Control-Oriented Modeling for Open-Cathode Fuel Cell Systems*

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Abstract— Due to numerous advantages of Polymer Electrolyte Fuel Cells (PEMFCs), they are becoming the mainstream fuel cell of choice for different applications. Open-cathode PEMFCs, in particular, are gaining increased popularity in low to medium power applications due to their simple structure and low parasitic losses. However, in order to achieve safe operation, increased durability and optimal performance, advanced control algorithms, which typically require control-oriented models, need to be implemented on open-cathode fuel cell systems. The open-cathode fuel cell system includes the fuel cell stack and all of the auxiliary components that are vital for its operation. In this paper, control-oriented nonlinear models are developed for individual components of air-forced open-cathode fuel cell systems. The models incorporate electrical, thermal, anode, and cathode system dynamics in addition to the interactions between different subsystems. Specifically, control-oriented purge modeling is given special attention in this paper due to lack of sufficient research in this area and in spite of its important role in the fuel cell performance. To the authors’ knowledge, this is the first work focusing on developing control-oriented models which are capable of capturing important open-cathode fuel cell dynamics and the interactions between them. All of these models are validated experimentally on a small scale open-cathode fuel cell system. Finally, control challenges that can be formulated using the proposed models are discussed.

I. INTRODUCTION

Increases in fossil fuel prices and environmental concerns in recent decades have made alternative energy systems a very promising substitute for traditional fuels. According to a study conducted in the United States [1], carbon dioxide (CO₂) emissions contribute to more than 80% of greenhouse gases, with the transportation sector accounting for approximately 32% of the total CO₂ production. The Federal Clean Air Act, which requires by 2020 a 20% decrease in emissions from 2005 levels, has made many companies invest their resources in alternative energy sources such as wind, solar, fuel cells, and geothermal. Among these technologies, fuel cells have garnered substantial research interest due to their clean by-products and almost zero emissions.

Polymer Electrolyte Membrane Fuel Cells (PEMFC), in particular, demonstrate high efficiency and power density, longer cell and stack life, low electrolyte corrosion, zero emissions, low noise levels, and system scalability. In addition to these advantages, the main advantage of PEMFCs is their low operating temperature; making them a great power source for portable applications such as consumer electronics and hybrid electric vehicles. Similar to other fuel cell types, multiple PEMFCs need to be stacked together in order to be able to provide typical power requirements. In addition to the PEMFC stack, some auxiliary components are also required for the fuel cell operation. A complete PEMFC system consists of a cathode subsystem for air/oxygen supply and an anode subsystem for hydrogen supply. Typically, the cathode subsystem consists of an air compressor, a humidifier, a supply and return manifold, a water separator, and cooling channels. The anode subsystem, on the other hand, consists of a hydrogen storage system, variable flow valves, a humidifier, and a controllable valve at the flow exit. Detailed functionalities of each of these subsystems are explained in Pukrushpan et al. [2].

Open-cathode PEMFCs differ from typical PEMFCs in that they have cathode channels exposed to atmosphere whereas typical PEMFCs are usually operated with a closed-cathode structure. In closed-cathode PEMFCs, the air is supplied by a compressor at pressures from near ambient to approximately 6 atm. On the other hand, open-cathode PEMFCs are usually operated at around atmospheric pressure with the air being supplied either by convection or low-power fans. Higher pressures in closed-cathode PEMFCs require cathode pressure regulation in order to match the anode pressure [3]. However, in open-cathode PEMFC systems, due to near-atmospheric operating pressures, pressure regulation is not required. It should also be noted that although operating at higher pressures results in better performance and higher voltages, it induces considerable parasitic loads (e.g., compressor, cooling system, humidification system). Open-cathode PEMFCs, on the contrary, owe their popularity to their portability and reduced number of required Balance-Of-Plant (BOP) components; no compressors, supply or return manifolds, no cooling system components such as pumps and radiators, and no humidifiers.

There are two open-cathode PEMFC system configurations; air-breathing and air-forced. The air-breathing open-cathode PEMFC system does not have any components for air flow management; thus, air is acquired by diffusion and natural convection from the surrounding atmosphere [4]. Also, the produced water in the cathode is removed via evaporation. This configuration is suitable for applications such as cell phone emergency chargers. However, for higher powers, the generated heat needs to be actively dissipated and therefore, more air is required for the cathodic reaction [4-5]. In this case, air-forced systems, in which the cathode system consists of a fan or a blower to provide airflow through the cathode channels, are more desirable.

