VII.H.2 Fiber Optic Temperature Sensors for PEM Fuel Cells

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Projected End Date: Project continuation and direction determined annually by DOE

Objectives

- Demonstrate low-cost, durable, accurate fiber optic temperature sensors in operating fuel cells.
- Explore the development of other sensor modalities, including humidity and pH measurement.
- Develop a sensor platform so that parametric (e.g., temperature, humidity, reactant species) distributions can be obtained within the gas diffusion layer.
- Provide precise characterization data for operating fuel cells to technology developers for model verification and design optimization studies.

Technical Barriers

Temperature and thermal management issues are mentioned in 10 areas of the Hydrogen, Fuel Cells, and Infrastructure Technologies Multi-Year Research, Development and Demonstration Plan. However, the following are the most critical areas in which an advanced temperature and other measurement technologies (e.g. intra-fuel cell humidity, pH, ionic and reaction species concentrations) will have an impact.

- A. Durability
- B. Cost
- C. Electrode Performance
- D. Thermal, Air, and Water Management
- H. Sensors
- J. Startup Time/Transient Operation

Technical Targets

The role of this project is to develop measurement tools and diagnostic methodologies and carry out experiments utilizing these tools and methods, in collaboration with fuel cell developers and users, for the express purpose of maximizing fuel cell performance. Using in situ techniques is leading to detailed characterization of design and operational limitations of operating fuel cells. Already demonstrated on an operating fuel cell is the ability to characterize performance limitations caused by various diffusion processes inherent to fuel cell designs, operational conditions that lead to water flooding events that dramatically reduce fuel cell power output, and flow field design limitations. Quantifying how these results impact the specific energy density of advanced fuel cell designs is proprietary to individual fuel cell developers and thus difficult for this project team to assess. However, design and operational limitations characterized by experiments undertaken with in situ measurement tools have shown that upset conditions can result in >10% degradation of fuel cell performance.

Having in situ measurement and diagnostic tools available for a rigorous fuel cell testing regimen will allow designers to directly access cause-and-effect relationships and fundamental chemistry and physics limitations of fuel cell designs, and use this information to drive advanced flow field designs. The tools being developed in this effort will have an impact on all technical targets, cataloged in Table 3.4.3 in the *Technical Plan*, by providing intimate knowledge of design and operational limitations of fuel cells systems and how they relate to internal process dynamics in operating fuel cells.

Approach

- Design and implement miniature optical fiber temperature sensors in operating fuel cells.
- Deploy both free space (cross-channel) and monolithic fiber probe temperature sensors in the flow channels of operating fuel cells.
- Deploy miniature capillary sampling, mass spectrometry diagnostics, inside the flow channel, within operating fuel cells.
- Use temperature and species distribution measurements, demonstrated in operating fuel cells, to characterize temporal and spatial variations along the flow field.
- Conduct temperature, temperature distribution, water concentration distribution (humidity), and hydrogen and oxygen distribution measurements on operating fuel cells under various operational conditions.
- Characterize internal cell dynamics under various load conditions to provide insight to fuel cell designers.
- Develop advanced sensor concepts for miniature direct humidity measurement, pH measurement, and highly spatially resolved temperature mapping.
- Use a diagnostic platform, including physical and chemical measurements, on operating fuel cells and continually enhance it to help fuel cell developers acquire knowledge that leads to optimized fuel cell designs.

Accomplishments

- Demonstrated low-cost (<$100), fast-responding (<25 millisecond), accurate (<0.25°C), and durable fiber optic temperature measurement system in an operating fuel cell.
- Demonstrated both monolithic fiber optic probes and free space temperature measurements in operating fuel cells.
- Demonstrated a (5+)-channel fiber optic temperature measurement system in an operating fuel cell.
- Demonstrated low-spatial-resolution thermal mapping in operating fuel cell.
- Verified potentially high spatial resolution (1–5 mm) thermal mapping, two-photon doped fiber temperature measurement in the lab.

- Sampled a miniature capillary-sampled mass spectrometry technique on an operating fuel cell.
- Demonstrated humidity, reactant species distributions on an operating fuel cell.
- Expanded collaborations to include three fuel cell original equipment manufacturers (OEMs) for testing.
- Presented five conference papers.
- Filed three patent disclosures.

