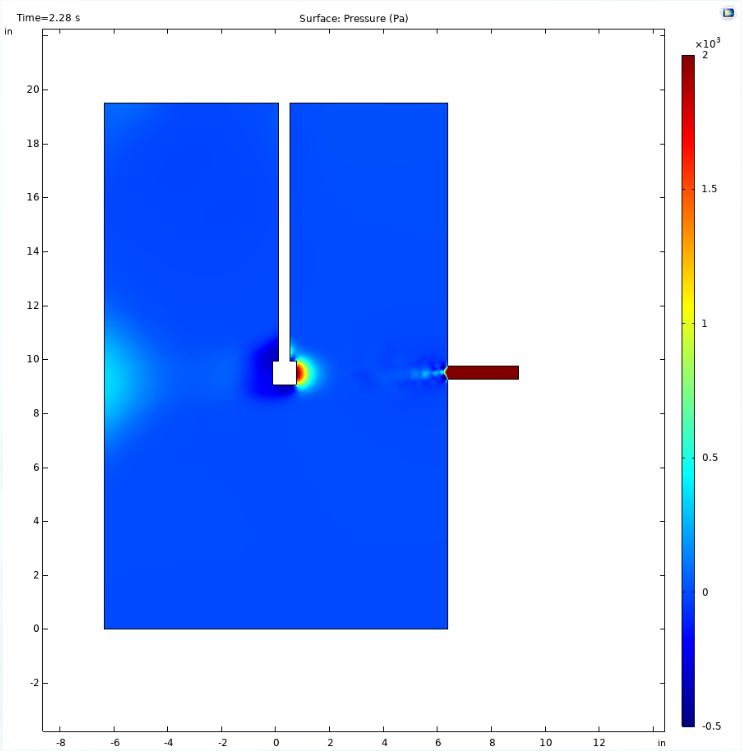


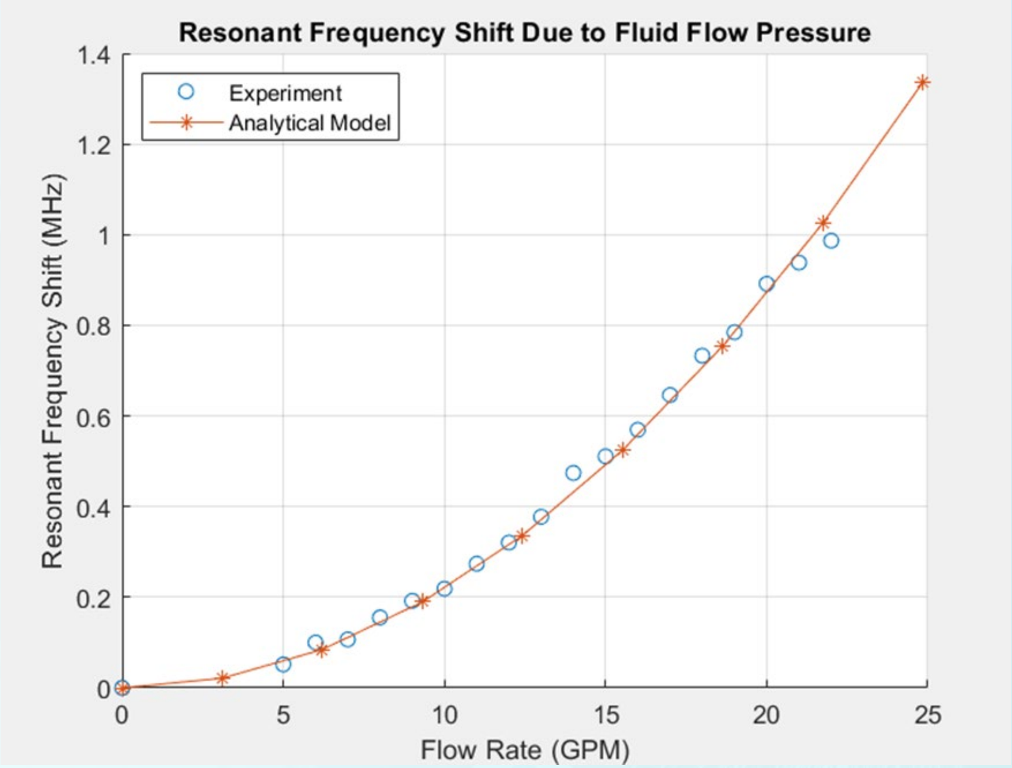
Results and Accomplishments

Proof-of-concept flow sensing with SS316 transducer in water vessel

- Increased flow rate in steps of 5gpm
- Measured microwave frequency shift with VNA
- Calculated microwave frequency shift with microwave perturbation theory