In this paper, a set of nonlinear control-oriented models are developed for the entire open-cathode fuel cell system. The novelty of this work is that it focuses not only on...
modeling the individual system components, but also on addressing the interactions between different subsystems. Furthermore, in order to address the lack of available literature, purge modeling and its effect on the anode dynamics and the fuel cell system performance is given special attention in this work. By analyzing numerous purging test results, empirical models are developed in order to accurately describe the anode dynamics with the ultimate goal of designing optimal control strategies for purge scheduling. For the cathode subsystem, a modified systematic approach for modeling the air dynamics in the cathode channels along with the fan dynamics is introduced. The cathode subsystem modeling is essential in controlling the fans to provide the air delivery in parallel with the thermal management. Similar to closed-cathode fuel cells, the fuel cell terminal voltage is obtained using the Nerst equation and overpotential terms inside the fuel cell. Furthermore, a lumped-parameter model is used to describe the temperature dynamics inside the fuel cell. The temperature model is based on an energy balance between hydrogen enthalpy change, energy lost to the cooling fans, and the output electrical energy. All of the developed models are identified and validated through experimental data. These models are suitable for control design and can describe the entire system behavior. Finally, some of the control challenges in the open-cathode fuel cell systems that can be addressed by the developed models are introduced.

II. EXPERIMENTAL FUEL CELL SYSTEM

The experimental fuel cell system used in this paper is composed of a 500 W air-forced open-cathode PEMFC stack manufactured by FuelCellsEtc. The auxiliary components used with the fuel cell stack include a mass flow controller manufactured by Aalborg (Model No. GFC17) to supply hydrogen into the anode channels, a solenoid hydrogen supply valve, a solenoid purge valve and two 12 VDC and 30 W fans to pull air through the cathode channels. The fans are 4-wire fans manufactured by NMB™ (Model No. NMB 3615KL-04W-B96) in which two wires are for power, one wire is the tachometer signal output, and one wire is the PWM input in order to change the rotational speed. The mass flow controller is also responsible for measuring the hydrogen mass flow rate passing through it. The voltage sensor used for the stack terminal voltage measurement is a custom-made voltage divider circuit with high precision resistors. The current measurements are obtained using a Honeywell current sensor (Model No.: CSLA2CD). Furthermore, ten temperature sensors manufactured by US Sensor (Model No. USP12397) are evenly placed in order to measure the internal fuel cell temperature. Two pressure sensors from Omega (Model No. PX209-015G5V) are used to measure the tank and anode inlet pressures. Finally, a programmable electronic DC load from BK Precision (Model No. 8514) is used to emulate different fuel cell loads in different applications.

The data acquisition (DAQ) and real-time control is achieved using two National Instruments cards. The multifunction card NI-PCI 6225 is mainly used for collecting the sensor measurements. The analog output card NI-PCI 6713 is used for the supply and purge valve control, fan speed control and communication with the mass flow controller. The user interface with the DAQ cards is established using Matlab xPC target toolbox.

III. OPEN-CATHODE FUEL CELL SYSTEM MODELING

A. Fuel Cell Voltage Model

Reversible or ideal voltage of a PEMFC, \( E^\circ \), can be computed using Gibbs free energy change [6] for the fuel cell electrochemical reactions. Based on the thermodynamic data tables in standard conditions, the value of \( E^\circ \) that is generated during the fuel cell reactions is 0.901 V. Under non-standard conditions, however, the reversible voltage of a PEMFC can be calculated using the Nerst equation

\[
V_{oc}(t) = E^\circ + \frac{\Delta S}{2F} (T_{FC}(t) - T_{0}) - \frac{RT_{FC}(t)}{2F} \ln \left( \frac{1}{p_{H_2}(t)p_{O_2}^{\gamma}} \right)
\]

where \( V_{oc}(t) \) is the reversible or open-circuit fuel cell voltage, \( \Delta S = -44.43 \) J/(mol.K) is the entropy change of the reaction given in (1), \( F = 96485.34 \) C/(mol) is Faraday’s number, \( T \) (K) is the operating fuel cell temperature, \( T_{0} = 298.15 \) K is the standard fuel cell temperature, \( R = 8.3144621 \) (J/(mol.K)) is the universal gas constant, and \( p_{H_2} \) and \( p_{O_2} \) are unitless hydrogen and oxygen partial pressures in the anode and cathode, respectively, with respect to the atmospheric pressure.

