DE-FE0031765

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

Project Team:

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NETL Sensors and Controls Project Review meeting, 5/4/2022

Project Objective and Background

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

Objective

To test, validate, and advance the TRL of a novel distributed coaxial cable sensing (CCS) technology for in situ monitoring of the boiler tube temperature in coal-fired power plants.

Background

- **Boiler tube failures**: extremely costly with significant economic impacts
  - 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 fiber 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 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

Monitoring sensors and instrumentation are needed for in situ distributed temperature monitoring of the boiler tubes

Technology Gaps

- **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 2 (04/2021-03/2022)

Scope of Work in Budget Period 2

- ❑ Engineer the sensors, test and evaluate the performance in industrial scale test facilities and in coal-fired power plants.

Update on Project Status

- ❑ To meet the outbreak window at the industrial testing site in Oct 2011, the field installation and testing of the coaxial cable sensor has been conducted ahead of the project schedule.
- ❑ The coaxial cable sensor has survived and successfully collected the sensing signals to the data acquisition system.

Progress of the project

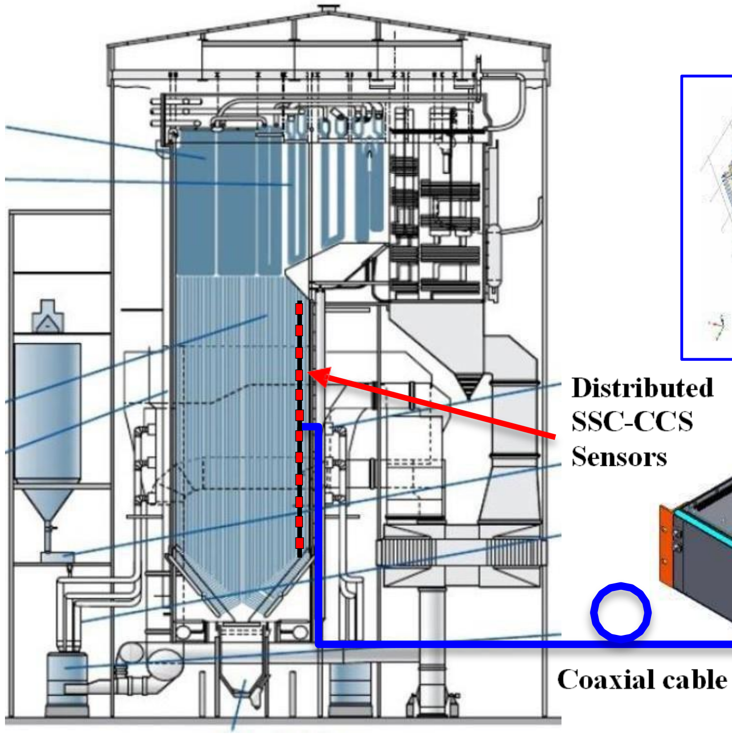
- ❑ The technical progress of the project is on track. All the milestones have been met.
- ❑ Progresses have been made in sensor design, fabrication, testing, boiler simulations, and installation.
- ❑ Continuation application submitted

Proposed Solution

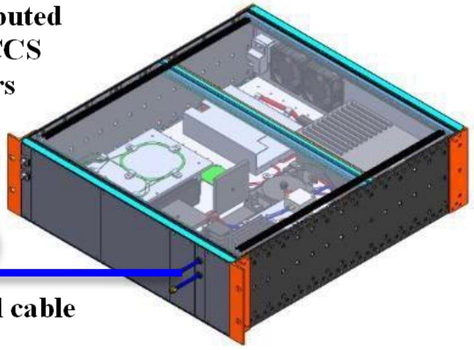
A boiler tube monitoring system with distributed coaxial cable temperature sensors

The system includes four parts:

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

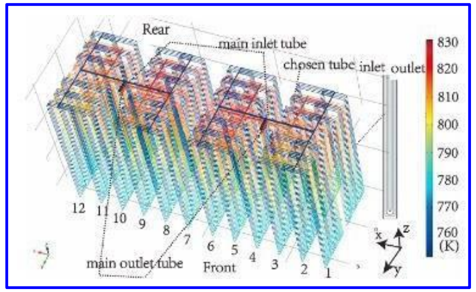


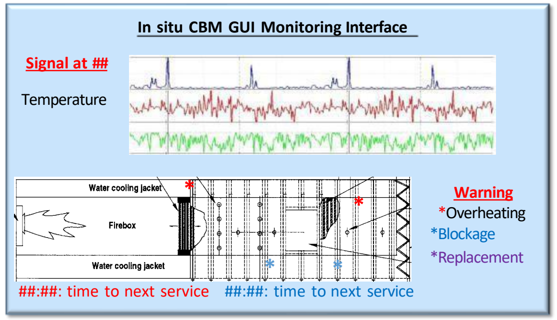
Coal-fired boiler



Instrumentation

Boiler tube temperature distribution





CBM

Project Update – Sensors

Sensor design: quartz as the insulator

Principles

- **Microwave reflections** are generated by polished notches along a quartz tube.
- The quartz tube **changes its length and dielectric constant** as a function of temperature.
- The change is measured accurately by **microwave interference**.

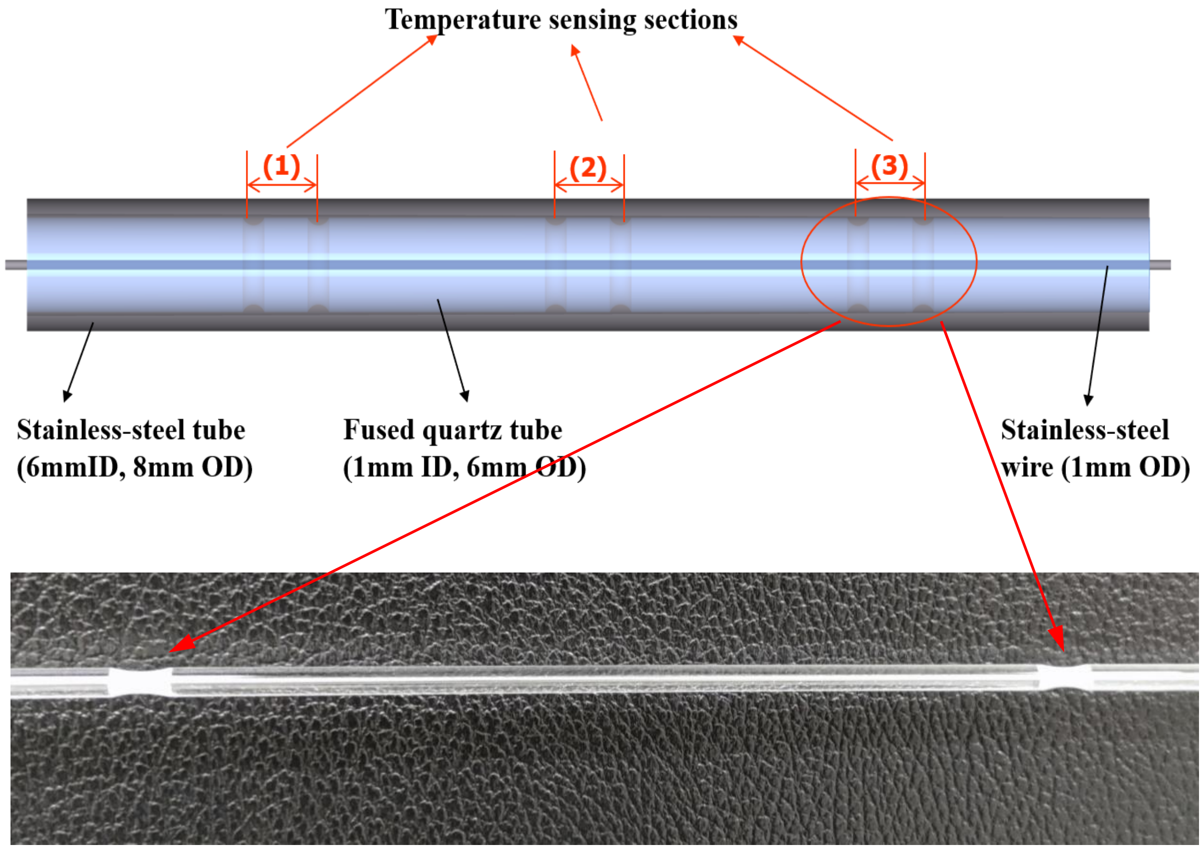
Advantages

- Sensing element is well protected.
- Quartz is stable (material and structure) at high temperatures.

Challenges

- Tight tolerance of the parts – **Custom made quartz tubes**

The **coaxial cable sensor** is made by a quartz tube concentrically separating a stainless-steel (SS) wire and a SS tube.

