Journal of Power Sources 256 (2014) 470–478

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

# Temperature dynamics and control of a water-cooled fuel cell stack

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## HIGHLIGHTS

- A model for a water-cooled PEM fuel cell stack was developed.
- A time-varying PID controller was implemented on this model.
- The controller was tested on an experimental power profile from a 3-bedroom house.

## ARTICLE INFO

*Article history:*
Received 13 September 2013
Received in revised form
17 December 2013
Accepted 19 December 2013
Available online 30 December 2013

*Keywords:*
Water-cooled fuel cell stack
Thermal modeling
PI controller
Stationary power

## ABSTRACT

In this paper, a time-varying proportional-integral (PI) controller is designed for controlling the temperature of a water-cooled 5 kW hydrogen fuel cell stack. This controller is designed using a mathematical model for the stack temperature, which is derived using basic chemical engineering material and energy balances. The controller affects the stack temperature by changing the flow rate of cooling water that passes across the stack. The model is then analyzed using a number of power demand profiles to determine the effectiveness of the controller. The results show that a time-varying PI controller is adequate for maintaining the stack temperature within 5 K of the target point.



## 1. Introduction

In the search for alternative fuel sources, hydrogen has become a popular option primarily due to the advantages offered by hydrogen fuel cells over the modern internal combustion engine [1]. Fuel cells have multiple advantages over conventional internal combustion engines such as improved efficiency, lack of moving parts, reduced noise during operation and the ability to store energy directly in batteries without any additional steps. Although fuel cells are already readily available for use as backup generators and other stationary power sources, the idea of using a fuel cell for a dynamic power demand is relatively new and the development of such a system is still being researched. One of the biggest concerns in this situation is the ability to keep the fuel cell stack at optimal conditions to maintain the highest efficiency in the face of fluctuating power demand. In the case of a constant power demand, it is much easier to maintain the stack at optimal operating conditions, but a dynamic power demand requires some reaction to the changes so that the efficiency of the stack can be maintained. In this paper, we focus on the dynamic analysis and control of a water cooled fuel cell stack, which is being used as a backup generator in a stationary environment (e.g. a residential house).

While there have been a large number of papers in the area of modeling fuel cells for different applications, very few of these papers have focused on the issue of temperature dynamics of the fuel cell and its effect on performance. Some of the earliest research into the thermal characteristics of a PEM fuel cell was actually experimental. Amphlett et. al. [2] conducted numerous physical experiments on a working fuel cell stack and determined properties such as the effective mass and surface area of the fuel cell stack. These values compared well with estimates based on bulk stack measurements. The fuel cell stack was also run at various experimental conditions to determine the stack response. These results were then used to experimentally determine further characteristics of the stack including a prediction for the cell voltage, the heat transfer coefficient, and the thermal capacity of the stack. A transient model was also constructed to determine the stack temperature with time, but relies on a large number of inputs that are, at

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http://dx.doi.org/10.1016/j.jpowsour.2013.12.100

this point, experimentally determined. Grasser and Rufer [6] developed a thermal model for liquid cooling of a PEM fuel cell in their dynamic model. With their experimental results, they were able to design the thermal model using simple energy balances to express the stack temperature in a first-order differential equation, similar to how Amphlett et al. performed their research.

A variety of theoretical models have been developed to study and model PEM fuel cells. Pukrushpan et. al. [12] developed a nonlinear dynamic model that is suitable for control study. Xue et. al. [14] developed a dynamic lumped-parameter model of a PEM fuel cell and discovered that hydrogen diffusion through the electrode affects the stack temperature. Pathapati et. al. [11] further developed the model set forth by Xue et. al. [14] specifically focusing on the dynamics and mechanisms that are of particular importance for automotive purposes. Chu et. al. [3] also developed a lumped parameter model, and investigated the changes in stack temperature for various inputs, but control of the stack temperature was not in the scope of their research. Meyer and Yao [9] presented a Multiple Input Single Output (MISO) cooling system model using linearization and $\mu$-synthesis, but this model is again rather complicated and integrated into an overall dynamic model for the stack. Other research has been performed to analyze how the fuel cell stack with perform under adverse conditions, such as starting the stack in freezing temperatures [13].

While various theoretical models have been developed to study the PEM fuel cell stack, they tend to have thermal models developed for a fuel cell stack open to the atmosphere. This air-cooled stack is of interest in the laboratory, but it does not realistically model what the temperature profile of the stack would begin to look like when used in an automobile. When in operation, the atmosphere under the hood of a vehicle can get much hotter than the surrounding environment outside of the vehicle, making the air in the engine compartment unsuitable for adequate cooling of the fuel cell stack. If an air-cooled system is not possible, the only other ways to reliably affect the stack temperature are to modify the inlet conditions or to use a liquid cooling system around the outside of the stack. Since modifications of the inlet conditions will obviously have an adverse effect on the desired power output, a liquid cooling system is the only other feasible option. Significantly less theoretical research has been done on liquid cooling of a fuel cell stack. Recently, Fang et. al. [5] developed a dynamic model using a liquid cooling thermal model, but control of the stack temperature was once again not in the scope of their research.