The Nerst equation describes the open-circuit voltage of the PEMFC; however, as soon as current is drawn from the fuel cell, the output fuel cell voltage will be

\[
V_{FC}(t) = V_{oc}(t) - V_{act}(t) - V_{ohm}(t) - V_{conc}(t)
\]

where \( V_{act} \) is activation overvoltage (V), \( V_{ohm} \) is ohmic overvoltage (V), and \( V_{conc} \) is concentration overvoltage (V). The activation overvoltage, induced by the fuel cell reaction kinetics, is the amount of voltage that is lost in order to overcome the energy barrier for the reactions. It can be described by Butler-Volmer equation (or the simpler Tafel equation). The ohmic overvoltage which is due to resistance against charge transfer in the fuel cell obeys Ohm’s law of conduction. While the fuel cell ohmic resistance is attributed to electrolyte, electrodes, and interconnect resistances, it is mainly dominated by electrolyte resistance against ionic charge transfer. Electrolyte conductivity can be modeled by calculating the water content in the electrolyte. The concentration overvoltage is the voltage losses that are caused by poor mass transport in supply and removal of reactants and products in the fuel cell. The concentration or mass transport losses depend mainly on the fuel cell geometry and mass transport properties. More details on the voltage losses inside the fuel cell can be found in [6].

As can be seen in [6], equations describing different voltage losses in a fuel cell can be complicated and might require identification of numerous parameters; however, it is shown in [7-8] that the following semi-empirical control-oriented model can be used to accurately describe the fuel cell output voltage. This model, which will be employed in this paper, is
\[ V_{\text{FC}}(t) = V_\infty(t) - \frac{RT_{\text{FC}}(t)}{2\alpha F} \ln \left( \frac{i_{\text{FC}}(t) + i_u}{i_o} \right) \]

where \( \alpha \) is the charge transfer coefficient, \( i_{\text{FC}}(t) = i_{\text{FC}}/A_{\text{FC}} \) is the current density (A/cm\(^2\)), \( A_{\text{FC}} \) (cm\(^2\)) is the fuel cell active area, \( i_o \) (A/cm\(^2\)) is the internal current density, \( i_u \) (A/cm\(^2\)) is the exchange current density, \( R_{\text{ohm}} \) (\( \Omega \) cm\(^2\)) is the ohmic resistance, and \( m \) and \( n \) are empirical constants obtained by fitting experimental data to the model in (3). Finally, the total voltage of the fuel cell stack is

\[ V_{\text{FC,at}}(t) = N_{\text{FC}} V_{\text{FC}}(t) \]

There are \( N_{\text{FC}} = 41 \) fuel cells in the experimental open-cathode fuel cell stack. Furthermore, the fuel cell active area is \( A_{\text{FC}} = 243 \) (cm\(^2\)). Rest of the parameters in Eq. (3) are obtained by data fitting the experimental data as \( R_{\text{ohm}} = 1.1334 \) (\( \Omega \) cm\(^2\)), \( \alpha = 0.25751 \), \( i_o = 0.0047758 \) (A/cm\(^2\)), \( i_u = 0.00037707 \) (A/cm\(^2\)), \( m = 0.095741 \) (V), and \( n = 0.076301 \) (cm\(^2\)/A). Fig. 1 shows the experimental fuel cell voltage measurements versus the model output in Eq. (4) obtained at 60% maximum fan speed while current steps are being drawn from the fuel cell stack.

![Experimental voltage measurements versus model output](image)

### C. Air Delivery Subsystem Modeling

In this section, the air-delivery subsystem for open-cathode fuel cells is analyzed. In open-cathode fuel cells, air delivery is achieved using fans which pull the air through cathode channels. In this section, fan dynamics will be discussed in two parts. First, the fan’s operating point will be determined for a given rotational velocity. Second, the procedure explained in the first subsection will be implemented on the experimental fans used for the fuel cell stack. Finally, some empirical models describing the relationship between fan PWM command and its rotational velocity will be developed.