Future Direction

- Continue field experiments with industrial partners to evaluate system design and performance limitations and validate sensor durability.
- Continue generating fuel cell thermo-chemical performance data for OEM model validation and optimization.
- Continue development of advanced sensor concepts including high-resolution thermal mapping techniques, direct humidity measurement (intra-flow channel and intra-membrane), and pH measurement according to input from industrial partners.
- Continue development of diagnostic methodologies to access intra-fuel cell dynamics and process limitations according to input from industrial partners.

Introduction

Accurate, reliable, fast-responding sensors have been identified as a critical need to support advanced fuel cell design and optimization studies. Temperature and thermal distribution, as well as humidity distribution, play a key role in determining the health of a fuel cell and its ability to respond to instantaneous power demands. Furthermore, real-time thermal-chemical diagnostic sensors will allow designers to increase stack power density by reducing operating margins and quickly identifying pathways toward advanced designs.

This project focuses on the development of miniature measurement and diagnostic tools that allow fuel cell designers to have access to critical internal dynamics of operating fuel cells. An optical–fiber-based temperature measurement technology that uses the unique luminescence properties of ruby micro-spheres and rods to detect temperature, along with a micro-capillary sampling mass spectrometer, have been implemented in operating fuel cells to characterize these dynamics. Cause-and-effect relationships that lead to operational inefficiencies are being explored in an effort to enhance fundamental understanding, validate fuel cell models, optimize designs, and refine operational methodologies.

Approach

The approach taken in this project includes the development of miniature, rugged, high-fidelity sensors and measurement methods to accomplish the goal of in situ, real-time measurements within an operating fuel cell. To that end, miniature optical fiber temperature sensors and micro-capillary-sampling mass spectrometer measurements were applied within the cathode gas flow channel of two operating fuel cells. These measurements were able to characterize the dynamic thermo-chemical conditions within the fuel cell under various load conditions.

Fuel cell bipolar plates, modified to accommodate our miniature sensors, are shown in Figure 1. A measurement platform was developed to process information coming from a nine-sensor array capable of producing thermo-chemical distributions during operation. These measurements were used to develop cause-and-effect relationships among fuel cell design parameters, operational conditions, and fuel cell performance.

Results

Significant progress has been achieved in a number of areas during this period of performance.

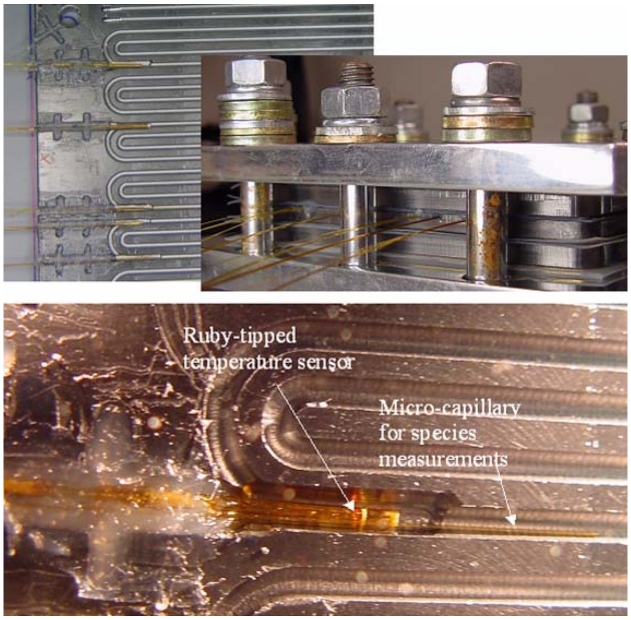

Figure 1. (a) Upper left, image of temperature/micro-capillary sensor pairs mounted in bipolar plate; (b) upper right, image of side of fuel cell stack with sensors protruding; and (c) lower image, close-up view of sensor pair within a gas flow channel.

- Demonstrated sensors in an operating fuel cell, exhibiting no degradation.
- Developed and demonstrated a multi-sensor diagnostics platform capable of characterizing real-time thermo-chemical distributions within an operating fuel cell.
- Developed advanced sensor concepts for high-spatial-resolution thermal mapping, direct humidity measurement, and pH measurement;
- Performed field trials using Oak Ridge National Laboratory (ORNL) sensor technologies to characterize in situ fuel cell dynamics with industrial collaborators.
- Filed a patent disclosure for a measurement apparatus and method for direct measurement of water concentration in Nafion® membranes.

