DE-FE0031765

Test and Validate Distributed Coaxial Cable Sensors for in situ Condition Monitoring of Coal-Fired Boiler Tubes

NATIONAL ENERGY TECHNOLOGY LABORATORY

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Project Objective and Background

A novel sensing technology for *in situ* monitoring in harsh conditions

Objective

To test, validate, and advance the technology readiness level (from TRL5 to TRL7) of a novel low-cost distributed stainless-steel/ceramic coaxial cable sensing (SSC-CCS) technology for in situ monitoring of the boiler tube temperature in existing coal-fired power plants.

Background

- **Boiler tube failures**: extremely costly with significant economic impacts
  - In US, nearly 30% of the electricity generated by coal as the primary fuel.
  - A single tube failure in a 500 MW boiler requires an average of 3.6 days of repair work and results in a loss of more than 1 million dollars per day
- **Tube failures**: complicated mechanism & difficult to predict
  - Harsh operation conditions (subcritical units): steam pressure: 2,400 psi and higher; steam temperature: 540-600°C; flame temperature: 1500°C
  - Various failure reasons: Overheating, corrosion, erosion, fatigue, welding flaws, etc.
- Current high-temperature sensors for coal-fired boiler tube monitoring
  - **Electronic sensors**: points sensors. **Issue:** limited lifetime and installation difficulties
  - **Optical sensors**: used for high temperature environment. **Issue:** Fragile to handle

Project Overview

Needs and Challenges

- Condition-based monitoring (CBM) is needed to handle frequent load changes and make sufficient maintenance schedules and planning strategies, due to the increasing contributions of renewable energy sources.
- Currently available sensors have low survival rate under harsh environment and too expensive to be widely deployed in existing boilers

Low-cost monitoring sensors and tools are needed for in situ distributed temperature monitoring of the boiler tubes

Technology Benchmarking

Gap #1: Need for low-cost robust distributed temperature sensors that can survive and operate in high temperatures

Gap #2: Need for practical methods to install/deploy sensors into existing coal-fired boilers at a low cost for reliable measurements

Gap #3: Need for validated models to integrate the distributed temperature information into the existing boiler control, operation and maintenance programs to realize CBM

Current Status of Project

Budget Period I (09/2019-03/2021)

Scope of Work in Budget Period I

- ❑ Engineer the sensors, test the welding-based sensor installation methods in high temperatures, and optimize the instrumentation.

Update on Team Member and Project

- ❑ Six month no-cost extension has been applied due to the Covid-19 pandemic and unexpected temporary closure of University labs
- ❑ GE decided to retract from the team due to strategic shift in business. The alternative plan for industrial testing is in place. The project goals will not change.

Progress of the project

- ❑ The technical progress of the project is on track. All the milestones have been met.
- ❑ Progresses have been made in sensor design and testing, boiler simulations, and plan on sensor testing and installation
- ❑ Guidance from the industrial partners on sensor design and installation plan is constantly provided.

Proposed Solution

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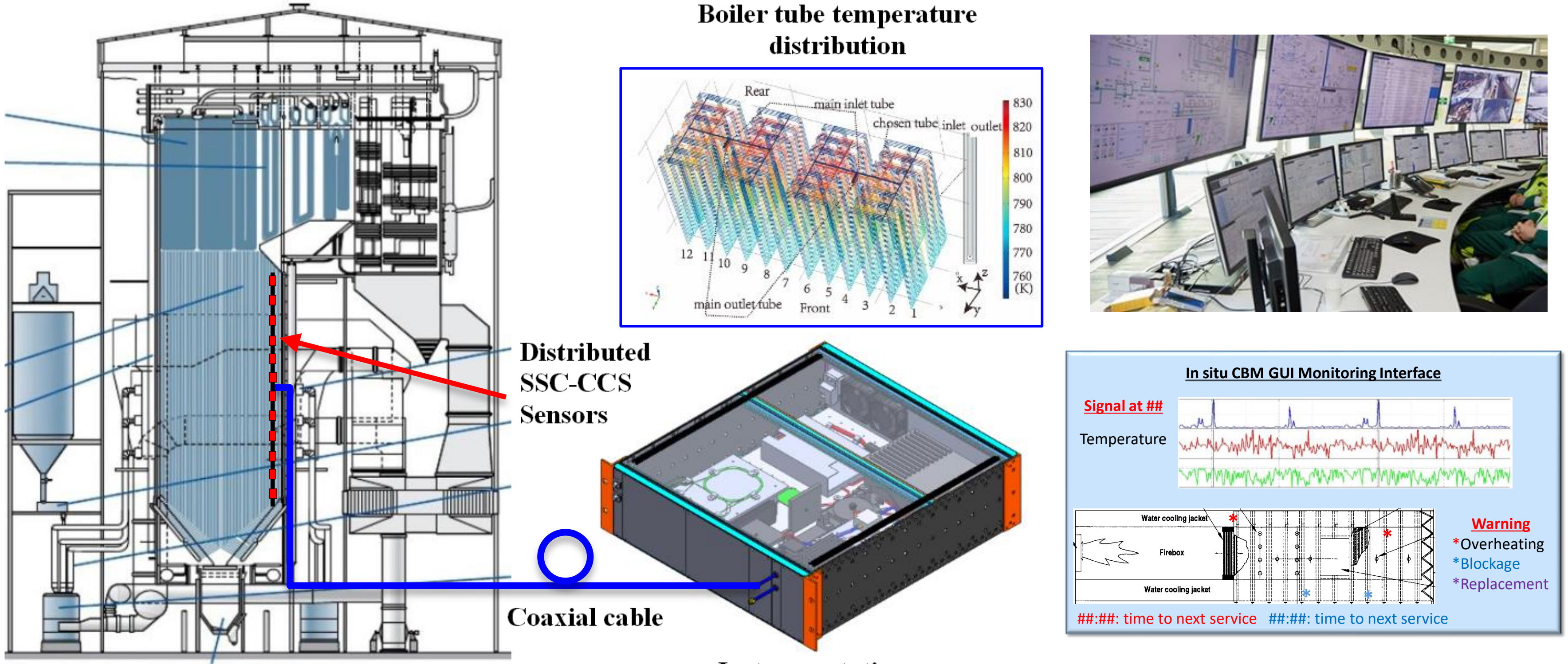
A boiler tube monitoring system with distributed coaxial cable temperature sensors

The system includes four parts:

- High temperature distributed stainless-steel/ceramic coaxial cable sensors (**SSC-CCS**)
- **Instrumentation** to interrogate SSC_CCS
- **Models** to optimize the sensor design and intemperate the measurement results
- Condition-based monitoring (**CBM**) system