#### C.1. Fan operating point determination

In open-cathode PEMFCs, the pressure drop, imposing the air flow by the air channels, depends upon the friction factor, \( f \) and is [4]

\[
\Delta p_{\text{total}}(t) = \frac{\rho v^2(t)}{2} \left( f \frac{l}{D_H} \right) + \frac{\rho v^2(t)}{2} \left( K_{\text{L,entry}} + K_{\text{L,exit}} \right)
\]

where the first term indicates the friction loss due to air flow along cathode channels and the second term accounts for the minor losses at the entry and exit sections of the cathode. In Eq. (5) \( \Delta p_{\text{total}} \) (Pa) is the total pressure drop, \( f \) is the friction factor, \( l \) (m) is the channels’ length, \( D_H \) (m) is the hydraulic diameter, \( \rho \) (1.1839 (kg/m\(^3\))) is the air density at Standard Temperature and Pressure (STP), \( v \) (m/s) is the air velocity. The parameters \( K_{\text{L,entry}} \) and \( K_{\text{L,exit}} \) are the minor loss coefficient at cathode entry and exit, respectively, which can be approximated using the tabulated values in [9]

\[
K_{\text{L,entry}} = 0.5 \quad K_{\text{L,exit}} = 1.00
\]

The hydraulic diameter is

\[
D_H = \frac{4(w_c h_c)}{2(w_c + h_c)}
\]

where \( w_c \) (m) and \( h_c \) (m) are channel width and height, respectively. In Barreras [4], a limiting Reynolds number of 500 between laminar and transitional-turbulent regions for open-cathode PEMFCs is calculated. The Reynolds number is

\[
\text{Re}(t) = \frac{\rho v(t) D_H}{\mu}
\]

where \( \mu = 1.85 \times 10^{-5} \) (Pa.s) is the air dynamic viscosity at STP. For the laminar region, the following empirical equation is proposed for the friction factor

\[
f = \frac{1}{\text{Re}} \left[ 58.91 + 50.66 \exp \left( \frac{-3.4}{w_c/h_c} \right) \right]
\]
For the turbulent region, the friction factor is empirically modeled as

\[
\frac{1}{\sqrt{f}} = -10\log_{10}\left(0.218 + \frac{65.6}{\text{Re}(t)\sqrt{f}}\right)
\]  

(10)

Furthermore, the relationship between air velocity, \(v\) (m/s), and air volumetric flow rate \(Q\) (m\(^3\)/s) is

\[
Q(t) = A_{Ca}v(t)
\]

(11)

where \(A_{Ca}\) (m\(^2\)) is the fuel cell cathode cross-sectional area. Using Eq. (11), the air mass flow rate passing through the fuel cell stack can be calculated as

\[
\dot{m}_{air}(t) = \rho Q(t)
\]

(12)

On the other hand, for a given fan, the performance curve illustrates the relationship between fan volumetric flow rate and pressure drop at the nominal rotational speed. In order to determine the fan operating point, its performance curve should be intersected with the pressure drop-air flow rate relationship of the fuel cell. To this end, for a range of air flow rates \(Q(t)\), the corresponding air velocity is calculated through (11). For each value of the air velocity, the corresponding pressure drop is then computed using Eqs. (5)- (10). The curve representing the relationship between air flow rates and the computed pressure drops is the performance curve of the fuel cell stack. The intersection of these two curves will result in the operating point of the fan at the rotational velocity at which the performance curve is expressed. For any other rotational speed, the fan’s operating point is

\[
Q(t) = \omega(t) \frac{Q_1}{\omega_1}
\]

(13)

where \(\omega_1\) is the nominal fan speed at which the operating curve is expressed (rpm), \(\omega\) is an arbitrary fan speed (rpm), \(Q_1\) is the operating flow rate of the fan (m\(^3\)/s), and \(Q\) (m\(^3\)/s) is the resulting flow rate corresponding to \(\omega\) (rpm).

