Experimental and thermodynamic investigation of a triangular channel geometry PEM fuel cell at different operating conditions

I. Khazaee*, M. Ghazikhanib, M. Mohammadiunc

a Department of Mechanical Engineering, Torbat-e-jam branch, Islamic Azad University, Torbat-e-jam, Iran
b Faculty of Engineering, Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, P.O. Box 9177948944-1111, Iran
c Department of Mechanical Engineering, Shahrood branch, Islamic Azad University, Shahrood, Iran

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Fuel cell;
Triangular channel;
Internal irreversibility;
Exergy efficiency;
Operating parameters.

Abstract In this study, the exergy analysis of a 11 KW triangular channel geometry PEM fuel, due to some parameters such as; input oxygen temperature (T O2), input hydrogen temperature (T H2), cell temperature (Tcell), input pressure (P), oxygen flow rate (˙mO2) and hydrogen flow rate (˙mH2), is investigated experimentally. A series of experiments are carried out to investigate the influence of the above parameters on the polarization curve and irreversibility under normal conditions. A PEM fuel cell with a 25 cm² active area and a Nafion 117 membrane with 4 mg Pt cm⁻² for the anode and cathode is employed as a membrane electrode assembly. The results show that an increase in the inlet temperature of oxygen and hydrogen, cell temperature and inlet pressure can enhance cell performance, exergy efficiency and reduce the irreversibilities of the cell.

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1. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) represent a viable alternative power source for various applications. However, to satisfy the requirements for compactness, low cost, high power density, performance and stability, various aspects of the PEMFC must be optimized [1]. Among the various fuel cell types, the Proton Exchange Membrane (PEM) fuel cell is drawing more attention, due to its low operating temperature, ease of start-up and shut-down and compactness. Furthermore, the PEM fuel cell is being investigated as an alternate power generation system, especially for distributed generation and transportation. The PEM fuel cell provides reliable power at steady state; however, it is not able to respond promptly to a load step change. Since the fuel cell is an electrochemical energy conversion device that converts fuel into electricity, its dynamic behavior depends both on chemical and thermodynamic processes [2].

There are several thermodynamic models and performance investigations of PEM fuel cells reported in the literature. These models can be categorized into two types, as theoretical models based on physical conservation laws, and semi-empirical models based on experiments.

In the present work, the effects of oxygen and hydrogen temperature, cell temperature, input pressure and oxygen and hydrogen flow rate on the performance and irreversibility and the exergy efficiency of a triangular channel geometry PEM fuel cell have been studied experimentally, and results were compared with available data. Several irreversibility curves have been obtained under different conditions, displaying the trend of the cell losses against the current. The experimental design, based on the design of experiment techniques, studied the effect of the main operation factors (temperature, pressure, gas flow) at different levels of power load. The objective of this paper is to analyze the influence of different operation factors on the internal irreversibility and exergy efficiency supplied to a PEM fuel cell at different levels of cell current.

2. Previous works

Kazim [3,4] studied the exergy and exergoeconomic analyses of a PEM fuel cell under variable operating conditions and...
presented an approach on determination of the minimal operating efficiency of a PEM fuel cell. He found that the fuel cell should operate at stoichiometric ratios less than 4 in order to maintain the relative humidity level in the product air and to avoid the membrane drying out at high operating temperatures.

Cowden et al. [5] gave a novel study on the performance analysis of a PEM fuel cell system, including the system components other than the fuel cell stack, such as the compressor, hydrogen supply and cooling system. Based on the first and second laws of thermodynamics, they suggested that substantial improvements can be made in the performance of the fuel cell system.

Xue and Dong [6] used a semi-empirical model of the Ballard Mark IV fuel cell and models for the auxiliary systems to create a model of the fuel cell system. Using this model and numerical optimization, the optimal active stack area and air stoichiometric ratio was obtained to maximize net power output, and, at the same time, minimize production costs.

Miansari et al. [7] investigated a parametric study to examine the effects of varying operating conditions on the exergy efficiency of the cell. They found that with an increase in cell operating temperature and pressure, the exergy efficiency of the cell increases and irreversibilities decrease. Also, they found that there is no appreciable increase in exergy efficiencies with an increase in air stoichiometry.