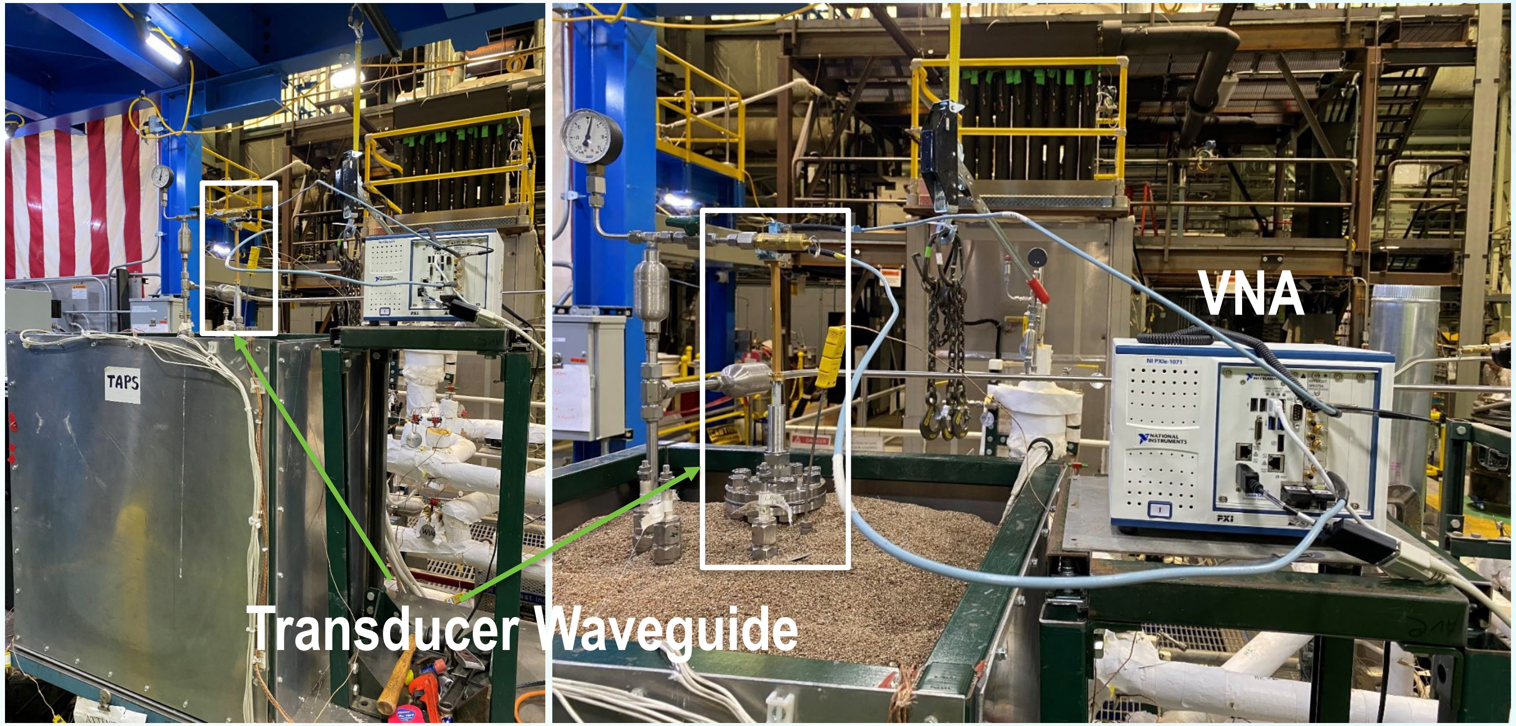


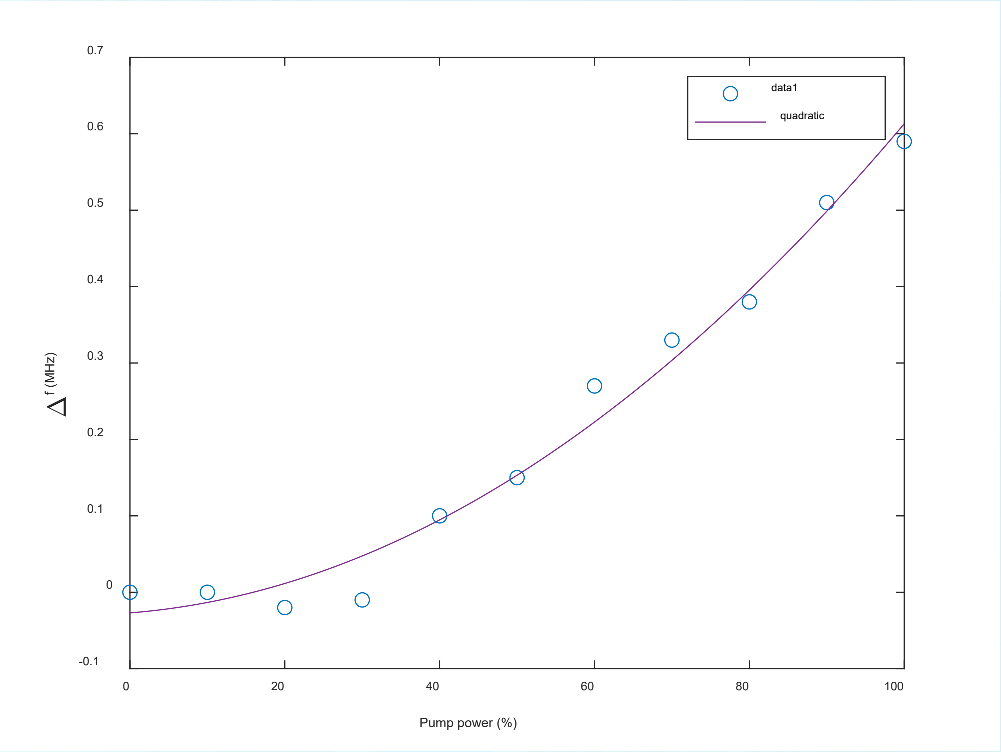
COMSOL simulation of dynamic flow pressure

Results and Accomplishments

Flow sensing in liquid sodium vessel in impinging jet geometry in TAPS (Thermoacoustic Power Sensing) vessel

- Temperature up to 350^{o}C, ambient pressure
- Measured microwave frequency shift for varying sodium pump power
- No commercial reference flow meter





