U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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
October 24 – 27, 2022

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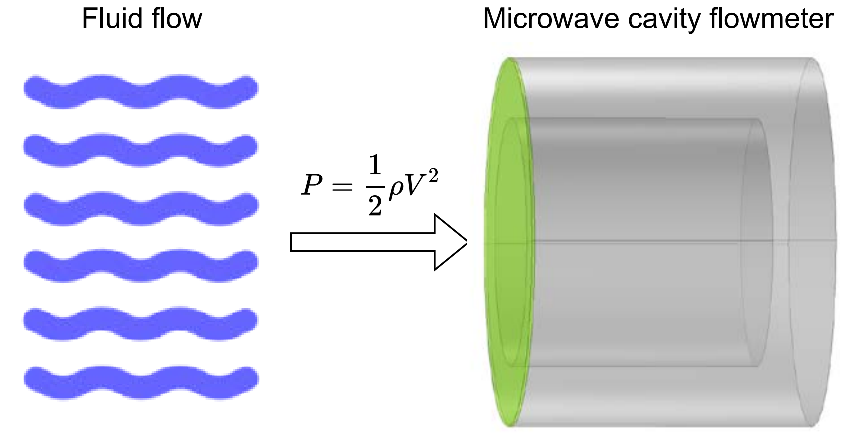
Project Overview

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

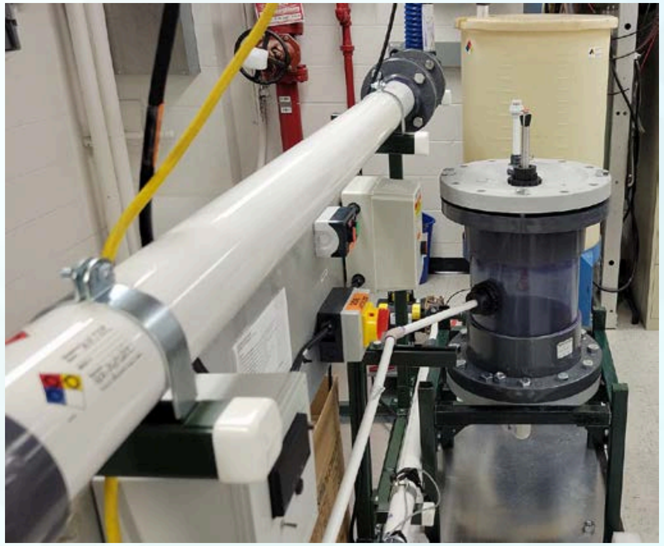
- **Project Schedule**

Y1

Sensor prototype design

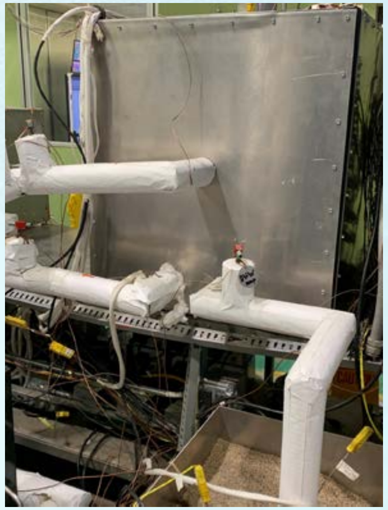
Y2

Flow sensing in water



Y3

Flow sensing in high temperature fluid



Current Status

Project Overview

- **Participants**

Argonne National Laboratory

Alexander Heifetz (PI)
Sasan Bakhtiari
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Illinois Institute of Technology

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David Aronson

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Dmitry Shribak
Victoria Ankel

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

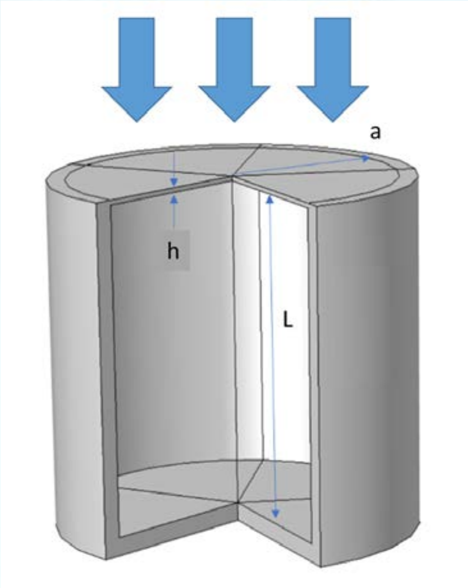
Developed analytic sensor model

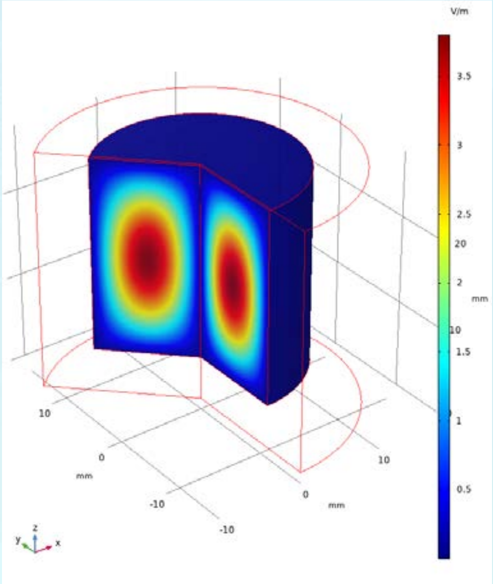
- Chose right circular cylinder design (L=2a) to achieve highest Q-factor
- Focused on low order TE_{011} mode

$$\Delta f_{nml}^{TE} = \frac{c}{2\pi L\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(2X'_{nm}\right)^2 + \left(l\pi\right)^2} \left(\frac{\Delta L}{L} \frac{\left(l\pi\right)^2}{\left(2X'_{nm}\right)^2 + \left(l\pi\right)^2} \right)$$

$$\Delta L = \frac{3\left(1-\nu^2\right)}{32E} \frac{a^4}{h^3} \rho \mathrm{v}^2$$

n,m,l = mode numbers
c = speed of light
X'_{nm} = n^{th} root of the derivative of the m^{th} order Bessel function
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