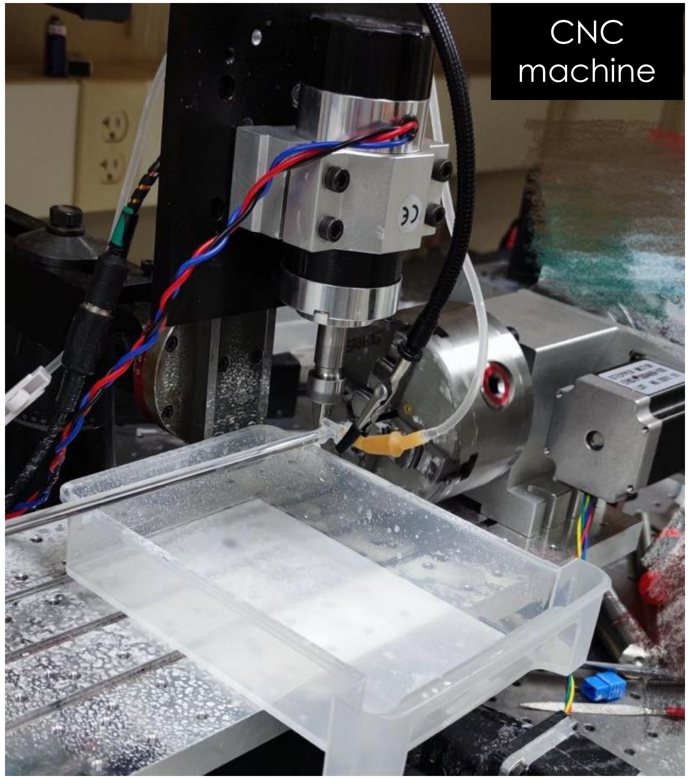


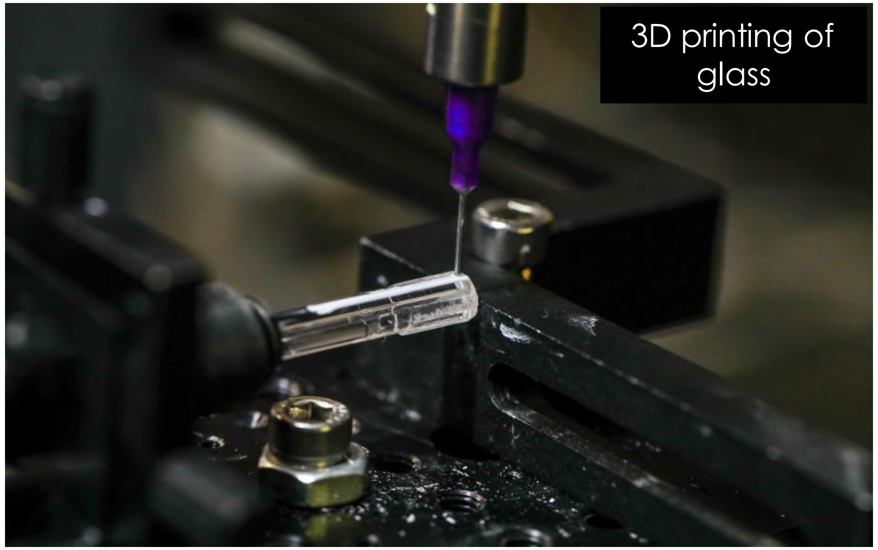
Project Update – Sensors

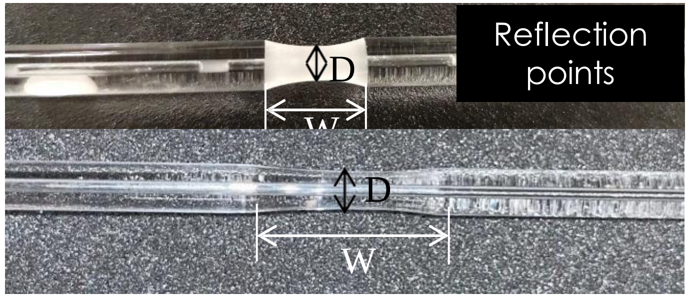
Sensor design: custom made quartz tubes

Technology and advantages

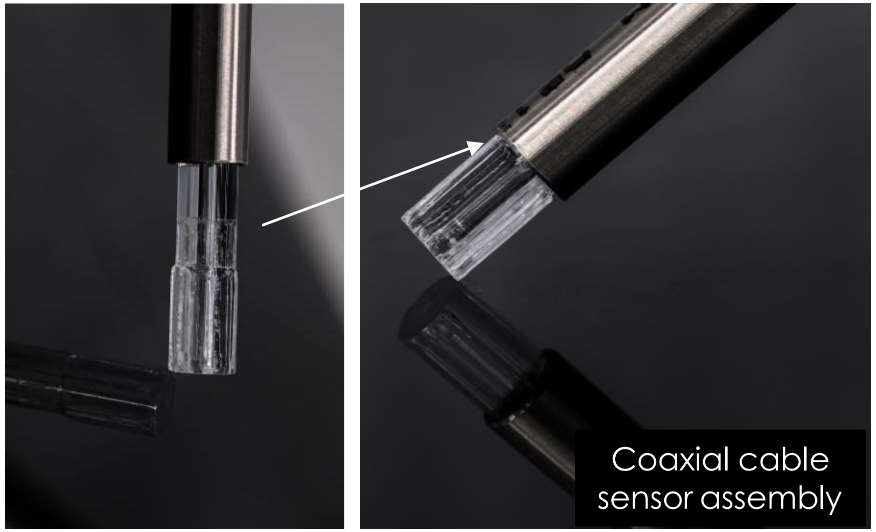
- ❑ Computer numerical control (CNC) machine: fabricate the reflection points on quartz tubes.
  - ➔**Precise control of the reflection intensity**
- ❑ CO_2 laser: heat and resurface the reflection points on quartz tubes.
  - ➔**Maintain mechanical strength of the quartz tubes at the reflection points.**
- ❑ 3D printing: increase the outer diameter of the tip of quartz tubes.
  - ➔**Keep the relative position of the quartz tube and conductors**


CNC machine


3D printing of glass

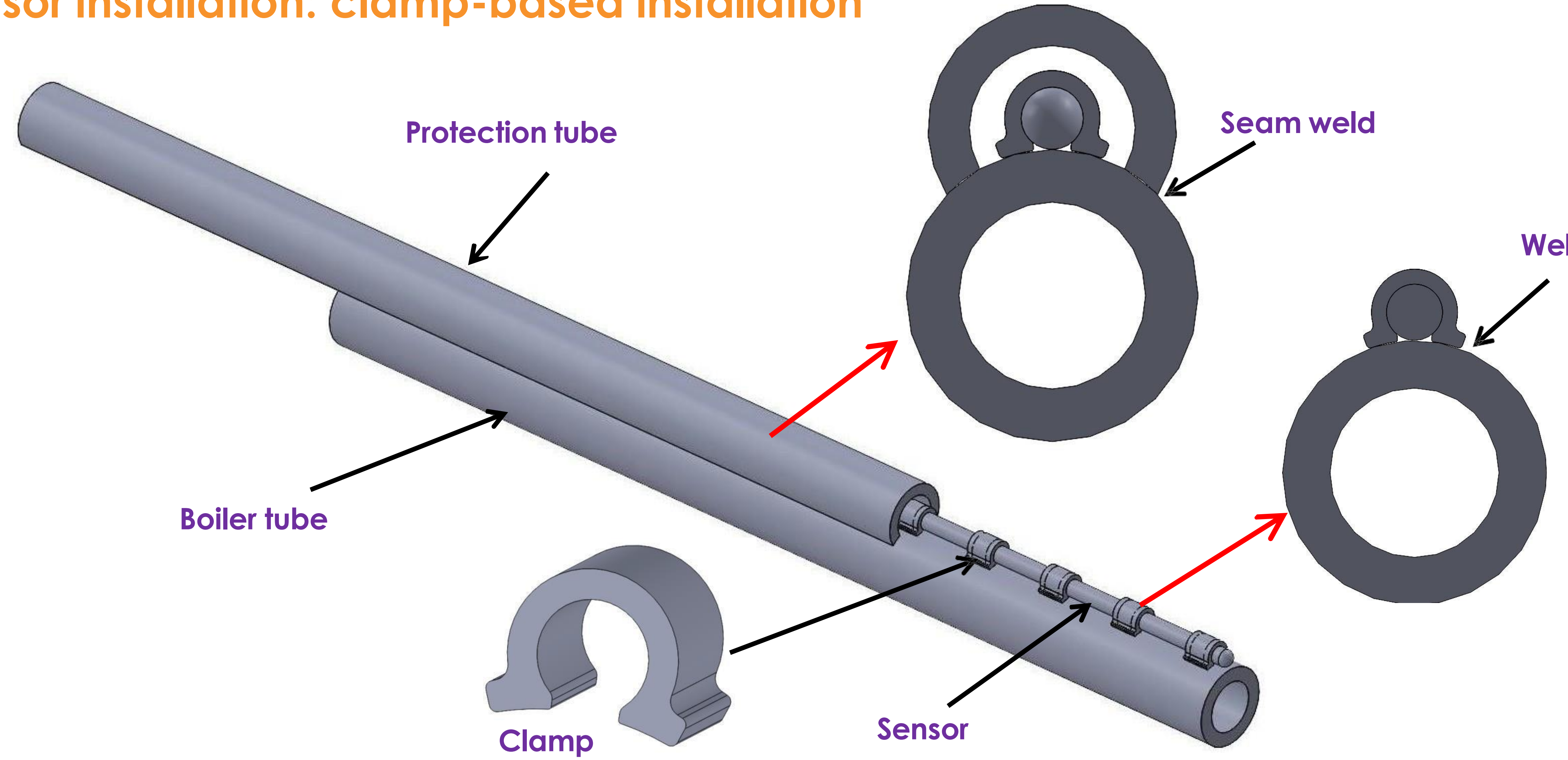


Reflection points


Coaxial cable sensor assembly

Project Update – Installation

Sensor installation: clamp-based installation



Project Update – Installation

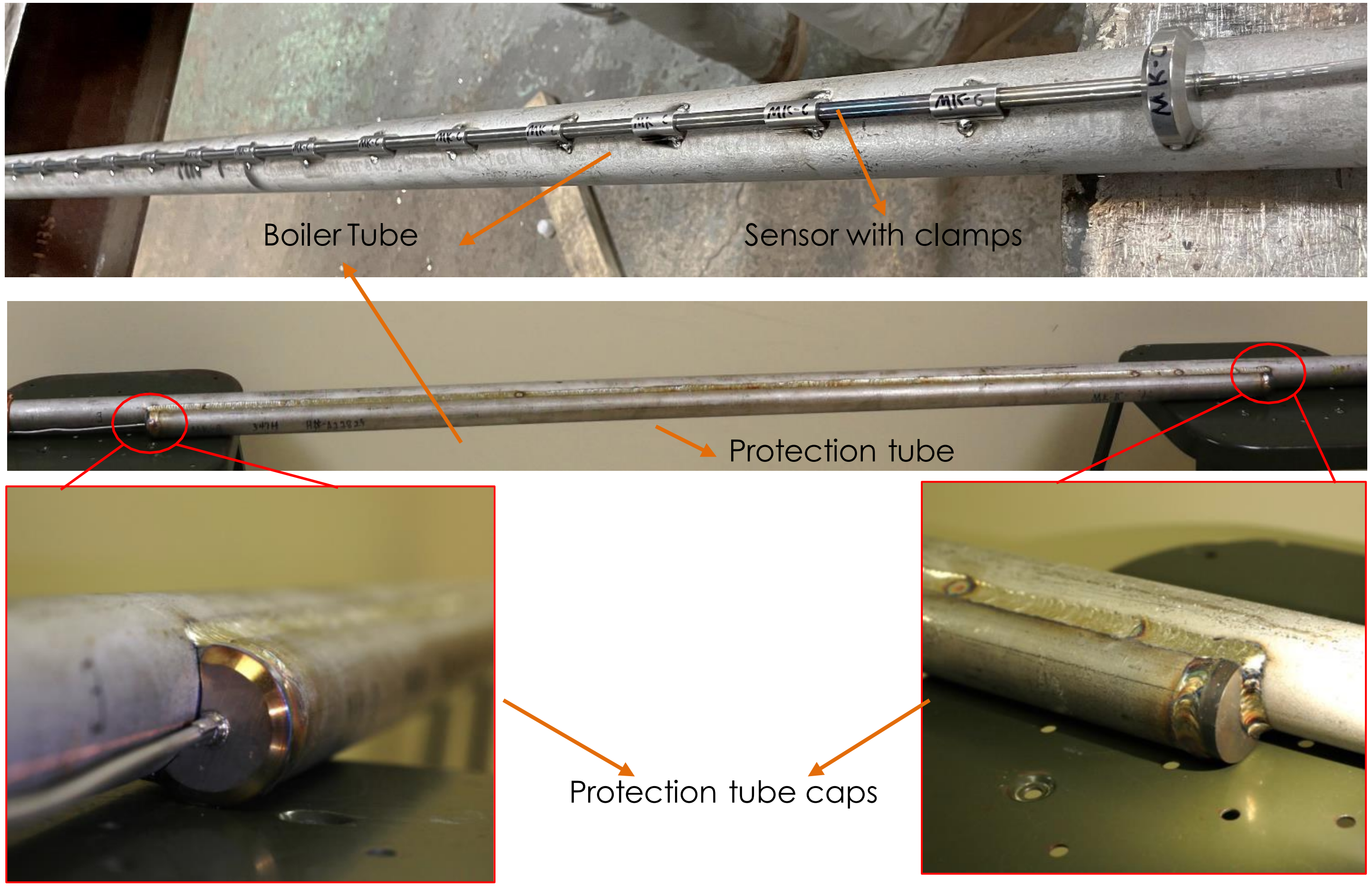
Sensor installation: protections

Structure:

- ❑ The sensor is attached to the boiler tube by several omega-shaped clamps.
- ❑ The sensor and clamps are placed inside a protection tube.
- ❑ The protection tube is sealed.

