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Parametric Effects on Proton Exchange Membrane Fuel Cell Performance: An Analytical Perspective

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Abstract
This paper introduces a regression study on the operating parameters of different types of fuel cells (FCs) such as fuel used, catalysts, efficiency, operating temperature, switching time, load carriers, applications with advantages. In addition, mathematical modeling of the Proton exchange membrane fuel cell (PEMFC) is considered for MATLAB simulation and the inter-relationships of the parametric effect schemes are discussed. In the current study, the significant operational parameters such as operating temperature, reactant (H_2 and O_2) flow pressure, and membrane resistance are considered. The procured results in the form of I-V or polarization curve, efficiency, power and current density have been utilized owing to study the PEMFC behavior. For the validation, designed a single MATLAB/Simulink model of PEMFC is compared with commercial existing model. The results reflect the fine coordination between the simulated and commercially available PEMFC model. Present study can be used as a supportive tool to beginners to select the appropriate parameters for a FC assisted applications.

Keywords- Current density, Fuel cell, Power density, Parametric effect, Polarization curve, Renewable energy.

1. Introduction
After the development of interfaces between power electronics, researchers are now working to reduce their installation costs and explore FC technology to produce electrical power for stationary and dynamic load applications. The FC technology is attaining the popularity with respect to distributed generation (DG) and hybrid power generation along with the non-conventional energy sources of energy such as, solar-photovoltaic (PV) system, wind-turbine system etc. (Peighambardoust et al., 2010). The FC operating parameters such as operating temperature, membrane resistance and fuel pressure are having key role to show the performance behavior of FC system directly/indirectly. In addition, a comprehensive study on the effect of performance parameters on FC performance can be observed with the non-linearity behavior of polarization (I-V) curve. In this aspect, it helps to new learners for efficient operation of FC system.

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The authors investigated the effect of different operating parameters such as the transfer coefficient, current density, diffusion coefficient, absolute permeability and conductivity of the membrane (Wee, 2007). An extensive study is carried out on parametric effects with the performance parameters temperature and reactants flow pressure (Min et al., 2006). It is endeavored to analyze the parametric influential impact and observed that the humidifier temperature and pressure are parameters to impact the PEMFC performance (Benchouia et al., 2013). The impact of operating parameters e. g. reactant flow pressure, temperature and interrogated the pattern is shown through the behavior of I-V curve, which shows the non-linear nature (Kaytakoğlu and Akyalm, 2007). A PEMFC model is developed and investigated the parametric impact incurred by various operating parameters and experimental results shows the impact on the performance of FC. This study was helpful to provide operating behavior of FC (Seyezhai and Mathur, 2011). Another parametric study is executed to estimate the effect of various parameters such as temperature, current density, fuel utilization factors and pressure on the performance of Solid Oxide fuel cell (SOFC) (Qingshan et al., 2008). Later, Bo et al. (2009) investigated the effect of temperature on the PEMFC performance and validated the results by implementing it on hardware. The effect of electrolyte temperature, air flow rate at cathode, fuel particle size on the cell voltage and power density was investigated to show the impact on the performance of fuel cell (Coppo et al., 2006; Kacprzak et al., 2013). In another study, authors investigated, and experimental results depicted the adverse effect of temperature on the performance of micro Direct Methanol fuel cell (DMFC) (Chaudhary and Chauhan, 2014). Mathematical modeling and parametric study of distinct types of FCs is carried out by taking the parameters such as temperature, reactants flow pressure and membrane resistance (Yuan and Yang, 2015).

On the basis of operative parameters such as temperature, efficiency, fuel utilization, power density and applications, FCs are categorized such as PEMFC, Phosphoric Acid Fuel Cell (PAFC), Alkaline FC (AFC), Solid Oxide FC (SOFC), Molten Carbonate FC (MCFC), Direct Methanol FC (DMFC), Direct Ethanol FC (DEFC), Direct Ethylene Glycol FC (DEGFC), Enzymatic FC (EFC), Direct carbon FC (DCFC) and Direct Boro-hydride FC (DBFC) etc. Recently, researchers are focusing on the development and performance enhancement of FCs, their size and cost also.

For the commercial applications, several types of FCs are available, and their operating parameters, advantages and applications are shown in Table 1-2 (Stambouli and Traversa, 2002; Kirubakaran et al., 2009; Peighambardoust et al., 2010; Giddey et al., 2012; Mekhilef et al., 2012; Hermida-Castro et al., 2013; Sharaf and Orban, 2014; Pachauri and Chauhan, 2015).