Figure 2 depicts the temperature mapping sensor platform deployed during a test at Plug Power. The data show that free space temperature sensors not only measure temperature profiles but also can indicate the passage of water droplets within the gas flow channel. Figure 3 shows a temperature sensor

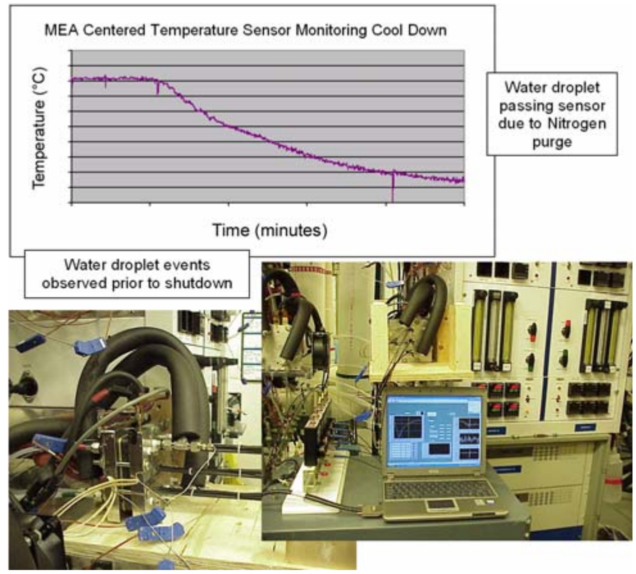

Figure 2. Sensor Platform Deployed on Plug Power Fuel Cell Test Stand and Fuel Cell Cool Down Curve Acquired During Testing

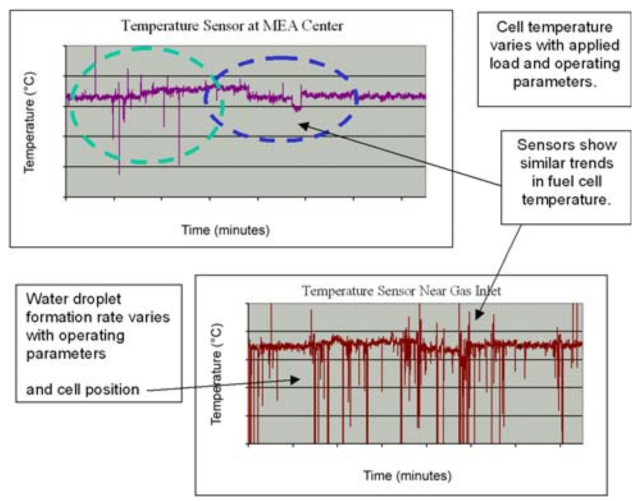

Figure 3. Temperature measurements at different locations within an operating fuel cell showing correlated behavior. The free space sensor near the gas inlet shows significant water droplet production.

responding to fast transients within the fuel cell resulting from changing load conditions. Again, water droplet events are easily observable.

Figure 4 represents a temperature distribution, measured with monolithic temperature sensors, during a 2-hour period in which the fuel cell load conditions and fuel supply rate were adjusted to

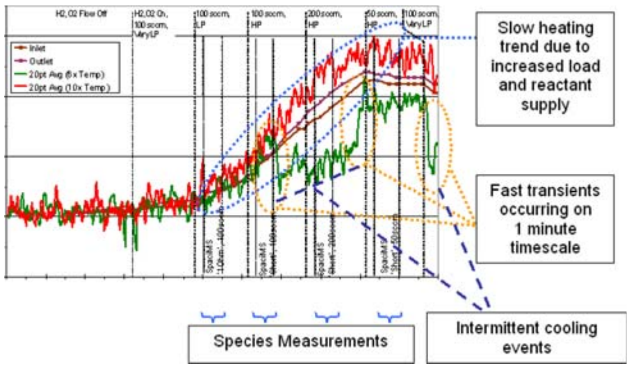

Figure 4. Temperature Sensors Resolving Transient Intra-Fuel Cell Distributions (The green curve shows an intermittent cooling event has taken place within the serpentine flow channel near the center of the fuel cell.)