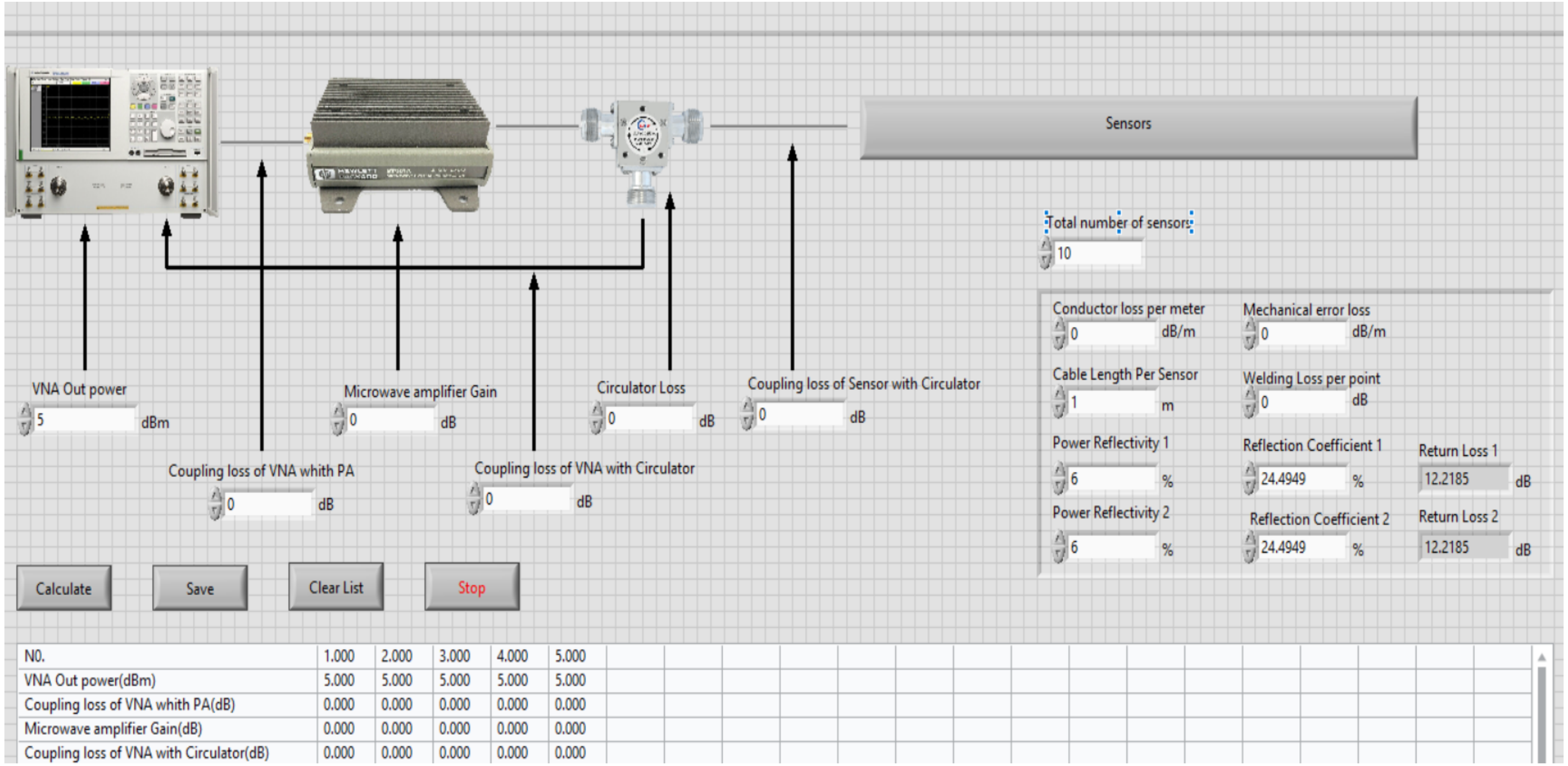
Coal-fired boiler

Instrumentation

CBM

Project Update – Team at Clemson University

Power budget, Signal-to-Noise Ratio and System Design



- Simulation software is developed to study the two reflections generated on the temperature sensing cylinder based on power budget and signal-to-noise ratio.

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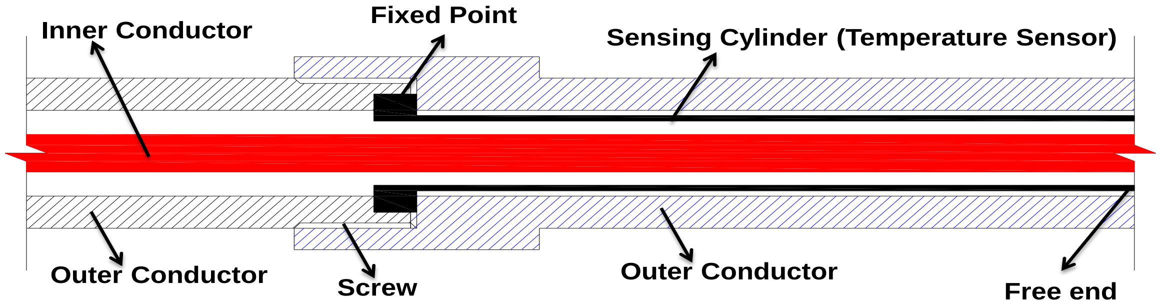
Sensor Design #1: Hollow Coaxial Cable Sensor

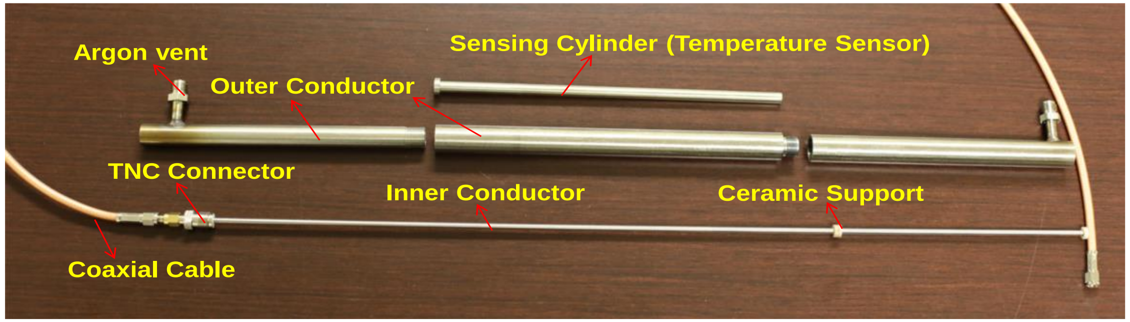
Design Principle

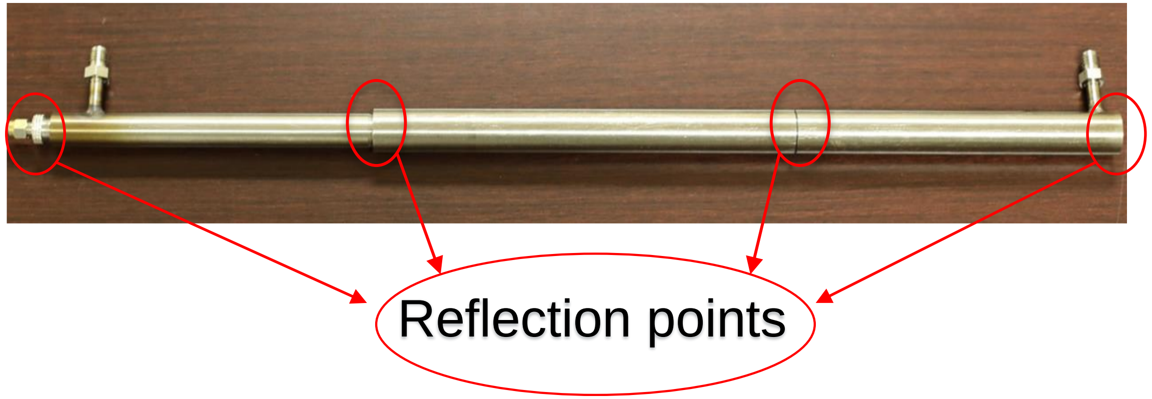
- **Two reflections** are generated at the two end-faces of temperature sensing cylinder. These two reflections travel backward to produce **an interference signal**.
- The temperature induced **length changes of the sensing cylinder** will produce a **frequency shift** (Δf) in reflection spectrum. By **tracking the frequency shift**, the temperature of the environment is measured.

Advantages

- Sensing element protected.
- Hollow structure ensure zero dielectric loss
- Inert gas filling the hollow part to minimize oxidation of the metal at high temperatures







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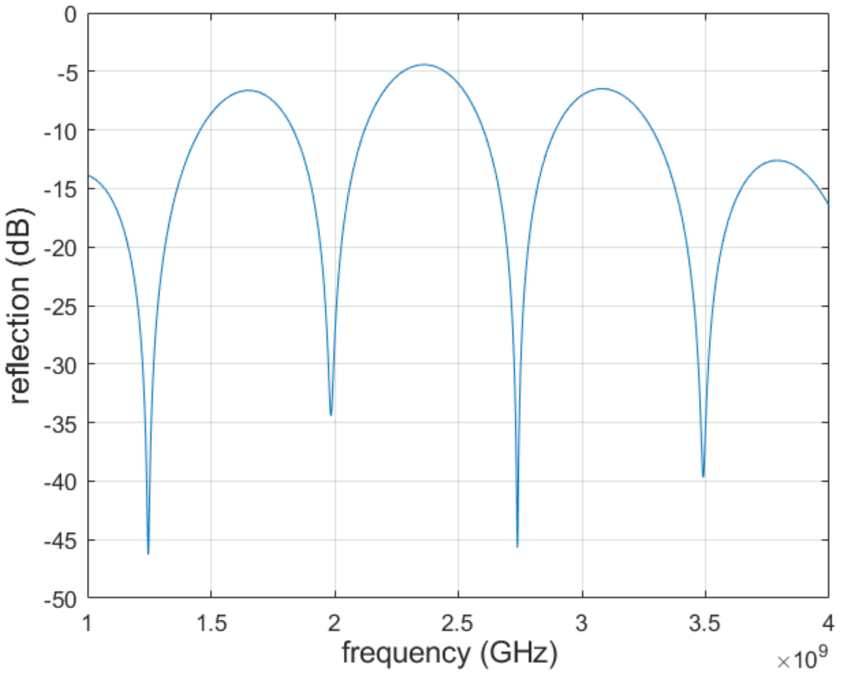
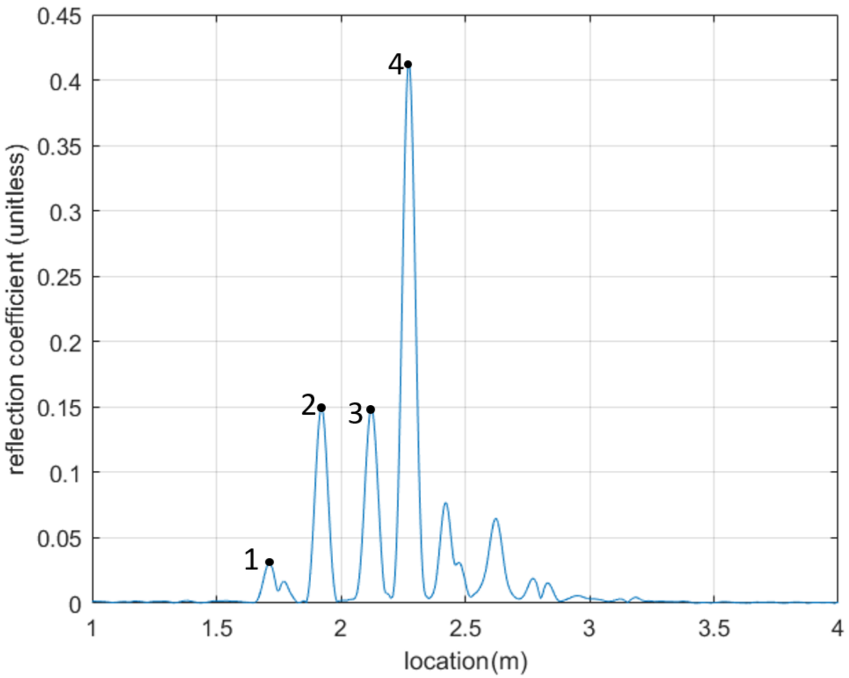
Distributed Reflectivity along the Hollow Coaxial Cable Sensor