Advantages:

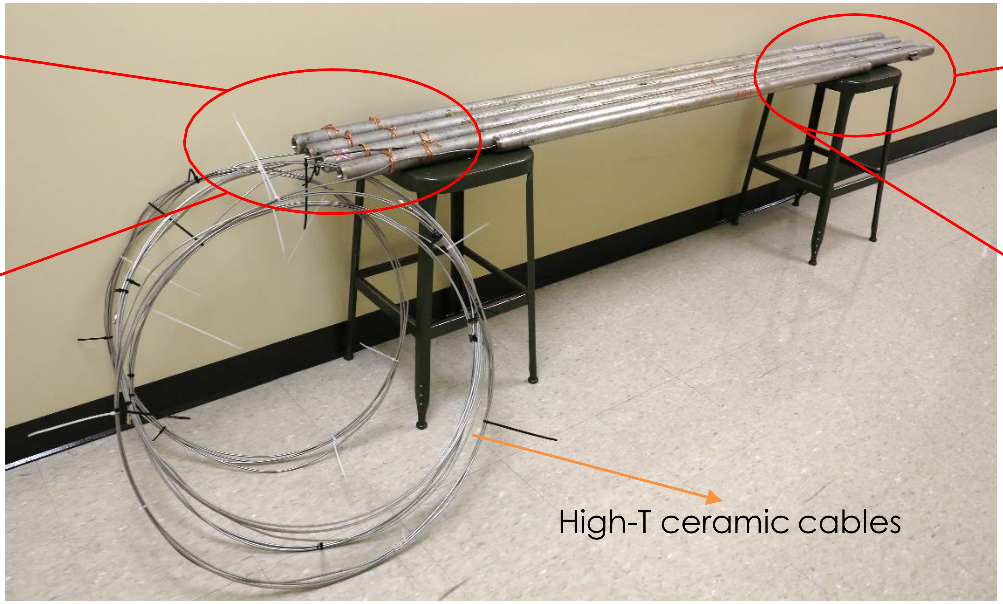
- ❑ Minimize the damages during the heating or welding process.
- ❑ Minimize the influences caused by the flue gas.

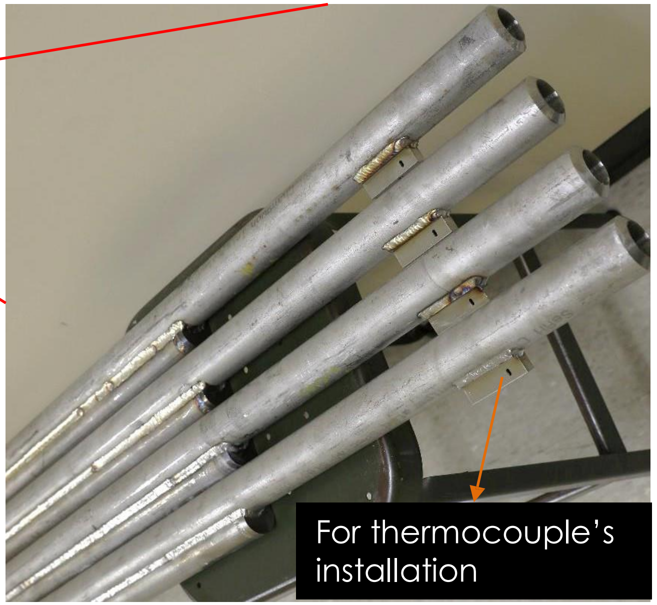


Project Update – Sensors

Sensor installation: fabrication and validation

- Four cables of coaxial cable sensors were prepared and welded to the boiler tube by BTA for industrial-sale test and field test.
- Thermocouple will be attached to the same segment of boiler tube for temperature data validation of the coaxial cable sensers.

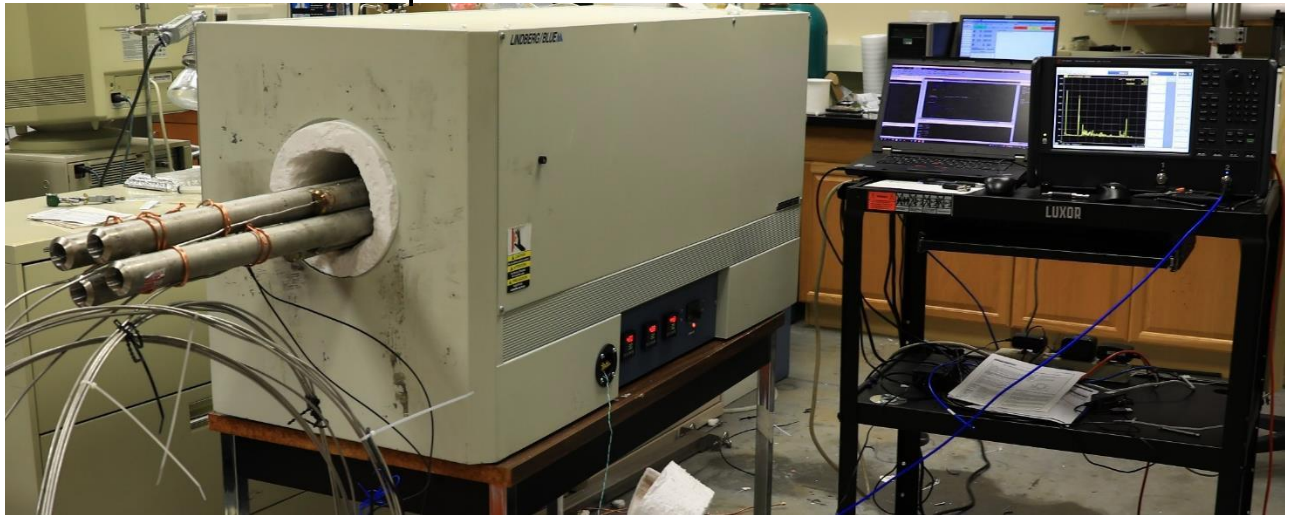




Project Update – In-house Test

Industrial-scale test at the University lab

- An in-house testing facility was set up at Clemson University.
- Four cables of coaxial cable sensors were tested.
- All sensors can follow the temperature changes. Two of them have better sensitivity and fast response.



Project Update – Installation

Sensor installation: data transfer

- **Inside the boiler:** High- Temperature ceramic cable (H-T-CC)
  - Route the signals from the sensors inside the boiler
  - Operating temperature: up to 1000℃
- **Outside of the boiler**: Low-Temperature coaxial cable (L-T-CC)
  - Transmit signal from the high-T ceramic cables to the DAQ terminal.
  - Low loss coaxial cable: 5dB/100ft
  - Operating temperature:-40℃ to 85℃
- **Challenges**
  - **Custom made connections** between coaxial cable sensor and high-T ceramic cable