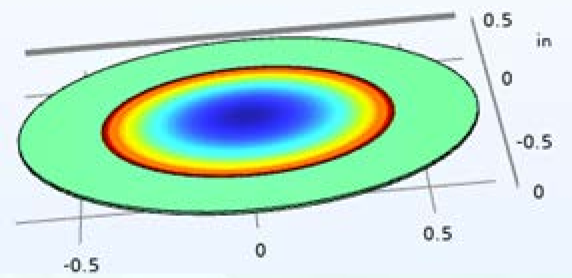
TE_{011} mode

Results and Accomplishments

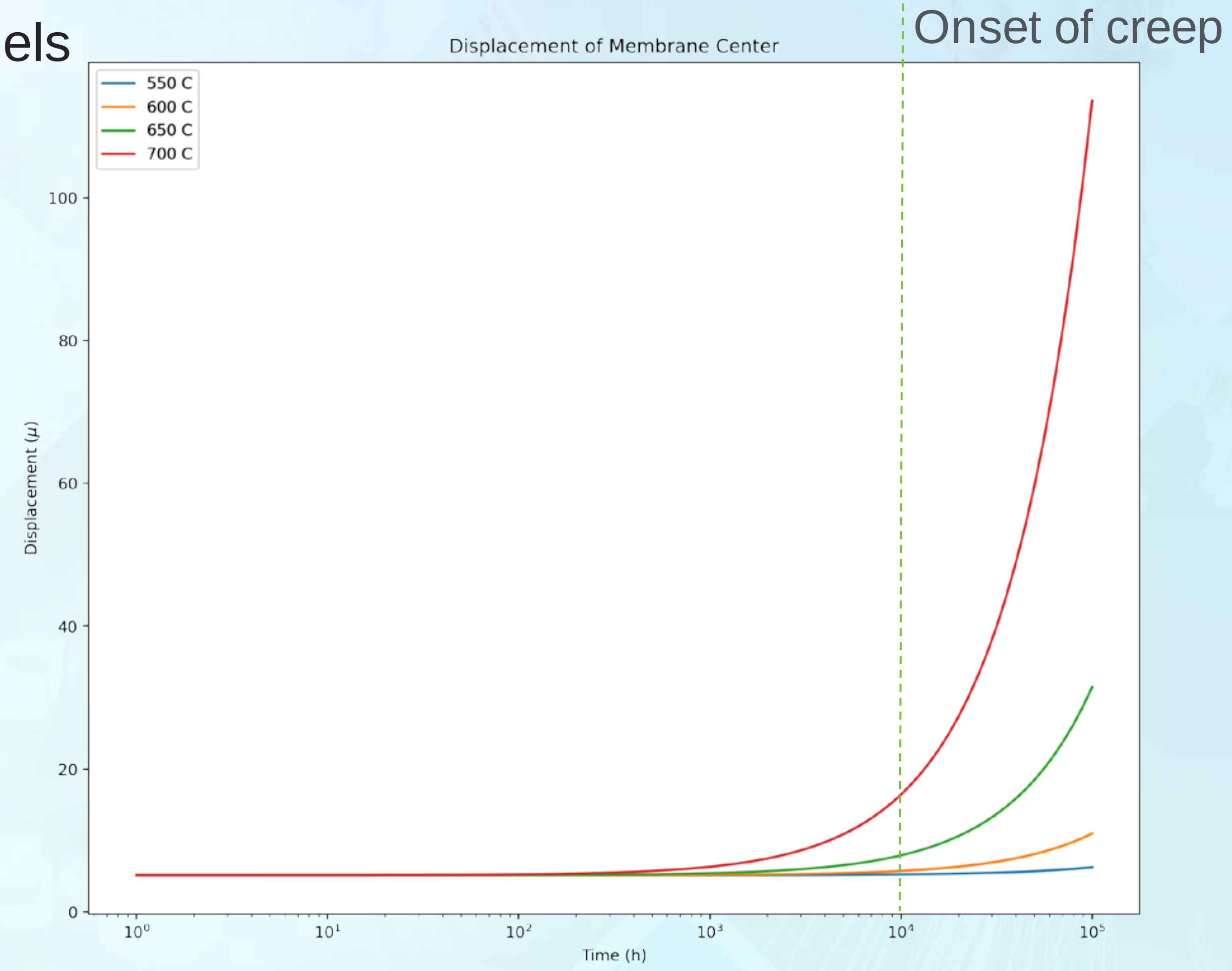
Conducted preliminary investigation of sensor drift due to membrane creep at high temperature

- Model implemented in COMSOL Structural Mechanics Module
- Combines Nabarro-Herring and Coble creep models
  - Arrhenius's Law type
  - Diffusion driven, high temperature, low stress
- Predict significant creep (>20% of displacement) after 10^4 hours (417 days) at constant T > 600C and 3kPa load
- Can be compensated during real-time flow measurements by monitoring temperature history