In this paper, a performance behavior study is carried out on the MATLAB / Simulink PEMFC model with support for operating parameter variations e.g. fuel pressure and temperature. This article is a new effort to pull together several facets of FC technology. An overview on FC technology addresses organizational and efficiency criteria, specifications, advantages and challenges compared to a comprehensive review. Therefore, the PEMFC mathematical analysis is used to build the MATLAB/Simulink model, which demonstrates the impact of different operating parameters on PEMFC performance.

Table 1. Comparisons of FCs with their operation parameters

Fuel Cell	Fuel Utilized	Efficiency (%)	Operating Temp.(ºC)	Switching time	Charge carrier
PEMFC	Pure H_2	53-58	50-100	Second (fast)	H^+
AFC	Pure H_2	60	90-100	Second (fast)	OH^-
PAFC	Pure H_2	>40	150-200	Hours (slow)	H^+
MCFC	H_2, CO, CH_4	45-47	600-700	Several hours (very slow)	CO_3^{--}
SOFC	CH_4	35-43	800-1000	Several hours (very slow)	O^{2-}
DMFC	CH_3OH	40	60-200	N/A	H^+
DEFC	Liquid ethanol-water solution	20-40	Ambient 120	NA	H^+
DEGFC	Liquid ethylene glycol	20-40	Ambient 130	NA	H^+
MFC	Glucose	15-65	20-60	NA	H^+
EFC	Glucose	30	20-40	NA	H^+
DCFC	Coal	70-90	600-1000	Several Hours	O^{2-}
DBHFC	$NaBH_4$	40-50	20-85	Seconds	Na^+

Table 2. Operating parameters of various FCs with applications and advantages

Fuel Cell	Electrolyte	Application	Advantages
PEMFC	Nafion	Hospital, banking power supply	High power density Quick startup time
AFC	KOH water solution	Military Space	High power density Quick response
PAFC	H_3PO_4 in Silicon carbide	Distribution generation	Catalyst flexibility In expensive catalyst
MCFC	Li_2CO_3, Na_2CO_3 in $LiAlO_2$	Transportation .g. marine, railway	High efficiency Fuel flexibility
SOFC	Yttria-stabilized Zirconia (YSZ)	Residential power backup	• High electrical efficiency • Inexpensive catalyst
DMFC	Solid Nafion	Power backup for computers and other portable devices	Compact size Cost minimized due to fuel reformer absence
DEFC	Nafion	Portable power	• Compact size Eco-friendly
DEGFC	Nafion	Electrical Utility	• Compact size Simple thermal management
MFC	Ion exchange membrane	Electrical Utility	• Fuel flexibility
EFC	Ion exchange membrane	Electrical Utility	• High response time Simple structure
DCFC	YSZ Molten hydride	Electrical Utility	High efficiency
DBHFC	Solid Nafion	Electrical Utility Distributive generation	• Compact size High fuel utilization efficiency

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2. Mathematical Modeling of PEMFC System

FC voltage (V_{fc}) can be stated using Eq. (1) (Ural et al., 2007; Pachauri and Chauhan, 2017). Where, Nernst voltage (E) is minimized by three voltage drop categories during the load condition as:

$$V_{fc} = E - V_{act} - V_{conc} - V_{ohm} \tag{1}$$

The E_V can be expressed in Eq. (2), which gives the O.C. potential (E) of FC. Moreover, V_{act} can be represented by Tafel's equation, shown in Eq. (3) respectively.

$$E = E_0 + \frac{RT}{2F}\left[\ln\left\{\left(\frac{P_{H_2}}{P_{H_2O}}\right)\left(P_{O_2}\right)^{\frac{1}{2}}\right\}\right] \tag{2}$$

$$V_{act} = -k_1 + k_2 T - \left[\ln\left\{\frac{\left(I_{fc}\right)^{k_3}}{\left(Conc.O_2\right)^{k_4 T}}\right\}\right] \tag{3}$$

Where, T demonstrates FC stack temperature (°C), $Conc.O_2$ demonstrates O_2 (di-Oxide) concentration and I_{fc} represents FC current (ampere). The O_2 concentration $\left(Conc.O_2\right)$ is taken as a function of O_2 pressure and FC stack temperature in Eq. (4) as:

$$Conc.O_2 = \left\{\frac{Po_2}{5.08\times10^6 \times e^{\left(-498/T\right)}}\right\} \tag{4}$$

Ohmic voltage is almost linear in nature and membrane resistance is observed in Eqs. (5)-(6) as,

$$V_{ohm} = I_{fc} R_{mem} \tag{5}$$

$$R_{mem} = \frac{t_m}{\sigma} \tag{6}$$

Concentration voltage is given in Eq. (7) as,

$$V_{conc} = \eta_1 - \eta_2 (T - 273) e^{\eta_3 l} \tag{7}$$

where, the η_1 , η_2 and η_3 are constant.