Yilanci et al. [8] investigated energy and exergy analyses for a 1.2 kW PEM fuel cell unit in a solar based hydrogen production system to investigate the performance of the system under different operating conditions, using an experimental setup and thermodynamic model. They found that there are reductions in energy and exergy efficiencies (about 14%) with an increase in current density. Also, they found that the PEM fuel cell system has lower exergy efficiencies than corresponding energy efficiencies, due to irreversibilities that are not considered by energy analysis.

3. Description of the experiments and method of the measurements

For experimental investigation of the performance of the fuel cell, a setup has been fabricated. A schematic flow of the test bench is shown in Figure 1. It allows the control of several physical parameters, and measurement of many output data. In fact, the polymeric membrane has permeability to hydrogen and oxygen. Due to the high-pressure gradient from cathode to anode, this driving force could push hydrogen from cathode to anode across the membrane and a dangerous mix with oxygen could occur; this concentration must always be kept below a safety level.

The test bench is made up of four main subsystems: First, the gas supply system, which sends the oxygen and hydrogen flow into the system for electrochemical reaction. Second, there are two humidifiers that humidify the oxygen and hydrogen before going into the cell for complete transfer of the proton from the membrane to the cathode side. Third, the nitrogen supply system is applied to inert any flammable mix inside the ducts and to purge the system before activation. Finally, there is the electrical power supply, regulated from an AC/DC voltage regulator driven from the control panel. The examined prototype can operate at a maximum 5 bar absolute pressure; a pressure regulator valve is included, to make possible a variation in the operating pressure of the FC system.

The examined prototype can operate at a maximum 5 bar absolute pressure; a pressure regulator valve is included to make possible a variation in the operating pressure of the FC system, and the accuracy of monitoring the pressure is ±2%. Two flow meters are used to measure the flow rate of the oxygen and hydrogen whose accuracy is ±1%. The resistors box, variable load, a resistors box was used whose accuracy in monitoring the voltage and ampere is ±1%. The resistors box, located outside the test chamber, is manually operated; the box and the cables do not introduce relevant errors because they are shielded from external magnetic fields (due to the very low current values). In order to operate under equilibrium conditions, current and voltage values corresponding to each particular value of the total resistance were measured after a sufficient time period to ensure stationary conditions to have been reached, concerning both fuel cell performance and the values of humidity and temperature in the test chamber. The

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Active cell area (cm²)</td>
</tr>
<tr>
<td>C接触</td>
<td>Concentration of hydrogen gas at the surface of the catalyst at the anode</td>
</tr>
<tr>
<td>C接触</td>
<td>Concentration of oxygen gas at the surface of the catalyst at the cathode</td>
</tr>
<tr>
<td>E</td>
<td>Reversible potential of each cell (V)</td>
</tr>
<tr>
<td>E^r</td>
<td>Reference potential (V)</td>
</tr>
<tr>
<td>E_N</td>
<td>Nernst voltage (V)</td>
</tr>
<tr>
<td>F</td>
<td>Faraday constant</td>
</tr>
<tr>
<td>G_f</td>
<td>Gibbs function</td>
</tr>
<tr>
<td>i</td>
<td>Current density (A cm⁻²)</td>
</tr>
<tr>
<td>I</td>
<td>Current (A)</td>
</tr>
<tr>
<td>I_m</td>
<td>Membrane thickness (cm)</td>
</tr>
<tr>
<td>I_h2</td>
<td>Hydrogen flow rate (L min⁻¹)</td>
</tr>
<tr>
<td>I_o2</td>
<td>Oxygen flow rate (L min⁻¹)</td>
</tr>
<tr>
<td>P</td>
<td>Cell pressure (bar)</td>
</tr>
<tr>
<td>P_H2</td>
<td>Pressure of hydrogen gas at the surface of the catalyst at the anode (bar)</td>
</tr>
<tr>
<td>P_O2</td>
<td>Pressure of oxygen gas at the surface of the catalyst at the cathode (bar)</td>
</tr>
<tr>
<td>P_sat</td>
<td>Saturation pressure of water vapor at a given temperature (bar)</td>
</tr>
<tr>
<td>R</td>
<td>Ohmic resistance (Ω cm²)</td>
</tr>
<tr>
<td>R^elec</td>
<td>Ohmic electronic losses resistance (Ω cm²)</td>
</tr>
<tr>
<td>R^prot</td>
<td>Ohmic protonic losses resistance (Ω cm²)</td>
</tr>
<tr>
<td>T</td>
<td>External temperature (K)</td>
</tr>
<tr>
<td>T cell</td>
<td>Cell temperature (K)</td>
</tr>
<tr>
<td>T_H2</td>
<td>Input hydrogen temperature (°C)</td>
</tr>
<tr>
<td>T_o2</td>
<td>Input oxygen temperature (°C)</td>
</tr>
<tr>
<td>V</td>
<td>Terminal voltage (V)</td>
</tr>
<tr>
<td>x_H2O</td>
<td>Molar fraction of water in gas for a given temperature</td>
</tr>
<tr>
<td>x_channel</td>
<td>Molar fraction of other gasses, apart from oxygen, in the air stream</td>
</tr>
</tbody>
</table>

### Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_air</td>
<td>Air stoichiometry</td>
</tr>
<tr>
<td>α</td>
<td>Charge transform coefficient</td>
</tr>
<tr>
<td>δ_j</td>
<td>Parameters of activation loss, Eq. (13)</td>
</tr>
<tr>
<td>η_o</td>
<td>Activation loss (V)</td>
</tr>
<tr>
<td>η_i</td>
<td>Ohmic loss (V)</td>
</tr>
<tr>
<td>η_c</td>
<td>Concentration loss (V)</td>
</tr>
</tbody>
</table>

Table 1: Operational characteristics of the test bench.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>0–2 V</td>
</tr>
<tr>
<td>Current</td>
<td>0–20 A</td>
</tr>
<tr>
<td>Power</td>
<td>0–22 W</td>
</tr>
<tr>
<td>Moisture</td>
<td>100%</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0–2 L/min</td>
</tr>
<tr>
<td>Gas temperature</td>
<td>Up to 75 °C</td>
</tr>
<tr>
<td>Cell temperature</td>
<td>Up to 75 °C</td>
</tr>
</tbody>
</table>

The temperature of the inlet gases was measured using a digital thermometer with ±0.1 °C accuracy.

The specifications of the test system for this study are:
- The humidifier system is membranous.
- The test bench has a system of announcing a leakage of hydrogen.
- The system can control and show the temperature of the oxygen and hydrogen.
- The system can control and show the temperature of the cell.
- The system can control and show the flow rate of the oxygen and hydrogen.
- The system can control and show the inlet pressure of the oxygen and hydrogen.
- The system can show the voltage of the cell.
- The system can show the current of the cell.

Table 1 shows the environs of operation of the experimental setup in this study.

The PEM fuel cell considered in this study is a single cell with the size of 45 × 95 × 101 mm² and an active area of 25 cm², and serpentine and triangular flow field geometries of channels with the weight of 1300 g. The width, land width and depth of the channel were selected to be 1, 0.8 and 2 mm, respectively. For a bipolar plate, non-porous graphite is selected. A Nafion 117 membrane with 4 mg Pt cm⁻² for the anode and cathode was employed as a membrane electrode assembly. On both sides of the MEA, there were 0.33 mm thick carbon papers that acted as diffusion layers. The thickness of the catalyst layer and the proton exchange membrane is about 0.01 mm and 0.051 mm. The maximum output power of the cell is 11 W at 0.6 cell voltage. The geometry of the channel of the cell in the experimental setup is shown in Figure 2.

The changed parameters are input oxygen temperature \( T_{O_2} \), input hydrogen temperature \( T_{H_2} \), cell temperature \( T_{cell} \), input pressure \( P \), oxygen flow rate \( \dot{m}_{O_2} \) and hydrogen flow rate \( \dot{m}_{H_2} \), and the measured parameters are voltage and current density.

At first, we perform the experiments by humidifying the membrane of the fuel cell by saturation water vapor and then changing the input oxygen temperature, input hydrogen temperature, cell temperature, input pressure, oxygen flow rate and hydrogen flow rate. Then, we measure the pointed parameters and the voltage and current of the cell after steady state condition. Figure 3 shows the experimental setup.

