Fuel 183 (2016) 432–440

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Functional characterization of current characteristic of direct methanol fuel cell

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HIGHLIGHTS

- Need for numerical modelling of direct methanol fuel cell (DMFC) is emphasized.
- Effect of five inputs on the current characteristic of DMFC is studied.
- Gene expression model is formulated for current characteristic of DMFC.
- Model values are well in agreement with experimental data.
- Cell temperature has highest impact on the current of DMFC.

ARTICLE INFO

Article history:
Received 13 December 2015
Received in revised form 10 June 2016
Accepted 14 June 2016
Available online 30 June 2016

Keywords:
Direct methanol fuel cell
DFMC
Fuel cell performance
Gene expression
Programming
M5 model tree

ABSTRACT

In the last few years, direct methanol fuel cells (DMFCs) are extensively considered as a viable alternative power source to batteries used in transportation and portable devices due to their high energy density properties. Despite these significant advantages, operational and technological improvements are still required to make them a cost effective process. Past studies reveal that experimental procedures were mainly used in optimizing the performance of DMFC systems. Alternatively, mathematical modelling can be a promising way of finding the best operating conditions for improving the performance of DMFC systems because it is a cost effective approach and also requires less time for its implementation. Therefore, the present work proposes two artificial intelligence methods (Gene Expression Programming (GEP) and M5 model tree) to study the current characteristic of fuel cell with respect to five input operating conditions of DMFC. Performance of the two methods is evaluated against the actual data based on the three statistical metrics, hypothesis tests and cross-validation procedure. The hidden relationships between the fuel cell current and the five operating conditions are extracted by performing a parametric analysis on the model. It is found that the cell temperature has the highest impact on the current characteristic of DMFCs. The insightful information extracted from the model analysis could be useful for improving the working efficiency of the fuel cell.

1. Introduction

Fuel cell is used as a potential alternative source of energy in the arising scenarios of shortage of natural resources, rising energy generation cost and hazardous environmental impacts from energy production processes [1]. Growing attention is being paid on direct methanol fuel cell (DMFC) which possesses the potential features of standard temperature operation, quick refuelling and longer life time as those of portable devices. The working mechanism of the μDMFC is shown in Fig. 1, where the electrons flow the outside circuit towards cathode and protons moves towards cathode via proton exchange membrane. Although a significant amount of research has been conducted on DMFC [2–4], its application in commercial scales is limited due to some bottlenecks in the process. With an advent of capital intensive fuel cells and its complex operating mechanism, the need for conducting research in improving the performance of DMFCs is strengthened.

Numerous experimental studies were conducted to investigate the operating conditions like temperature and concentration of methanol in fuel cells for the efficient and effective functioning of DMFCs. A two-phase steady state model was formulated by Chippar et al. [5] to investigate the input conditions such as operating temperature, methanol feed concentration and properties of

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http://dx.doi.org/10.1016/j.fuel.2016.06.069

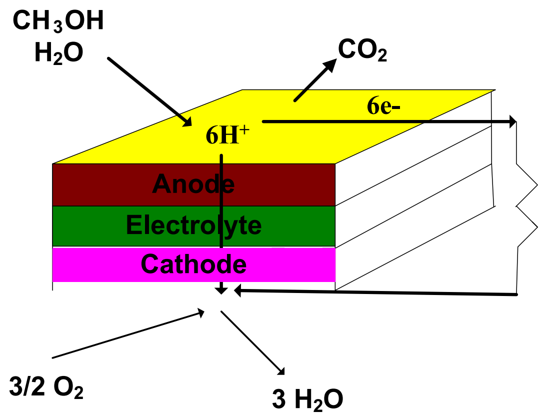

Fig. 1. Schematic diagram showing the functioning of the DMFC.

DMFC. The effect of the five inputs including operating temperature, anode flow rate, cathode humidification, air flow rate and concentration of methanol on the performance efficiency of the DMFCs was studied by Ge et al. [6]. Similarly, the study conducted by Jung et al. [7] investigated the influence of cell operating temperature and methanol concentration on the cell performances. Nakagawa and Xiu [8] conducted the quantitative analysis on liquid based DMFC by varying the cell operating temperature till 100 °C and the oxidant gas flow rate. It was found that both these inputs have an impact on the power density with the performance becoming optimum at 80 °C and 900 °C, respectively. In a study conducted by Surampidi et al. [9], the performance of the liquid based DMFC was found to be increased with cell operating temperature and became optimized at methanol concentration of 2 M. K. A thorough analysis was conducted on the small scale DMFC to study the effect of three inputs (concentration of methanol in the cell, methanol solution flow rate and air pressure) on the voltage output under varying conditions of current [10].