Eqs. (1)-(7) could be helped to evaluate for cell potential (V_{fc}). If all the FCs are arranged in stack to produce the FC stack voltage, expressed in Eq. (8) as,

$$V_{stack} = N V_{fc} \tag{8}$$

H_2, O_2 and H_2O flow pressures are shown in Eq. (9) as,

$$P_{H_2} = \left\{ \frac{\left(m_{H_2} R_{H_2} \right)}{V_{anode}} \right\} T \quad , \quad P_{O_2} = \left\{ \frac{\left(m_{O_2} R_{O_2} \right)}{V_{cathode}} \right\} T \text{ , and } P_{H_2O} = \left\{ \frac{\left(m_{H_2O} \right)^{\frac{1}{2}}}{k_{cathode}} \right\} q_{H_2O} \tag{9}$$

FC Power and current density can be formulated using Eq. (10) as,

$$J = \frac{I_{fc}}{A} \qquad\qquad P_d = \frac{P_{fc}}{A} \tag{10}$$

Where, J is the current density (A/cm^2), I_{fc} is current (Amp) and A is area (cm^2) of FC and P_d is power density and it is expressed as Watt/cm^2.

Efficiency can be computed by Eq. (11) as,

$$Efficiency = \frac{U_f V_{fc}}{1.48} \tag{11}$$

where, U_f is the fuel utilization factor (range of 95%) and 1.48V shows the max. voltage (V_{fc}) that can be achieved using the higher heating value (HHV) for the hydrogen enthalpy.

2.1 Validation of MATLAB/Simulink Model of PEMFC

Designed PEMFC model is compared with the commercially available FC model number FC-H_2-051C (manufactured by ARBIN Instruments) for validation. Various parameters are considered for the comparison, shown in Table 3. MATLAB/Simulink modeling of single PEMFC, all the used constants/parameters are taken from the benchmark papers.

Table 3. Single PEMFC model performance (Pachauri and Chauhan, 2015)

Specifications of PEMFC	PEMFC Model: FC-H_2-051C (Mfd. By ARBIN INSTRUMENTS)	Designed PEMFC model for validation
Fuel cell area	5 cm^2	5 cm^2
Fuel required	H_2/O_2	H_2/O_2
DC voltage	0.7 V	0.74 V
Current	3 A	3.025 A
Current density (Nominal)	600 mA/cm	605 mA/cm
Power rating (Nominal)	2 W	2.11 W
Efficiency	45 % at 2 W	44.8 % at 2.11 W
Operating temp. range	70-80 °C	70-120 °C
Maximum temperature	120	

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3. Results and Discussion

MATLAB/Simulink PEMFC model is investigated by important parametric effect for the considered test cases:

3.1 Performance of PEMFC System at Constant Temperature and Variable Reactants Flow Pressure

(i) Efficiency, Power Density and Voltage of Single PEMFC

The efficiency, voltage and power density for a single FC at fixed temperature and variable reactants flow pressure are shown in Figure 2 (a)-(d). It is evident from the figure that the operating temperature of PEMFC is considered fixed as 80 ^{0}C and reactants flow pressure $\left(P_{H_2}/P_{O_2}\right)$ are raised in considered four test cases as; 1/1, 5/1, 1/5 and 1/10 atm. The obtained results reflected the changes into the single PEMFC efficiency, voltage and power density. Initially, the reactant flow-pressure P_{H_2}/P_{O_2} is kept 1/1 atm. at anode and cathode, the obtained ranges of efficiency, power density and voltage of single FC are 45-33%, 0.0055-0.030W/m^2 and 0.70- 0.505V respectively, which are illustrated in Figure 1(a). In Figure 1(b), the H_2 flow pressure $\left(P_{H_2}\right)$ is increased as 5/1 atm, so obtained range of efficiency, power density and voltage of single PEMFC are 46-34%, 0.010-0.030W/m^2 and 0.66-0.59V. Furthermore, the reactant flow pressure $\left(P_{H_2}/P_{O_2}\right)$ at anode and cathode is kept 1/5 atm, the ranges of efficiency, power density and voltage of single PEMFC are 40-33%, 0.0089-0.024W/m^2 and 0.66-0.49V respectively, which shown in Figure 1(c). Moreover, the reactant flow pressure $\left(P_{H_2}/P_{O_2}\right)$ at anode and cathode is increased up to 1/10 atm, the ranges of efficiency, power density and voltage of single FC are 41-30%, 0.008-0.023W/m^2 and 0.64-0.47V, shown in Figure 1(d). Overall conclusion of this investigation under case: Fixed temperature and reactants flow pressure variation is that the increment in hydrogen reactant flow pressure enhances the FC efficiency, power density and voltage but increment in oxygen reactant flow pressure decreases the FC performance. The obtained results are summarized in Table 4.