4. Fuel cell models

A proton exchange membrane fuel cell uses the following electrochemical reaction, which produces heat and electrical current:

\[
\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}.
\] (1)

This phenomenon in a fuel cell is the change of Gibbs free energy of formation, \( \Delta G_f \), which gives us the energy released. If the system is reversible, the Gibbs free energy released will be equal to the electrical work done, moving the charge on one mole of electrons. Electrical work done is \(-2FE\) Joules, so the reversible open circuit voltage of the hydrogen fuel cell is:

\[
E = -\frac{\Delta G_f}{2F}.
\] (2)
The output voltage of a single cell under any operating condition is given by:

\[ V = E^\circ + \eta_a + \eta_o + \eta_c, \]

(3)

where \( E^\circ \) is the Nernst equation, which is an expression for the electromotive force (EMF) for a given product and reactant activities. The (EMF) calculated from such equations is known as the Nernst voltage, and is the reversible cell voltage that would exist at a given temperature and pressure. Also, \( \eta_a \) are the activation losses that are the most important irreversibility and cause of voltage drop, and which occurs mainly at the cathode. \( \eta_o \) are the ohmic losses, which is due to the electrical resistance of the electrodes and the resistance to the flow of ions in the electrolyte and, finally, \( \eta_c \) are the concentration losses, which is the voltage lost when the concentration of reactant at the electrode is diminished.

### 4.1. Nernst equation

The Nernst voltage for a hydrogen fuel cell is:

\[ E^\circ = E^\circ - 0.85 \times 10^{-3} (T_{cell} - 298.15) + 4.31 \times 10^{-5} T_{cell} \left[ \ln(p_{H_2}^{contact}) + 0.5 \ln(p_{O_2}^{contact}) \right], \]

(4)

where \( E^\circ \) is the open circuit voltage and is equal to \( E^\circ = 1.229 \) V, \( T_{cell} \) is the surface cell temperature (K), \( p_{H_2}^{contact} \) is the hydrogen partial pressure (bar) at the surface of the catalyst and anode and \( p_{O_2}^{contact} \) is the oxygen partial pressure at the surface of the catalyst and cathode that is proposed by Amphlett et al. [9] as:

\[ p_{H_2}^{contact} = (1/2)p_{H_2}^{sat} \left[ \frac{1}{\exp(1.653/T_{cell})} - x_{H_2O}^{sat} - 1 \right], \]

(5)

\[ p_{O_2}^{contact} = P \left[ 1 - x_{H_2O}^{sat} - \chi_{othergases} \exp(0.291/T_{cell}) \right], \]

(6)

where \( i \) is the current density, \( x_{H_2O}^{sat} \) is the molar fraction of water in a gas stream at saturation for a given temperature, \( p \) is the cell pressure and \( \chi_{othergases} \) is the molar fraction of other gases apart from oxygen in the air stream. These equations come from the Maxwell–Stefan equations in which all constants and the approximate diffusion coefficient come from the kinetic theory.

The molar fractions of water and other gasses is proposed by Amphlett et al. [9] as:

\[ x_{H_2O}^{sat} = \frac{p_{H_2O}^{sat}}{p}, \]  

(7)

\[ x_{channel} + x_{othergases} = \frac{0.79(1 - x_{H_2O}^{sat})}{\ln(0.79(1 - x_{H_2O}^{sat}))}, \]  

(8)

where \( \lambda_{air} \) is the stoichiometry of the air stream, and the 0.21 term and 0.79 term refer to the dry molar fraction of oxygen and other gases in air. The saturation pressure of water vapor can be computed from the following empirical equation:

\[ \ln(p_{H_2O}^{sat}) = 70.43646 - \frac{7362.698}{T_{cell}} + 0.006952 T_{cell} \]

\[ -9 \ln(T_{cell}). \]  

(9)

### 4.2. Activation losses

The activation voltage loss is present when the rate of the electrochemical reaction at the electrode surface is controlled by sluggish electrode kinetics. Activation loss increases as the current increases. The activation losses can be obtained by the Tafel equation, which is proposed by Mann et al. [10] as:

\[ \eta_a = \delta_1 + \delta_2 T_{cell} + \delta_3 T_{cell} \ln(C_{O_2}^{contact}) + \delta_4 T_{cell} \ln(I), \]

(10)

where:

\[ C_{O_2}^{contact} = \frac{\rho_{O_2}^{contact}}{5.08 \times 10^6 \exp(-498/T_{cell})}, \]  

(11)

and coefficients \( \delta_i \) are obtained from the experimental data of Mann et al. [10], and they are all constant, apart from \( \delta_2 \), which varies with the active area of the fuel cell (A):

\[ \delta_1 = -0.948, \]

\[ \delta_2 = 0.00286 + 0.0002 \ln(A) + 4.3 \times 10^{-5} \ln(C_{H_2}^{contact}), \]  

(12)

\[ \delta_3 = 7.6 \times 10^{-5}, \]

\[ \delta_4 = -1.93 \times 10^{-4}, \]

where:

\[ C_{H_2}^{contact} = \frac{\rho_{H_2}^{contact}}{1.09 \times 10^6 \exp(77/T_{cell})}. \]  

