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In situ simultaneous measurements of temperature and water partial pressure in a PEM fuel cell under steady state and dynamic cycling

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Abstract

In situ, line-of-sight measurements of water vapor partial pressure and temperature were performed in a gas channel on the cathode side of an operating PEM fuel cell. Tunable diode laser absorption spectroscopy was employed for these measurements for which water transitions sensitive to temperature and partial pressure were utilized. The previously demonstrated methodology for water partial pressure measurements was extended to include temperature by including additional features of the water spectra in the data analysis. The combined technique was demonstrated in a PEM fuel cell operating under both steady state and time-varying load conditions. For steady state operation, the water partial pressure increases with increasing current density on the cathode side due to production of water by electrochemical reaction. Temperature in the gas phase remains relatively constant since the fuel cell housing temperature is controlled externally. For unsteady operation of the fuel cell through a time varying current profile, it is found that the water partial pressure responds to the load changes rapidly and follows the current profile. The gas temperature varies in response to the dynamic loading and departures from steady state conditions become more apparent at higher fuel cell operating temperatures.

Keywords: Fuel cell diagnostics; In situ measurements; Laser absorption spectroscopy; Water concentration; Temperature

1. Introduction

Proton exchange membrane (PEM) fuel cells generate electricity directly through two electrochemical reactions, which take place at the interface between a proton conductive membrane and catalyst electrodes. In a PEM fuel cell, controlled hydration of the membrane is required for proper operation. The hydrogen and oxygen feed streams are typically hydrated to bring water vapor into the cell, but several transport processes are responsible for nonhomogeneous distribution of water across the cell cross-section, including diffusion due to partial pressure gradients and electro-osmotic drag of water by protons through the membrane [1,2]. In addition, the cathode reactions produce water that may condense depending on local temperature and partial pressure. The fuel cell's overall performance can be very sensitive to water management since excessive water can lead to flooding and limit the rate of reactant transport to the electrodes and a reduction in water can decrease the protonic conductivity of the membrane. Nafion©, which is the most common membrane material exhibits a protonic conductivity change of an order of magnitude due to variation of relative humidity between 35 and 85% [3].

Similarly, the temperature of a PEM fuel cell impacts performance of the catalyst electrodes and impacts water transport and liquid/vapor balance. For these reasons, understanding of the distribution of water and local temperatures within operating fuel cells is important for optimizing system operation and design. Accurate, fast, in situ measurements of water concentration would enable both better understanding of water transport for improved cell design and advanced control strategies. In this paper, we describe an optical technique for simultaneously measuring water partial pressure and temperature in PEM cells based on water absorption of laser transmission through the flow passages in the bipolar plate. This approach permits non-intrusive in situ measurements and extends the capabilities of existing measurement techniques. The measurement approach is validated in steady state operation of a PEM cell with controlled humid-

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ity of incoming gas streams and cell temperature. The optical measurement is then applied to the PEM cell undergoing cyclic loading to simulate the conditions that might be present in transportation applications where instantaneous power requirements fluctuate. The measurements of water partial pressure and temperature in the cathode flow passages detail the time response of the system to transient events.

2. Background

Development of tools for sensing of temperature and chemical species in fuel cells is a relatively new area of research. Prior to the last 5 years, most measurements in fuel cell systems were limited to global measurements of electrical cell performance. Polarization curve measurements, for example, are routinely used to track cell performance and can be combined with simple models to diagnose component problems in the cell [4]. More recent refinement of global measurement techniques has permitted monitoring of flooding or drying conditions based on pressure drop across the cell [5,6], separation of anode and cathode contributions to cell polarization based on impedance spectroscopy [7], and diagnosis of gas diffusivities at electrodes based on rapid gas supply interruption [8]. However, these techniques are generally limited to providing only information integrated across the cell.

More recent developments have enabled characterization of local cell conditions. The development of segmented fuel cells enabled measurements of local electrical performance [9,10]. Observation of local chemical conditions have been made using simple visual observations of bubble formation through windowed direct methanol fuel cells [11], physical probe measurements using gas chromatography [12,13], and more sophisticated optical approaches such as liquid water measurements via neutron scattering [14,15], membrane hydration via X-ray scattering [16], catalyst composition via X-ray absorption [17,18], Fourier transform infrared (FT-IR) spectroscopy [19], and membrane water content and acidity via fiber-based fluorescence [20,21].

Of the techniques available for local measurements of chemical composition, most are limited by either requiring extractive sampling as in the case of gas chromatography and FT-IR spectroscopy, which limits their temporal response, or by using facilities that are not easily implemented in routine system measurements, as in the case of neutron scattering and X-ray absorption. Consequently, Basu et al. [22,23] recently developed an in situ non-intrusive method of monitoring water vapor partial pressure in each of the gas distribution channels in the bipolar plate of a PEM fuel cell using tunable diode laser absorption spectroscopy (TDLAS). This technique provided the first water vapor measurements without using physical probes in active fuel cells. However, the diode laser system used by Basu et al. [22] was not able to resolve the temperature variation in the PEM fuel cell due to the temperature insensitivity of the water absorption profiles at the chosen laser wavelength. In the current work, the TDLAS system has been modified by altering the laser wavelength to access multiple water transitions with different temperature sensitivities, enabling simultaneous recovery of both water vapor partial pressure and gas-phase temperature. The improved system has sufficient temporal resolution to examine the variations in gas-phase composition and temperature in a single localized flow passage of the bipolar plate during unsteady fuel cell operation. Results are reported for a fuel cell running under both steady and dynamic conditions simulating the nonuniform loading that might occur in real life transportation applications.

In the following sections, the theoretical and experimental approaches taken for water vapor concentration and temperature measurements are first described. Results on the application of the measurement technique to a laboratory scale PEM fuel cell are subsequently presented.

3. Experimental approach

The experimental methodology is based on that reported by Basu et al. [22]. Tunable diode laser absorption spectroscopy was used to measure water vapor absorption profiles as a function of excitation wavelength. However, the laser was changed from the previous experiments to enable measurement of water transitions in a different wavelength regime. In this work, the fiber pig-tailed output of a distributed feedback (DFB) diode laser (NEL # NLK1S5G1AA) at a wavelength of 1470 nm in the near-IR range was split using a 2×2 fiber splitter. One leg of the splitter was directly coupled to a photodiode as a reference measurement of the laser power without water absorption (I_0). The output from the other leg was passed through an optically accessible PEM fuel cell using a modified bipolar plate described by Basu et al. [22]. The bipolar plate had a serpentine geometry so that long flow passages extended over the entire fuel cell width [22]. The bipolar plate contained 17 channels of which the third channel from the air inlet on the cathode side was milled out to the end of the bipolar plate and fitted with miniature collimating optics so that the laser emission could pass through the cell. However, the diagnostic technique works equally well for all channels and could be extended to multiple channel monitoring by multiplexing. In this configuration, the total absorption path length is 7 cm. Since the measurement technique for determining water partial pressure is linear, the measurement recovers the path averaged value of partial pressure. With the current setup, variations along the line-of-sight cannot be determined. In previous work, these passages were sealed with small windows at the end of the passage and the laser was collimated externally. The alignment of this system was tedious since the length to width ratio of the channel is approximately 100. For these new experiments, our previous bipolar plate was modified by placing small collimating lenses, coupled with the optical fibers, directly in the ends of the flow passages, which served to both seal the flow passage and collimate the laser beam. The fiber output from the laser was then placed directly in the fuel cell improving the repeatability of laser alignment.

The laser output was captured using an identical photodiode as for the reference channel and measured the attenuated laser power through the cell including absorption from water