FOA 2193 Joint Project Kickoff Meeting

High-Accuracy and High-Stability Fiber-Optic Temperature Sensors for Coal Fired Advanced Energy Systems

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Research Goal

Develop a temperature sensor system that can operate at a temperature level above **1000 °C** with **accuracy** and **long-term stability** comparable to the sensors of low-temperature versions.

- Using “gas” as the sensing element
- A sensing mechanism unaffected by the structural changes of the sensor head
Temperature control in advanced coal-fired energy systems

- Operation at extreme temperature levels (> 700 °C) for improved efficiency and reduced emission of green-house gases
- Temperature control critical for sustained operation at optimal conditions, e.g. for USC
  - Annual average increase of 2 °C from ideal → 1-month reduction in USC lifetime
  - Annual average decrease of 2 °C from ideal → 1% increase in fuel consumption
- Need for temperature sensors w/ high accuracy and high stability in harsh environment.
Challenges of existing contact temperature sensors

Sensing elements are some “solid” materials

- Limited temperature capability
- Degraded performance at high temperature: drift, reduced accuracy
  - Structural changes (e.g. crystallization)
  - Chemical changes (e.g. oxidation)
- Cross-sensitivity to other parameters (e.g. strain, bending)
- Self-heating; electromagnetic interference

Thermocouples
https://www.ni.com/

Resistance Temperature Detectors
https://www.designworldonline.com/

Optical Sensor
https://www.epsilonoptics.com/
- Optical property (refractive index) of “Gas” is a function of temperature
- Inherently stable at high temperature (gas does not degrade at high temperatures)
  - No interactions among gas molecules
  - No chemical reactions
- Optical properties do NOT drift → good stability; high accuracy
- Signal cannot be affected by structural changes of the enclosure of the gas.
Fiber-optic temperature sensor – “gas” as the sensing element

- Refractive index of gas, $n$, is function of absolute temperature ($T$) & pressure ($P$):
  - $\lambda$ change linearly with $P$
  - $P$ can be varied and controlled to obtain slope $k$
  - $T$ can be deduced using $T = \alpha \lambda / k$.
- $\alpha$: Inherent stable; $k$: insensitive to FP cavity length variation (0.1% change in $k$ for 1000 $\mu\varepsilon$).

\[
n - 1 = \alpha P / T \quad (\ll 1)
\]
\[
\lambda = \frac{2L}{m} \left( \frac{\alpha}{T} P + 1 \right)
\]
\[
k \equiv \frac{\partial \lambda}{\partial P} = \frac{2\alpha L}{mT}.
\]
\[
T = \alpha \lambda / k.
\]
Preliminary result – Experimental setup

SMF (Lead in Fiber)

Fiber Tube (F-P Cavity)

Light

Chamber

Air

Vacuum/Pressure Pump

SMF (Reflection Fiber)

~60 µm
Preliminary result – Experimental setup
Pressure increases from 0 to 1500 psi in a step size of 300 psi
Preliminary result – Spectral shift vs. Pressure

\[ T = \frac{\gamma \lambda}{k}. \]

\[ \gamma = 5.38 \text{ mK/psi} \]
**Preliminary result – Strain-insensitive measurement**

- Measurement at room temperature;
- Strains of different levels (0 – 3600 με) applied by adjusting weights
- T measurement variation < 1 °C (FBG Sensor: 3600 με ~ 360 °C)
Pressurization through a ceramic tube rather than through the small holes in the fiber → faster speed
Venting hole on sensor head to avoid pressure-induced structural changes
All-silica photonic crystal fiber to increase the temperature range to > 1200 °C (temperature of regular fiber is limited by dopant diffusion)
Research work – Pressurization system

- Dry air for consistent air compositions
- Miniaturized air pump and pressure controller
- High-accuracy pressure sensor (0.01%)
Research work – Sensor Interrogation

Interrogation using white light system

Interrogation using wavelength scanning laser
Research work – Sensor Characterization and Test

- Using metal fixed point cells to generate temperature references (accuracy: ~ 0.001 °C)
  - Tin – 231.928 °C
  - Aluminum - 660.323 °C
  - Silver – 961.78 °C
  - Copper - 1084.62 °C

- Resolution
- Accuracy
- Long-term drift
- Compare with thermocouples (R, S, or B type)
- Test results will provide feedback for sensor system optimization.
Summary

- High-accuracy, high-stability temperature sensor is critical for the safe and efficient operation of advanced coal-fired energy systems
- Using “gas” as the sensing element eliminates many drawbacks inherent to sensors using solid materials as the sensing elements
- Preliminary study has shown promising results
- To make this technology a viable solution in coal-fired energy system
  - Portable pressure system with automatic and precise control
  - Accurate sensor interrogation methods
  - Characterization and testing at high temperature levels
  - Other issues: sensor packaging; effects of air composition variations; effect of maximum pressure on measurement accuracy and resolution