Reflection point	Reflectivity
Reflection 1	0.09%
Reflection 2	2.24%
Reflection 3	2.22%
Reflection 4	17.15%

- The measured reflectivity is reliable and consistent with the theoretically calculation results.
- The optimal reflectivity can be realized by modifying dimensions of the sensors according to the models.

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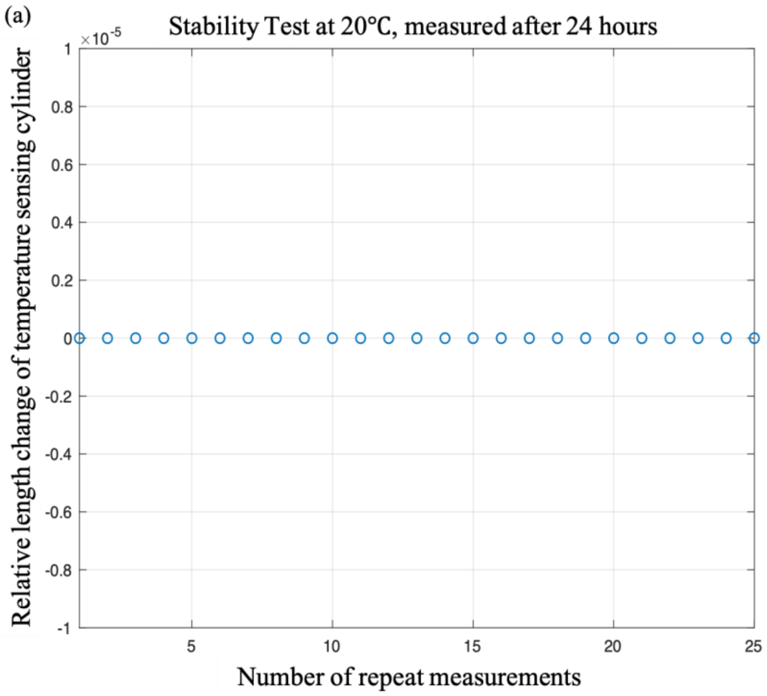
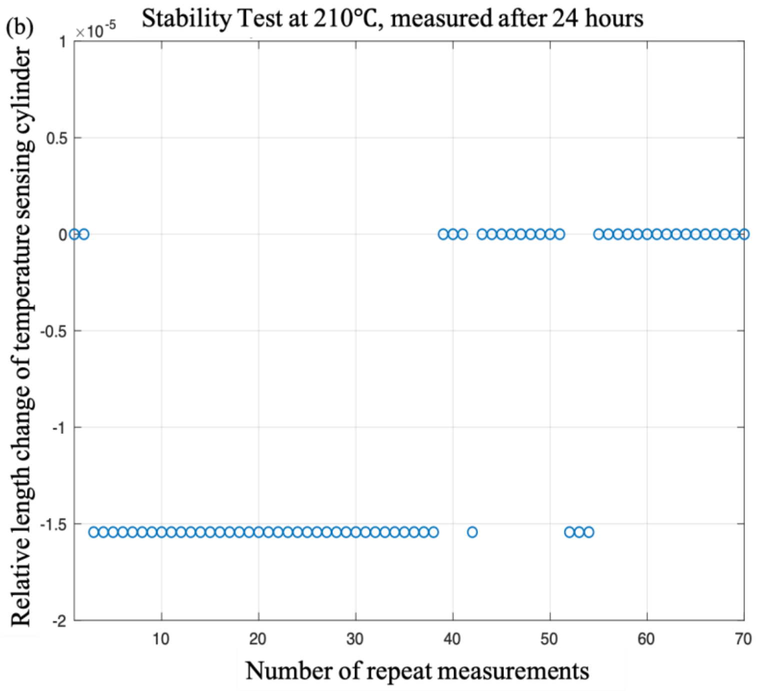
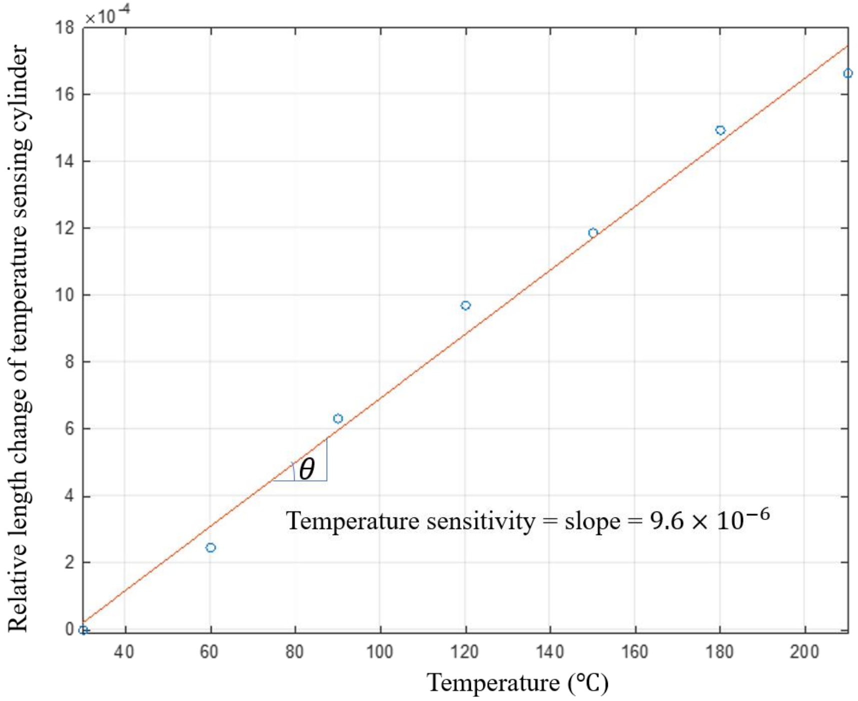
Tests of the Hollow Coaxial Cable Sensor Prototype

Stability tests





Temperature Sensitivity



- ❑ The measurement results show that the sensor is stable in both low- or high-level temperatures.
- ❑ The temperature sensitivity is close to the CTE of the stainless-steel material.