Membrane



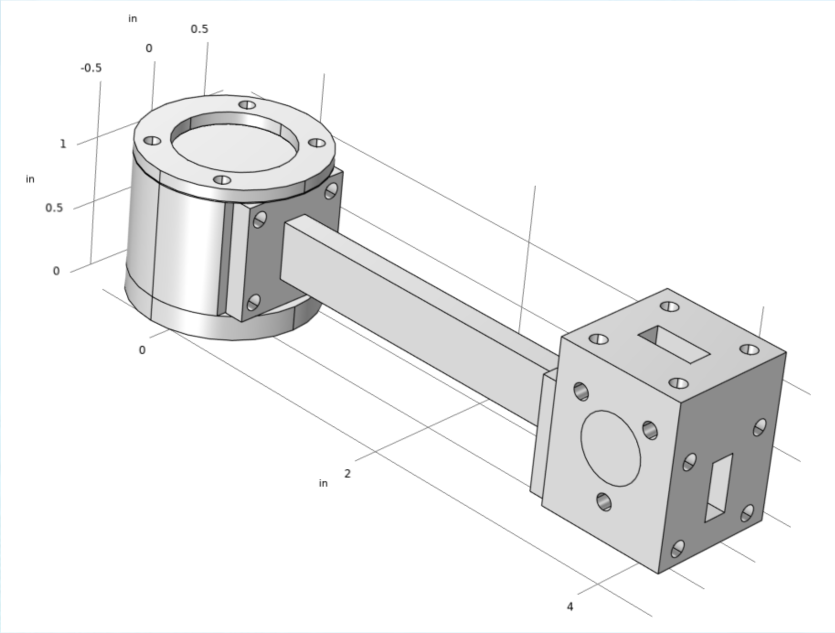
0.008in thickness

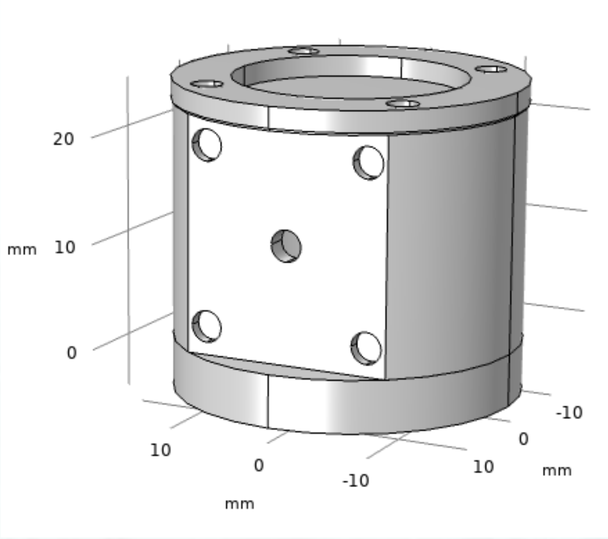


Results and Accomplishments

Designed K-band (18-26.5GHZ) microwave cavity

- Cavity excited through subwavelength hole
- Signal readout with a microwave circulator
- Dimensions matched to commercial WR-42 microwave waveguide 22.2mm flange
- Membrane thickness 8mil = 203µm
- Fabricated Brass cavity prototype for initial testing in water