In brief, these studies are based on (a) experiment findings and/or (b) trial-and-error approach. With limitations of rising materials costs and time involved in implementing the experiments, a novel strategy of conducting the quantitative analysis needs significant attention. Yao et al. [11] presented a review on mathematical modelling of hydrogen and DMFC by classifying the models into single fuel cell models and manifold stack models. The single cell models were further studied into two subcategories as empirical performance and mechanistic models [12–17]. Mechanistic models were developed to study the fundamental phenomena (electrochemical and transport mechanisms) occurring in DMFC in details [18–21]. The inputs for modelling the electrochemical and transport mechanisms include the flow conditions (temperature, pressure, flow rate) of fuel, dimensions (width, length and height), etc. Numerical integration [22–25] and analytical solutions [26,27] were proposed to solve the 1-D models taking into account the electrochemical and transport mechanisms in DMFC. Polarization plots from experiments were used to validate the formulated models. It was reported [11] that there are hardly any studies which compare the current, temperature profiles with that of experimentally obtained values.

Recently, a critical review based on the numerical modelling of DMFC was also conducted by Bahrami and Faghri [28] to study the complex electrochemical and transport mechanisms occurring in the diffusion layers, catalyst layers and membrane in DMFC. Yang and Zhao [29] developed the 2-D steady state model considering the isothermal and two-phase flow characteristics. The two-phase flow characteristics were modelled using the multi-fluid multiphase mixture (MFM) approach. Yang et al. [30] developed the 3-D model considering the isothermal and two-phase characteristics modelled using the MFM approach. Yan and Jen [31] used the multiphase mixture (M^2) approach in 2-D model for modelling the two-phase flow characteristics in the DMFC. Xiao and Faghri [32] developed the 2-D transient state model considering the non-isothermal flow characteristics in DMFC. MFM approach was used to model the DMFC two-phase flow characteristics. Miao et al. [33] considered the DMFC as multiple domains in developing the 2-D steady state model and consider the non-isothermal two-phase flow characteristics. Garvin and Meyers [34] formulated the 1-D model considering the isothermal characteristics in the Single domain DFMC. The chemical equilibrium was considered while formulation of the model. 2-D steady state model for the multiple domain DMFC was developed by He et al. [35].

Recently, modelling based on statistical (response surface methodology (RSM)) and artificial intelligence (AI) methods (regression tree, gene expression programming (GEP) and the support vector regression) seems a suitable alternative for researchers in optimizing the power output features of DMFC because of their ability to formulate the models based on only the given input-output data and in uncertain systems behaviour [36,37]. Experimental studies are used to understand physics and collect the data. The analytical studies including the differential equations and RSM model are further used to define the functions for the current characteristics. These statistical methods are based on pre-assumption of the model structure (e.g., polynomial expression of 2nd or higher order) which induces the ambiguity in the prediction ability of the model. Alternatively, GEP and regression trees are well known for formulating functional expressions and capturing dynamics of a given complex system [38,39]. A thorough literature study (Fig. 2) suggests that hardly any research that discusses the ability of AI methods in simulating the performance features of DMFC was noticed [17].

Therefore, the present study explores the ability of AI methods such as GEP and M5 regression tree in the formulation of mathematical models for the prediction of DMFC fuel cell current based on the five input variables as referred in studies conducted by Taymaz et al. [17]. The procedure of modelling the power output features of microfluidic DMFC involves performing the experiments to obtain the data which is then used to develop the models based on GEP and M5. The relationships between the fuel cell current and the five inputs are extracted by sensitivity and parametric analysis, which can be used for monitoring of DMFC.

2. Experimental set-up for DMFC and data acquisition

Experimental conditions considered for performing measurements on DMFC are the same as those discussed by Taymaz et al. [17]. Experiments were conducted to analyse the effect of temperature and flow rate parameters. To perform the experiment, the

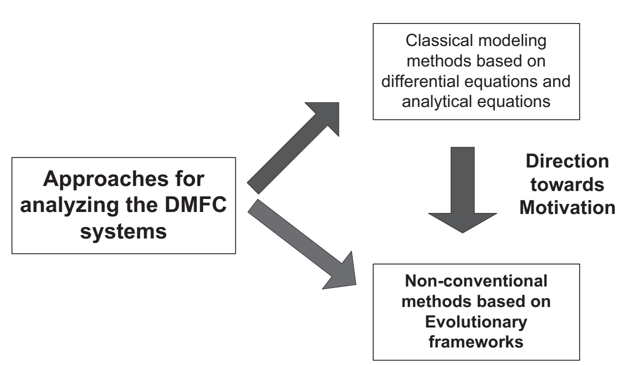

Fig. 2. Motivation and trend towards use of evolutionary frameworks in DMFC.