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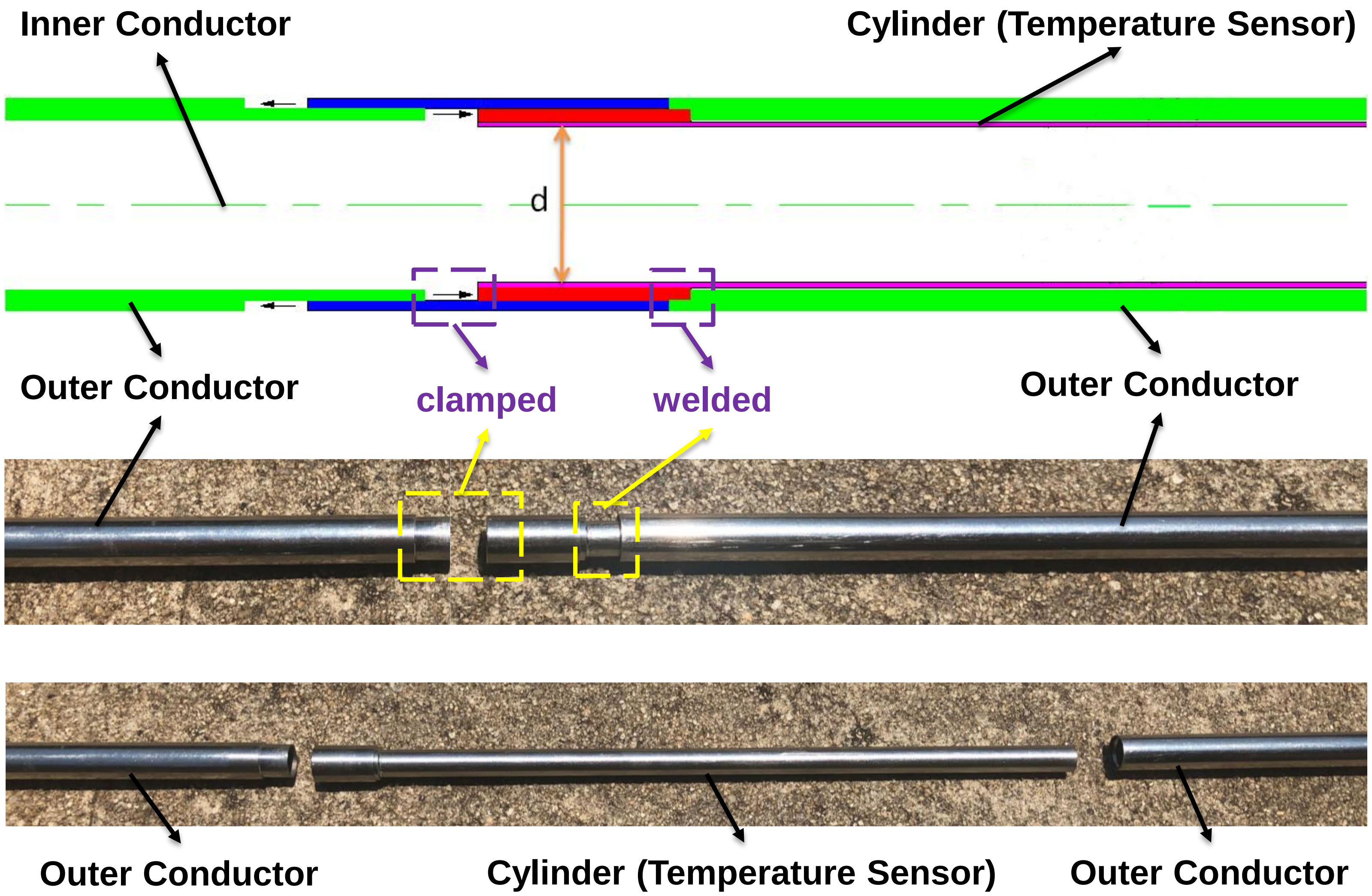
Sensor Design #2: Revised Hollow Coaxial Cable Sensor



Sensing Principle

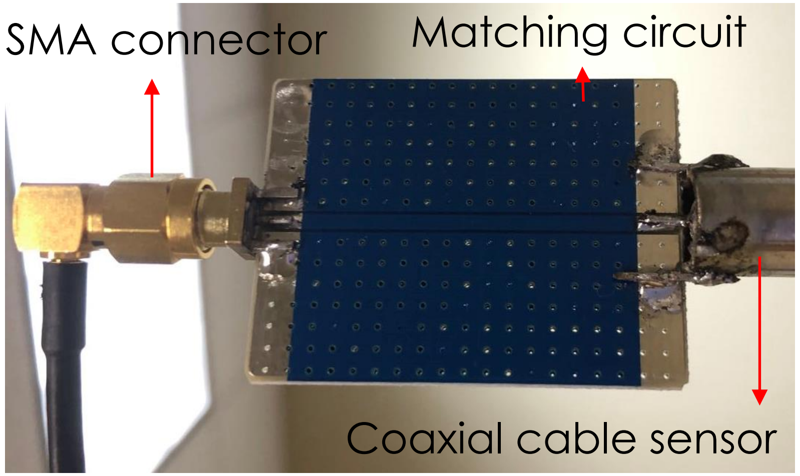
- ❑ same as the previous design.

Advantages

- ❑ The relative insensitivity of the sensor signal to the machining tolerance
- ❑ The better control of the reflectivity
- ❑ Welding based connection ensure good robustness at high temperatures

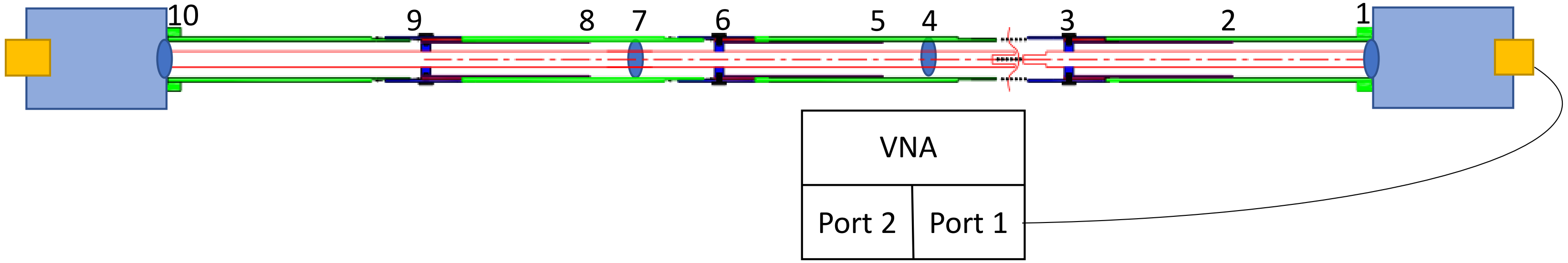
Coaxial Cable Sensor (CCS) Connection

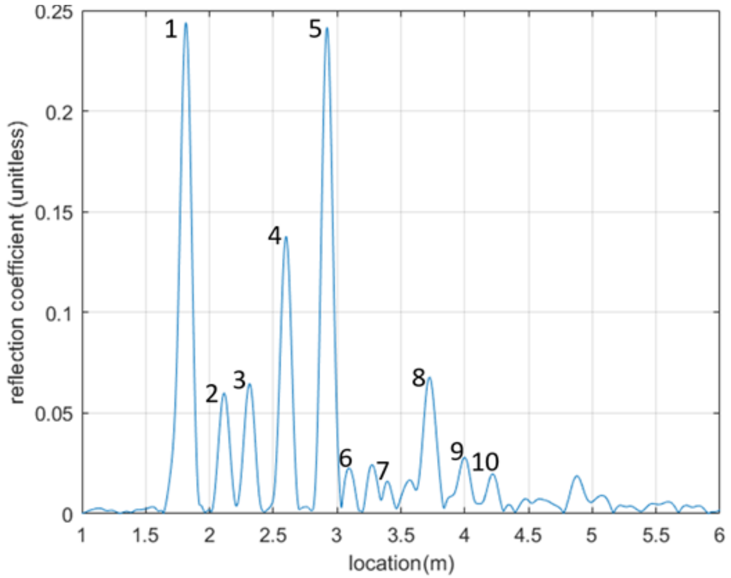
Matching circuit



- Match the impedance of the CCS and the SMA connector for optimal signal transmission and termination
- Secure the connection reliability
- Match the dimension of the CCS and SMA connector

Prototypes of Three Cascaded CCSs





Reflection Points	Distance(m)	ID of sensor(mm)	Reflection coefficient
1	1.815		0.2438
2	2.115	7.0	0.0601
3	2.314	7.0	0.0646
4	2.6		0.1378
5	2.92	6.2	0.2415
6	3.094	6.2	0.0227
7	3.394		0.0243
8	3.723	5.8	0.0679
9	3.998(?)	5.8	0.0280
10	4.219		0.0197