(13)
4.3. Ohmic losses

Ohmic loss is due to the electrical resistance of the electrodes and the resistance to the flow of ions in the electrolyte. Ohmic loss is proposed by Mann et al. [10] as:

$$\eta_o = -i(R^{\text{elec}} + R^{\text{prot}}).$$  (14)

where $R^{\text{elec}}$ is assumed to be a constant over the operating temperature of the PEM fuel cell. The electronic resistance is further assumed to be inconsequential in comparison to protonic resistance, and is thus ignored. The term, $R^{\text{prot}}$, is known to be a complex function of water content and distribution in the membrane, which in turn is a function of the cell temperature and current.

$$AR^{\text{prot}}/I_m = 181.6 \left[1 + 0.03 i + 0.062(T_{\text{cell}}/303)^{2/5}\right]/(14 - 3i)\exp(3.25(T_{\text{cell}} - 303/T_{\text{cell}})),$$  (15)

where $A$ is the active area and $I_m$ is the thickness of the membrane (cm).

4.4. Concentration losses

Concentration loss is the loss of voltage, which is when the concentration of a reactant at the electrode is diminished. If the anode of a fuel cell is supplied with hydrogen, then there will be a slight drop in pressure if the hydrogen is consumed as a result of a current being drawn from the cell. The expression for the concentration loss is proposed by Larminie and Dicks [2] as:

$$\eta_c = -m\exp(mi),$$  (16)

where $m$ is the electrolyte conductivity that varies with the cell temperature:

$$m = 1.1 \times 10^{-4} - 1.2 \times 10^{-6}(T_{\text{cell}} - 273.15)$$  (17)

$$T_{\text{cell}} \geq 39 \degree C,$$

$$m = 3.3 \times 10^{-3}6 - 8.2 \times 10^{-5}(T_{\text{cell}} - 273.15)$$  (18)

$$T_{\text{cell}} \leq 39 \degree C,$$

and $n$ is the porosity of the gas diffusion layer, which, in this paper, is $n = 0.3$. For low current density, the concentration losses can be dispensed with.

Depending on the current density and voltage output, the gross power produced by a single PEM fuel cell can be calculated as:

$$W_{\text{FC}} = V \times i \times A,$$  (19)

where $A$ is the effective geometric area of the cell (cm$^2$).

4.5. Exergy analysis

The usage mass flow rates of oxygen and hydrogen and product water in (kg s$^{-1}$) are calculated, based on Faraday’s law [2]:

$$\dot{m}_{\text{O}_2,\text{usage}} = 8.29 \times 10^{-8}i,$$  (20)

$$\dot{m}_{\text{H}_2,\text{usage}} = 1.05 \times 10^{-8}i,$$  (21)

$$\dot{m}_{\text{H}_2O,\text{product}} = 9.34 \times 10^{-8}i.$$  (22)

Therefore, the output mass flow rates of the above gases are:

$$\dot{m}_{\text{O}_2,\text{out}} = \dot{m}_{\text{O}_2,\text{in}} - 8.29 \times 10^{-8}i,$$  (23)

$$\dot{m}_{\text{H}_2,\text{out}} = \dot{m}_{\text{H}_2,\text{in}} - 1.05 \times 10^{-8}i,$$  (24)

$$\dot{m}_{\text{H}_2O,\text{out}} = \dot{m}_{\text{H}_2O,\text{in}} + 9.34 \times 10^{-8}i.$$  (25)

Exergy analysis is an effective thermodynamic method for using the conservation of mass and energy principles, together with the second law of thermodynamics, for the design and analysis of thermal systems, and is an efficient technique for revealing whether or not and by how much it is possible to design more efficient thermal systems by reducing inefficiencies. The total exergy of a stream divided into four different exergies: physical exergy ($ex^{\text{ph}}$), chemical exergy ($ex^{\text{ch}}$), kinetic exergy ($ex^{\text{kin}}$) and potential exergy ($ex^{\text{po}}$) [11]:

$$ex = ex^{\text{ph}} + ex^{\text{ch}} + ex^{\text{ki}} + ex^{\text{po}}.$$  (26)