C.2. Modeling the experimental fuel cell fans

As mentioned earlier, the four-wire fan structure, employed in the experimental fuel cell system, facilitates speed measurements and also speed control using a PWM input signal. The performance curve of the fans and the fuel cell stack are shown in Fig. 2. Both Eqs. (9) and (10) are used in order to compute the friction factor in generating the fuel cell performance curve. Using the maximum air flow rate through the fans, i.e., 0.0716 m\(^3\)/s, the maximum Reynolds number that can be achieved is approximately 2200. Therefore, depending on the air velocity, air flow rate through cathode channels can demonstrate a laminar or turbulent behavior. The intersection of the two performance curves is used in order to determine the operating point of the fans which is \(\Delta P_{\text{total}} = 104.3597\) (Pa) and \(Q = 2.2231\) (m\(^3\)/min). It is assumed that the fan performance curve is expressed at the fan speed mentioned in the datasheet. Therefore, for any given rotational speed, the air flow rate through the fans is calculated using Eq. (13) where \(\omega_1 = 6000\) (rpm) is assumed to be the speed at which the performance curve is expressed and \(Q_1\) is obtained from Fig. 2.

An empirical static model is used to express the relationship between the input PWM command to the fans and their rotational speed

\[
\omega(t) = 159.1u_{\text{fan}}(t) - 1211
\]

(14)

where \(u_{\text{fan}}\) (%) is the PWM command to the fans.

D. Hydrogen Delivery Subsystem Modeling

As mentioned earlier, one of the advantages of dead-end fuel cell operation is that it will only consume as much hydrogen as it needs. The amount of hydrogen required for a given fuel cell current [6] is

\[
\dot{m}_{H_2,\text{nom}} = N_{FC}\left(\dot{m}_{H_2,OCV} + M_{H_2} I_{FC} \frac{L_{EC}}{2F}\right)
\]

(15)

where \(\dot{m}_{H_2,\text{nom}}\) is the hydrogen mass flow rate (g/s), \(N_{FC}\) is the total number of fuel cells in the fuel cell stack, \(\dot{m}_{H_2,OCV}\) is the hydrogen mass flow rate (g/s) required in order to generate the fuel cell open-circuit voltage, and \(M_{H_2} = 2\) (g/mol) is the hydrogen molar mass.

Due to water concentration gradient across the membrane, water molecules, produced in the cathode, can diffuse back to the anode. Nitrogen molecules in the cathode air stream will also transfer to the anode side due to a similar nitrogen concentration gradient. Therefore, during normal fuel cell operation, water and nitrogen molecules are accumulated in the anode channels. This accumulation might circumvent hydrogen delivery from that portion of the channel which can lead to voltage losses and stack degradation issues [10]. Occasional anode purging is, thus, performed in order to prevent this phenomenon. Inert nitrogen and water molecules along with hydrogen are removed from the anode during purging, resulting in an improved performance. However, special care should be given to the purge scheduling as purging too often will result in hydrogen loss in addition to membrane drying. Therefore, high importance of purging in the fuel cell operation necessitates designing optimal purging control strategies which usually require control-oriented models. In this section, based on numerous purging tests and analysis performed on different open-cathode fuel cells, empirical

![Figure 2. Performance curve of the fans along with the fuel cell stack performance curve.](image-url)
control-oriented models are developed that address the purging effects on the hydrogen pressure and mass flow rate dynamics. Purging is usually performed using a solenoid valve which is controlled by an on/off digital signal. Fig. 3 shows a typical command waveform for the purge valve.

\[
p_{H_2}(t) = p_{tank}u(t) - \Delta p_{ purge} \cdot u(t-t_1) \\
+ \Delta p_{ purge} \left( 1 - \exp \left( -\left( t-t_2 \right)/\tau_p \right) \right)
\]  

(16)

where \( p_{tank} \) is the hydrogen tank pressure (kPa), \( \Delta p_{ purge} \) is the pressure drop during purging (kPa), \( \tau_p \) is an empirical time constant (s) indicating the time it takes for the hydrogen pressure to reach back to 63% of the tank pressure, \( u(t) \) is the unit step function and the time instances \( t_1 \) and \( t_2 \) indicate the beginning and end of purging, respectively.