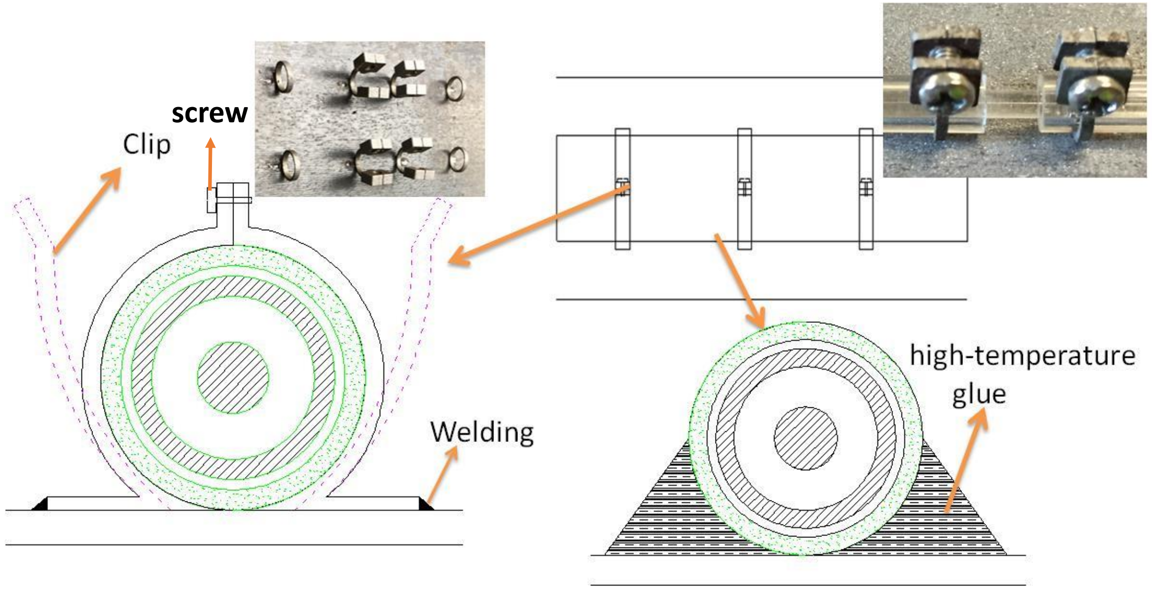
- Ten reflection points distributed along the tested sensor prototypes can be easily identified in the spectrum.

Project Update – Team at Clemson University

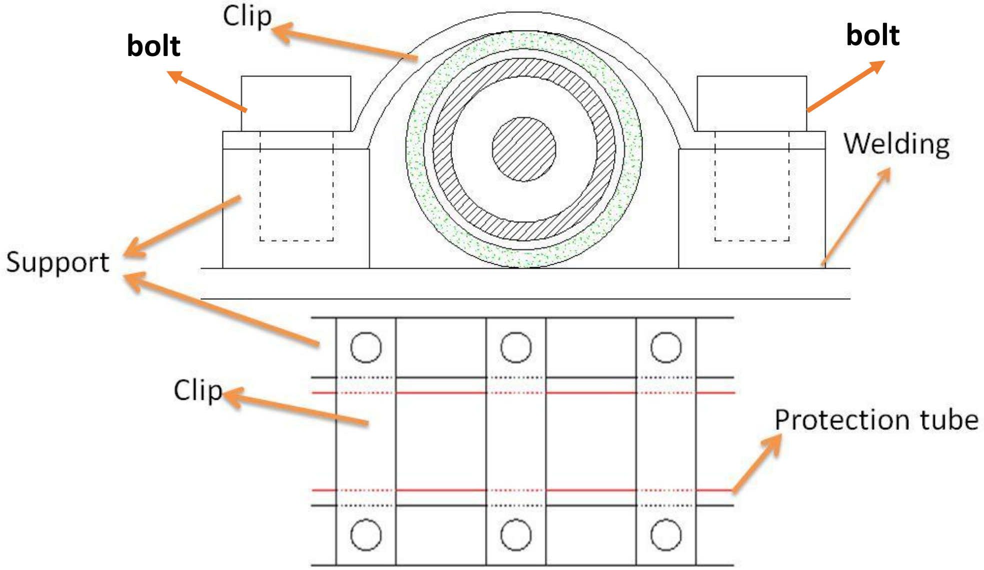
CCS Installation: Design of Protection Tube

- **Protection tube:** isolate the CCS from the deformation of the boiler tube
- Attachment methods
  - **Welding-based attachment**: Directly welding the protection tube to the boiler pipe.
  - **Clamp-based mechanical attachment**: Two kinds of clamps are designed to be welded on the boiler pipe and used to hold the protection tube.

Clamp #1



Clamp #2



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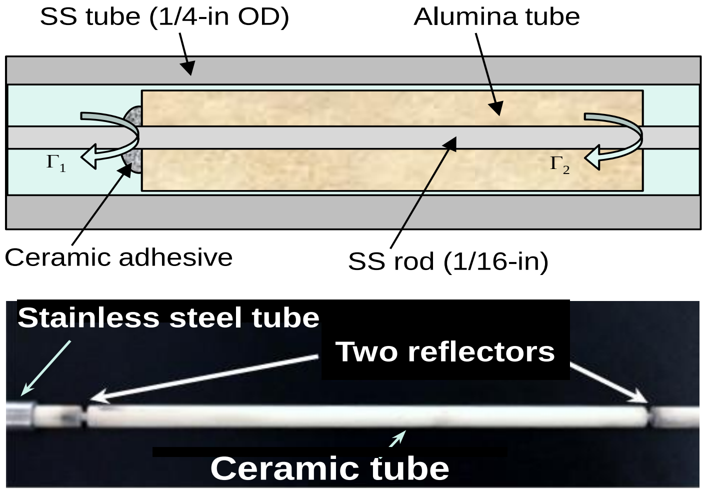
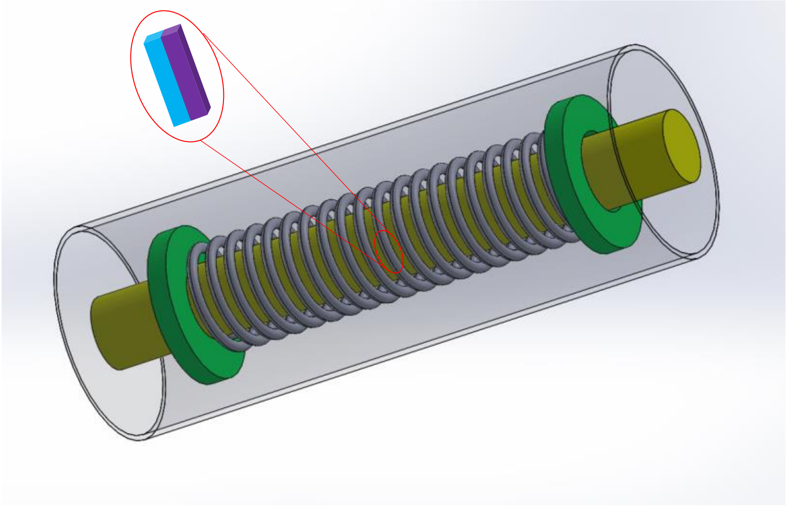
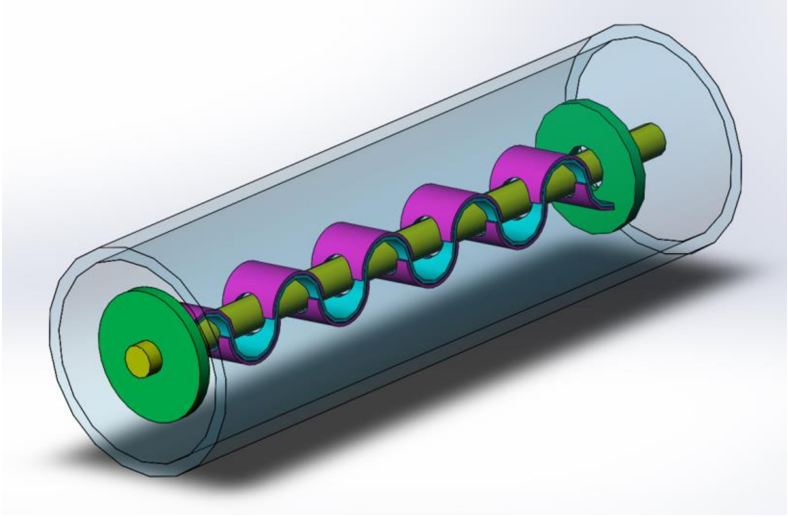
Other Sensor Designs



Sensing principle:
As the temperature changes, the interferogram shifts due to the thermal expansion and the temperature dependence of dielectric constant of the ceramic.



Sensing principle:
The spiral tube is comprised of two nonmetal materials. As the temperature changes, the length of the spiral tube changes and cause the interferogram shifts.

