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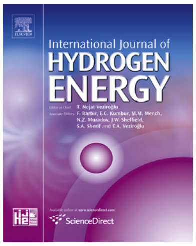

Full Length Article

An investigation of temperature effect on performance of dead-end cascade H_2/O_2 PEMFC stack with integrated humidifier and separator

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ABSTRACT

In this paper, the effect of temperature on the performance of a dead-end cascade H_2/O_2 polymer electrolyte membrane (PEM) fuel cell stack is investigated. The PEM fuel cell stack, humidifier and separator are modeled mathematically. The cascade stack with two stages is considered to use almost all reactant gases during operation. Accumulated water of both cathode and anode sides is removed by the use of periodical purging. The obtained model can simply present the behavior of dead-end PEM fuel cell, which can further be used for identification and control purposes. Moreover, comparison of cascade PEM fuel cell operation in a dead-end mode with an open-end mode is presented.

Introduction

Polymer electrolyte membrane fuel cell (PEMFC) systems are considered as sources for energy generation and an alternative for both stationary and mobile applications. PEMFC systems have nonlinear and time varying dynamic with coupling effects of fluid, heat, phase change, electrochemical reaction and etc. [1]. Furthermore, some physical properties of PEMFC components are unknown. Therefore, proposing accurate mathematical models for designing or controlling or performing both tasks for the system under study is instrumental [2]. In addition, the mathematical models can be utilized to supply the value of internal variables which are difficult to measure [3,4], to analyze and predict the behavior of PEMFCs.

Researchers used 0-D, 1-D, 2-D and 3-D models of PEM fuel cells with various degrees of complexity and details with respect to required information [5]. In according to the low computational time of 0-D or lumped approaches, these models were proven to be highly effective to improve real-time control and even to perform both model-based system sizing and control strategies' definition [2]. Wishart et al. [6] presented a systematic method to obtain the optimal operating conditions of a fuel cell system using zero-dimensional model. Their proposed method is based on the coupling of a semi-empirical fuel cell stack model and an associated

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balance of plant model with an optimization algorithm in order to efficiently explore the range of possible operating conditions. Muller and Stefanopoulou [7] developed control-oriented mathematical model of a PEM fuel cell stack. They predicted the bulk fuel cell transient temperature and voltage as a function of the current drawn and the inlet coolant conditions. In addition, they performed a first-law control volume analysis to separate the relevant from the negligible contributions to the thermal dynamics and to determine the sensitivity of the energy balance to sensor errors and system parameter deviations. Damour et al. [8] designed a nonlinear model-based predictive control strategy and a global linearizing control approach based on MIMO dynamic nonlinear model to control the output power and the stack temperature. Panos et al. [3] designed a reduced order state space model for optimal control studies of a PEMFC system. Shan and Choe [9] proposed a dynamic model for the PEMFC to predict responses of the electric load on the cell. They used a 1-D single-phase model to represent the dynamics present in the GDL. The results demonstrated the effects of electric loads on temperature, voltage and efficiency. Najafi et al. [10] demonstrated a method to reduce the model of a nonlinear dynamic fuel cell stack which is suitable for control and fault detection studies. Moreover, they proposed model for the temperature distribution in a fuel cell. Saygili et al. [11] considered a closed loop water circulation strategy and evaluated a cooling a 3 kW PEM fuel cell. They developed a first principles based model for the integrated cooling system through an energy balance containing the relevant terms. They used the resulting semi-empirical model to evaluate possible control strategies managing the cooling loop. Ettihir et al. [12] proposed a semi-empirical model for online identification in order to improve the performances of Fuel Cell Vehicles. The Adaptive Recursive Least Square method has been considered to update the semi-empirical model parameters online to cope with Fuel Cell System parameter variations. They design a Matlab/Simulink model to define the initial parameters for the online identification in real time. Hu et al. [13] proposes a model-based approach to estimate the liquid saturation and current density difference simultaneously. They formulated the cathode GDL flooding and oxygen starvation diagnoses as state estimation problems. They also validated the proposed approach through an offline simulation using experimental data.

Cascade PEMFCs are operated in such a way to produce the minimum quantity of exhaust gases. Using integrated humidifier and separator leads to decrease the occupied space and increase the modularity of the system. In addition, it causes the PEMFC stack to reduce the number of leaking points. This results in needing less supply of reactant gases, in particular with a fuel cell system which is used in submarines or aerospace applications. A fuel cell system of this type is usually fed by pure hydrogen and pure oxygen. Cascade fuel cells include a plurality of stages, each having at least one fuel cell block, operating gas feed and operating gas discharge. An end stage of cascade fuel cell has an operating gas feed which is connected to an operating gas discharge of the preceding stage. In a dead-end mode, the end stage is designed in such a way to entirely use reactants in operation (Stoichiometry ~ 1) [14].

Water separators are arranged between the stages. Therefore, the product water of each stage is separated from the gas and not flushed into the following stage that prevents the PEMFCs from being flooded by water [15]. Moreover, maintaining proper membrane humidity is very important to guarantee optimal operation of a PEM fuel cell system. For this, oxygen and hydrogen humidifiers are utilized to humidify the dry reactants [5]. Liso et al. [16] formulated a novel mathematical zero-dimensional model for the water mass balance and hydration of a polymer electrolyte membrane. They considered the effect of diffusivity model, surface roughness and water content driving force. Moreover, they validated the model against experimental data.

The objectives of this study are to first model a dead-end cascade H_2/O_2 PEM fuel cell stack with integrated humidifier and separator mathematically. The main three modules of this model are fluid dynamic model, thermodynamic model and electrochemical static model. Then, advantages and disadvantages dead-end and open-end mode PEM fuel cell stacks are investigated through comparing the operation of the two mentioned types of PEMFCs. In addition, an obtained mathematical model is used to analyze thermal dynamics of PEM fuel cells with integrated humidifier and separator. The presented mathematical model of PEM fuel cell is nonlinear and zero-dimensional. The model can predict the bulk humidifier and fuel cell temperatures and the stack voltage as a function of the coolant inlet temperature and the stack current. Since PEM fuel cell system has multidisciplinary nature with many interacting process, it has so many unknown parameters. Hence, it is tried to present basic formulation for characterizing the behavior of dead-end PEMFC. The obtained model can further be utilized for system identification and control purposes, and for studying the effect of different parameters on performance of fuel cells.

Mathematical modeling

The schematic figure of the PEMFC stack with integrated humidifier and separator is shown in Fig. 1. Cascade region has two stages which the first stage has three cells and the second one has one cell. As shown in Fig. 1, hydrogen is channeled in the anode side of the fuel cell while oxygen in the cathode side. Proper humidity of reactants is ensured by using the humidifier in order to minimize the danger of dehydration of the membrane. Number of humidifier cells is considered to be two that each of cells humidifies a dry reactant. Moreover, it is assumed that there are water separators between the first and the second stages for both cathode and anode sides of PEMFC stack.

The mathematical model is composed of three main modules: fluid dynamics model (hydrogen, oxygen, liquid water and vapor), thermodynamic model (bulk humidifier and fuel cell temperatures) and electrochemical static model. The dynamic mathematical model (zero-dimensional) includes mass balances for the oxygen and hydrogen humidifiers, anode and cathode side of PEMFC stack, equations for the membrane, thermodynamic equations of humidifier and PEMFC stack and electrochemical equations. In according to

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