U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory

Successes

Single-Crystal Sapphire Optical Fiber Sensor Instrumentation for Coal Gasifiers

Advanced Research

To support coal and power systems development, NETL's Advanced Research Program conducts a range of pre-competitive research focused on breakthroughs in materials and processes, coal utilization science, sensors and controls, computational energy science, and bioprocessing—opening new avenues to gains in power plant efficiency, reliability, and environmental quality. NETL also sponsors cooperative educational initiatives in University Coal Research, Historically Black Colleges and Universities, and Other Minority Institutions.

Accomplishments

- ✓ Process improvement
- ✓ Cost reduction
- ✓ Greater efficiency
- ✓ Innovative materials

Description

Sponsored by the U.S. Department of Energy's Office of Fossil Energy (DOE-FE), through the National Energy Technology Laboratory (NETL), the Center for Photonics Technology at the Virginia Polytechnic Institute and State University (Virginia Tech) has developed a new, robust, accurate temperature measurement system that can withstand the harsh conditions found in commercial gasifiers for an extended period, thus allowing improved reliability and advanced process control. In this system, a sapphire-based fiber sensor head provides temperature data from inside the gasifier at temperatures up to 1,600 °C using an extrinsic Fabry-Perot interferometric (EFPI) sensor.

Accurate measurement of temperature inside a coal gasifier is essential for safe, efficient, cost-effective operation. Current sensors are prone to premature failure due to the extremely harsh operating conditions including high temperature (1,200–1,600 °C), high pressure (up to 500 pounds per square inch gauge), chemical corrosiveness, and high flow rates, all of which lead to corrosion, erosion, embrittlement, and cracking of gasifier components. These extreme physical conditions often cause difficulties or entirely prevent conventional temperature sensors from being used. Because temperature measurement is a critical gasifier control parameter, premature failure of measuring tools impacts the efficiency and reliability of the entire system.

Single-crystal sapphire (see Figure 1) was chosen for the new sensor head for its high temperature stability and corrosion resistance. Unlike other ceramic materials, such as polycrystalline alumina, single-crystal sapphire has shown superior corrosion resistance as a result of eliminating polycrystalline grain boundaries, which have proven vulnerable to attack. Therefore, optical grade single-crystal sapphire fiber waveguides are especially attractive for fabricating sensors for the harsh high-temperature, corrosive environments found in gasifiers.

The current research builds directly on a number of key technologies developed at Virginia Tech, including silica-to-sapphire fiber connectors, sapphire-to-sapphire material bonding, various sapphire fiber sensing schemes, and cost-effective optoelectronic signal processing. In addition, previous research at Virginia Tech regarding the corrosion kinetics of refractory materials for gasifier linings has been extended to determine the corrosion resistance of single-crystal sapphire fibers.

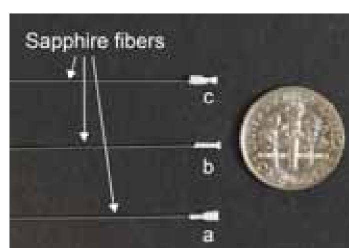

Figure 1. Single-crystal sapphire sensor heads with sapphire fiber waveguides achieve greater precision through miniaturization

Project Duration

Start Date

09/14/99

End Date

07/19/08

Cost

Total Project Value

$1,744,004

DOE/Non-DOE Share

$1,389,733 / $354,271

Partner

Virginia Polytechnic Institute and State University

Technical Approach and Accomplishments

The prototype temperature sensor developed in this research is intended for non-intrusive, direct high-temperature measurement, in the primary and secondary stages of slagging gasifiers. Development has taken place in two phases.

During Phase 1 of the project, researchers evaluated various sensor designs and selected a Broadband Polarimetric Differential Interferometry (BPDI)-based design for its self-calibrating capability, simplicity, and accuracy. In this approach, a light beam propagates in free space to interrogate the temperature dependence of the optical birefringence of a single-crystal sapphire disk. Laboratory demonstration of the sensor showed that it was capable of accurately measuring temperature from room temperature up to 1,600 °C with a close resolution of approximately 0.26 °C. Laboratory testing also showed that the single-crystal sapphire material was highly resistant to penetration or corrosion from coal slag that is formed in coal gasifiers.