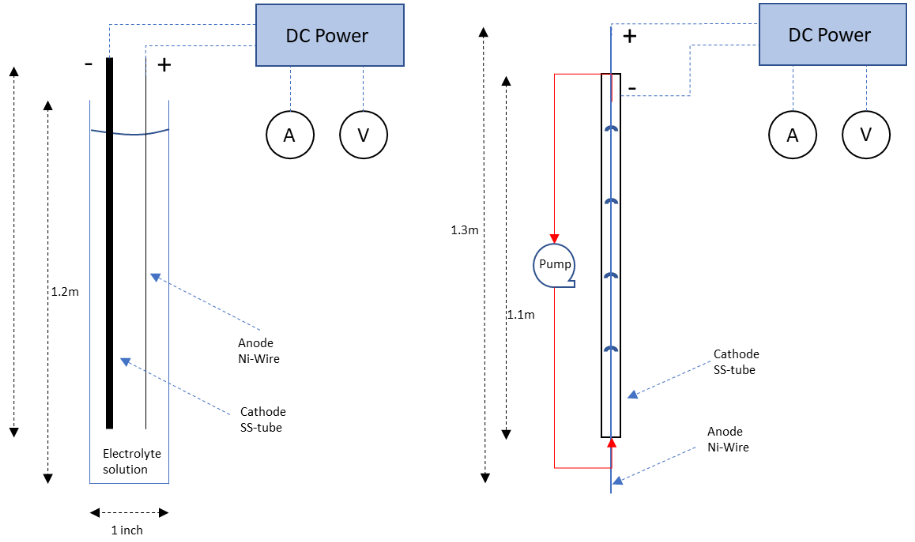


Sensing principle:
The wave structural element is comprised of two different materials. As the temperature changes, the length of this element changes to cause the interferogram shifts.

Project Update – Team at University of Cincinnati

Nickel Coating Development

- Development of surface coated conductors for enhancing the metal ceramic coaxial cable sensor performance
  - Establishment of lab apparatus for electroplating of Ni thin films on inner surface of the stainless steel (SS) tube and outer surface of SS wire for surface electric conductivity enhancement
  - The Ni coating thickness is varied between 10 – 40 µm for performance evaluation in the CCSs.



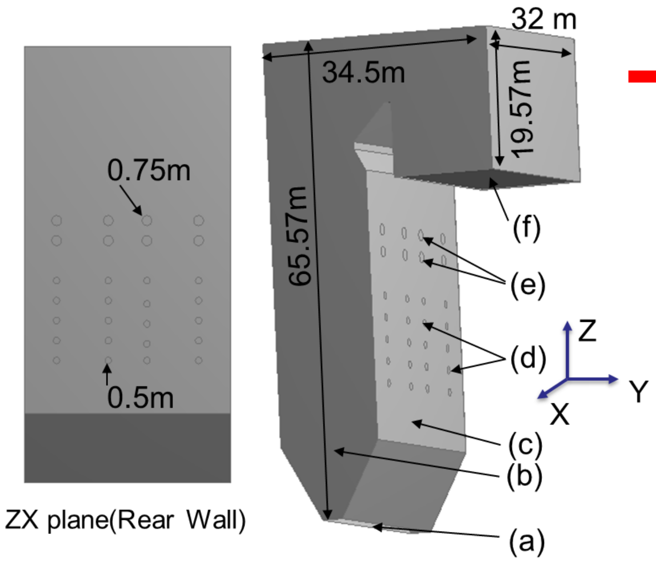
- Schematic showing the apparatus arrangements for electroplating (left) on outer surface of small SS tube or wire, and (right) on inner surface of large SS tube.

Sample dimensions	Quantity	electroplating duration, h	Voltage, V	Ave. current, A	Thickness, µm
Tube: OD = ¼"; L = 1.10 m	4	2	1.5	1.4	20±2
Tube: OD = ¼"; L = 1.10 m	2	2	1.3	0.7	10±1
Tube: OD = 3/8"; L = 1.10 m	4	4	1.3	0.6	40±3
Tube: OD = 3/8"; L = 1.10 m	2	2	1.3	0.7	20±2
Wire: φ = 1/16"; L = 1.10 m	4	2	1.5	1.3	20±2
Wire: φ = 1/16"; L = 1.10 m	2	2	1.3	0.5	10±1
Tube: OD = 1/8"; L = 1.10 m	4	4	1.3	0.5	40±3
Tube: OD = 1/8"; L = 1.10 m	4	2	1.3	0.4	20±2

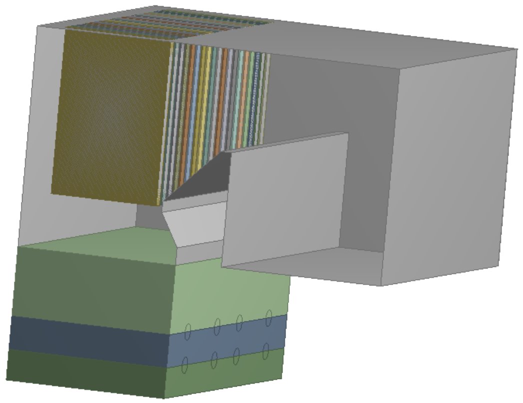
Project Update – Team at Clemson University

Multi-physics Modeling on Reference Boilers

❑ **Establish 3-D computational fluid dynamics and heat transfer model for coal fired boiler**



(a) Ash hopper
(b) Side wall
(b) Front wall
(d) Coal and primary air inlet
(e) Secondary air flow inlet
(f) Outlet for flue gases



Adopt 19 steam panels (10m×15m×1m)to approximate the super heater steam pipes:

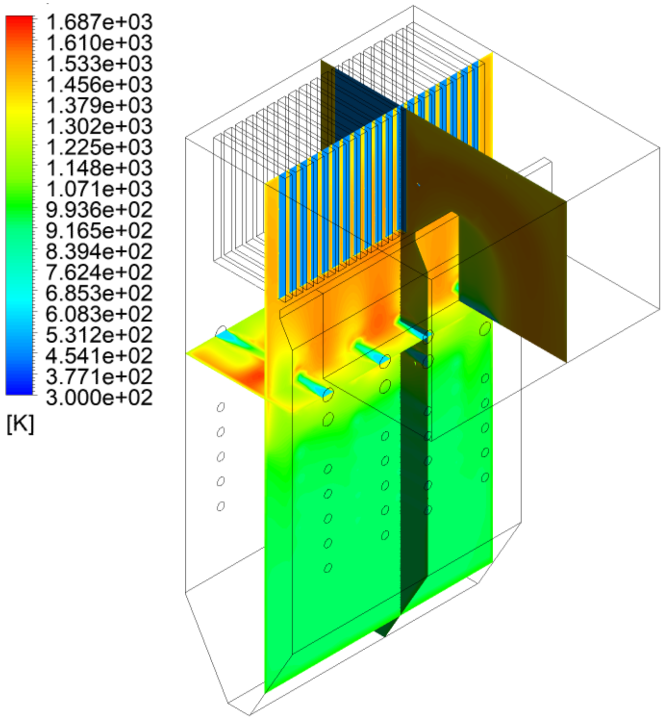
Boundary Conditions

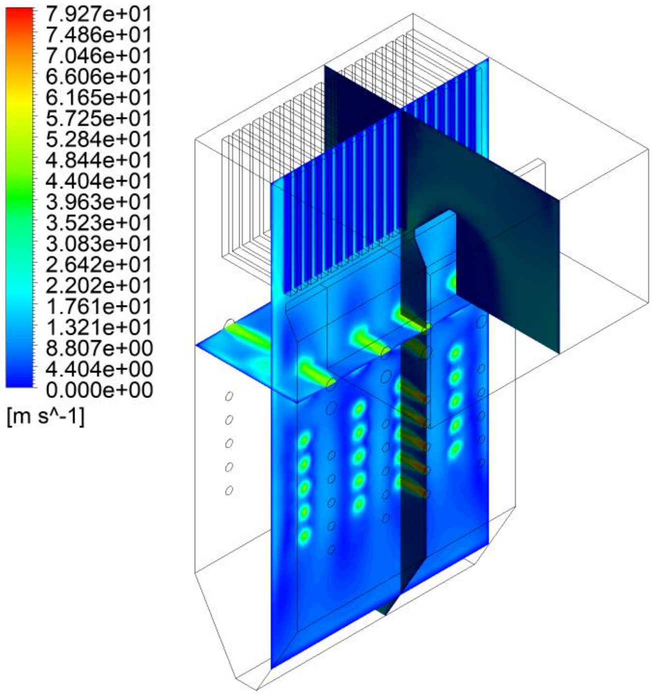
- ❑ Coal inlet and primary air inlet
  - Velocity : 30 m/s
  - Temperature: 358 K
  - Species: Coal (0.79)+ Primary air(0.21)
- ❑ Secondary air Inlet
  - Velocity: 45 m/s
  - Temperature: 596 K
  - Species: Air
- ❑ Outlet for flue gases and ash hopper
  - Pressure-outlet boundary conditions
- ❑ Steam Panels
  - Heat flux boundary condition (100 W/m^2)

