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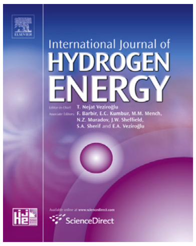

Cooling strategy for effective automotive power trains: 3D thermal modeling and multi-faceted approach for integrating thermoelectric modules into proton exchange membrane fuel cell stack

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ABSTRACT

The 3D Thermal modeling utilizes a Finite Differencing heat alteration method augmented with empirical boundary conditions is employed to develop 3D thermal model for the integration of thermoelectric modules with proton exchange membrane fuel cell stack. Hardware-in-Loop was designed under pre-defined drive cycle to obtain fuel cell performance parameters along with anode and cathode gas flow-rates and surface temperatures. The fuel cell model is used to conjugate the experimental boundary conditions with the Finite Differencing code, which implemented heat generation across the stack to depict the chemical composition process. The structural and temporal temperature contours obtained from this model are in compliance with the actual recordings obtained from the infrared detector and thermocouples. The model is harmonized with thermo-electric modules with a modeling strategy, which enables optimize better temporal profile across the stack. This study presents the improvement of a 3D thermal model for proton exchange membrane fuel cell stack along with the interfaced thermo-electric module. The model provided a virtual environment using a model-based design approach to assist the design engineers to manipulate the design correction earlier in the process and eliminate the need for costly and time consuming prototypes.

Introduction

Among various fuel cell types, proton exchange membrane fuel cells (PEMFCs) are the most promising for automotive applications due to their higher power density and lower operating temperature. The PEMFCs are getting more attention due to improvement in performance and durability of catalysts and electrolyte [1]. The operating temperature of PEMFC's is $<90\ ^{\circ}\mathrm{C}$ with air in cathode at relatively lower

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pressure leading to water formation. This leads to thermal and water management issues as water formed is in liquid state [1,2].

There has been an intensive research conducted in order to improve the performance of the PEM Fuel Cells. Setareh et al. developed 3D model that can be used for heat transfer rate design and cooling devices for PEMFC systems, and is validated for an air-cooled fuel cell stack [3]. This model was used to replicate the 3D temperature signature and estimate the maximum temperature in an air-cooled PEMFC stack. Authentic preliminary information of various tests was required in order to model the thermal and water transport. Special importance should be given in developing fuel cells for automotive applications which involve transient heat issues like start-up, shut down and freezing [4]. A 3D flow simulation was created by Shimpalee and Dutta [5] to study the numerical analysis of the flow channel. The results showed that the overall performance of fuel cell not only depends on inlet setup conditions like membrane thickness, inlet flow rate but also temperature variation inside the fuel cell model. Nguyen et al. [6] proposed a two-dimensional heat and mass-transfer to gauge the effectiveness of various humidification strategies. The results showed that the anode gas stream must be humidified before letting into the fuel cell as the back diffusion of water is insufficient to maintain the membrane hydrated.

Computational Fluid Dynamics Analysis was intensively used in analyzing the thermo fluid aspect of the PEM Fuel Cell. For instance, Matian et al. [7] developed a computational model of the PEMFC to study the heat generated and distribution of heat of the surface of the model using thermal imaging cameras. The validated results showed that the temperature distribution in a stack is significantly influenced by stack composition and drawn power density.

Alternatively, Del Real et al. [8] provided key inputs to develop powerful model and validate the results through a dynamic system (for 1.2 KW NEXA) which is very commonly used by research groups. The main contribution was the unique way of obtaining polarization curves experimentally, and modifying the thermal equations for an air cooled stacks and model flooding event in the FC stack. Similarly, Khemili et al. [9] established a thermal model to investigate the temperature distribution in the PEMFC and evaluate the effect of the liquid water on this temperature deviation at high current density.

Djilali et al. [10] analyzed the integration of PEMFC models into multi-dimensional CFD codes and illustrated their application in plate and frame unit cells. Analyzing the performance of a fuel cell as a function of voltage–load current characteristics was conducted by Sharifi et al. [11], where two complete fuel cell models under steady-state and dynamic conditions were proposed. The results showed the transient phenomenon combined together simultaneously three prominent dynamic aspects like Temperature changes, Fluid flow and pressure changes through channels of double layers. Yi Zong et al. [12] proposed a non-isothermal and non-isobaric model with non-uniform stack temperature. The Model consisted several parts like mass balance, energy balance, pressure drop and cell output voltage. The mass balancing equations are used to calculate the energy balance equation and Newton–Raphson method is applied to calculate the local current density. Based on the simulation on both anode and cathode, it was found that the anode and cathode should supply with humidified fuel, to prevent the membrane from dehydrating.

A one-dimensional, steady state, isothermal fuel cell model was established by Bao et al. [13] focusing design methodology and analysis of water and thermal management of the fuel cell. More recently, Cao et al. [14] developed a three dimensional two phase, non-isothermal model of the PEMFC to perceive the interaction between water and heat transport, fluid flow of the model, electrochemical reaction and heat transfer process. Musio et al. [15] established a modeling access which was implemented in Matlab-Simulink context. The stack model was set up based on elementary equations for fluid dynamics, thermal dynamics and kinetic behavior of the system. A thermal control model for the system was progressed for an air cooling system which enabled in differentiating various heat removal techniques. Finite differencing (FD) have been used to understand the heat transfer mechanism. For example, Mayyas et al. [16] compounded a 3D model using FD heat transfer technique correlated with experimental boundary conditions for hybrid power train containing battery pack and power electronics. The model predicted the spatial and temporal temperature portrait in accord with the actual vehicle conditions. Similar, approach is used in this paper, but in this case the subject of study 3D fuel cell model.

In this study, a 3D thermal model is developed and validated to analyze and predict the thermal performance of air-cooled PEMFCs. The model is developed based on a multifaceted approach; this combines both finite differencing code (FDC) and experimental boundary conditions obtained during an implementation of various simulated standard and artificial driving cycles. The fuel cell system was tested in Hardware In-the-loop (HiL) configuration. The HiL uses a complete model of FCV where the modeled fuel cell system was replaced with a real fuel system. This type of set up and configuration aimed to mimic the real-world loading scenarios. Air-cooled FC system serves two purposes, the cooling function and cathode flow which reduces the overall cost of auxiliary systems. A focal plane array infrared detector [7] is used in order to obtain 2D thermal maps for the FC stack mount surface. The thermal images from the infrared detector are used to validate the thermal signature of the FC stack mount surface by a comparison with the model output. In addition, the model has been integrated with the thermo electric module for optimizing the FC stack performance.

Experimental

This part provides the fundamental procedures and mechanisms required to establish a model and attain the required boundary conditions from an operating Fuel cell system (FC). This empirical work helps to get stack temperature, stack voltage, flow rates, net power and temperature distribution through the surface of the stack.

Fuel cell system

The experimental set up shown in Fig. 1 consists of NEXA 1.2 KW fuel cell stack (FC GEN 1020 from BALLARD) with