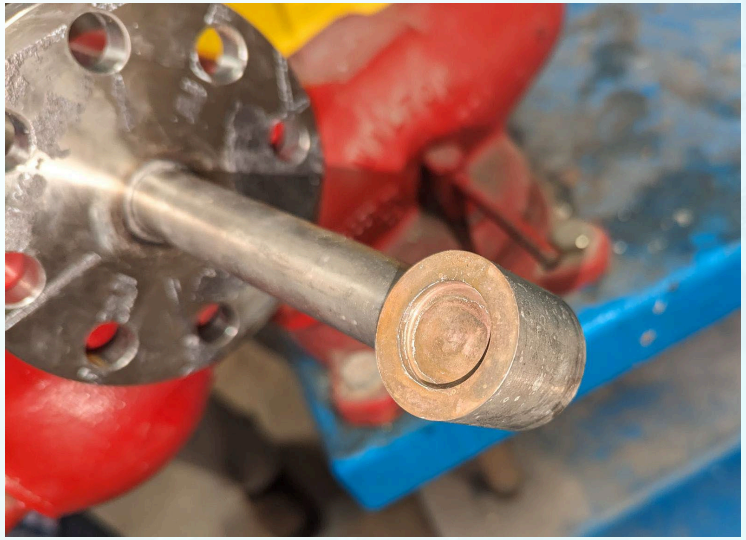
Results and Accomplishments

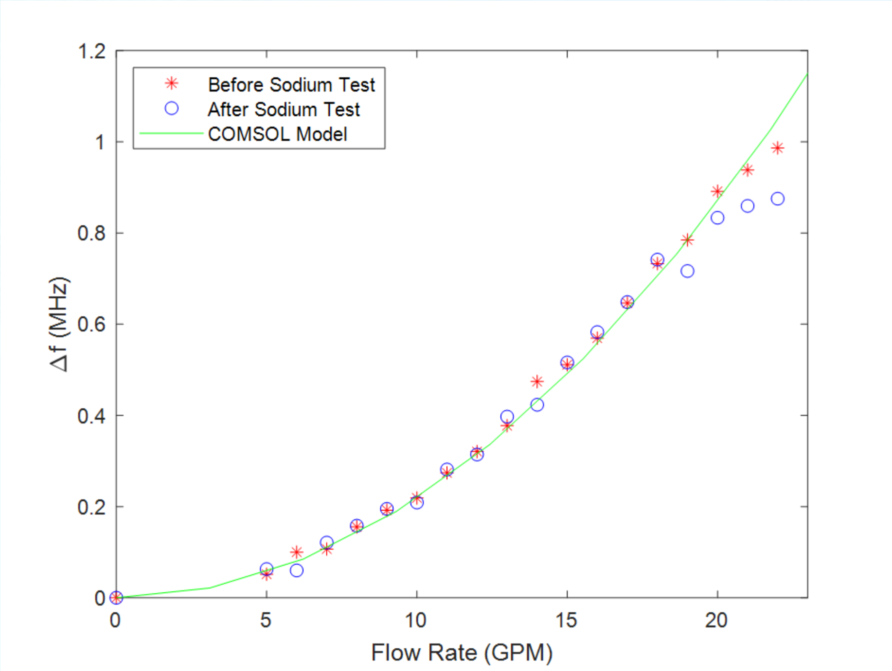
Transducer remained in liquid sodium for 70 days