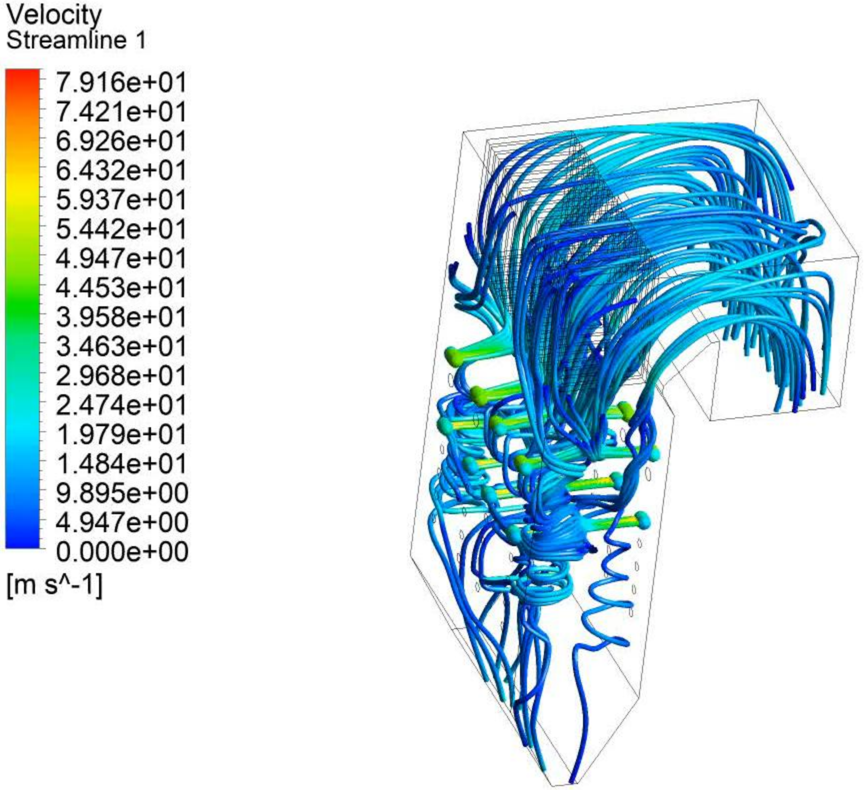
Project Update – Team at Clemson University

Multi-physics Modeling on Reference Boilers

- **Predict the flue gas condition at the superheater/reheater region for sensor modeling and sensor installation guidance**





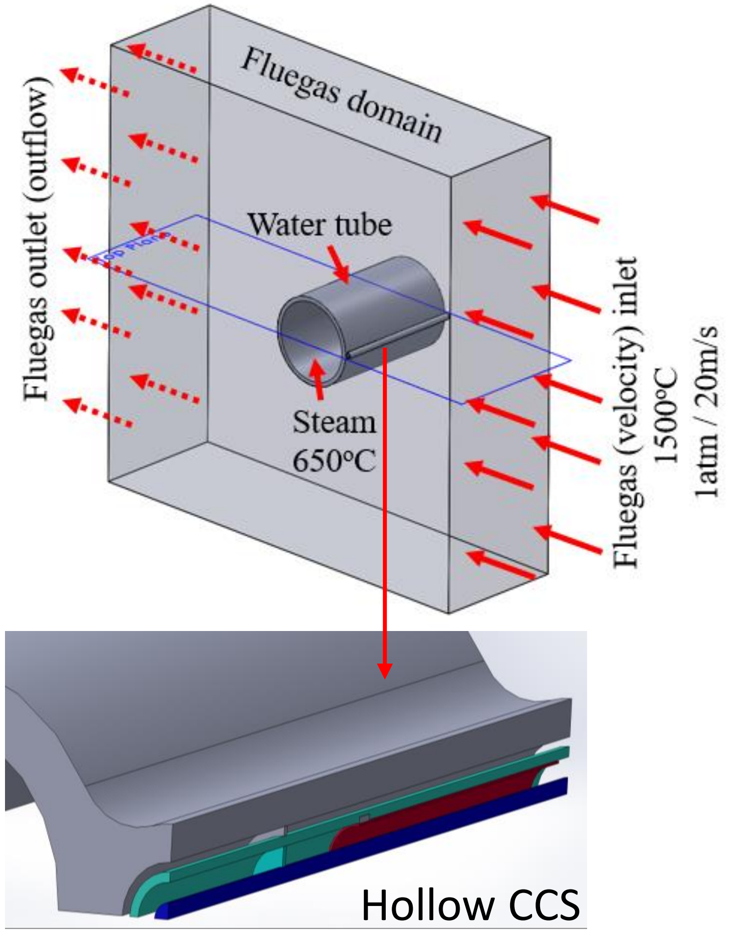


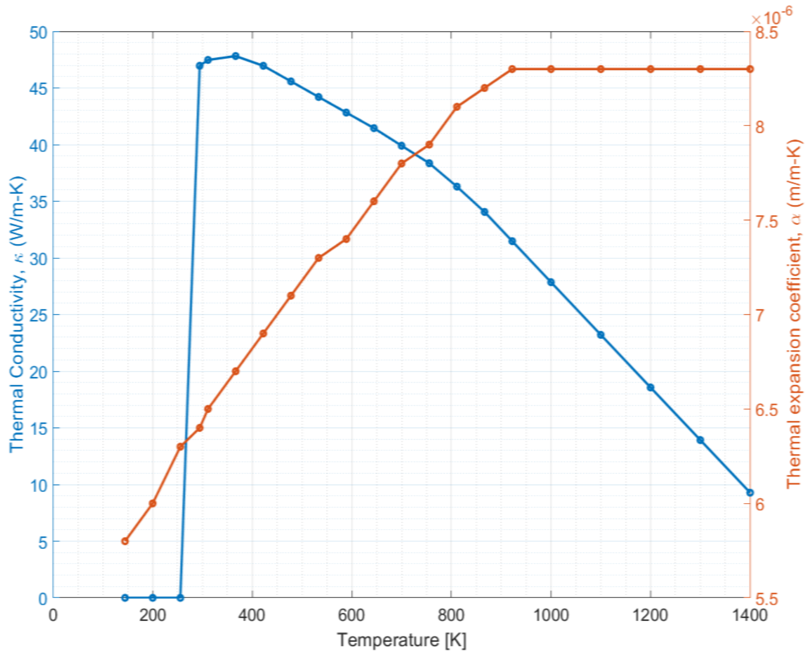
- Temperature Profile at the Steady State
- Velocity Profile at the Steady State
- Velocity Steamline starting from the coal inlets for air flow behavior

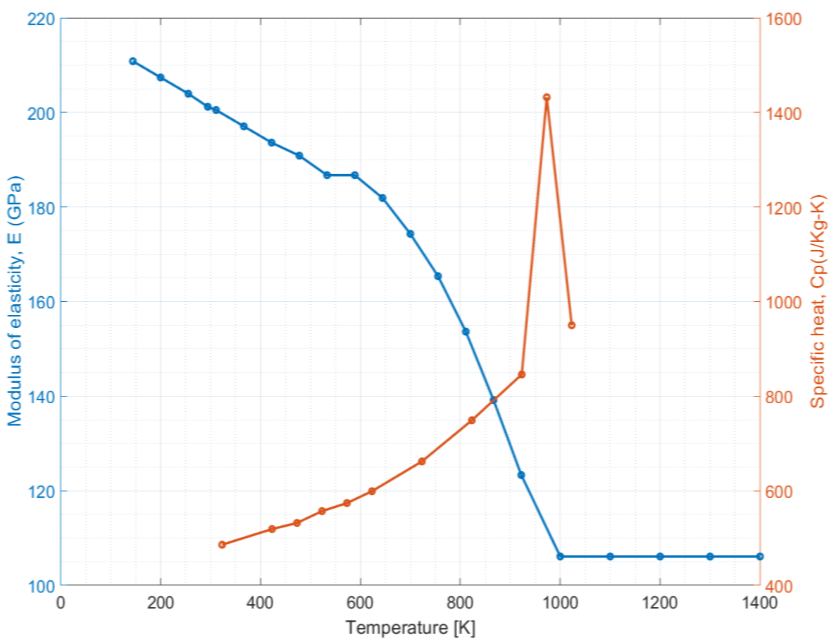
Project Update –Team at Clemson University