During Phase 2, an alternative high-temperature sensing system based on Fabry-Perot interferometry was developed that offers a number of advantages over the BPDI solution. A sapphire fiber is used to guide the light, so the sensor size can be significantly reduced. By using a sapphire wafer to achieve high cavity surface quality and excellent parallelism, the sensor overcomes the difficulty of traditional EFPI sensors in generating interference fringes for highly multimoded optical fibers.

This approach is based on the measurement of the optical path difference (OPD) between two light beams reflected from the sapphire wafer surfaces, as shown in Figure 2. Reflections at both sides of the diaphragm will interfere with each other, producing a modulated spectrum, whose pattern is determined by the optical thickness (OT) of the wafer. The OT is the product of the refractive index and the thickness of the wafer, both of which have thermal dependence, resulting in a temperature-sensitive OT and spectrum. Therefore, the temperature can be demodulated from the change in the reflected spectrum.

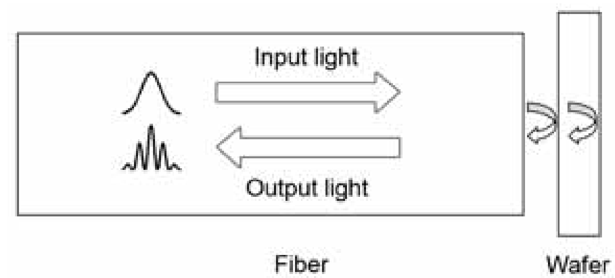

Figure 2. Principle of operation of an interference device using polarized light waves

As shown in Figure 3, light from the LED travels through the 3-dB coupler to the sensor head and is reflected. When temperature varies, the interference signal from the wafer will also change. By monitoring this spectrum shift, the temperature information can be demodulated. The data generated in repeated laboratory tests showed excellent consistency, and conformed closely to data for a B-type thermocouple, a standard metallic type of high-temperature sensor used as a control device for comparison.

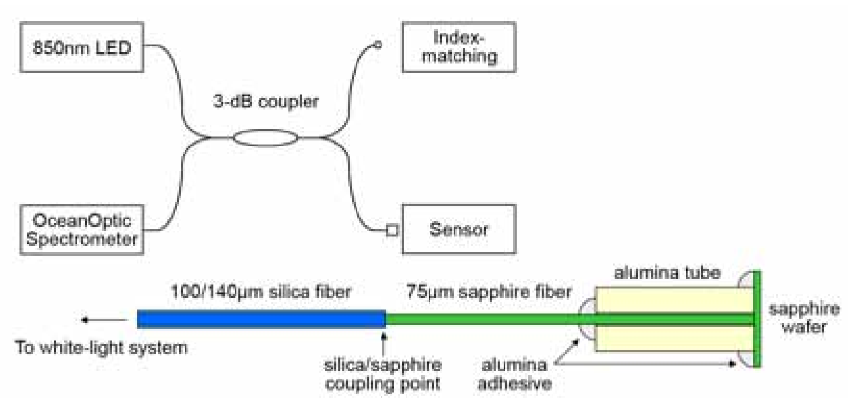

Figure 3. Schematic design of the single-crystal sapphire-based optical high-temperature sensor

During Phase 2, Virginia Tech teamed with Tampa Electric Company's Polk Power Station to finalize the design of the sensor prototype and test it at full scale in a TECO coal gasifier. Research focused on designing the sensor's mechanical packaging to ensure reliability and deployability under conditions of high temperature, high pressure, and chemical corrosion. The mechanical structure was simplified, and the stability of the system increased thanks to the new sensing probe design.

The sensor is mounted to the gasifier shell through a mounting flange. Functionally, the sensor package is divided into three sections: the probe, a first pressure isolation chamber for gasifier operating pressure, and a second pressure isolation chamber for room pressure. The double pressure isolation design minimizes the chance for accidental pressure loss due to flange failure during operation.