High-T ceramic cable

Cross-section view of stripped high-T ceramic cable

SMA connector

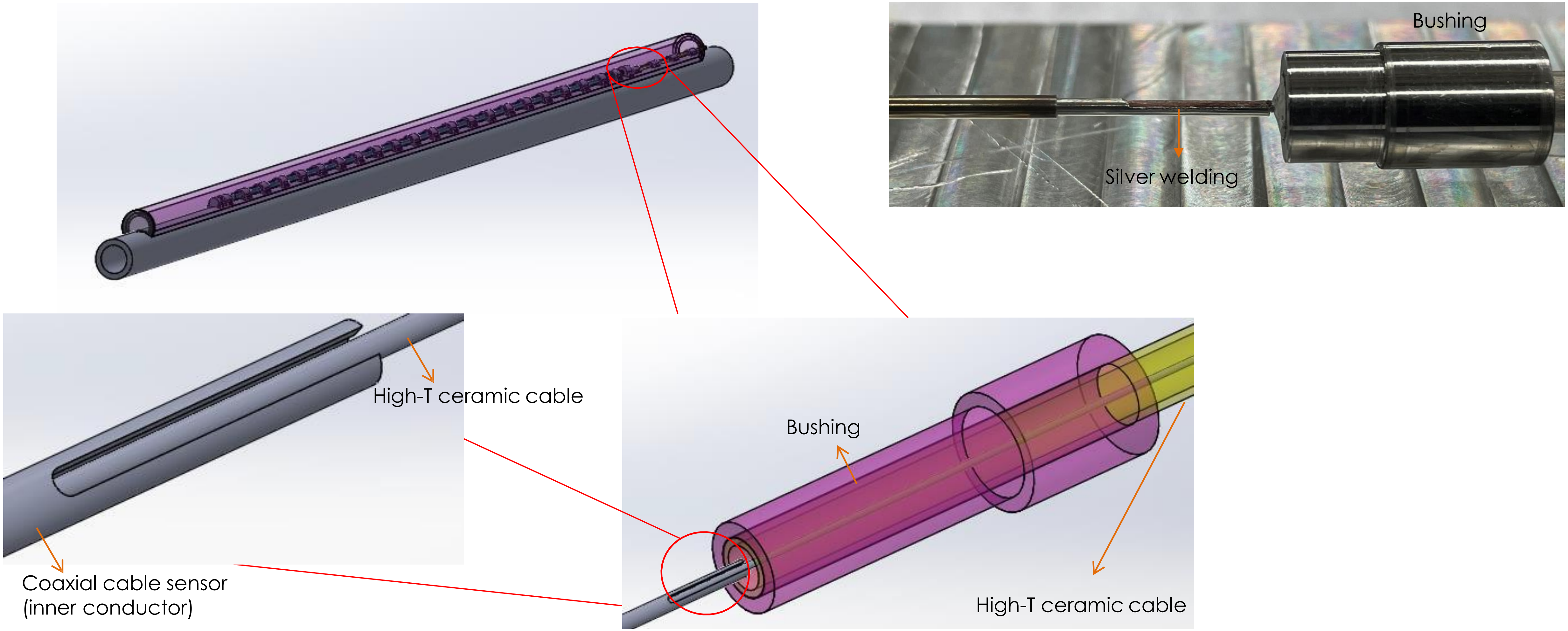
Low-T coaxial cable

N-type connector

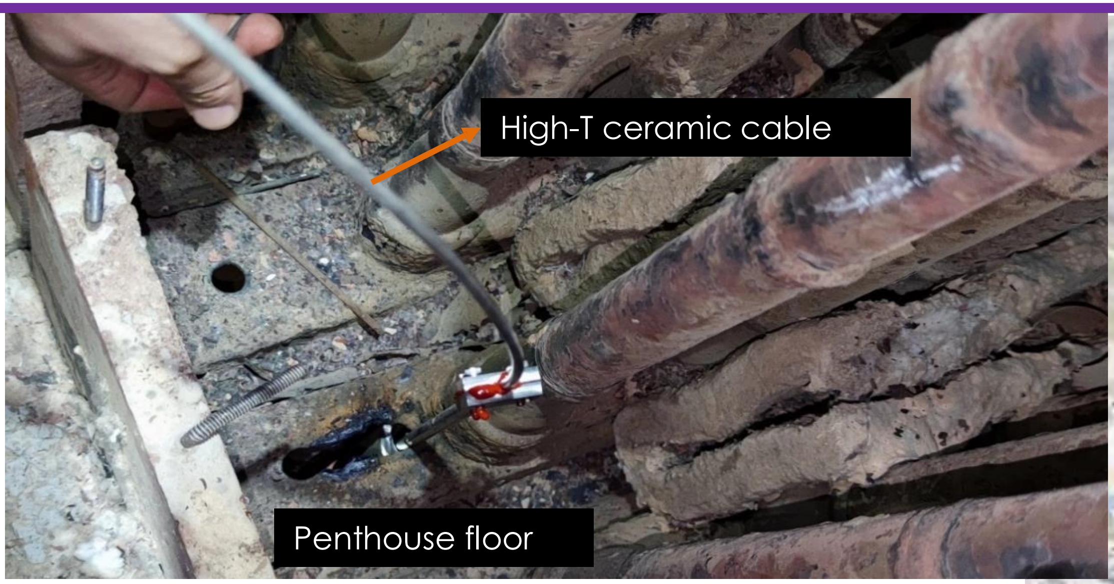
Connection between L-T-CC and H-T-CC

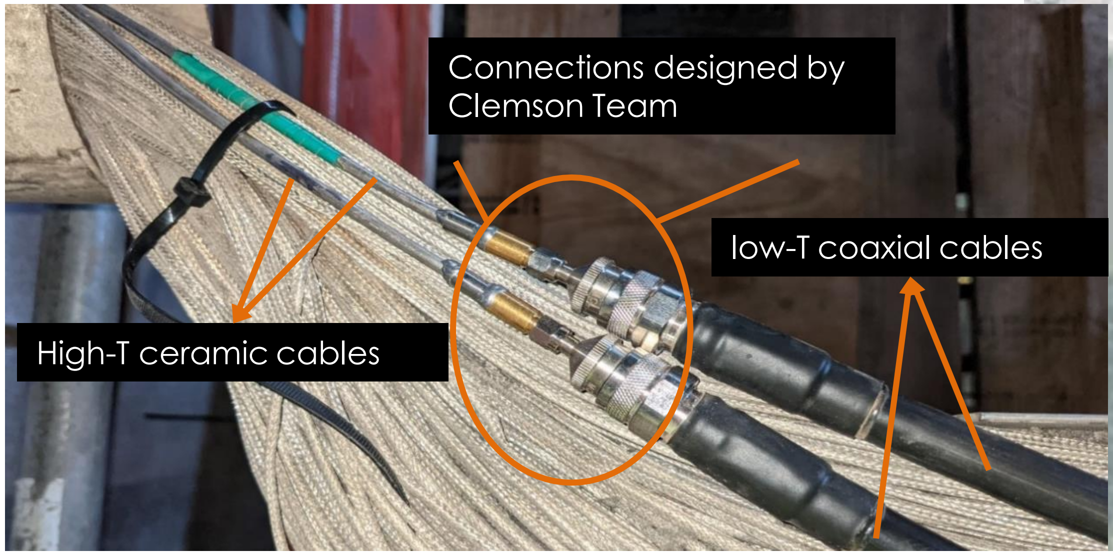
Project Update – Installation

Connection between high-T ceramic cable and the coaxial cable sensor



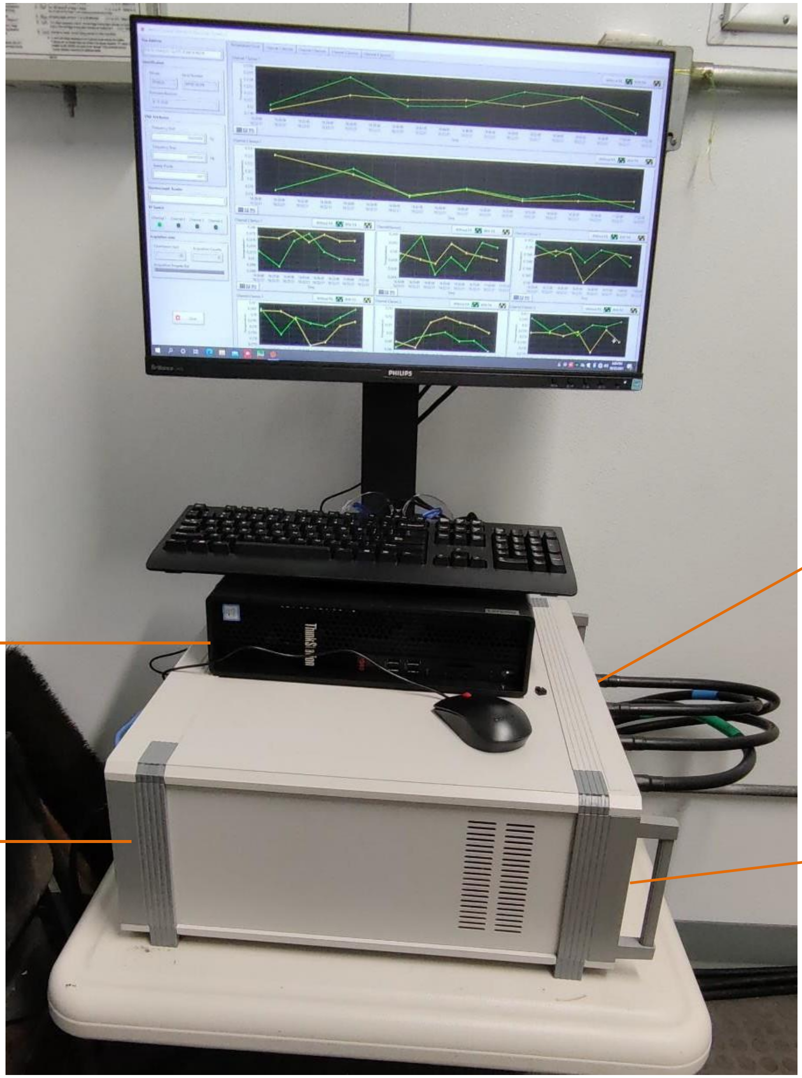
Project Update – on-site Installation





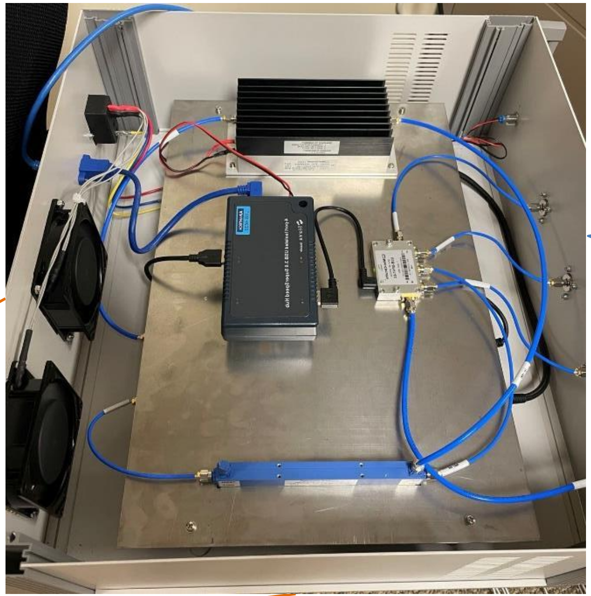
Project Update – on-site Installation

Clemson sensors' DAQ system



Workstation

Clemson sensor acquisition terminal



VNA: Vector Network Analyzer

PA: Power Amplify

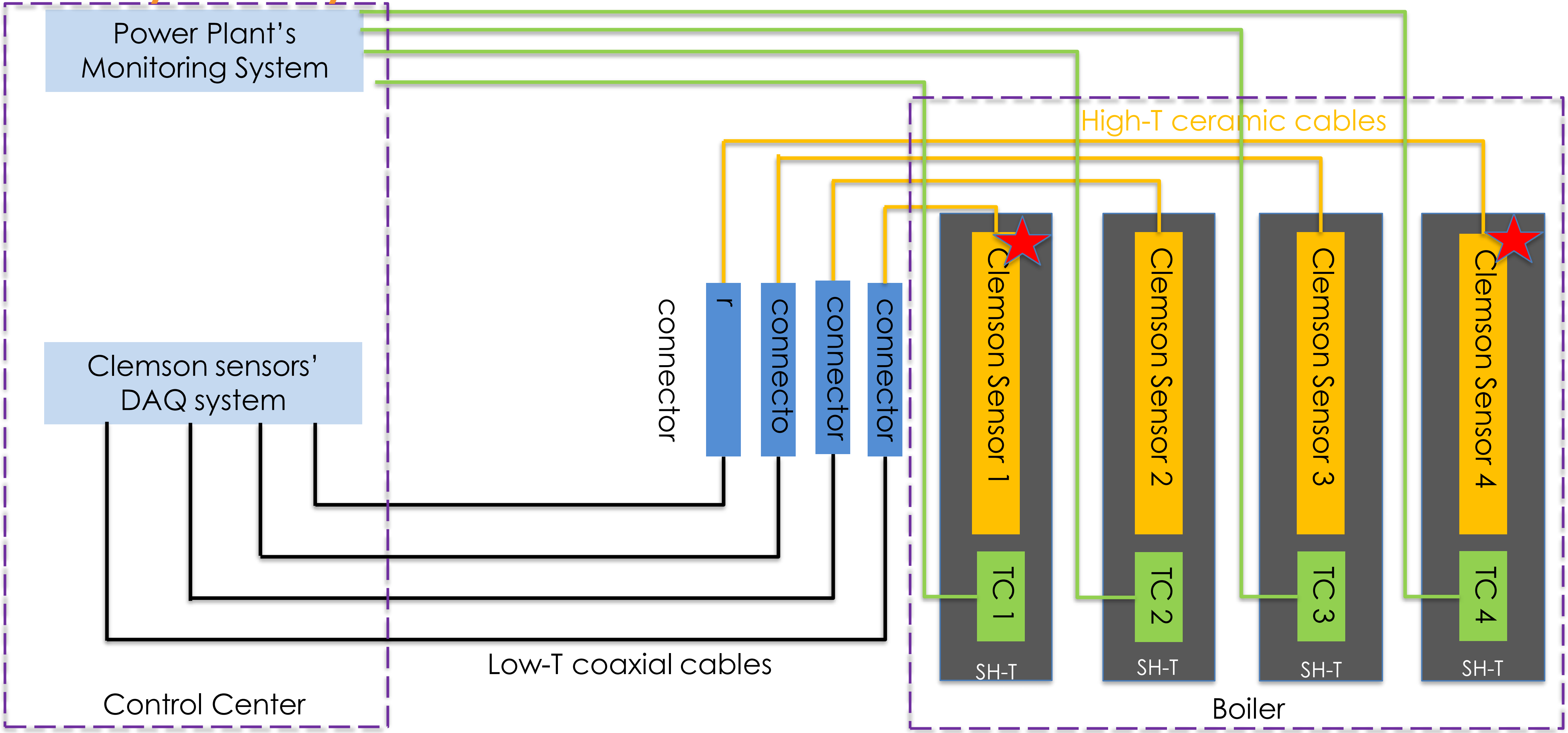
Multiple switch

Directional coupler

USB hub

Project Update – on-site Installation

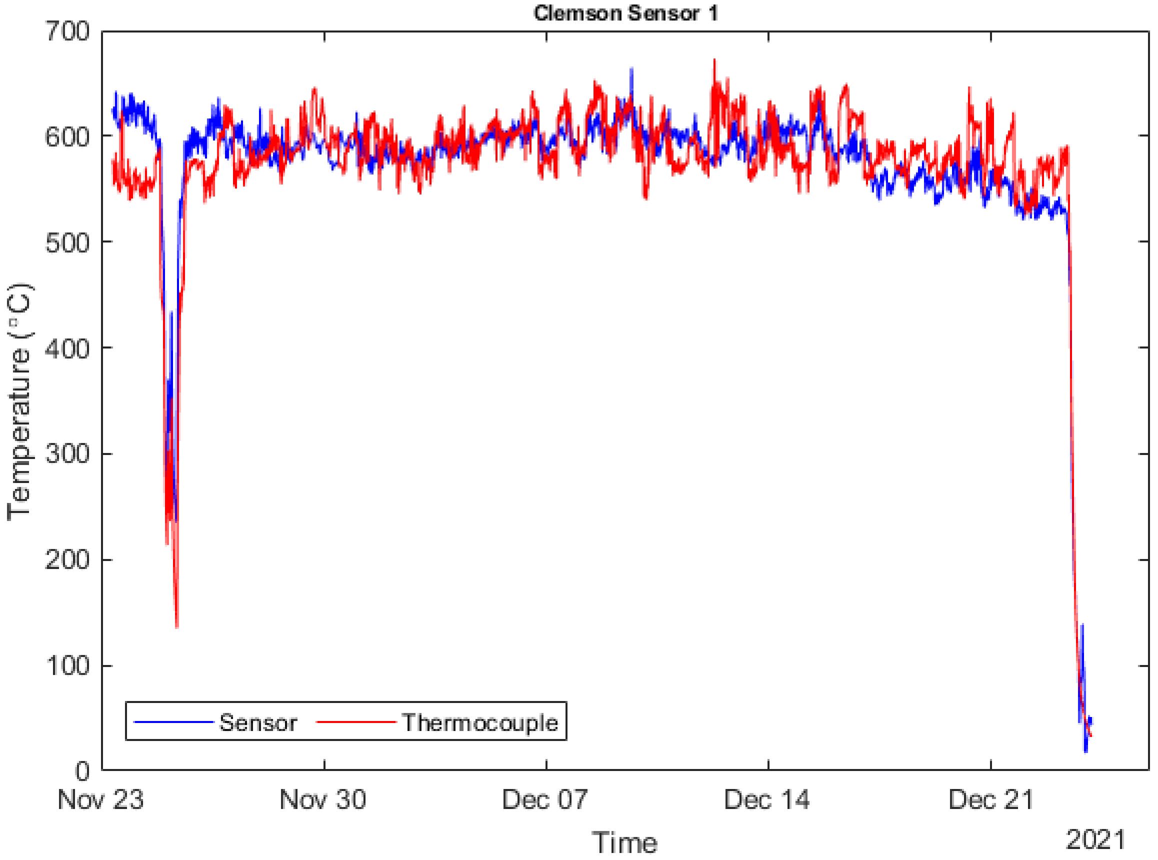
Sensor System Layout for Field Test

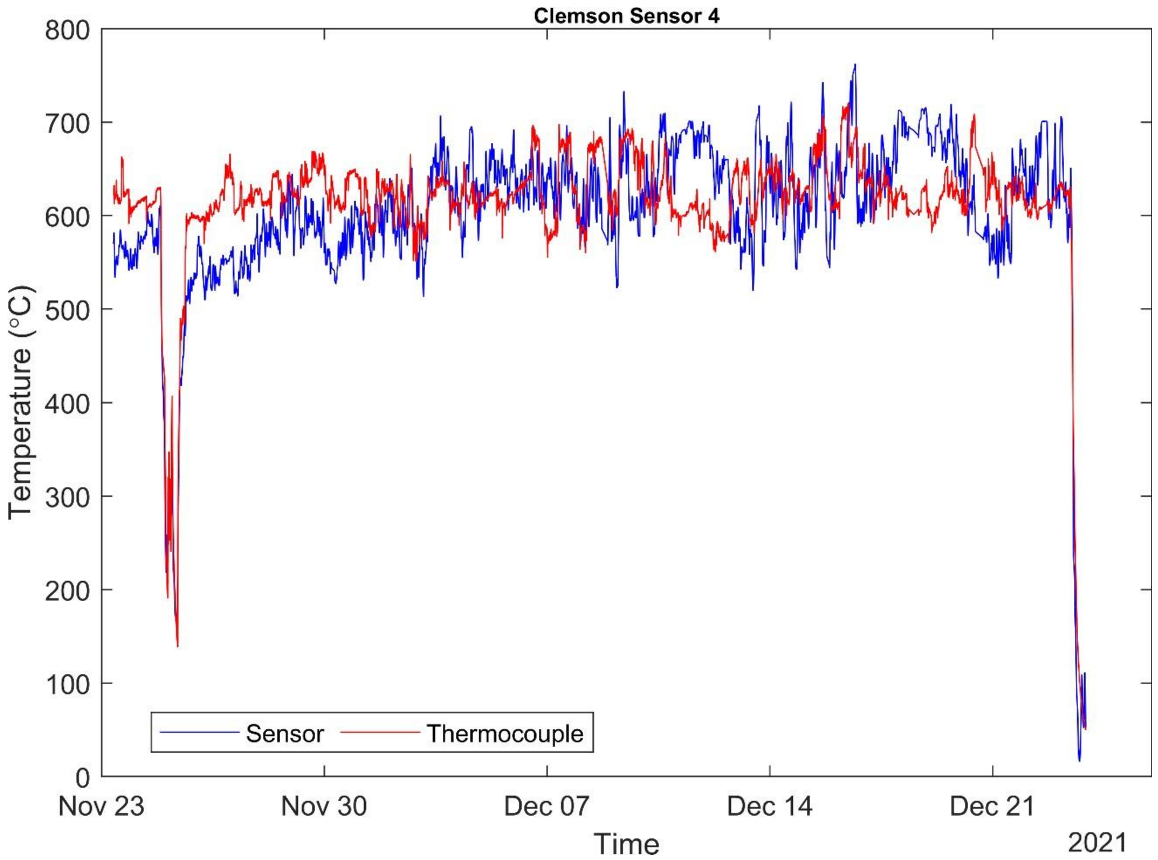


DAQ: Data Acquisition TC: Thermocouple SH-T: Superheat-Tube

Project Update – Test

- Four sensors have been installed to measure the temperature of four Superheat-Tubes.