In this research, a theoretical model is developed to model the thermal characteristics of a hydrogen fuel cell stack, as well as its response to changes in parameters that can be used in temperature control. A schematic of the system under consideration is shown in Fig. 1.

The specific objectives are (1) to develop a time-varying proportional-integral (PI) controller for cooling water flow rate across a jacketed PEM fuel cell stack with the intent of controlling the stack temperature and (2) test the controller using a variety of power profiles.

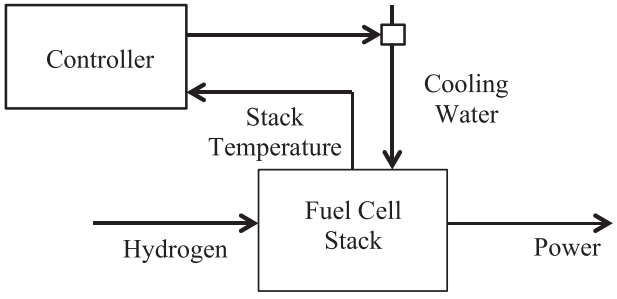


**Fig. 1.** Basic schematic of fuel cell system.

Fuel cell stacks currently offer one of the best, cleanest alternatives to the fossil fuels used in modern engines, thereby reducing the amount of harmful greenhouse gases released into the atmosphere. Improvement in the design and efficiency of fuel cell stacks will also make them more affordable for stationary power applications.

## 2. Development of thermal model

A fundamental premise of the approach taken here is that the electrical characteristics of a fuel cell change much more rapidly than the temperature. A time-scale analysis of this system indicated that the electrical time-scale was of the order of milliseconds, the mechanical flow process time-scale was of the order of seconds and the thermal time-scale was of the order of minutes [8]. Thus we can examine the dynamics of the stack temperature assuming that the voltage adjusts nearly instantaneously when current draw changes. This does not mean that the voltage–current relationship does not depend on temperature, just that the changes occur so rapidly that this part of the overall model can be represented by an algebraic model.

If the fuel cell stack and its contents are chosen as the system, the energy balance can be written as:

$$\frac{dU}{dt} = \sum_i \dot{N}_{i,\text{in}} H_{i,\text{in}} - \sum_i \dot{N}_{i,\text{out}} H_{i,\text{out}} - \dot{Q} - \dot{W} \tag{1}$$

The material balance for any species $i$ is the following:

$$\frac{dN_i}{dt} = \dot{N}_{i,\text{in}} - \dot{N}_{i,\text{out}} + \nu_i \dot{\xi} \tag{2}$$

Even though there are separate reactions occurring at the anode and cathode, we combine them into an overall water formation reaction. The accumulation of the species $i$ is very small compared to the mass of the stack. It is therefore safe to assume steady-state for all gaseous and liquid species. This assumption allows the accumulation term in the material balance to be set equal to zero, resulting in:

$$\dot{N}_{i,\text{out}} = \dot{N}_{i,\text{in}} + \nu_i \dot{\xi} \tag{3}$$

The material and energy balances may now be combined to give:

$$\frac{dU}{dt} = \sum_i \dot{N}_{i,\text{in}} (H_{i,\text{in}} - H_{i,\text{out}}) - \Delta H_{\text{rxn}}(T_{\text{out}}) \dot{\xi} - \dot{Q} - \dot{W} \tag{4}$$

where the heat of reaction for the overall reaction, the formation of water, will be evaluated at the actual cell outlet temperature. Note that since the $\dot{N}_{i,\text{out}}$ term can be written in terms of the $\dot{N}_{i,\text{in}}$ term from Eq. (3), the combined equation presented in Eq. (4) is a function of $\dot{N}_{i,\text{in}}$ only.

If the hydrogen for the fuel cell is generated by the reforming of a hydrocarbon then the anode inlet flow has hydrogen ($H_2$), carbon dioxide ($CO_2$), carbon monoxide ($CO$) and water ($H_2O$). The cathode inlet flow is made up of oxygen ($O_2$), nitrogen ($N_2$), and water ($H_2O$). All required species flows can be related to the inlet hydrogen flow. The mole fraction of hydrogen in the inlet is given by:

$$y_{H_2} = \frac{\dot{N}_{H_2,\text{in}}}{\dot{N}_{H_2,\text{in}} + \dot{N}_{\text{other,in}}} \tag{5}$$

Then all of the other gas flows (carbon dioxide, carbon monoxide, and water) can then be expressed by