Multi-physics Modeling on Sensor Design and Optimization

- **Establish 3-D Computational Fluid Dynamics, Heat Transfer, and Structural Mechanics Model for Sensor Design and Optimization**







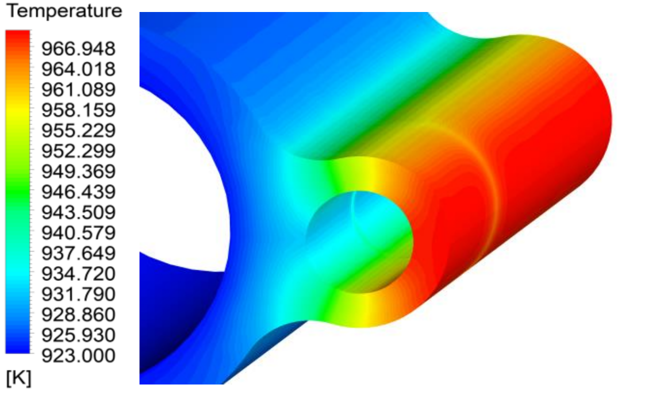
- Temperature dependent properties of the Carbon steel (Melting temperature at 1698.2 °C) is considered in the simulation to ensure the accuracy

Project Update –Team at Clemson University

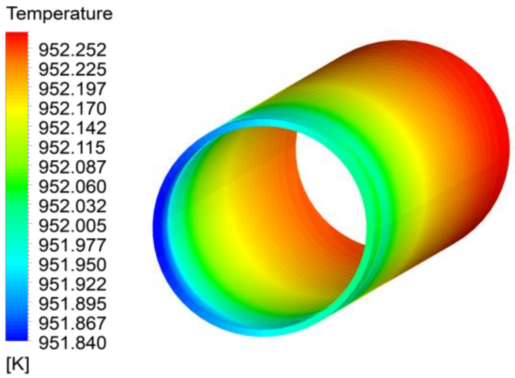
Multi-physics Modeling on Sensor Design and Optimization

- **Predict the sensor response with respect to various steam pipe/flue gas condition in order to guide the sensor design and optimization**

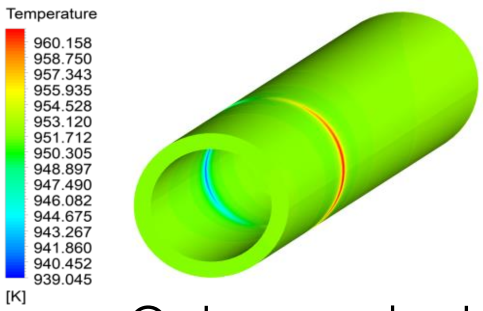
- Steady State Temperature Distribution



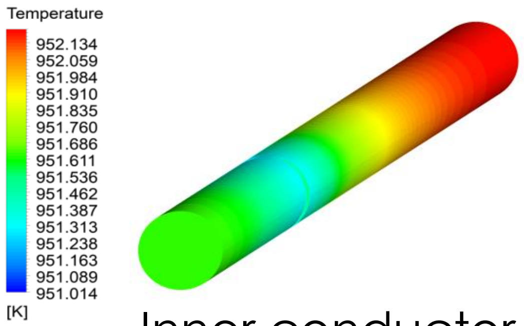
Steam pipe, protection tube



Temperature sensor

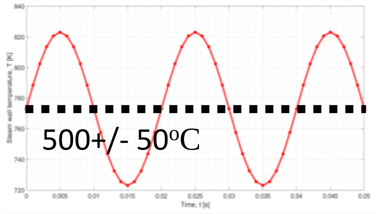


Outer conductor

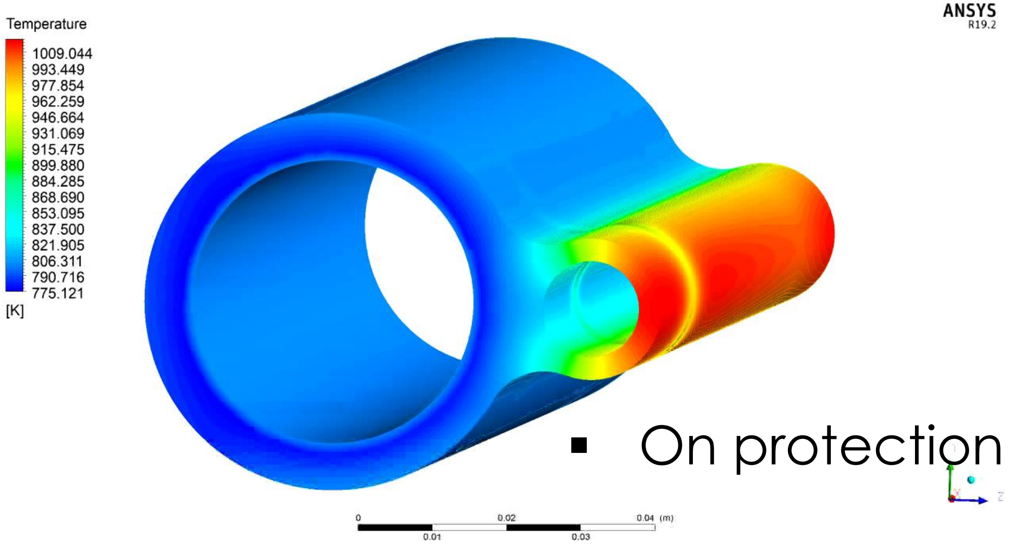


Inner conductor

- Temperature Variation v.s. Time



- on steam pipe



- On protection tube

Project Update –Team at CU, UC, and EPRI

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Industrial Testing Planning

Plant Barry

- Plant Barry has a scheduled outage in October - November 2021
- Sensor testing plan has been initiated
- Two sets of 3-6 meter long coaxial cable sensors will be installed and tested during the scheduled outage
- A potential collaboration with West Virginia University has been initiated
- All the planning for installation and testing will be guided by EPRI and Plant Barry field technicians

Areal picture of Plant Barry

Preparing Project for Next Steps

Applicability to Monitor Existing Boilers

Market Benefit of the Proposed Coaxial Cable Sensor

- ❑ Robustness and long lifetime.
  - Existing temperature sensors cannot survive long enough for condition-based monitoring (CBM).
  - The coaxial cable sensors will be developed into a long lasting monitoring tool for CBM
- ❑ High sensitivity/accuracy, fast response, and large dynamic range
  - The coaxial cable sensor has a large dynamic range so it can survive the harsh conditions
  - The coaxial cable sensor has the necessary sensitivity and accuracy for CBM
- ❑ Easy installation by welding the sensor to the boiler tube
  - The sensors can be welded onto the boiler tube. As a result, the installation is fast and easy. The easy installation is the key feature of the coaxial cable sensor that enables the cost savings
- ❑ Fully distributed sensing
- ❑ Low-cost because the signal processing unit can be shared by many sensors
- ❑ Wide applicability to many sections of existing utility plants

Technology-to-Market Path

Working with our industry partners to bring the technology to Market

Technology-to-Market Path

- ❑ Currently the technology is at TRL 5
- ❑ Upon completion of the project, the field tests and demonstration in an operating power plant will bring the level to TRL 7
- ❑ New patents will be resulted from the proposed R&D activities
- ❑ The Clemson University Research Foundation (CURF) will coordinate the technology transfer plan, find business partners and provide leadership and expertise for technology transfer.
- ❑ Will work directly with the industry partners (EPRI and Southern Companies) to commercialize the technology.

Summary of Budget Period 1 Work

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On schedule to meet the milestones set for budget period 1

- ❑ The coaxial cable sensors will provide key capability to in situ monitor the health conditions of boiler tubes to prevent catastrophic failures
- ❑ The technology will enable condition based monitoring, which avoids catastrophic failures, improves the efficiency, reduces the pollutant emission, increases the availability, and reduces the cost
- ❑ In budget period 1 work, we have proved that
    - The sensor has been tested at and successfully survived high temperatures
    - The sensor was stable for a long time when exposed to high temperatures
    - Simulations were conducted to guide the sensor design and installation
    - The sensor designs and installation methods have been finalized, guided by the simulation results
    - Preliminary simulations were performed at the boiler level to guide the sensor installation and data processing

Plan for Next Year

Sensor Design and Testing

- ❑ Conduct the multi-physics simulations on boiler and coaxial cable sensor (CCS) to design and optimize the CCS for better sensibility and predict the sensor performance under various static/dynamic conditions.
- ❑ Optimize and finalize the CCS design for best censing capability, stability and robustness.
- ❑ Test and weld the CCSs to the boiler steam pipe.
- ❑ Develop the data analytics for the field testing.
- ❑ Preliminary field tests at Plant Barry.