- Two sensors, which have better performance, are shown below. In general, the coaxial cable sensors recorded the glitch event and matches those produced by thermocouples.





Project Update – Modeling

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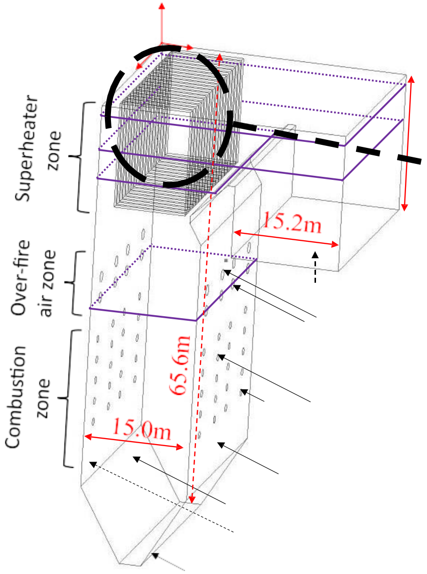
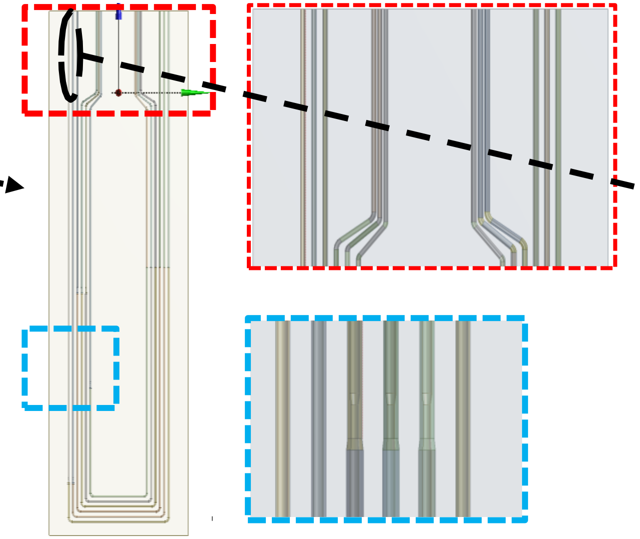
Multi-physics Modeling on Reference Boilers

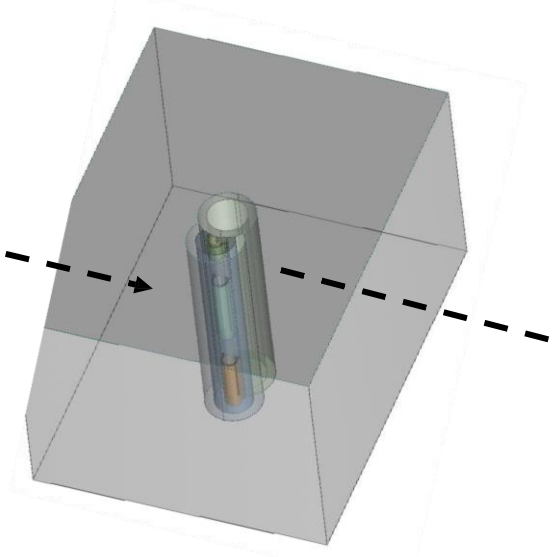
(A)Coal Fired Boiler Model
CFD + HT Analysis



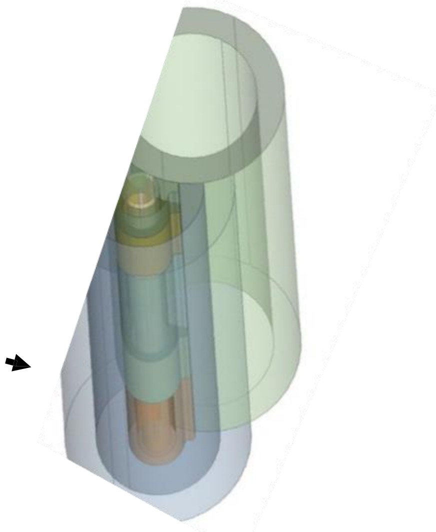
(B) Boiler Tube Model
CFD + HT Analysis



(C) Sensor Model
CFD + HT Analysis



(D) Sensor Model
Structural Analysis



Input → (A) → (B) → (C) → (D) → Output

Input
- Coal/air inlet condition
- Steam condition

(A)
- Mass flow rate
- Temperature of flue gas in the boiler tube panel region

(B)
- Mass flow rate
- Temperature of flue gas and steam in the sensor region

(C)
- Body temperature of sensor
- Pressure on the surface

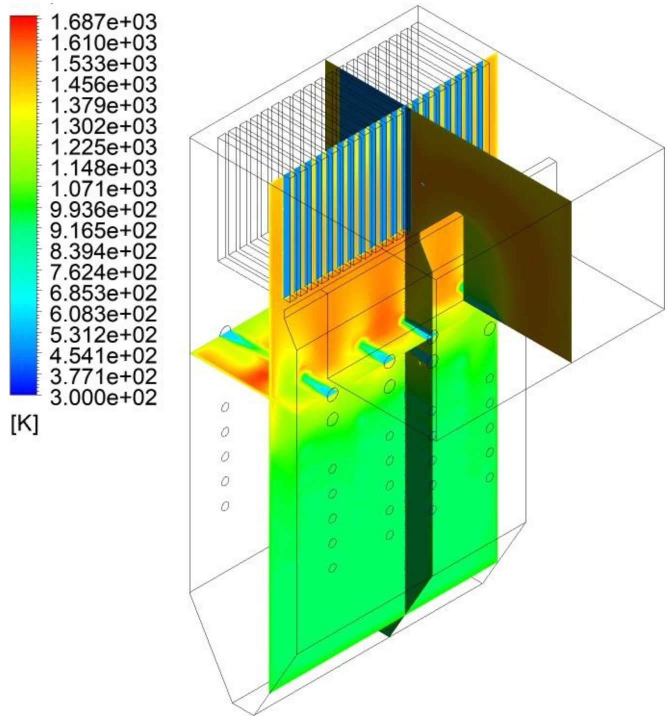
Output
- Sensor temperature
- Sensor deformation
- Stress distribution