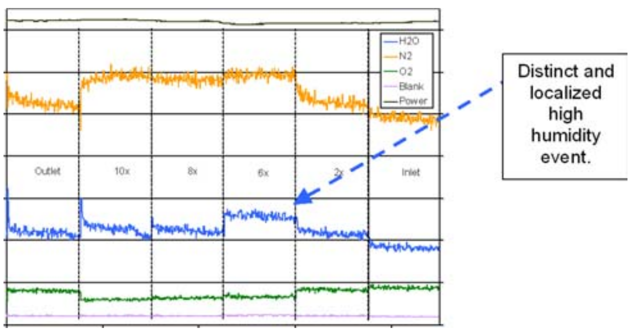

Figure 5. Species Distribution Data Showing High Localized Water (Humidity) Concentration at the (6X) Location (Significant oxygen usage (green curve) is also evident at the (2X) and (6X) locations, indicating strong reactivity near the front of the fuel cell produces excess water.)

characterize transient behavior. The most notable features in Figure 4 are the fast thermal excursions showing an intermittent internal cooling event has taken place. Figure 5 shows the distribution of various species within the fuel cell during operation, including oxygen concentration, water concentration, nitrogen carrier gas concentration, and power output of the cell. The important feature in Figure 5 is the high localized humidity measurement at the same time and location as the thermal cooling events shown in Figure 4. The two sensor systems (temperature probe and capillary mass spectrometer probe) independently detect an upset condition related to high localized water production and the impact on localized temperature within the fuel cell.

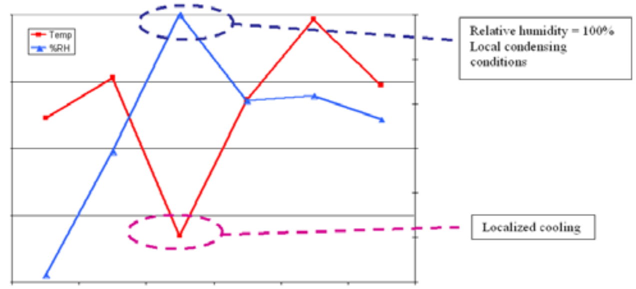

Figure 6. Spatial Distribution of Temperature and Humidity Showing Strong Correlation Between Water Condensation and Localized Cooling Within an Operating Fuel Cell

Figure 6 depicts a spatial distribution of temperature and humidity, clearly indicating the correlation between the high water concentration condition and the localized cooling event within the fuel cell. By using the real-time diagnostic tools developing in this project, fuel cell designers will be able to perform parametric studies that illustrate relationships among cell design, operational methodologies, and load profiles and assess impacts on fuel cell efficiency.

Conclusions

- Two distinct temperature sensor designs (free space probes and monolithic optical fiber probes) have been used in operating fuel cells to characterize thermal distributions.
- Free space temperature probes provide fast, accurate, reliable temperature measurements and can detect water droplet movement within the fuel cell.
- A measurement platform that includes 5+ temperature sensors and 5+ gas species sensors has demonstrated the ability to map thermo-chemical distributions during fuel cell operation.
- The measurement and diagnostic platform enables parametric studies of fuel cell design limitations, enables operational methodologies that lead to upset conditions or inefficiencies, and provides feedback on modeling activities.
- Further experiments are planned with industry collaborators to utilize ORNL's diagnostic tools to identify design/process limitations under myriad operating conditions.

FY 2005 Publications/Presentations

1. "Fiber Optic Temperature Sensors for PEM Fuel Cells" was presented at the Department of Energy Hydrogen, Fuel Cells, and Infrastructure Program Review Meeting in Crystal City, VA.
2. "Fiber Optic Temperature Sensors for PEM Fuel Cells" was presented to several OEMs and fuel–cell-related organizations, including New Energy and Industrial Technology Development Organization (NEDO), Nissan Motor Company, Ballard Fuel Cells, General Motors Corporation, Numark Associates, and The Global Environment and Technology Foundation.
3. "Converting Luminescence Decay to Pulse Width for Accurate Determination of Temperature" was submitted to the *IEEE Journal of Electronics* for publication.
4. "Fiber Optic Temperature Sensors for PEM Fuel Cell Applications" was presented to the Instrument Society of America.
5. A paper on spatially resolved temperature measurement and embedded wave guide sensors is being prepared for submission to *Review of Scientific Instruments*.