Table 4. Performance of single PEMFC at constant temperature and reactants flow pressure variation

P_{H_2}/P_{O_2} **(atm)** **(T= 80 ºC Fixed)**	**Efficiency (%)**	**Voltage (V)**	**Power density (W/m^2)**
P_{H_2}/P_{O_2} =1/1	45-33	0.70-0.505	0.0055-0.030
P_{H_2}/P_{O_2} =5/1	46-34	0.66-0.59	0.010-0.030
P_{H_2}/P_{O_2} =1/5	40-33	0.66-0.49	0.0089-0.024
P_{H_2}/P_{O_2} =1/10	41-30	0.64-0.47	0.008-0.023

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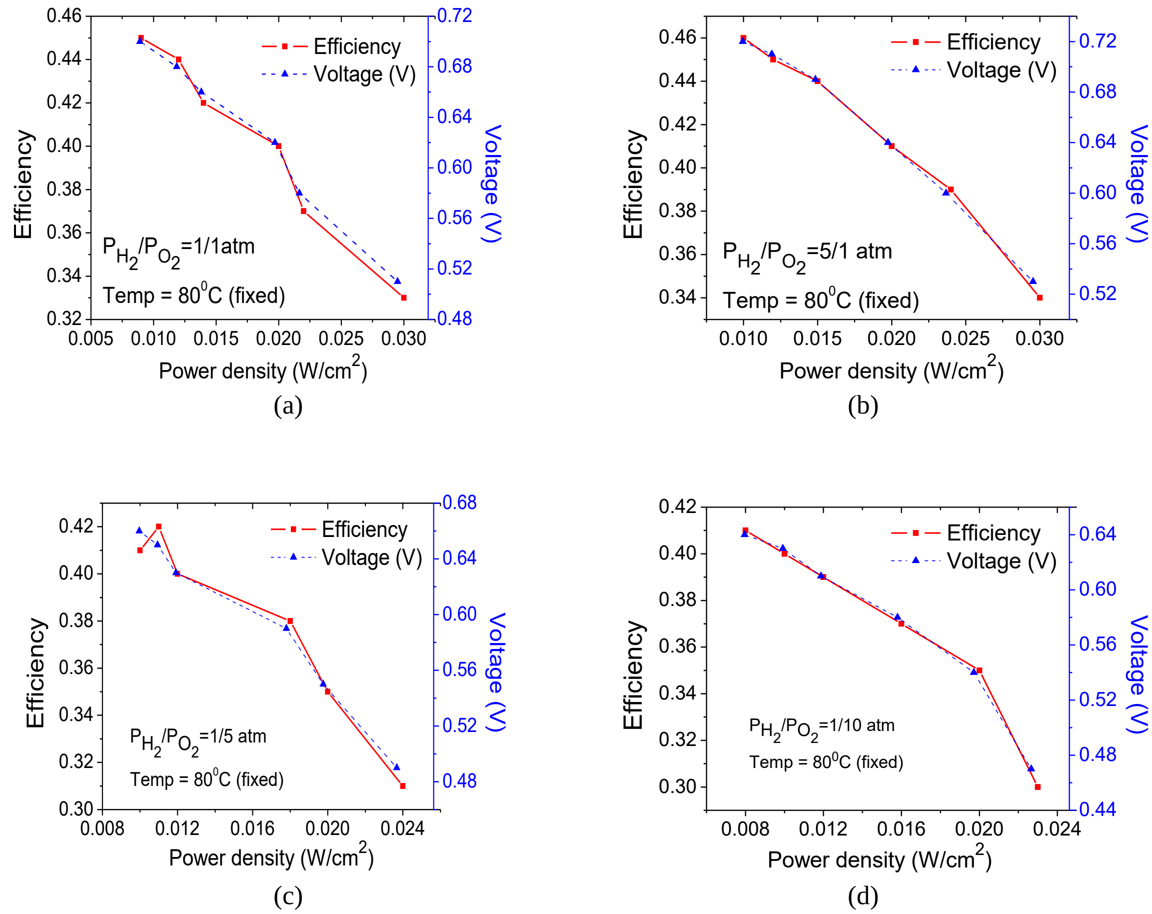