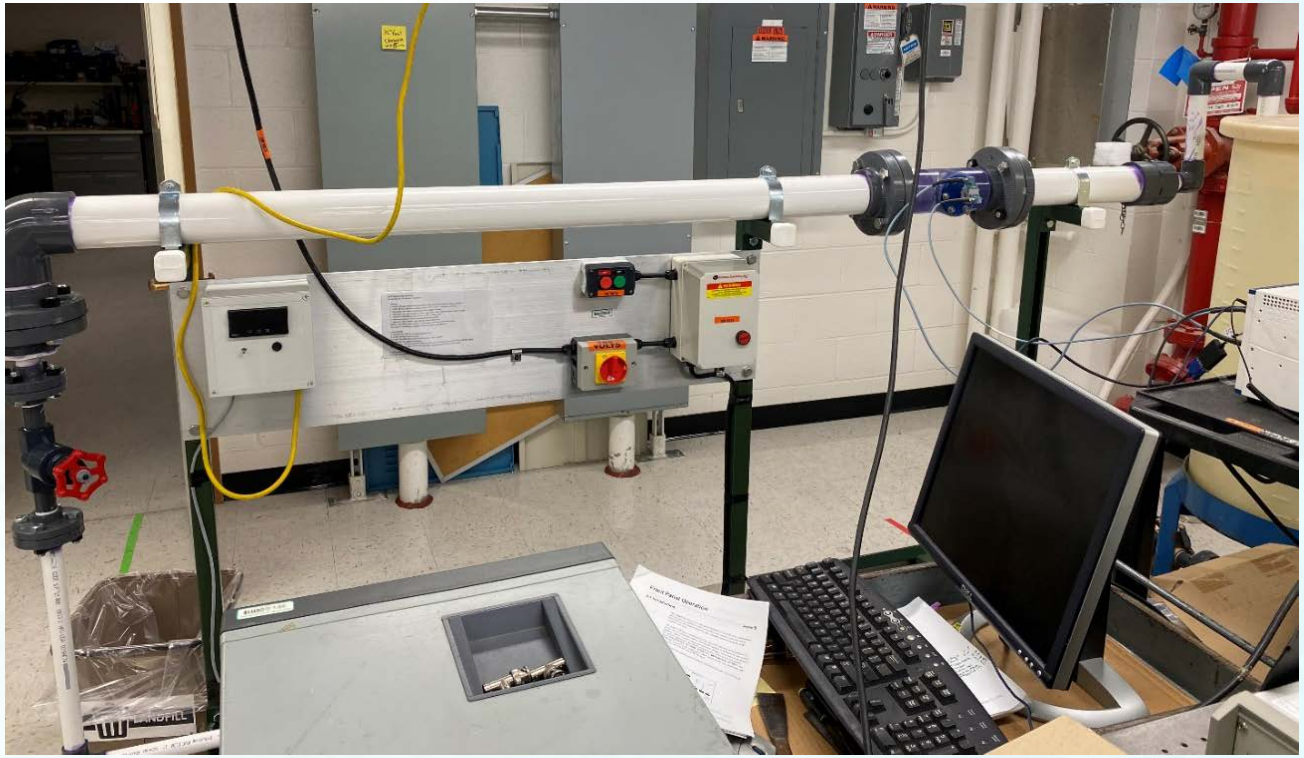


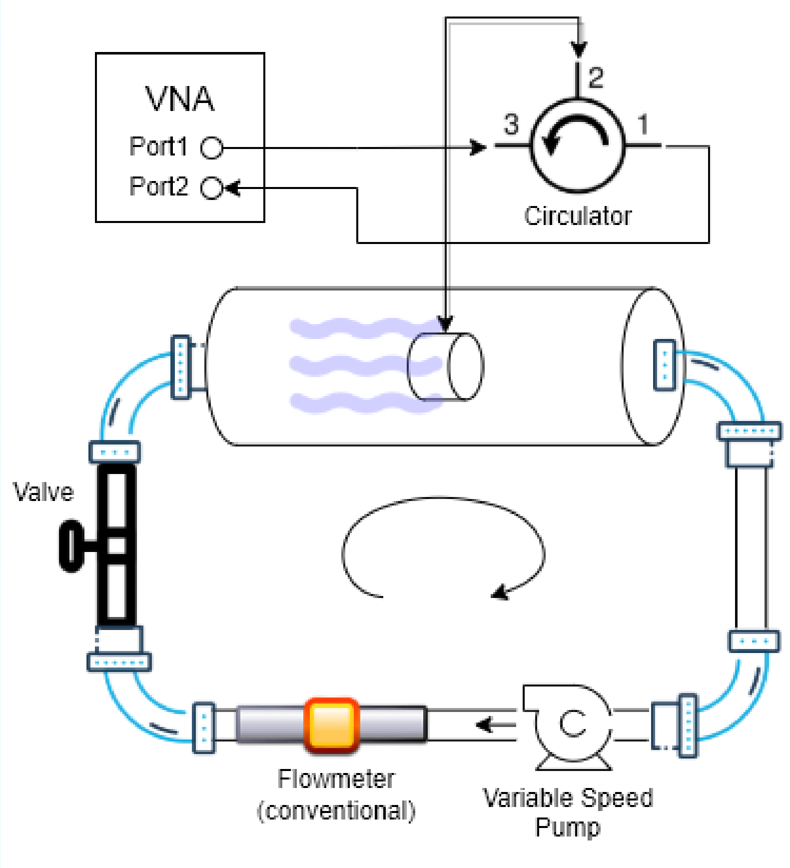


Results and Accomplishments

Developed water flow loop for proof-of-principle tests

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

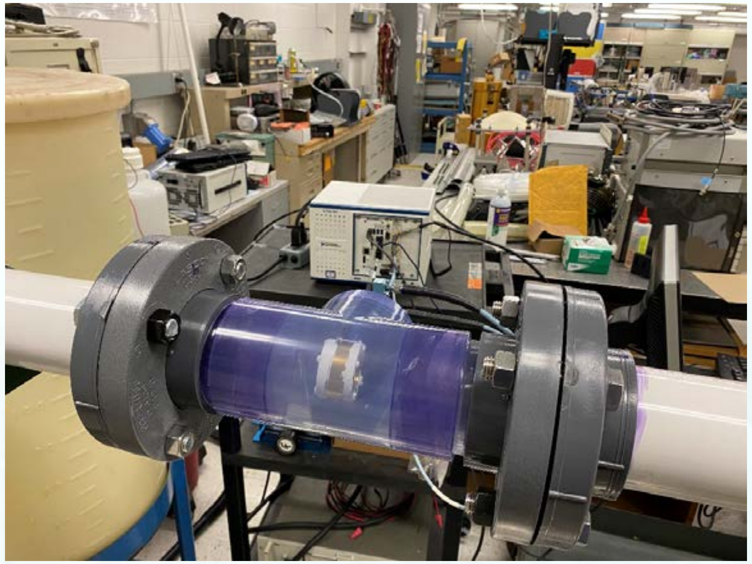


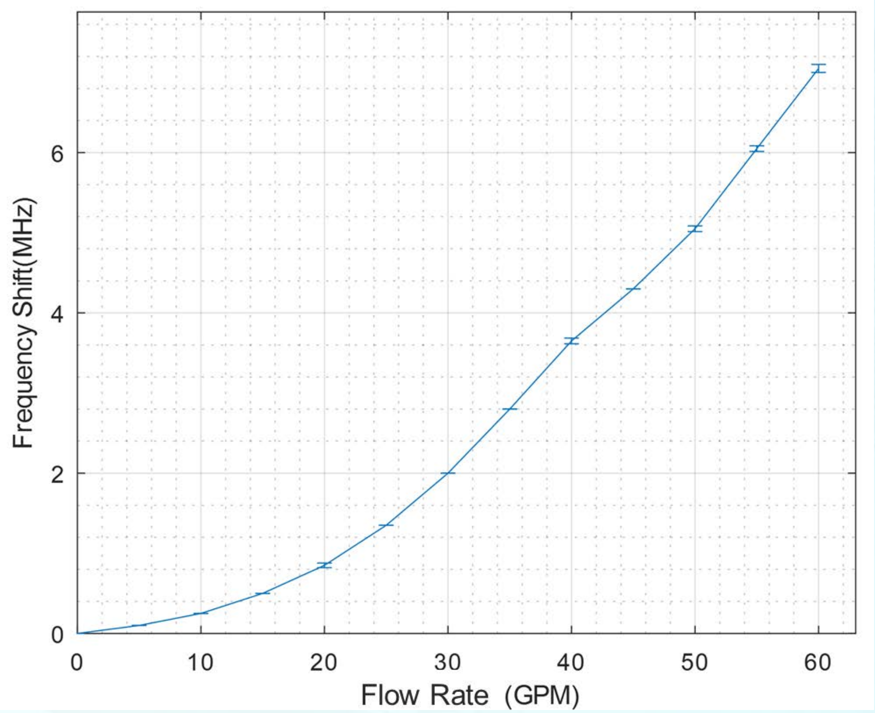


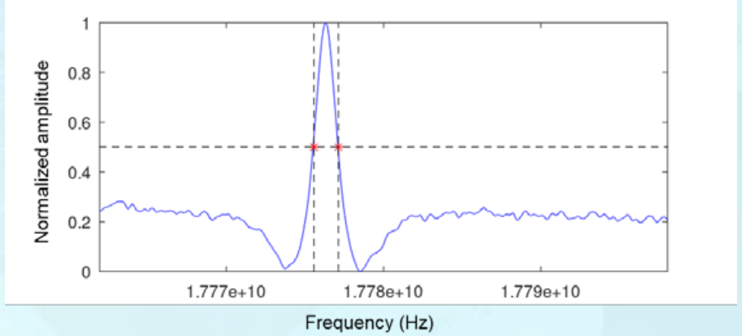
Results and Accomplishments

Obtained initial results of water flow measurement

- Measure frequency shift of TE_{011} mode vs. reference volume flow rate
