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Using the multiple regression analysis with respect to ANOVA and 3D mapping to model the actual performance of PEM (proton exchange membrane) fuel cell at various operating conditions

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ABSTRACT

The performance of PEM (proton exchange membrane) fuel cell was experimentally investigated at three temperatures (30, 50 and 70 °C), four flow rates (5, 10, 15 and 20 ml/min) and two flow patterns (co-current and counter current) in order to generate two correlations using multiple regression analysis with respect to ANOVA. Results revealed that increasing the temperature for co-current and counter current flow patterns will increase both hydrogen and oxygen diffusivities, water management and membrane conductivity. The derived mathematical correlations and three dimensional mapping (i.e. surface response) for the co-current and countercurrent flow patterns showed that there is a clear interaction among the various variables (temperatures and flow rates).

1. Introduction

Scientists are using fuel cells in order to reduce the GHG (green house gases) [1]. Among the commercially available fuel cells, PEM (proton exchange membrane) fuel cells are considered excellent candidates for alternative power sources in future applications, i.e., green vehicle [2]. They are becoming more popular as direct electrical energy conversion devices because of their high efficiency, simplicity in design and operation. Some attractive characteristics of the PEM fuel cells include, self-starting at low temperatures and high power density [3]. The basic physical structure or building block of a fuel cell consists of an electrolyte layer (i.e. Nafion) in contact with porous electrode (i.e. carbon sheets coated with a catalyst layer of Pt/C) working as anode and cathode [3].

Generally fuel cell is considered like a battery because it has the same chemical reaction, but there is no need to recharge it again [4]. The operation of PEMFC is based upon the electrochemical reaction given in equation (1) and Fig. 1 [3,5]:

Overall reaction

$$2H_2\,(\text{gas}) + O_2\,(\text{gas}) = 2H_2O + \text{energy} \tag{1}$$

Equation (1) could be written in the following forms:

$$\text{Cathode (Reduction) } 1/2\ O_2 + 2H^+ + 2e^- = H_2O \tag{1a}$$

$$\text{Anode (Oxidation) } H_2 = 2H^+ + 2e^- \tag{1b}$$

The electrons can be utilized to provide electricity in a consumable form through a simple circuit with a load. Problems arise when simple fuel cells are constructed. A design solution includes manufacturing a flat plate for the electrodes with an electrolyte of very small thickness between the two electrodes. A very porous electrode is recommended so that penetration by the electrolyte and gas can occur. This design gives the maximum area of contact between the electrodes, electrolyte and gas thus increasing the efficiency and current of the fuel cell [6]. The mobile ion in the used polymer or electrolyte is H^+ ion or proton, taking into consideration that the electrolyte work at low temperatures, which has the advantage that a PEM fuel cell can start quickly [7]. Fuel cells have no moving parts, making them more reliable and quieter than generators [8]. Fuel cell reactions do not degrade over time and can theoretically provide continuous electricity unlike batteries that must be disposed of once the chemicals are used up. It can achieve higher efficiencies at any scale, making them perfect for small portable, residential, and transportation uses. In fact fuel cell systems operate at higher thermodynamic efficiency than heat