Figure 1. (a)-(d). Efficiency, power density and voltage at constant temperature and reactants flow pressure variation

(ii) Efficiency, Current Density and Voltage of Single PEMFC

The efficiency, voltage and current density for a single PEMFC at constant temperature and variable flow pressure (of reactant) are shown in Figure 2(a)-(d). It is evident from the figure that the operating temperature of PEMFC is considered to be static at 80 ^{0}C and reactants flow pressure $\left(P_{H_2}/P_{O_2}\right)$ are raised in considered four test cases as; 1/1, 5/1. 1/5 and 1/10 atm. The obtained results reflected the changes into the single PEMFC efficiency, voltage and power density. Initially, the reactant flow pressure $\left(P_{H_2}/P_{O_2}\right)$ is kept 1/1 atm. at anode and cathode. The obtained ranges of efficiency, power density and voltage of single PEMFC are 45-33%, 0.012-0.052 W/m^2 and 0.70-0.50V respectively, which are shown in Figure 3(a). In Figure 2(b), the reactant flow pressure $\left(P_{H_2}/P_{O_2}\right)$ is increased 5/1 atm, so obtained range of efficiency, power density and voltage of single FC are 46-34%, 0.08-0.050 W/m^2 and 0.72-0.53V. Furthermore, the reactant flow pressure $\left(P_{H_2}/P_{O_2}\right)$ at anode and cathode is kept 1/5 atm, the ranges of efficiency, power density and voltage of single PEMFC are 41.5-31%, 0.008-0.048 W/m^2 and 0.66-0.49V respectively, which shown in

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Figure 2(c). Moreover, the reactant flow pressure $\left(P_{H_2}/P_{O_2}\right)$ at anode and cathode is increased up to 1/10 atm, the ranges of efficiency, power density and voltage of single FC are 41-30%, 0.009-0.050 W/m^2 and 0.62-0.46V, shown in Figure 2(d). Overall conclusion of this investigation under case: Fixed temperature and reactants flow pressure variation is that the increment in hydrogen reactant flow pressure enhances the FC efficiency, current density and voltage but increment in oxygen reactant flow pressure decreases the FC performance. The obtained results are depicted in Table 5.