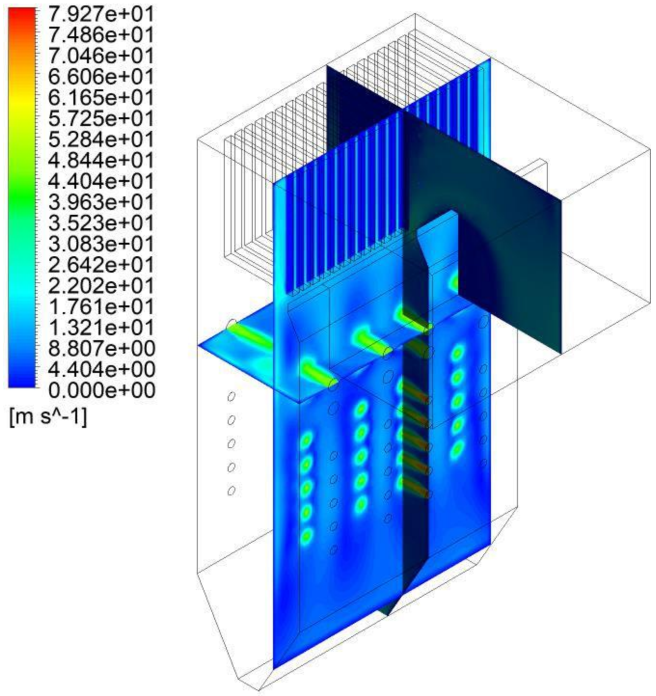
Data Exchange

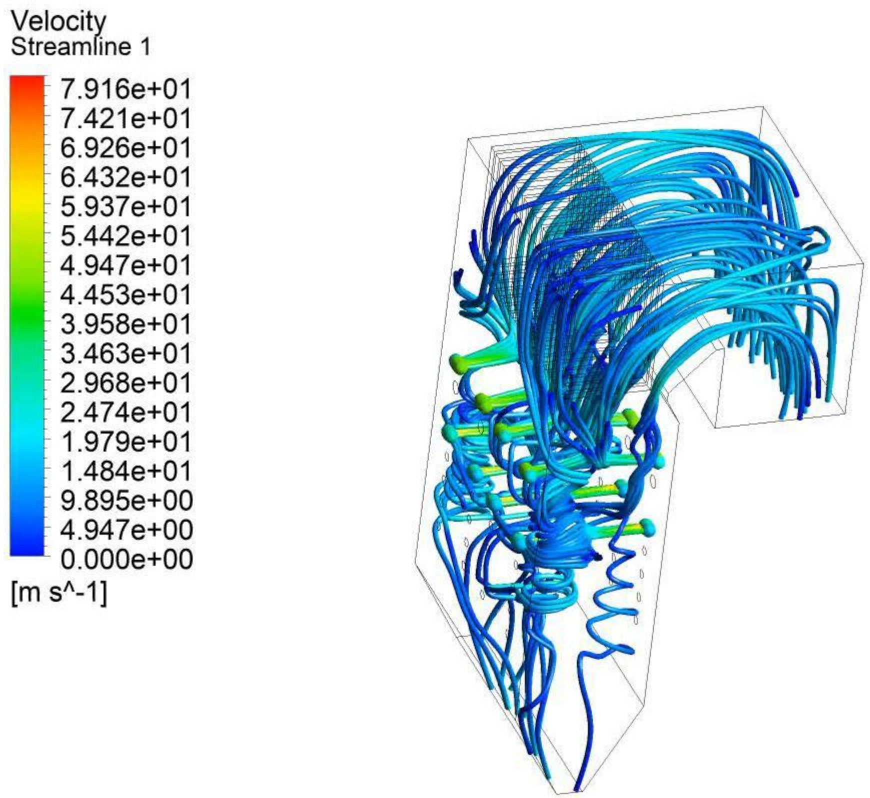
Project Update – Modeling

(A) 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 Streamline starting from the coal inlets for air flow behavior

Project Update – Modeling

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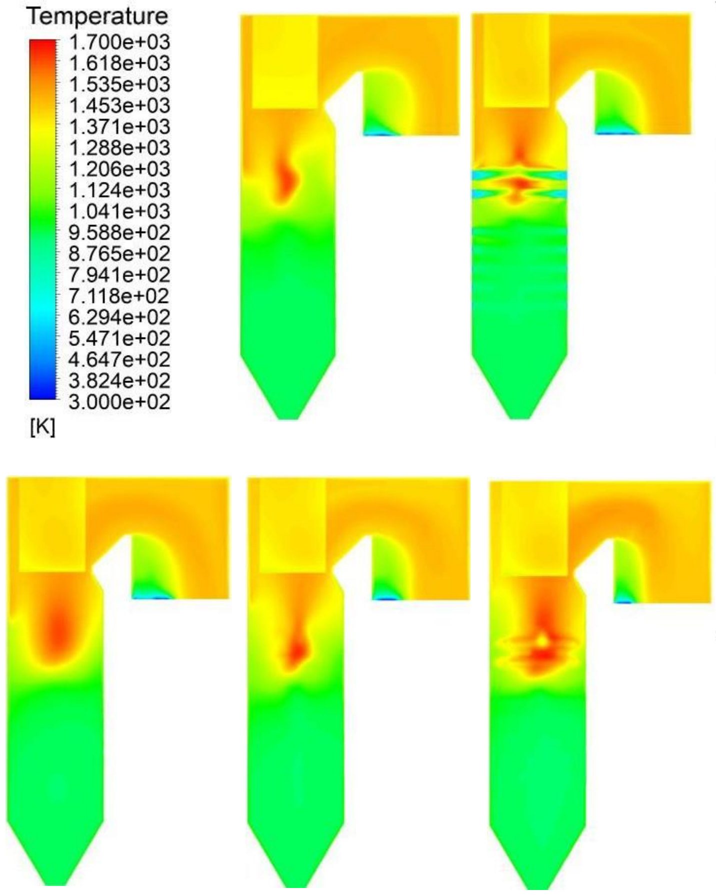
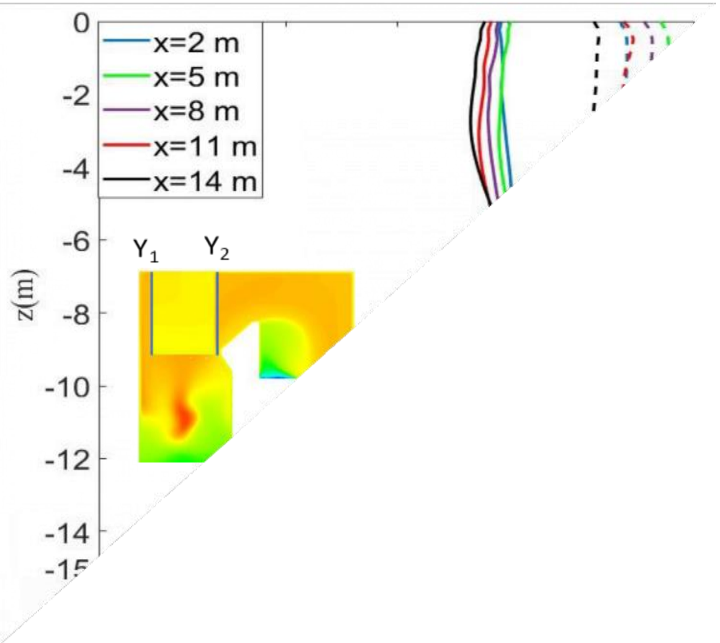
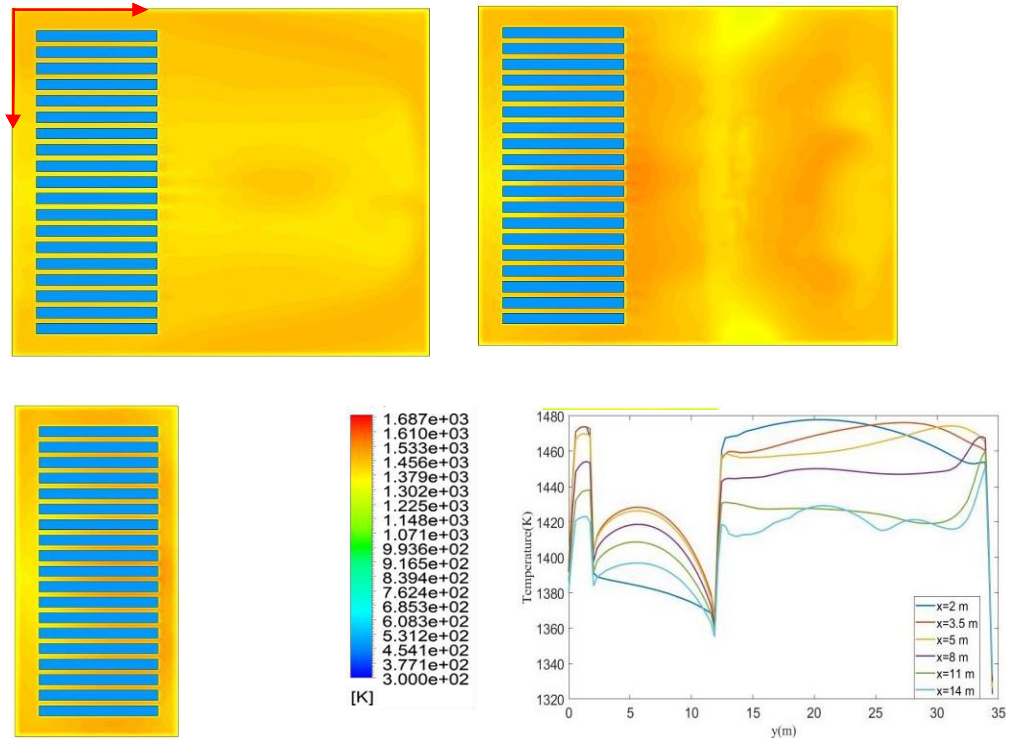
(A) Criteria to Determine the Temperature Sensor Insta llation Location







- Select the boiler tube panel away from the side walls.
- Select the boiler tube section closer to the top wall of the boiler.
- Select the boiler tube on the back of the boiler panel (not directly facing the flue gas flow).

Project Update – Modeling

(B) Boiler Tube Panel Modeling

- Predict the temperature/stress distribution along the steam pipe for sensor installation plan and failure mechanism study