The prototype sensor was subjected to a full-scale field performance demonstration in 2006 and 2007. The sensor's performance under actual operating conditions was evaluated and optimized at temperatures up to 1,400 °C. Initial testing was very successful. As indicated in Figure 4, the sensor lasted seven months in the gasifier, surpassing an initial goal of around 45 days. In comparison, the thermocouples installed in proximity to the sensor had to be replaced at least twice during the 7-month period.

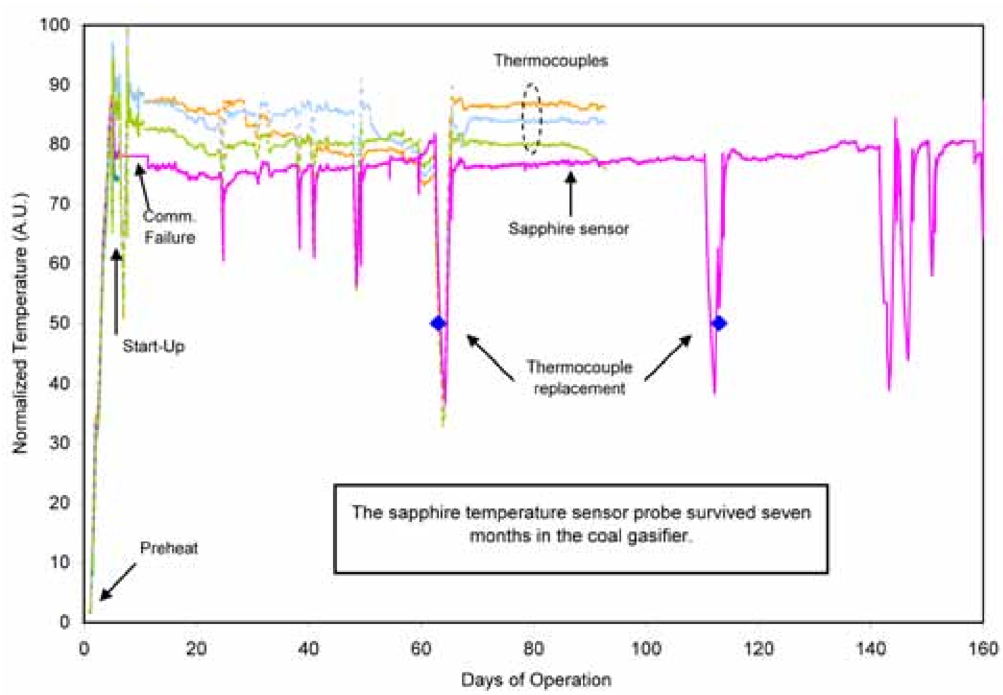

Figure 4. Comparison of sapphire fiber sensor temperature data to conventional thermocouple data. Both sets of thermocouples have now been replaced, as indicated by the blue diamonds on the graph. Differences in port sizes and sensor positions resulted in lower temperature readings from the fiber sensors

One more full-scale test remains. At the conclusion of field testing, Virginia Tech will evaluate the potential for commercializing the sensor technology. To date, this is one of the only successful and longer-term demonstrations of a novel temperature measurement technology for the gasifier section of the plant. According to TECO, its benefits (if proven to be accurate and reliable) are likely to be significant in improving gasifier performance.

Benefits

Development of a single-crystal sapphire temperature sensor that can accurately measure gasification conditions in such harsh conditions will increase the reliability and efficiency of gasifier systems. Gasifiers are central to many advanced high-temperature power systems, including Integrated Gasification Combined-Cycle. Tomorrow's advanced power generation systems such as FutureGen will benefit from this development. Other high-temperature applications may benefit as well.

"...Optical grade single-crystal sapphire optical fiber waveguides are especially attractive for fabricating sensors for the harsh high-temperature, corrosive environments found in gasifiers."

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