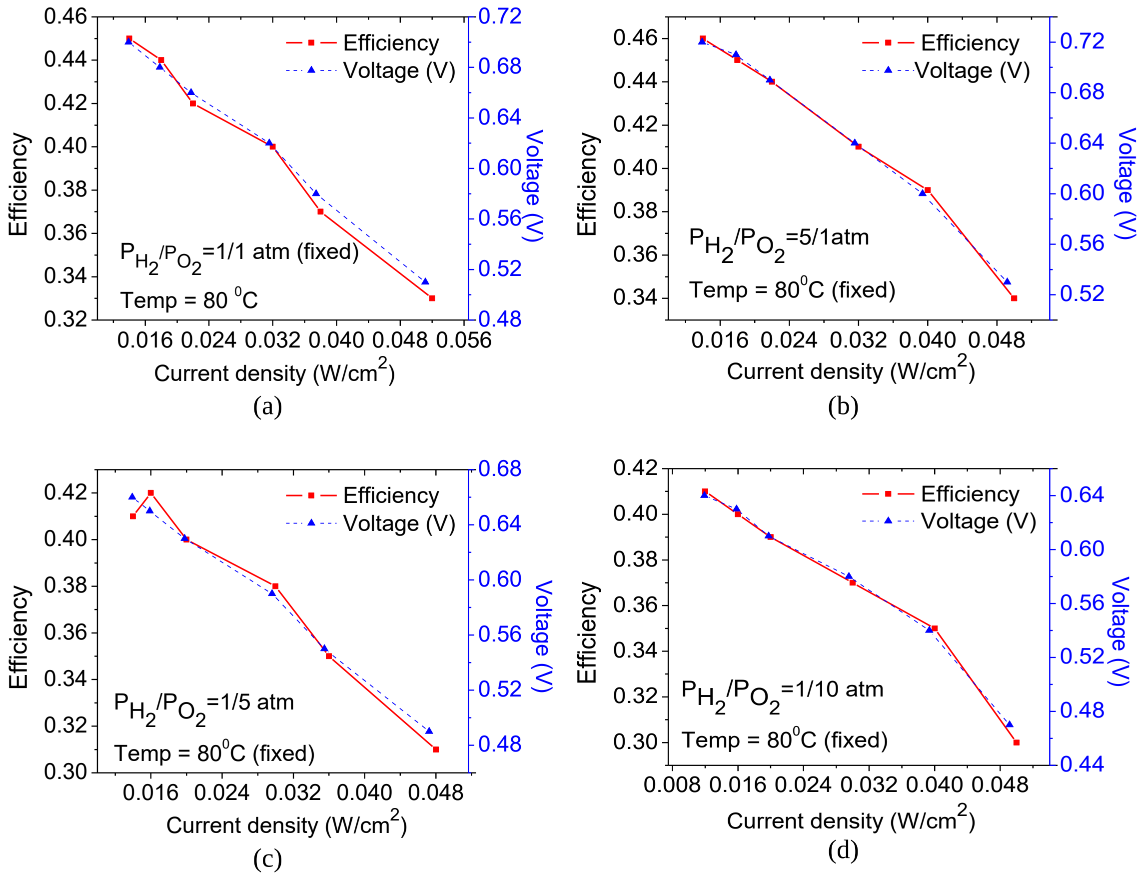

Figure 2. (a)-(d). Efficiency, current density and voltage at fixed temperature and reactant flow pressure variation

Table 5. PEMFC performance at constant reactants flow pressure and temperature variation

P_{H_2}/P_{O_2} **(atm)** **(T= 80 ºC Fixed)**	**Efficiency (%)**	**Voltage (V)**	**Current density (A/m²)**
P_{H_2}/P_{O_2} =1/1	45-33	0.70-0.50	0.012-0.052
P_{H_2}/P_{O_2} =5/1	46-34	0.72-0.53	0.08-0.05
P_{H_2}/P_{O_2} =1/5	41.5-31	0.66-0.49	0.008-0.048
P_{H_2}/P_{O_2} =1/10	41-30	0.62-0.46	0.009-0.050

3.2 Performance of PEMFC System at Constant Reactants Flow Pressure and Temperature Variation

(i) Efficiency, Power Density and Voltage of Single PEMFC

The efficiency, voltage and power density for a single PEMFC at constant flow pressure (reactants) and variable temperature are shown in Figure 3(a)-(d). It is evident from the figure that the reactant flow pressure of PEMFC is kept fixed 1/1 atm. at anode and cathode and the operating temperature is considered four test cases: 60 ºC, 70 ºC, 80ºC and 90ºC. The obtained results reflected the changes into the single PEMFC efficiency, power density and voltage. Initially, the operating temperature is considered 60ºC. The ranges of efficiency, power density and voltage of single PEMFC are 50-36%, 0.015-0.031W/m^2 and 0.78- 0.58V respectively, which are shown in Figure 3(a). In Figure 3(b), the operating temperature is raised up to 70ºC, so resultant range of efficiency, power density and voltage are found as 48-35%, 0.010-0.029 W/m^2 and 0.73-0.53V. Furthermore, the operating temperature is increased up to 80ºC, the ranges of efficiency, power density and voltage are decreased as 45-33%, 0.0054-0.028 W/m^2 and 0.68-0.52V respectively, which are shown in Figure 3(c). Moreover, the operating temperature is taken 90ºC, the range of efficiency, power density and voltage are evaluated as 41.5-31%, 0.009-0.023 W/m^2 and 0.65-0.475V, shown in Figure 3(d) as,

Overall conclusion of this investigation under case: Fixed reactant flow pressure and variable temperature is that the increment in operating temp. is more than it rated value, then the efficiency, power density and voltage of single PEMFC are decreased. The obtained results are summarized in Table 6 as,

Table 6. PEMFC performance at constant reactants flow pressure and temperature variation

Temp (ºC) P_{H_2}/P_{O_2} **(atm) Fixed**	**Efficiency (%)**	**Voltage (V)**	**Power density (W/m²)**
60	50-36	0.78-0.58	0.015-0.031
70	48-35	0.73-0.53	0.010-0.029
80	45-33	0.68-0.52	0.0054-0.028
90	41.5-31	0.65-0.47	0.009-0.023