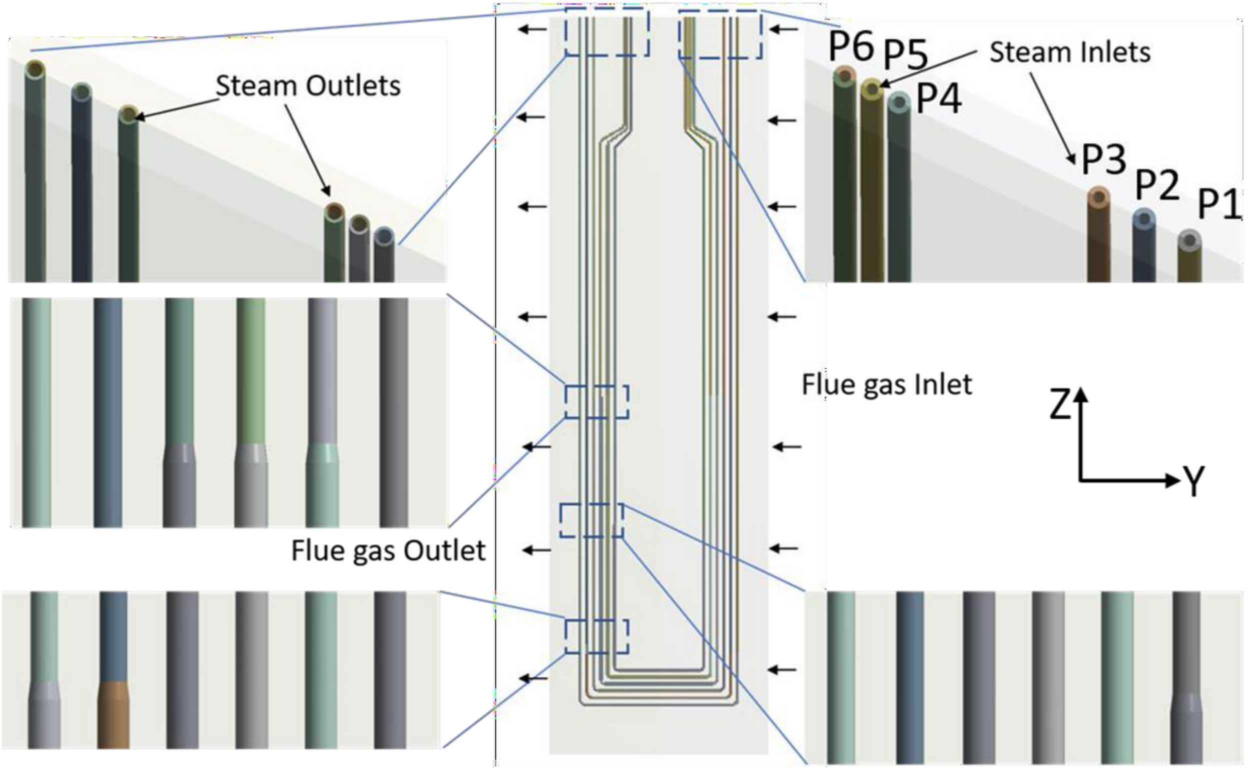
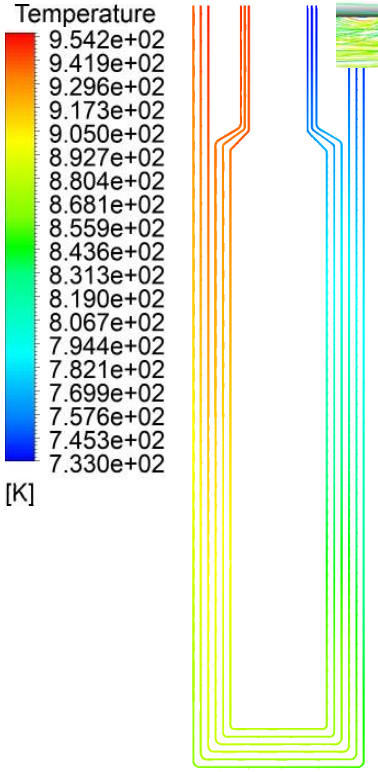
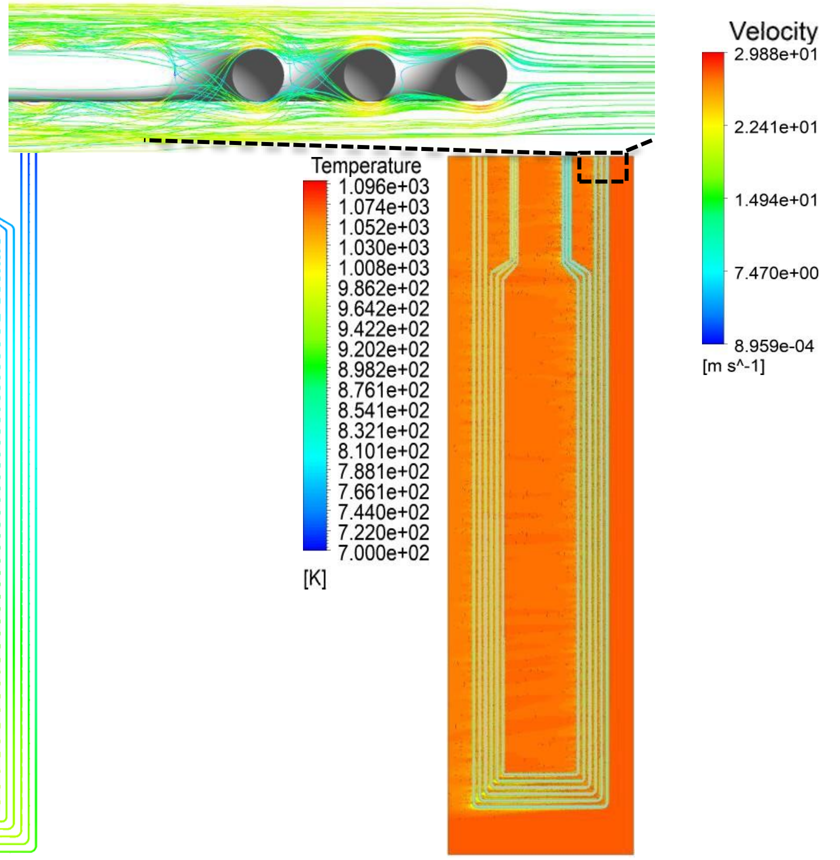


Figure 1: Steam panel with steam tubes

- More than 60 million of elements



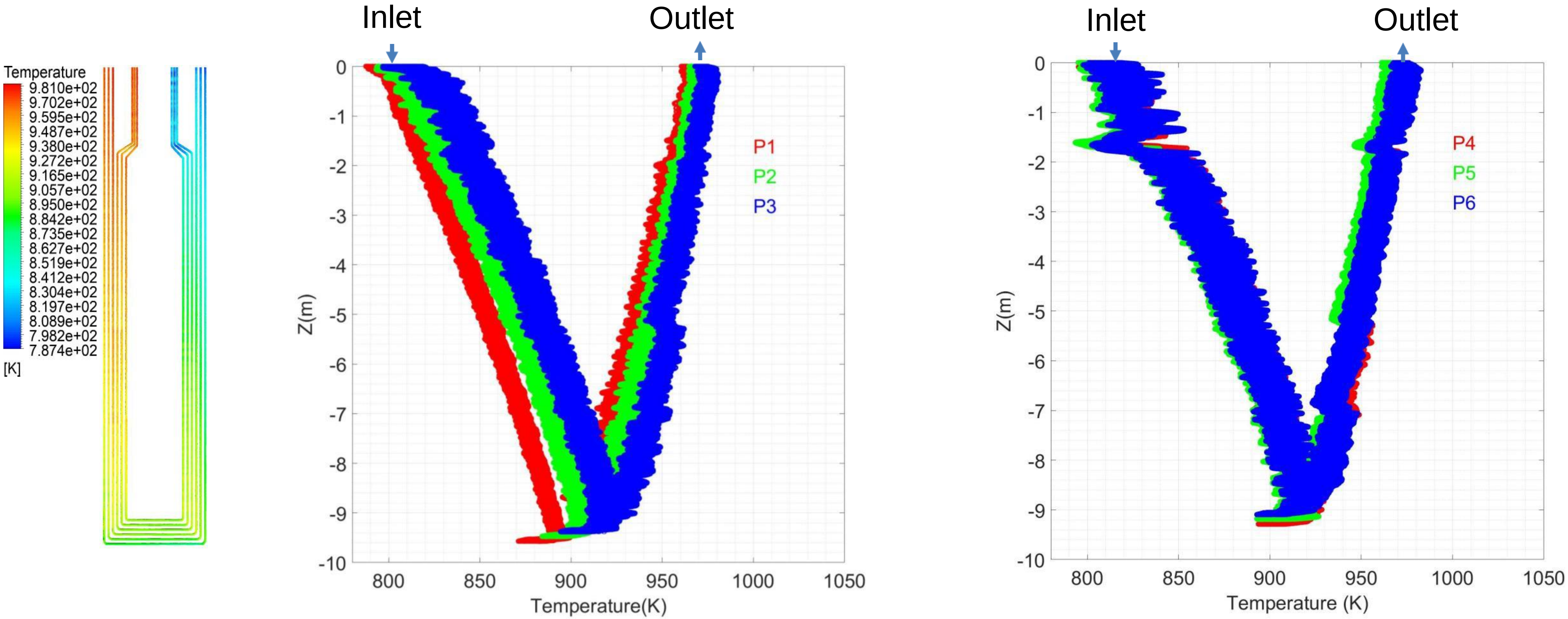
- Steam Temperature



- Flue gas Temperature & Velocity

Project Update – Modeling

(B) Boiler Tube Panel Modelling

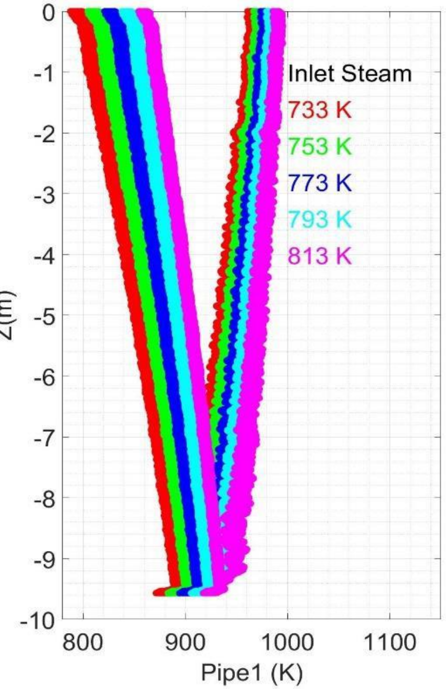


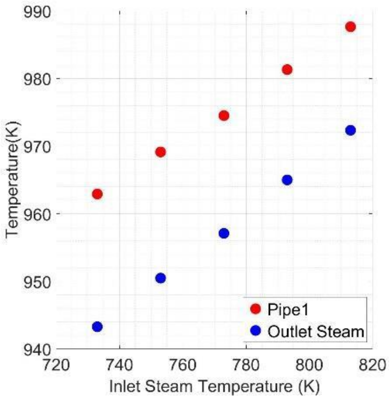
- Boiler tube temperature is relatively stable near the outlet of the steam.
- Coaxial cable sensor is installed near the steam outlet of pipe 1 of 4 different steam panels.

Project Update – Modeling

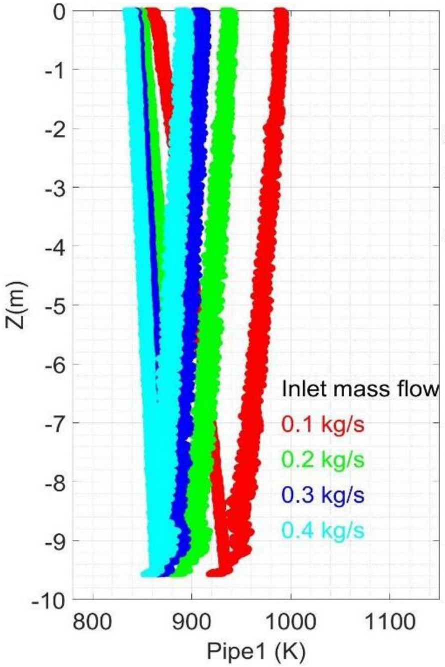
(B) Boiler Tube Panel Systematic Study

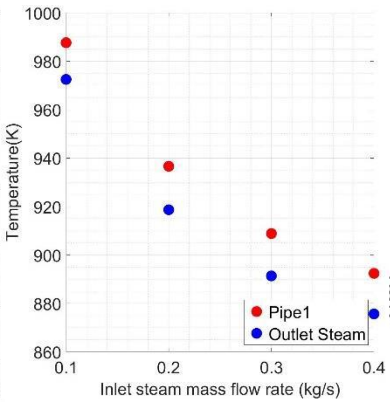
- ❑ Understand the correlation between input parameters and boiler tube temperature near the outlet of pipe 1 (1m below the outlet, where the coaxial cable sensor is installed).



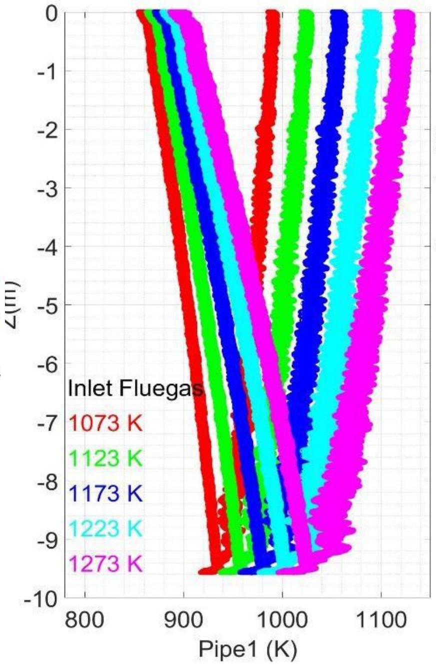


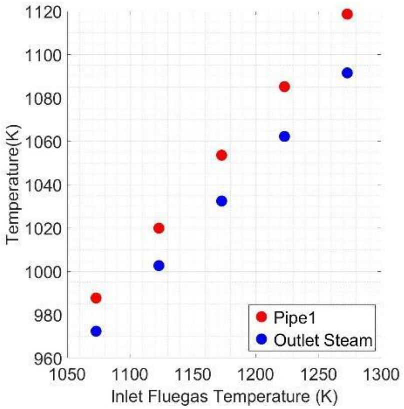
Inlet steam temperature





Inlet steam mass flow rate





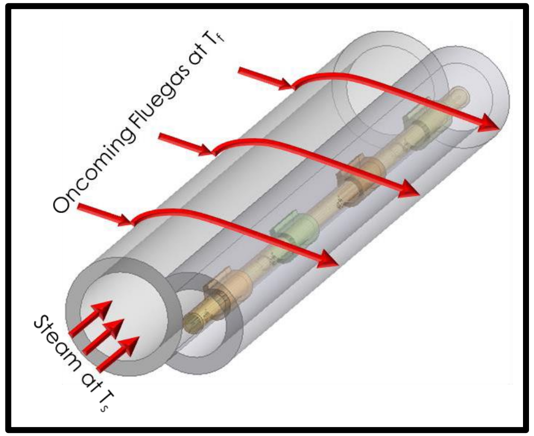
Flue gas temperature

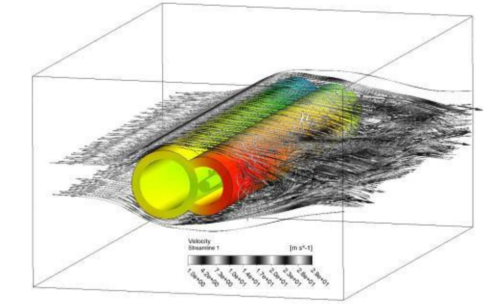
- Boiler tube temperature can be well controlled by the inlet steam mass flow rate.

