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Dynamic modeling and experimental investigation of a high temperature PEM fuel cell stack

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ABSTRACT

High temperature polymer fuel cells operating at 100 to 200 °C require simple fuel processing and produce high quality heat that can integrate well with domestic heating systems. Because the transportation of hydrogen is challenging, an alternative option is to reform natural gas on site. This article presents the development of a dynamic model and the comparison with experimental data from a high temperature proton exchange membrane fuel cell stack operating on hydrogen with carbon monoxide concentrations up to 0.8%, and temperatures from 155 to 175 °C. The dynamic response of the fuel cell is investigated with simulated reformate gas. The dynamic response of the fuel cell stack was compared with a step change in current from 0.09 to 0.18 and back to 0.09 A/cm^2. This article shows that the dynamic model calculates the voltage at steady state well. The dynamic response for a change in current shows that the model compares well with some of the cells in the stack while other cells may have typically lower voltages levels during dynamic operation.

Introduction

Distributed generation can provide electricity with fewer emissions of greenhouse gases and pollutants compared to traditional centralized power generation. By generating the electricity close to the point of use, both electricity and heat can be used and losses from the transmission and distribution system can be avoided. In developed countries, installing distributed generation provides means to increase the reliability and resiliency of the electrical grid, and allows incremental and pointed investment. In developing countries where the electrical infrastructure is sparse or not reliable, installing distributed generation is an attractive alternative to provide electricity without huge infrastructure investments.

The technologies available for distributed generation include reciprocating engines, gas turbine engines, and fuel cells. High temperature proton exchange membrane fuel cell systems are the focus of this paper. Currently, most fuel cells installed for stationary power generation are typically operating at steady-state base-load conditions. While this is currently the easiest and most economical way to operate a fuel cell system, the dynamic operation of the fuel cells is necessary for off-grid operation. For example, to accommodate for the intermittent electrical power output from renewable energy sources such as wind and solar, fuel cell

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systems could be dynamically dispatched [1]. In addition, the ability to follow the electrical load will help fuel cells to gain more acceptance from the electric utility companies.

PEM fuel cells can typically change power output settings quickly, especially when operating on pure hydrogen. This ability is one of reasons for the extensive use of PEM fuel cell technology in automotive applications. The PEM fuel cells used in cars operate at temperatures between 20 and 80 °C. A limitation of these so-called "low temperature" PEM fuel cells is the requirement of an input stream almost free of carbon monoxide (CO) and other impurities. In the use of fuel cells for stationary power generation, researchers have developed and deployed integrated low temperature PEM fuel cells and fuel processors [2,3,4]. More recently, PEM fuel cell technology with higher operating temperatures, higher CO levels and better integration with heat recovery has been investigated [5]. Researchers have developed and tested multiple alternative high temperature PEM fuel cell types [6,7]. Among the materials evaluated, the polybenzimidazole (PBI) membrane doped with phosphoric acid allows fuel cells to operate between 160 and 200 °C and have desirable mechanical properties for use in fuel cells. This is the type of high temperature PEM short stack that is studied in this paper.

High temperature PEM fuel cells have demonstrated tolerance of carbon monoxide and other impurities in reformate gases such as methanol and carbon dioxide. Researchers have studied in detail the adsorption of carbon monoxide on the catalyst sites. The common tool used in these studies is electro-chemical impedance spectroscopy (EIS) used to diagnose the effect of CO poisoning on fuel cell performance [8,9,10,11]. Following the EIS results, researchers have developed equivalent circuit models to quantify the effect of impurities such as CO on the fuel cell performance [12], developed a finite two-dimensional model of the electrode structure and of the diffusion process at the interfaces, and fitted the model to the measured polarization curve [13]. Some researchers studied the kinetics of CO coverage as it was adsorbed on the catalyst [14]. These research projects have indicated that CO has a less severe effect on the high temperature PEM fuel cell operation at temperatures between 160 and 200 °C compared to low temperature PEM fuel cells. However, the presence of methanol and carbon dioxide may compound the negative effect on the catalyst [8].

An important aspect of system design for the high temperature PEM fuel cell is thermal management and integration with fuel processing equipment. During a start-up process, the thermal management system of the fuel cell must heat up the fuel cell from the environment temperature to a reasonable fuel cell operating temperature ($T > 100$ °C, boiling point of water). Andreasen and Kær studied the heating of the fuel cell stack by electrical heating and by hot air heating [15]. A dynamic model exploring the heat transfer and the heat generated within the fuel cell was developed and compared with the experimental results. During operation, the thermal management system maintains the operating temperature by rejecting heat produced within the fuel cell to its surrounding, or using it for other processes. Harikishan Reddy and Jayanti studied the cooling options of a fuel cell stack for a scooter by considering the use of cooling plates or forced draft on the system [16]. Supra et al. proposed a different method of using a heat pipe within the system [17]. In summary, these investigators have studied various thermal management methods for bringing the fuel cell stack to its operating point effectively and maintaining the operating temperature in a safe and desired range.

During operation, voltage and current are the two most important parameters one must know to evaluate the performance of a fuel cell. Increasing temperature tends to improve the performance of the fuel cell as it overcomes activation polarization, but higher temperatures also accelerate degradation processes, as presented in [18,19]. In parallel with the experimental data, models have been developed to study the phenomena of interest such as the influence of the charge double layer [20], or the distribution of current and gases in the flow channels [21]. These models make use of computational fluid dynamics to gain insights into the performance of the fuel cell. Another approach in predicting cell voltage and current is the use of a bulk model or simplified geometry model for fast simulation. Such bulk model- can be used for control systems development and can be more readily used to simulate a complete system with all of the balance-of-plant components (e.g. heat exchangers, blowers). First principles are used by many in a bulk control volume to determine the temperature and species concentration (sometimes spatially resolved). For example Park and Min modeled a fuel cell in quasi-three dimensional geometry that included first principles equations solved in several control volumes to determine the local current, temperature and species concentrations in the cell [22]. The investigators have shown that a dynamic model can calculate the dynamic response of rapid demand changes, and can be implemented to model a complete fuel cell system consisting of a fuel processing system, heat exchangers, blowers, off-gas combustor, and a fuel cell stack [23].

Previous models that have been developed have limitations. First, the experimental verification is usually performed at one set of operating conditions, whereas the actual fuel cell will experience different temperatures, for example, during start-up processes and during transient operation. Thus it is important to test the model ability and limits when subjected to changes in temperature and fuel flow composition. Second, only a few models in the literature are dynamic models [24,25,26,27,28]. Understanding the transient behavior of the fuel cell is important for developing control systems and for the dynamic dispatch operation of fuel cell systems that will be required in the future. A dynamic model that can compute accurately and quickly, and can be integrated with other balance-of-plant components is necessary for control system development.

The objectives of this paper are (i) to present a dynamic model of a high temperature PEM fuel cell that can calculate the thermal response of a fuel cell stack accurately, and (ii) to acquire experimental data on a fuel cell short stack for both steady state and transient conditions that are then used for model verification. A recent publication presented a dynamic model with a very similar modeling approach [22]. The current work further extends the dynamic model results by comparing them with experimental data from a high temperature PEM fuel cell short stack. The experiments on steady state operation are used to verify the model at different