  - Calculated f_0 = 17.80GHz
  - Measured f_0 = 17.78GHz
- Sensitivity to flow ≈ 100KHz/GPM







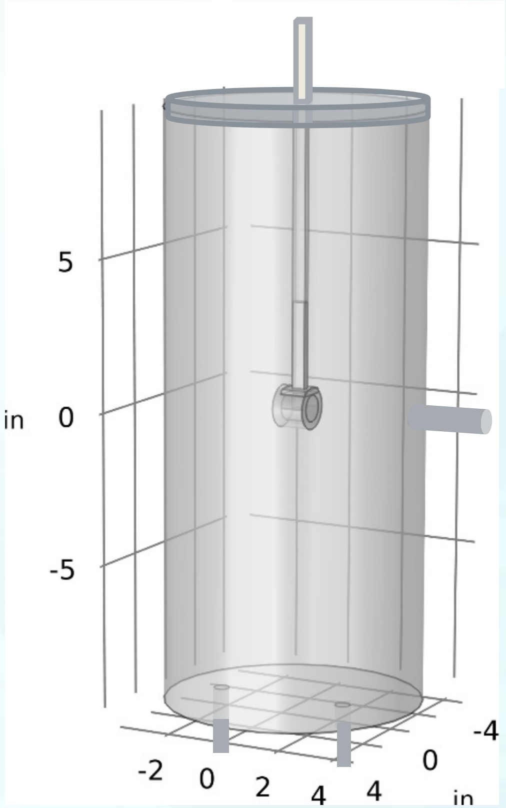
Estimated Q≈11,000

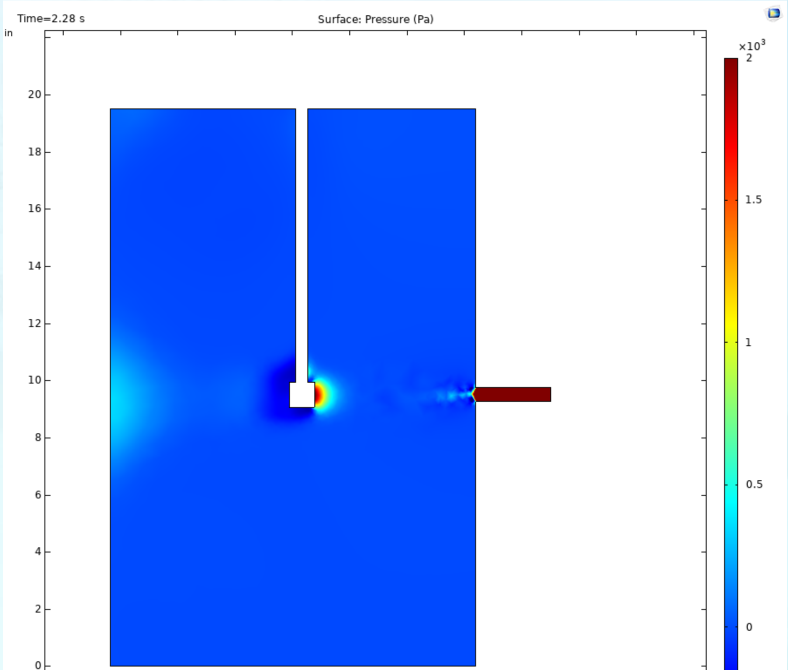
$$Q = \frac{f_0}{\Delta f_{FWHM}}$$

Results and Accomplishments

Identified existing experimental setup for liquid sodium flow sensing test

- Impinging jet flow
- Insulated cylindrical tank 19.5in x 9.5in with ½in center feed line
- Reference ultrasonic flow meter installed on EM pump