The changes in the kinetic and gravitational potential exergies are considered to be negligible in the present study. The general expression of the physical exergy can be described as:

$$ex^{\text{ph}} = (h - h_0) - T_0(s - s_0),$$  (27)

where $h_0$ and $s_0$ denote the specific enthalpy and entropy evaluated under standard conditions, respectively. The physical exergy of an ideal gas with constant specific heat, $C_p$, and specific heat ratio, $k$, can be written as:

$$ex^{\text{ph}} = C_p T_0 \left(\frac{T}{T_0} - 1 - \ln \left(\frac{T}{T_0}\right) + \ln \left(\frac{P}{P_0}\right)^{k-1}\right).$$  (28)

The chemical exergy is associated with the departure of the chemical composition of a system from that of the environment. For the sake of simplicity, the chemical exergy considered in the analysis is rather a standard chemical exergy that is based on the standard values of the environmental temperature of 298 K and pressure of 1 atm, and can be written as follows [12]:

$$ex^{\text{ch}} = \sum \mu_{\text{m}} \dot{m} - \sum \mu_{\text{m}0} \dot{m}.$$  (29)

Heat will be lost to the surroundings and to the air stream through two heat transfer processes: radiation and convection. Thus, the amount of heat lost to the air stream and surroundings can be calculated using the following expression:

$$\dot{Q}_{\text{out}} = \dot{Q}_{\text{rad}} + \dot{Q}_{\text{conv}},$$  (30)

$$\dot{Q}_{\text{rad}} = \sigma A_{\text{cell}} (T^4 - T_0^4),$$  (31)

$$\dot{Q}_{\text{conv}} = \dot{Q}_{\text{conv,top + bottom}} + \dot{Q}_{\text{conv,sides}},$$  (32)

whose constants are in [8].

The exergy balance for a system can be written as:

$$\sum \dot{E}_{\text{mass, in}} - \sum \dot{E}_{\text{mass, out}} + \sum \dot{E}_{\text{q}} - \dot{E}_{\text{w}} = \sum i = 0,$$  (33)

where the $\dot{E}_{\text{mass, in}}$, $\dot{E}_{\text{mass, out}}$, $\dot{E}_{\text{q}}$, and $\dot{E}_{\text{w}}$ and $i$ are the exergy transfer by inlet mass, exergy transfer by outlet mass, exergy transfer by heat, exergy transfer by work and total irreversibility, respectively. Therefore, the exergy balance for a PEM fuel cell system can be written as:

$$i_{\text{CV}} = \left(1 - \frac{T_0}{T_{\text{cell}}}ight) \dot{Q}_{\text{CV}} - W_{\text{FC}} + \left(\dot{m} \cdot ex\right)_{\text{H}_2,\text{in}} + \left(\dot{m} \cdot ex\right)_{\text{O}_2,\text{in}} + \left(\dot{m} \cdot ex\right)_{\text{H}_2O,\text{in}} - \left(\dot{m} \cdot ex\right)_{\text{H}_2,\text{out}} - \left(\dot{m} \cdot ex\right)_{\text{O}_2,\text{out}} - \left(\dot{m} \cdot ex\right)_{\text{H}_2O,\text{out}}$$  (34)

in Eq. (34), if $T_{\text{cell}} = T_0$, then the irreversibility changes to total irreversibility, and can be compared to internal irreversibility.

The exergy efficiency of the cell can be written as [13]:

$$\eta_{\text{el}} = 1 - \sum \dot{E}_{\text{mass, in}}.$$  (35)
5. Results and discussion

The main goal of this study is to investigate the effects of important parameters on the irreversibility and exergy efficiency of the triangular channel geometry PEM fuel cell. The range of changing parameters in this study is shown in Table 2 and the experiments for each of the parameters are done and repeated, while the steady state condition occurred.

Figure 4 shows the experimental and calculated irreversibility and exergy efficiencies at different current density values for $T_{cell} = 60^\circ C$, $T_{O_2} = 55^\circ C$, $T_{H_2} = 55^\circ C$, $\dot{m}_{O_2} = 0.5 \text{ L min}^{-1}$, $\dot{m}_{H_2} = 0.3 \text{ L min}^{-1}$ and $P = 2.905 \text{ bar}$. It can be seen that exergy efficiency decreases while net power production increases, but the irreversibility of the cell increases. It is also clear from Figure 4 that these results from the thermodynamic model for given operating conditions are consistent with corresponding experimental data.