Project Update – Modeling

(C, D) Multi-physics Modeling on Sensor Design and Optimization

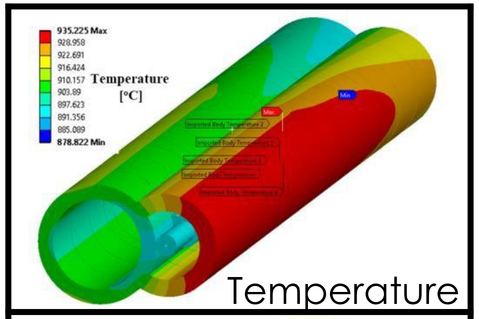
(C) Computational Fluid Dynamics & Heat Transfer



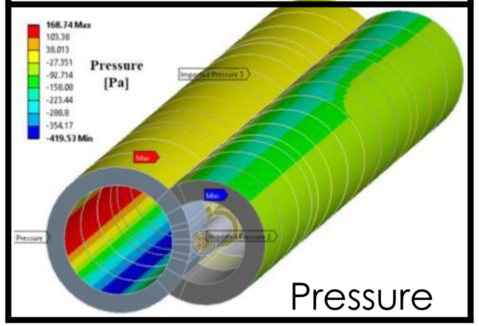


Data Exchange

Output: Temperature and pressure profiles on boiler tube, protection tube and coaxial cable sensor.

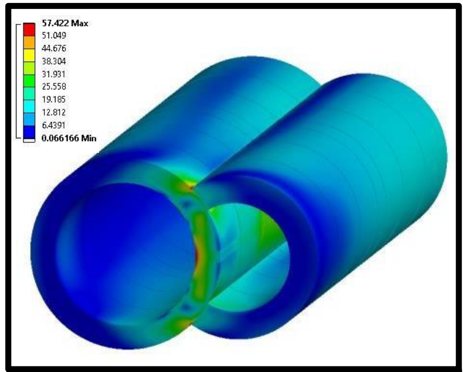


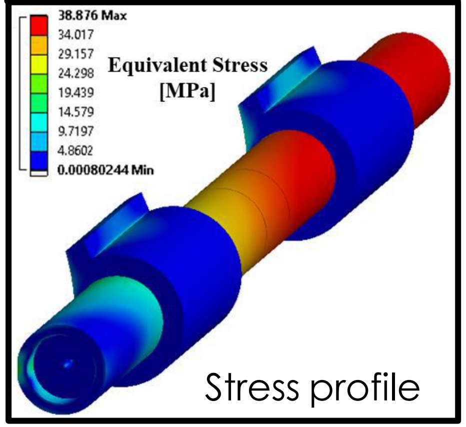
Temperature



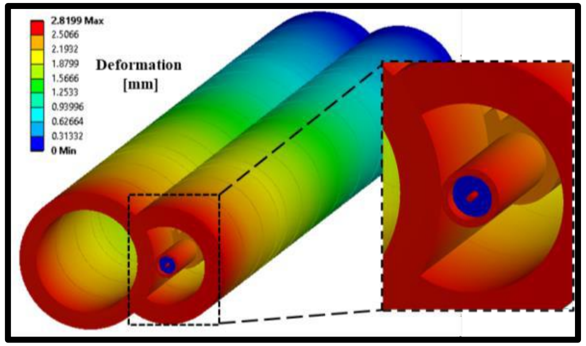
Pressure

(D) Structural Analysis

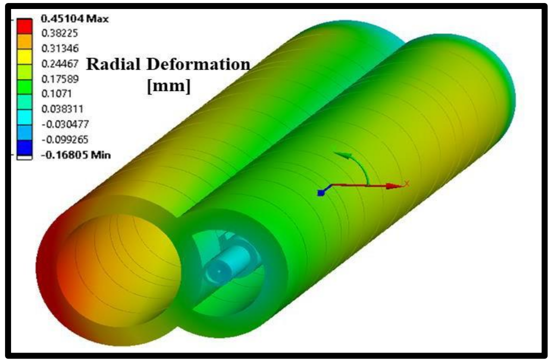




Stress profile



Axial deformation



Radial deformation

Output: stress and deformation profiles

- The maximum temperature/stress on coaxial cable senor and steam pipe are within the material limit.

Project Update – Modeling

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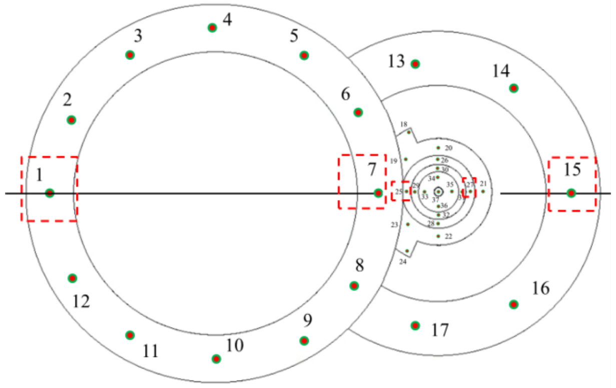
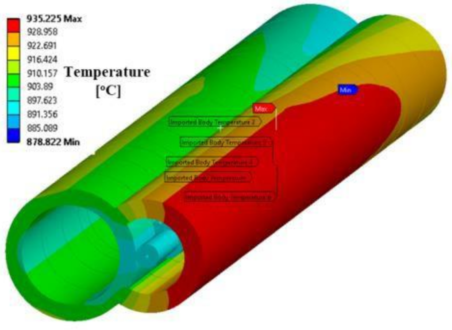
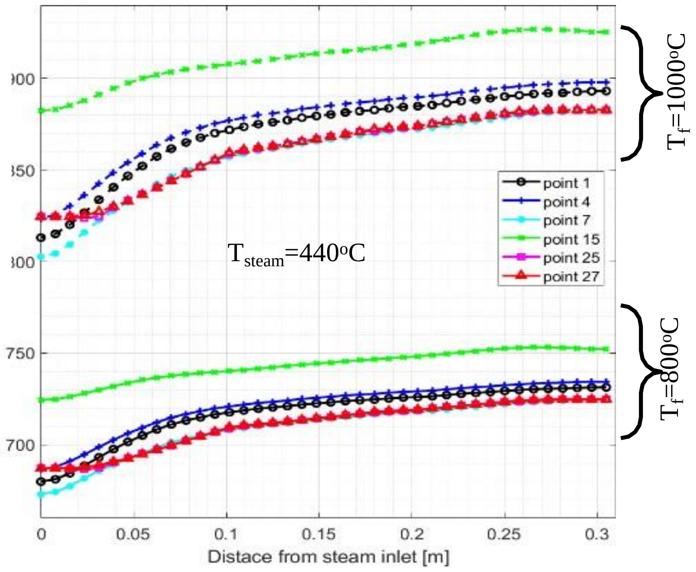
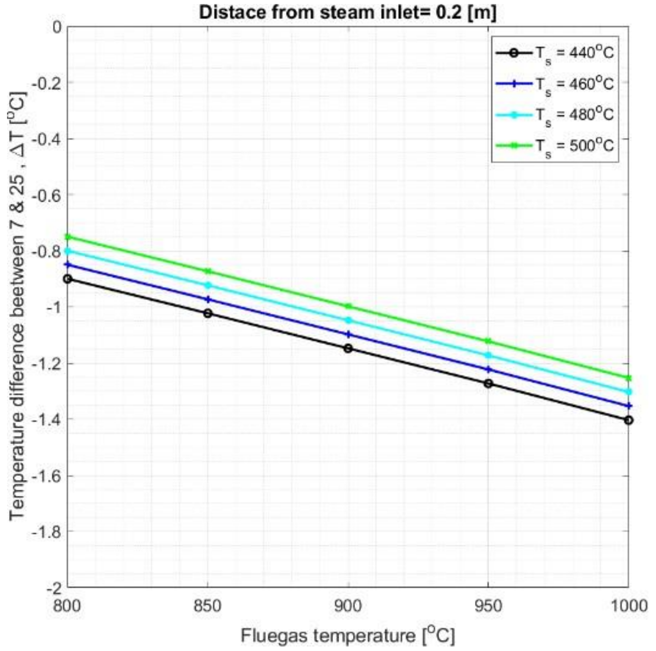
(C, D) Multi-physics Modeling on Sensor Design and Optimization

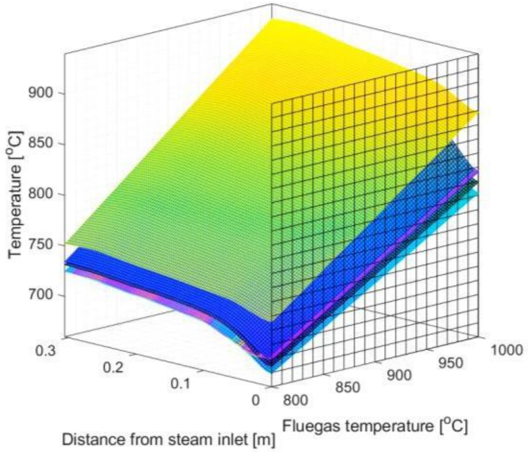
- Temperature correlation between coaxial cable sensor and boiler tube

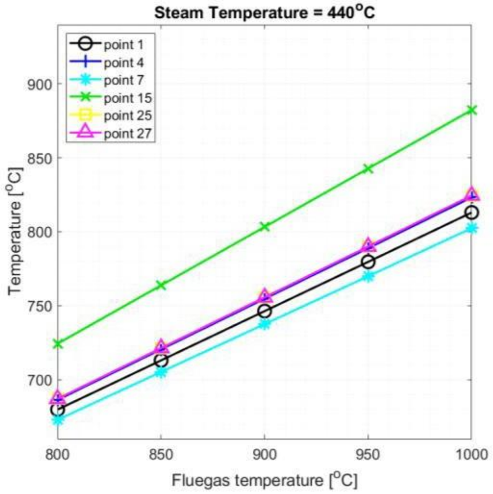












- Coaxial cable sensor (CCS) can capture the temperature variation of the boiler tube.
- The temperature difference between CCS and boiler tube is within 1.5 degree, regardless of the steam temperature and flue gas temperature variation.

Plan for Next Year

Data Analytics, Condition Based Monitoring, and more

- ❑ Collect sensing data from the field-testing site.
- ❑ Develop the data analytics system and benchmark the temperature sensing accuracy with the thermal couple data.
- ❑ Conduct the multi-physics simulations on boiler and coaxial cable sensor (CCS) for better sensibility and predict the sensor performance under various static/dynamic conditions.
- ❑ Establish the prototype of the Condition Based Monitoring (CBM) system.
- ❑ Explore other applications of the designed coaxial cable sensor.

Thank you!

Acknowledgment and Disclaimer

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number DE-FE0031765.