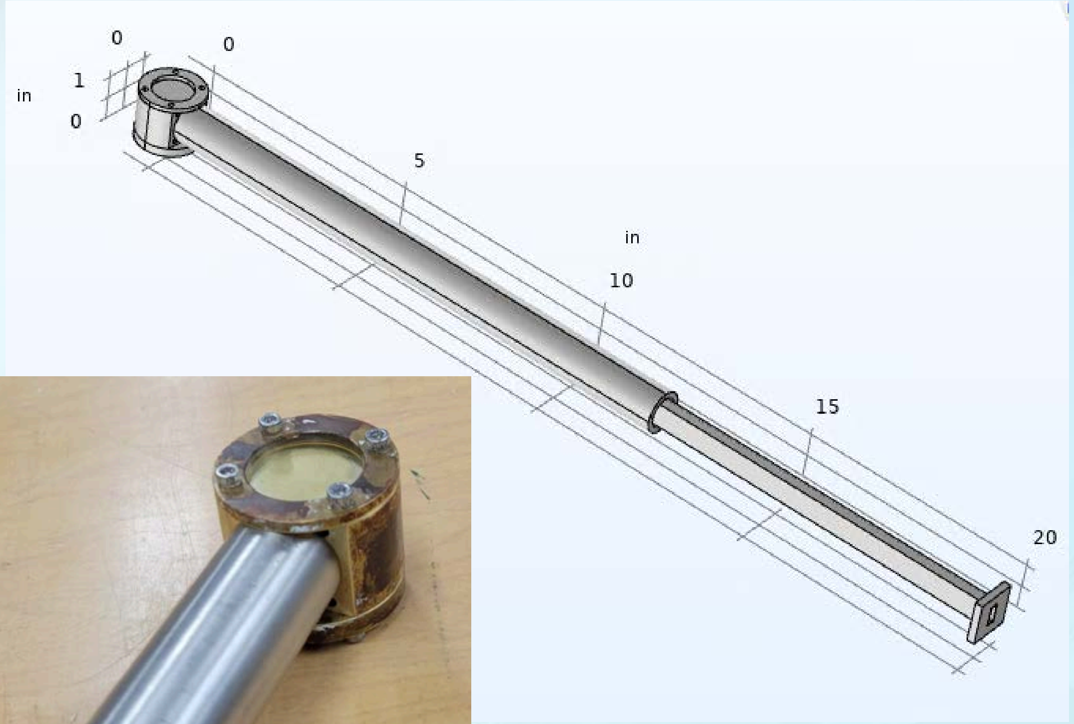


COMSOL simulation of dynamic flow pressure

Results and Accomplishments

Redesigned insertion probe for flow sensing in water tank

- 20in-long K-bad microwave waveguide
- Enclosed in SS316 protective tube



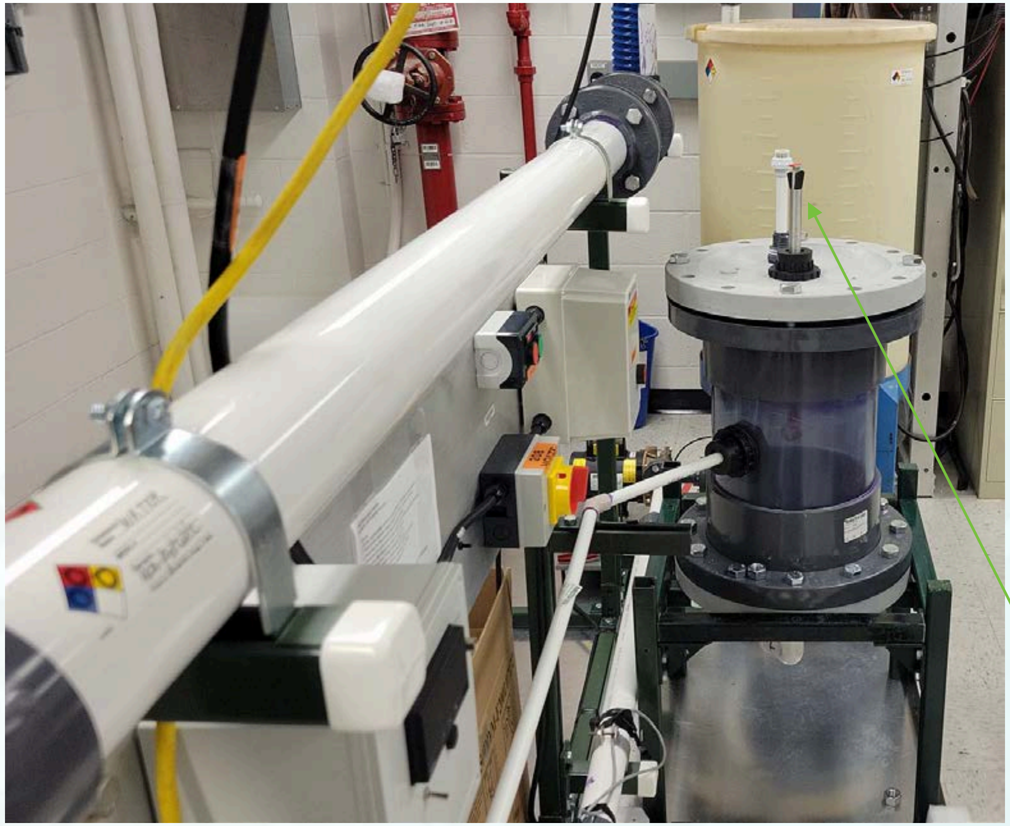
Original K-band rectangular flange

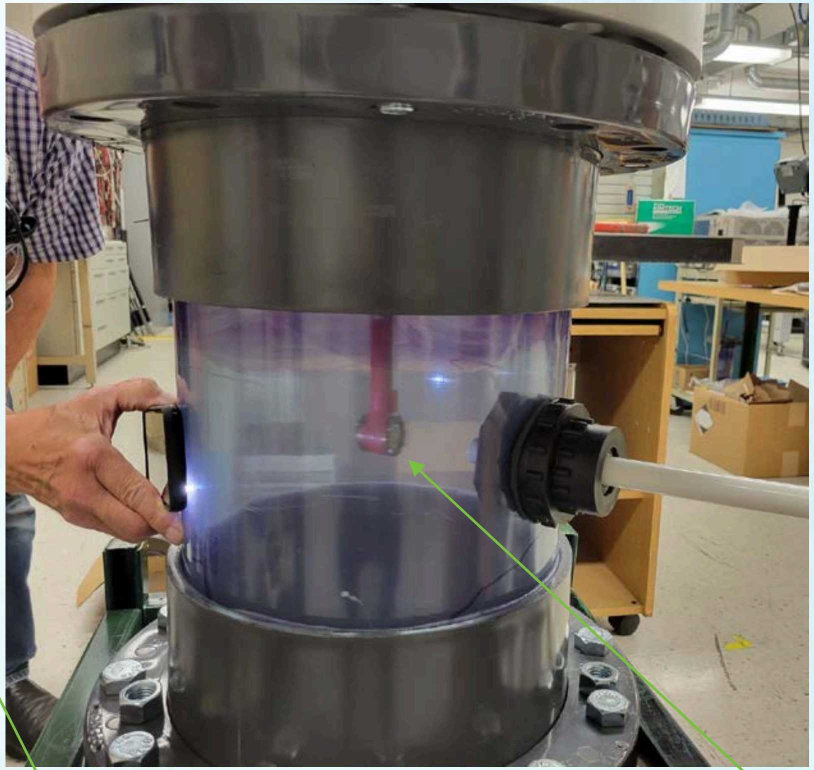
Modified circular-chamfered flange with protective SS316 tube 0.875in diameter and 0.065in wall thickness

Results and Accomplishments

Developed vessel integrated into loop for flow sensing in impinging jet geometry2-8 slides that describe the following:

- Water vessel with the same geometrical parameters as liquid sodium vessel (20in x 10in cylinder with ½ in center feed line



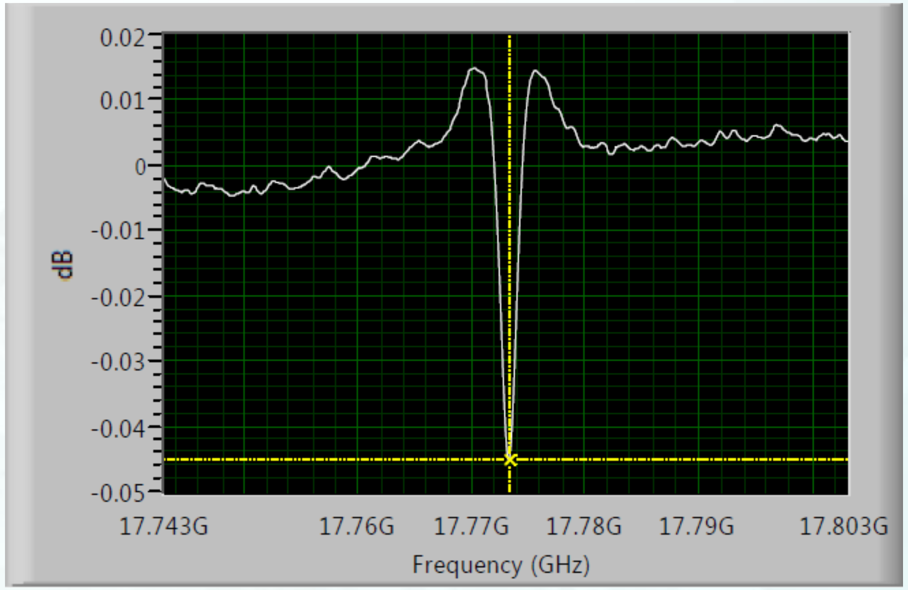


Waveguide insertion probe with cylindrical sensor

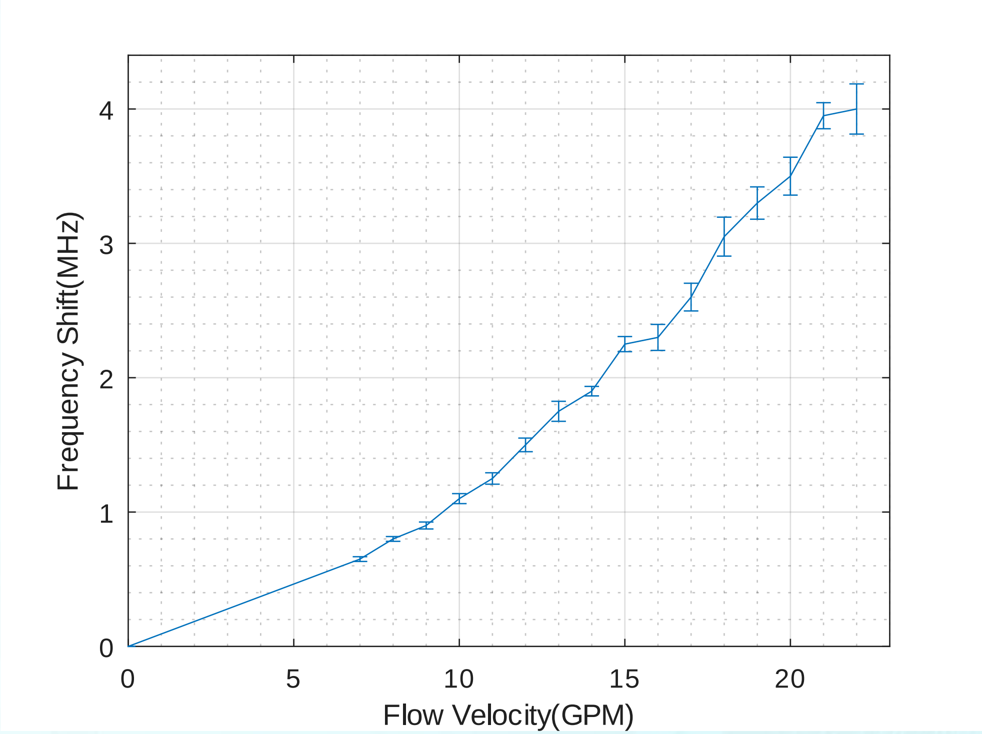
Results and Accomplishments

Preliminary results of flow sensing in water vessel

- Measured frequency shift of TE_{011} mode vs. reference volume water flow rate
  - Calculated f_0 = 17.80GHz
  - Measured f_0 = 17.78GHz
- Sensitivity to flow ≈ 100KHz/GPM
  - Need to adjust for increasing temperature in fluid