Figure 5 shows the effect of inlet oxygen temperature on the irreversibility and exergy efficiency of the PEM fuel cell at $T_{cell} = 60^\circ C$, $T_{H_2} = 55^\circ C$, $\dot{m}_{O_2} = 0.5 \text{ L min}^{-1}$, $\dot{m}_{H_2} = 0.3 \text{ L min}^{-1}$ and $P = 2.905 \text{ bar}$. Heat transfer, friction, mixing, chemical reactions, activation, ohmic and concentration polarizations can also increase thermodynamic irreversibility and decrease the exergy efficiency of the PEM fuel cell.

It can be seen that with an increase in oxygen temperature, the exergy efficiencies of the cell increase and irreversibilities decrease. This is in fact due to a decrease in the irreversible voltage losses of the cell with the increase in temperature, which in turn enhances the membrane conductivity and diffusion of proton in the membrane.

Figure 6 shows the effect of inlet hydrogen temperature on the irreversibility and exergy efficiency of the PEM fuel cell at $T_{cell} = 60^\circ C$, $T_{O_2} = 55^\circ C$, $\dot{m}_{O_2} = 0.5 \text{ L min}^{-1}$, $\dot{m}_{H_2} = 0.3 \text{ L min}^{-1}$ and $P = 2.905 \text{ bar}$. It is clear that with an increase in hydrogen temperature, the exergy efficiencies of the cell increase and irreversibilities decrease. The irreversibilities in the PEM fuel cell varied from 8.3 to 13.7 W in 40 °C of temperature and 7–9.8 W in 60 °C of temperature, while the

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Table 2: Range of changing the parameters in this study.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen flow rate</td>
<td>L/min</td>
<td>0.5–1.3</td>
</tr>
<tr>
<td>Hydrogen flow rate</td>
<td>L/min</td>
<td>0.3–1.1</td>
</tr>
<tr>
<td>Anode inlet pressure</td>
<td>bar</td>
<td>1–4</td>
</tr>
<tr>
<td>Cathode inlet pressure</td>
<td>bar</td>
<td>1–4</td>
</tr>
<tr>
<td>Cell temperature</td>
<td>°C</td>
<td>40–60</td>
</tr>
<tr>
<td>Oxygen temperature</td>
<td>°C</td>
<td>45–65</td>
</tr>
<tr>
<td>Hydrogen temperature</td>
<td>°C</td>
<td>40–60</td>
</tr>
</tbody>
</table>
current density changed from 0.2 to 0.6 A cm\(^{-2}\), respectively. This is in fact due to the decrease in irreversible voltage losses of the cell with the increase of temperature, which in turn enhances the membrane conductivity and diffusion of proton in the membrane.

Figure 7 shows the effect of cell temperature on the irreversibility and exergy efficiency of the PEM fuel cell at \(T_{\text{H}_2} = 55 \, ^\circ\text{C}, T_{\text{O}_2} = 55 \, ^\circ\text{C}, \dot{m}_{\text{O}_2} = 0.5 \, \text{L min}^{-1}, \dot{m}_{\text{H}_2} = 0.3 \, \text{L min}^{-1}\) and \(P = 2.905 \, \text{bar}\). It is clear that with an increase in cell temperature, the exergy efficiencies of the cell increase and irreversibilities decrease. The exergy efficiencies in the PEM fuel cell varied from 58\% to 42\% in 40 °C of temperature and 64\%–49\% in 60 °C of temperature, while the current density changed from 0.2 to 0.6 A cm\(^{-2}\), respectively.

Figure 8 shows the effect of the inlet pressure of gases on the irreversibility and exergy efficiency of the PEM fuel cell at \(T_{\text{cell}} = 60 \, ^\circ\text{C}, T_{\text{H}_2} = 55 \, ^\circ\text{C}, T_{\text{O}_2} = 55 \, ^\circ\text{C}, \dot{m}_{\text{O}_2} = 0.5 \, \text{L min}^{-1}\) and \(\dot{m}_{\text{H}_2} = 0.3 \, \text{L min}^{-1}\). It is clear that with an increase in inlet pressure, the exergy efficiencies of the cell increase and irreversibilities decrease. Increasing the inlet pressure leads to an increase in the concentration of the reactants at the reaction sites and decreases the irreversible losses in the anode and cathode, which in turn enhances the performance of the cell with the increase of the reversible thermodynamic potential according to the Nernst equation. Also, it is clear that for current density less than 0.38 A cm\(^{-2}\), the exergy efficiency of the cell decreases with increasing inlet pressure.