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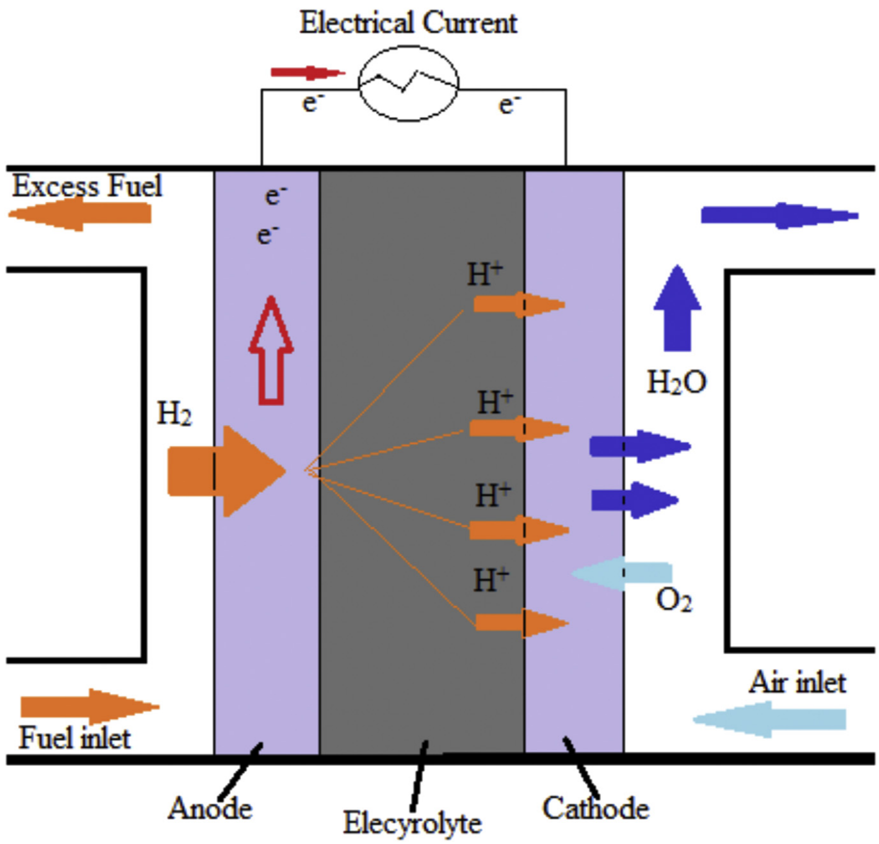

Fig. 1. Typical PEM fuel cell.

engines [9]. Several research activities have been implemented to develop the fuel cells and improve their performance, by studying the effect of several operating conditions on the fuel cell. Basically, Buchi et al. [10] showed the effect of temperature on the performance of the fuel cell. The geometrical characterization of the serpentine flow-field in relation to discharge of condensed water, maximization of cell voltage, uniformity of current density over the entire surface area and pressure drop were studied by Kap-Seung et al. [11]. Luis et al. [12], studied the influence of the relative entry positions of hydrogen and oxygen on the distribution of gases. Sreenivasulu et al. [13] worked on fuel cell with 4-Serpentine flow channels to show the effect of hydrogen flow rate, the humidification temperature and oxygen flow rate. Park et al. [14] studied non-isothermal stack model as well as the effect of reactant flows and temperature distribution. Saeed et al. [15] studied the performance of PEM fuel cell and found that the power density was inversely proportional with the increase of the hydrogen and oxygen flow rates at 80 °C. Yan et al. [16], studied the effects of various operating conditions including cathode inlet gas flow rate, cathode inlet humidification temperature and cell temperature using conventional flow field and interdigitated flow field. Yadav et al. [17] studied the performance of the PEM fuel cell with different operating temperatures and low mass flow rates (1–2 ml/s). Belkhiri et al. [18] developed two-dimensional mathematical model with a complete set of governing equations valid in different components of a PEM fuel cell. Sun et al. [19] studied the effect of different anode and cathode humidification temperatures on local current densities of PEM fuel cell with a co-flow serpentine flow field. Hsieh et al. [20] studied the effects of flow field configuration under fixed operating condition and found that the interdigitated flow channel has the most uniform transient current distribution. Obvious gaps in studying the interaction among variables (e.g. temperature, flow rate and flow direction) on the general performance of PEM fuel cell were found after revising the literature and research activities during the elapsed years. The main objective of the paper is to study the effect of temperature, gases flow rates and the flow patterns and their interactions on the PEM fuel cell performance.

2. Experimental work

MEA (membrane electrode assembly) made of Nafion membrane sandwiched between two electrodes constructed from carbon sheets coated by Pt–Ru/C catalyst working as cathode and anode kept inside the fuel cell given in Fig. 2 in order to perform forty eight experiments to investigate the following operating conditions: three temperatures (30, 50 and 70 °C) and four flow rates for hydrogen and air (5, 10, 15 and 20 ml/min) using two flow patterns (Co-current and Counter current).

3. Results and discussion

Data were obtained for the voltage and current, at the given operating conditions in order to draw the (i–v) and power curves. These results were divided into two groups according to the flow patterns (co-current and counter current) as follows:

3.1. Co-current flow pattern

3.1.1. Effect of flow rate at constant temperature

Figs. 3 and 4 show that increasing the flow rates of hydrogen and air (5–20 ml/min) at constant temperature (30 or 70 °C) have direct influence on the values of current and power densities. The result of the mentioned interaction between flowrates and temperatures was reflected directly on the water management at the cathodic