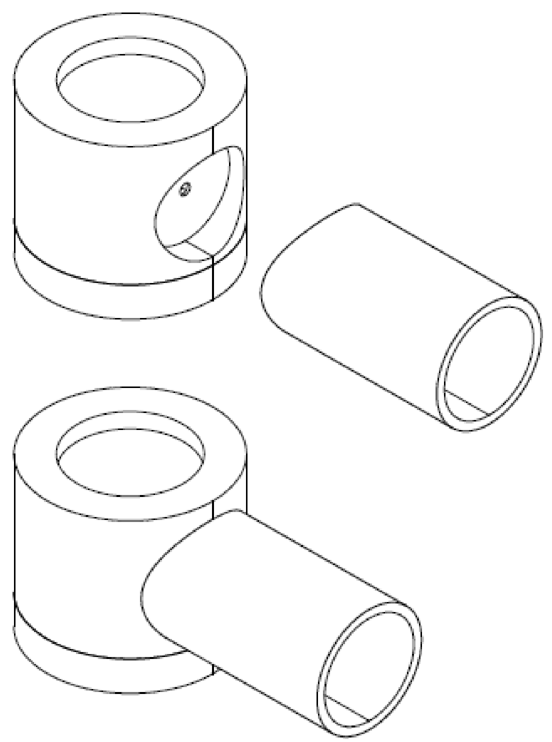
Frequency response of TE_{011} mode

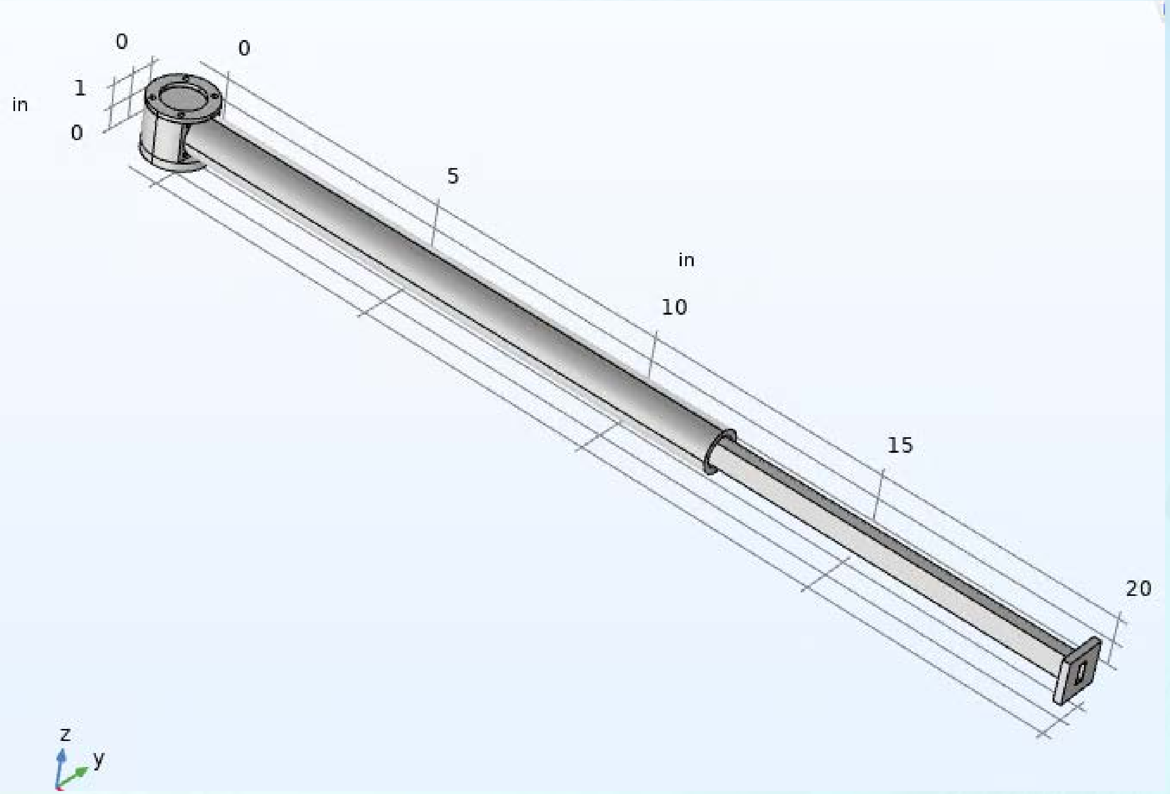


Results and Accomplishments

Designed probe assembly for liquid sodium flow test

- Stainless steel 316 welded structures
- Silver-plated interior surfaces to achieve high Q of resonator


Welding Assembly



Concluding Remarks

- Publications
  - 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 presentation/accomplishments in FY21 and FY22

- Developed microwave K-band sensor prototype
- Demonstrated initial performance in proof-of-principle test in water
- Completed design of sensor for high temperature test

Future work in FY23

- Fabricate sensor prototype for high temperature fluid environment
- Demonstrate flow sensing in liquid sodium

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Thank You