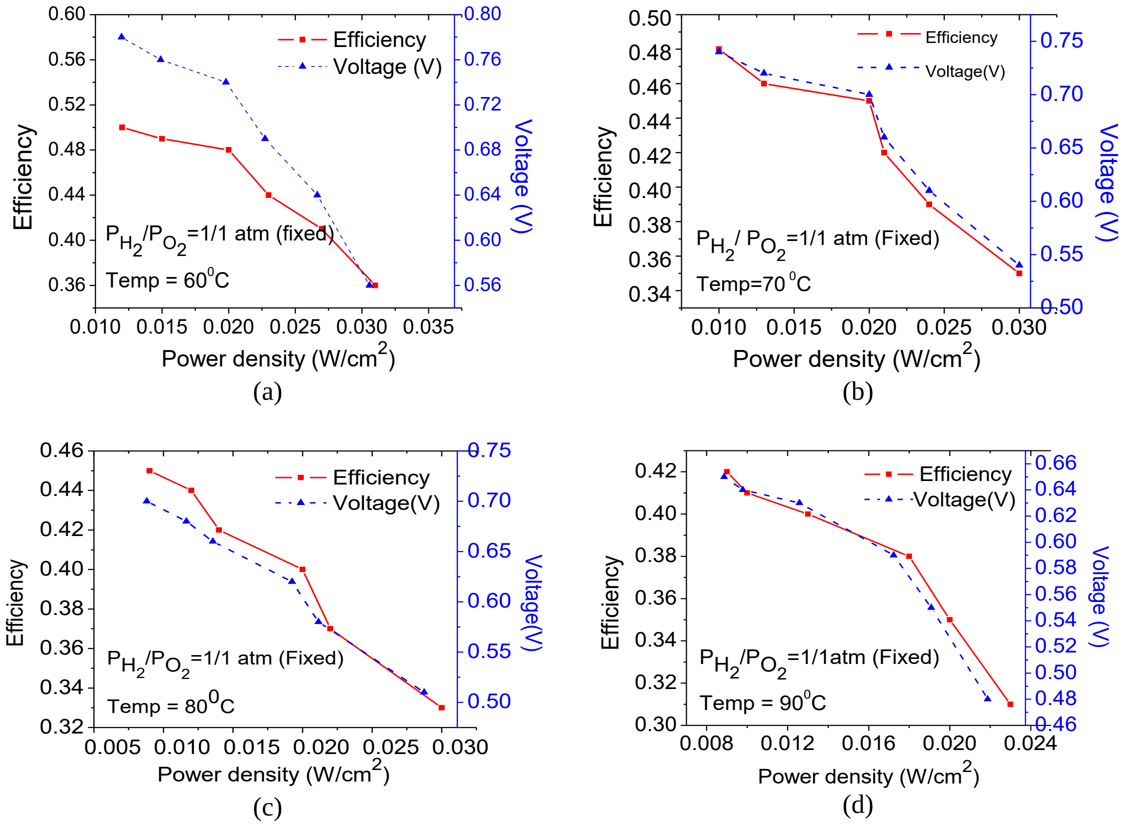

Figure 3. (a)-(d). Efficiency, power density and voltage at fixed reactants flow pressure and temperature variations

(ii) Efficiency, Current Density and Voltage of Single PEMFC

The efficiency, voltage and power density for a single PEMFC at constant flow pressure (reactants) and variable temperature are shown in Figure 4(a)-(d). It is evident from the figure that the reactant flow pressure of PEMFC is kept fixed 1/1 atm. at anode and cathode and the operating temperature is considered four test cases: 60 ºC, 70 ºC, 80ºC and 90ºC. The obtained results reflected the changes into the single PEMFC efficiency, power density and voltage. Initially, the operating temperature is considered 60ºC. The ranges of efficiency, power density and voltage of single FC are 50-36%, 0.015-0.055A/m^2 and 0.77-0.56V respectively, which are shown in Figure 4(a). In Figure 4(b), the operating temperature is raised up to 70ºC, so resultant range of efficiency, power density and voltage are found as 48-35%, 0.015- 0.055A/m^2 and 0.74-0.53V. Furthermore, the operating temperature is increased up to 80ºC, the ranges of efficiency, power density and voltage are decreased as 45-32.5%, 0.015-0.055A/m^2 and 0.658-0.51V respectively, which are shown in Figure 4(c). Moreover, the operating temperature is taken 90ºC, the range of efficiency, power density and voltage are evaluated as 42-31%, 0.015-0.048A/m^2 and 0.64-0.47V, shown in Figure 4(d). Overall conclusion of the present investigation under case: Fixed reactant flow pressure and variable temperature is that the increment in operating temperature is more than it rated value, then the efficiency and voltage of single PEMFC are decreased but current density is almost same for all temperature cases. The obtained results are summarized in Table 7.