Figure 9 shows the effect of oxygen flow rate on the irreversibility and exergy efficiency of the PEM fuel cell at \(T_{\text{cell}} = 60 \, ^\circ\text{C}, T_{\text{H}_2} = 55 \, ^\circ\text{C}, T_{\text{O}_2} = 55 \, ^\circ\text{C}, P = 2.905 \, \text{bar}\) and \(\dot{m}_{\text{H}_2} = 0.3 \, \text{L min}^{-1}\). It is clear that when the flow rate of oxygen is 0.9 L min\(^{-1}\), the irreversibility of the cell is at a lower value and the exergy efficiency is at a higher value. This is due to increasing the output power of the cell at 0.9 L min\(^{-1}\) for the oxygen flow rate. It is because, by increasing the flow rate of oxygen, more oxidizer transports from GDL to the catalyst layer and the electrochemical reaction enhances.

Figure 10 shows the effect of hydrogen flow rate on the irreversibility and exergy efficiency of the PEM fuel cell at \(T_{\text{cell}} = 60 \, ^\circ\text{C}, T_{\text{H}_2} = 55 \, ^\circ\text{C}, T_{\text{O}_2} = 55 \, ^\circ\text{C}, P = 2.905 \, \text{bar}\) and \(\dot{m}_{\text{O}_2} = 0.5 \, \text{L min}^{-1}\). It is clear that when the flow rate of hydrogen increases, the irreversibility of the cell increases, but the exergy
efficiency is at a higher value at $\dot{m}_{H_2} = 0.5 \text{ L min}^{-1}$. This is due to increasing the output power of the cell at 0.5 L min$^{-1}$ for hydrogen flow rate. This is because, by increasing the flow rate of the hydrogen, more fuel transports from GDL to the catalyst layer and the electrochemical reaction enhances.

6. Conclusion

In this study, the effects of input oxygen temperature ($T_{O_2}$), input hydrogen temperature ($T_{H_2}$), cell temperature ($T_{\text{cell}}$), input pressure ($P$), oxygen flow rate ($\dot{m}_{O_2}$) and hydrogen
flow rate (\(\dot{m}_{H_2}\)) on the irreversibility and exergy efficiency of a triangular channel geometry PEM fuel cell have been investigated experimentally. We have found that:

- With an increase in oxygen and hydrogen temperature, the exergy efficiencies of the cell increase and irreversibilities decrease. This is in fact due to the decrease in irreversible voltage losses of the cell with the increase in temperature.
- With an increase in cell temperature, the exergy efficiency of the cell increases and irreversibilities decrease. The exergy efficiency varied from 58% to 42% at 40°C, while the current density changed from 0.2 to 0.6 A cm\(^{-2}\).
- With an increase in inlet pressure, the exergy efficiency of the cell increases and irreversibilities decrease.
- When the flow rate of oxygen is 0.9 L min\(^{-1}\), the irreversibility of the cell is at a lower value and the exergy efficiency is at a higher value. This is due to increasing the output power of the cell at 0.9 L min\(^{-1}\) for oxygen flow rate.
- When the flow rate of hydrogen increases, the irreversibility of the cell increases, but the exergy efficiency is at a higher value: at \(\dot{m}_{H_2} = 0.5\) L min\(^{-1}\).

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References


Iman Khazaee was born in Mashhad, Iran, in 1983. He received his B.S. degree in Mechanical Engineering from Ferdowsi University of Mashhad in 2006 and his M.S. degree in the same subject from Amirkabir University of Technology in 2008. He obtained a Ph.D. degree from Ferdowsi University of Mashhad in 2011. Currently, he is working on PEM fuel cells and their optimization.

Mohsen Ghazikhani is Associate Professor of Mechanical Engineering at Ferdowsi University of Mashhad. He received his B.S. degree in Mechanical Engineering from Ferdowsi University of Mashhad in 2006 and his M.S. degree in the same subject from Amirkabir University of Technology in 2008. He obtained a Ph.D. degree from Ferdowsi University of Mashhad in 2011. He has published more than 30 articles in well-recognized journals, books and proceedings.

Mohammad Mohammadiun was born in Shahrood, Iran, in 1977. He received his B.S. degree in Mechanical Engineering from Khajeh Nasir Toosi University of Technology, Tehran, in 2001, and his M.S. degree in Bio-mechanics from Amirkabir University of Technology in 2004. He has been a doctoral student in the Department of Mechanical Engineering at Ferdowsi University of Mashhad since 2008.