The hydrogen mass flow rate inside the fuel cell is not only a function of a purging pulse, it is also dependent on the hydrogen pressure dynamics. In other words, prior, during, and post purging, the hydrogen mass flow rate is

\[
\dot{m}_{H_2}(t) = \dot{m}_{H_2,\text{nom}} \cdot u(t) + \left( \dot{m}_{H_2,\text{max}} - \dot{m}_{H_2} \right) \cdot u(t-t_1) \\
- \left( \dot{m}_{H_2,\text{max}} - \dot{m}_{H_2,\text{nom}} \right) \left( 1 - \exp \left( -\left( t-t_2 \right)/\tau_m \right) \right)
\]  

(17)

where \( \dot{m}_{H_2,\text{max}} \) is the maximum mass flow rate (g/s) allowed by the mass flow controller, \( t_1 = t_2 + t_r \) is the time instance at which the mass flow rate starts to decay with \( t_r = k_1 \tau_p \) and \( \tau_m \) is the mass flow rate dynamics time constant (s) which is observed to be equal to the pressure dynamics time constant, i.e., \( \tau_m = \tau_p \). The parameters \( \Delta p_{ purge}, \tau_p, \tau_m, \dot{m}_{H_2,\text{max}}, \) and \( k_1 \) are empirical parameters that depend on the fuel cell stack size, its power rating, and its auxiliary components.

For the experimental open-cathode fuel cell stack, the parameter values in Eq. (16) - (17) are obtained based on numerous test results as \( p_{tank} = 120 \) (kPa), \( \Delta p_{ purge} = 19.7 \) (kPa), \( \tau_p = \tau_m = 0.22 \) (s), \( \dot{m}_{H_2,\text{max}} = 0.1483 \) (g/s), and \( k_1 = 1.6 \).

Fig. 4 shows the time evolution of the experimental and modeled hydrogen pressure and mass flow rate for a single purge pulse. As can be seen from this figure, there is a good agreement between model output and experimental results in spite of the model being control-oriented.

\[ C_i \frac{dT_{FC}(t)}{dt} = P_{total}(t) - P_{FC}(t) - \dot{Q}_{\text{coolant}}(t) \]  

(18)

where \( C_i \) (J/°K.s) is the thermal capacitance, \( T_{FC} \) (°K) is the fuel cell stack temperature, which is assumed to be the average temperature inside the fuel cell, \( P_{total} \) (W) is the total power released by the electrochemical reactions, \( P_{FC} \) (W) is the electrical power output, and \( \dot{Q}_{\text{coolant}} \) (W) is the heat lost to the cooling air flow. The total power released from the electrochemical reactions as a function of the hydrogen consumption rate is

\[ P_{total}(t) = M_{H_2,\text{used}} \Delta H = \frac{N_{FC} I_{FC}(t)}{2F} \Delta H \]  

(19)

where \( M_{H_2,\text{used}} \) (mol/s) is the used hydrogen molar flow rate, and \( \Delta H = 285.5 \times 10^3 \) (J/mol) is the enthalpy change of hydrogen. The electrical output power is

\[ P_{FC}(t) = V_{FC}(t) I_{FC}(t) \]  

(20)

As mentioned earlier, in open-cathode PEMFC systems cooling is performed by the fans blowing air through the cathode. The amount of heat removed by the blown air is

\[ \dot{Q}_{\text{coolant}}(t) = \eta_{\text{fan}} \dot{m}_{\text{air}}(t) c_p(T_{\text{fc}}(t) - T_{\text{amb}}) \]  

(21)

where \( \eta_{\text{fan}} \) is the fan efficiency, \( \dot{m}_{\text{air}} \) (g/s) is the air mass flow rate, \( c_p = 1006 \) (J/kg.K) is specific heat coefficient of air, and \( T_{\text{amb}} \) (K) is the ambient temperature. The values of the fan efficiency and thermal capacity are computed by fitting the experimental data as
In order to validate the model (18), a series of current steps are drawn from the fuel cell stack. This test is repeated for three different fan commands. Fig. 5 demonstrates the modeled, actual, and ambient temperature for these three tests.

IV. SUMMARY, CONCLUSIONS, AND FUTURE WORK

In this paper a set of nonlinear control-oriented models are developed for air-forced open-cathode fuel cells. These models shed light on important phenomena affecting the open-cathode fuel cell system performance; specially the anode purging dynamics. The developed models are identified experimentally on an actual open-cathode fuel cell test bench. The validation test results between the model output and experimental data show a good prediction capability for the models. Some of the important control challenges that can be addressed using the developed models include: fan control in order to fulfill its dual functionality, i.e., air delivery and thermal management. Optimal purge scheduling in order to ensure safe and efficient fuel cell operation is another open control problem in open-cathode fuel cell systems. Increasing the overall system efficiency by a combination of optimal purging and temperature control along with minimizing the auxiliary power consumption is one of our main future research topics on the experimental fuel cell system.

REFERENCES