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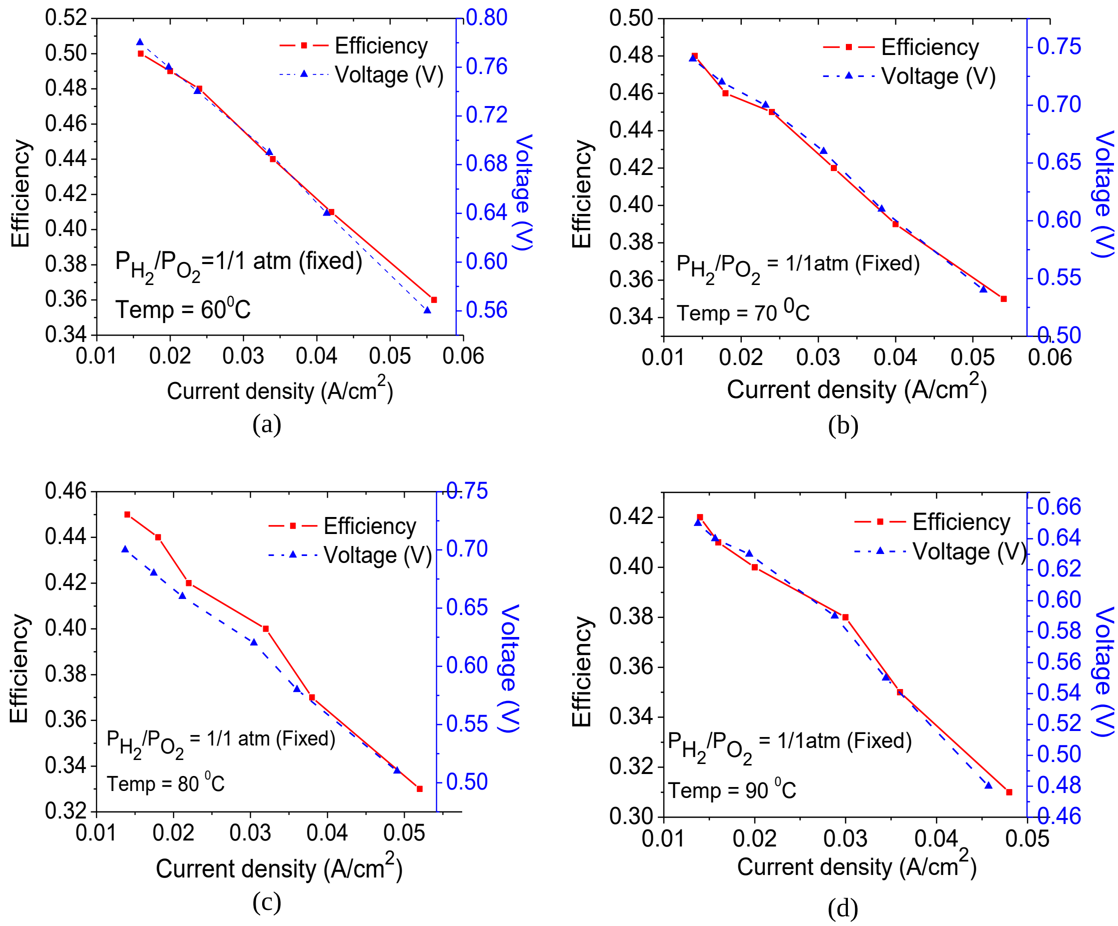

Figure 4. (a)-(d). Efficiency, current density and voltage at fixed reactants flow pressure and temperature variation

Table 7. Performance of single PEMFC at constant reactants flow pressure and temperature variation

Temp (°C) P_{H_2}/P_{O_2} **(atm) Fixed**	**Efficiency (%)**	**Voltage (V)**	**Current density (W/m^2)**
60	50-36	0.77-0.56	0.015-0.031
70	48-35	0.74-0.53	0.015-0.055
80	45-32.5	0.65-0.51	0.015-0.055
90	42-31	0.64-0.47	0.015-0.048

4. Conclusion

An investigation on the FC performance such as power density, current density, efficiency, single PEMFC voltage is calculated. In addition, the qualitative analysis of parametric effect on single FC system, various parameters e.g. reactants flow- pressure, operating temperature and membrane resistance are considered. A brief assessment of FCs operating parameters e.g. fuel utilized, catalysis, switching responses, power density, efficiency and operating temperature range for comparison study. A comprehensive simulation of single PEMFC is executed and acceptable results are obtained in MATLAB/Simulink environment.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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