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

Before

After

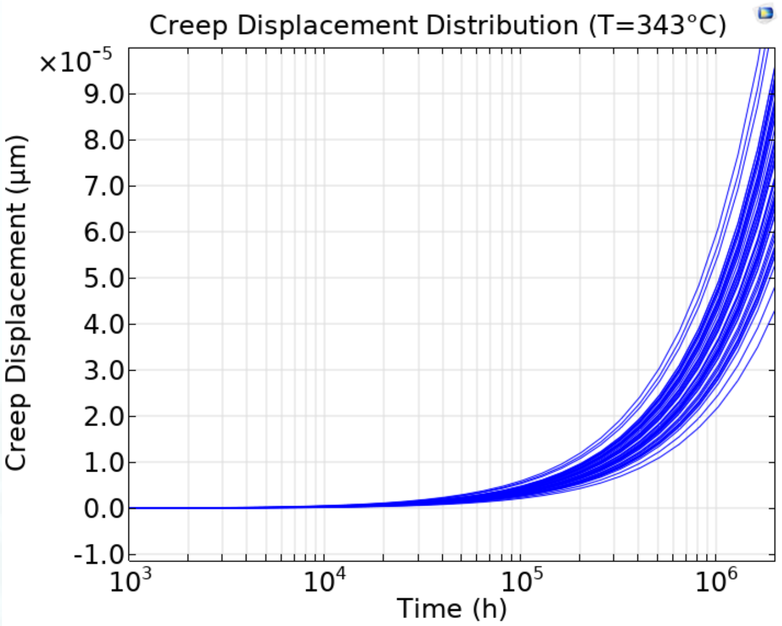




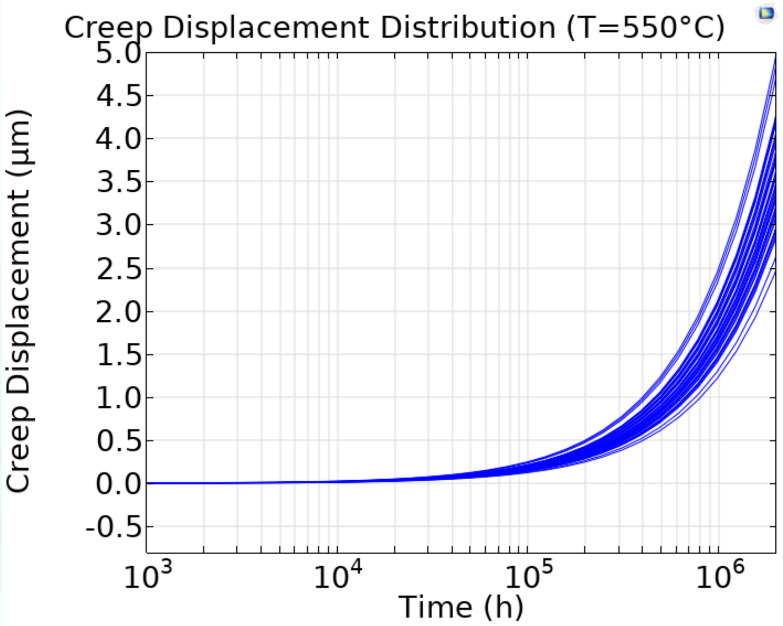
Results and Accomplishments

Probabilistic analysis of transducer degradation from creep

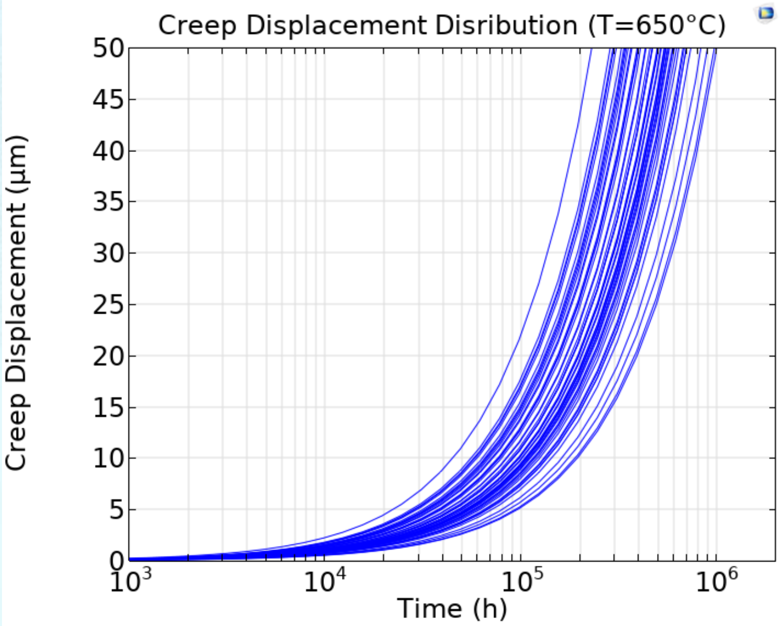
- Diffusion creep mechanism in low pressure and high temperature environment (Nabarro-Herring model)
- Calculated creep displacement (inelastic) at the center of the circular membrane (maximum displacement) for randomly varying load and temperature distributions
- Elastic displacement $w_0 \approx 35\mu m$



TAPS facility



KP-FHR core inlet



KP-FHR core outlet

Concluding Remarks

- **Publications**
  - T. Fang, J. Saniie, S. Bakhtiari, A. Heifetz, “Probabilistic Creep Model for Recalibration of Microwave Cavity Flow Meter,” 552 – 555, *IEEE International Conference on Electro Information Technology (EIT2024).*
  - 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

- Developed transducer performance model
- Designed and fabricated Brass transducer prototype
  - Proof-of-concept flow sensing in water agrees with transducer model
- Designed and fabricated Stainless Steel sensor prototype for high temperature fluid environment
  - Proof-of-concept flow sensing in water agrees with transducer model
  - 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