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Research Paper

Computational Analysis of PEM Fuel Cell under Different Operating Mode

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Abstract- The polymer electrolyte membrane fuel cells one of the amazing energy sources and also its have incredible properties. The studies are purely theoretical based and compare with few other models, and experimental results. It is reported in several studies. The PEM fuel cell can be used as energy source in future, but for future energy source, few modifications are require, like enhance PEMFCs performance and decrease its cost. In overall investigation a three dimensional steady state model are used for study the pin-type flow field using with the membrane thickness 0.054mm and water transport coefficient 1.15cm^2/sec. The parallel and serpentine membranes analysis data are used to compare with the pin-type membrane data, whereas compare with experimental data. The experimental data provide good approximation with pin-type, parallel and serpentine flow field. Therefore theoretical study is much useful when the experimental data are not available. So the theoretical data of PEM fuel cells are much necessary for design a new PEM fuel. The computation fluid dynamic (CFD) tool are used to monitoring its statically performance, where as the CFD software are amazing tool and used to analysis and simulation the data. Overall study approaches to enhance the performance of PEMFCs, decreasing its cost and make it reliable as retail use.

Keywords- PEMFC; Mathematical model; Flow field design; Electrochemical reaction; Membrane; Computational fluid dynamics.

1. Introduction

The proton exchange membrane fuel cells (PEMFCs) are one of the efficient sources of energy [1]. In this scenario, the chemical fuels directly convert in to electrical energy, where as the atmospheric hydrogen is used as a fuel. It is eco-friendly, used in wild areas; military application, space operation and electric vehicles [2]. There are some other advantages like high efficiency, low in weight, easy to transportation and portable etc. Its incredible properties refer it, as a future energy sources [3-5].Due to increasing energy demand day to day, only conventional energy sources will not be able to fully meet our needs at future as it is limited. Now we have to focus on other sources of energy apart from the conventional energy sources, and PEM fuel cells can be a better energy source because these sputum precedent properties. The studies of PEM fuel cells much important for future energy power sources. Its present approach is not sufficient. Therefore should be more modification in its present state [6].

The three dimensional model is one of the most important tool to be solved the membrane problem before successful designing the membrane and Proton Exchange Membrane fuel cells (PEMFC). The membrane is major component of fuel cells. Those are heart of any fuel cells. There are many models to analyse the fuel cell statically but three dimensional are much accurate and attach with real problem. A three dimensional CFD model is propose to design a membrane and analysed its performance under different flow channels, where as the parallel and serpentine membranes data are used to comparing the data corresponding to pin-type membrane. The experiments validate data for uniform depth and step-wise depth flow channels and, single-path and multi-path flow channels are given in ref [7].

The experimental performances of PEM fuel cells are investigated from gas flow field design with 20W power were used [8]. ***C. Suarez et al.*** suggested the PEMFCs with experimental performance using novel bio inspired channels design from CFD, analysed effect and researching flow field designs with its enhanced performance [9]. ***A.R. Vijay Babu, P.M. Kumar and G.S. Rao*** are studied the parametric analysis of PEMFCs to enhance its performance under fabrication of membrane electrode assembly at 40% Pt/C loading. These PEMFCs are in fuel cell based electric vehicle and perform an experiment under different parameters such as, cell temperatures, oxygen and hydrogen flow rates and humidification temperatures in both electrodes. The performance of fuel cell vehicle is investigated with load tests and the vehicle continuously run without any auxiliary power supply support [10].

A 1KW PEMFC with self-humidifying stack are investigated by zero-dimensional mathematical model and Matlab Simulink tools zero used to data simulation. A new mathematical equation are predicted with instead of pure oxygen used in the concentration losses and its impact in air to supply PEM fuel cell with output voltage, and the current is drawn from it [11]. ***L. Placca and R. Kouta*** analysis the effect of fault tree for degradation process modeling on proton exchange membrane fuel cell. Here the fault tree modeling is used to discuss two main reasons. First reason show the effects on the global degradation of the fuel cell and second one show the causal relations of the degradation mechanisms [12]. ***M. Chandran, K. Palaniswamy, N.B. Karthik Babu and O. Das*** are investigated the performances of polymer electrolyte membrane fuel cell under fixed influence current rate as 0.1, 0.3, and 0.25 A/cm^2/s for 0.2, 0.6, and 1.0 A/cm^{2}respectively. Two similar cells are used the active 25 cm^2 was tested under two different load step for the same dynamic load cycle. In this investigation the total degradation is found in those studies the performance as 20.67% and 10.72% in tow different dynamic load cycles respectively [13].

H. Rezk et al. are studies and identifying optimal operating parameters for enhance the performance of PEMFC and the same strategy is used for modeling and optimization stages. An experimental datasets is utilized in creating the model for adaptive network-based fuzzy inference system. The most important parameters is used to enhance the performance fuel cell, the parameters provide the best values of fuel pressure, oxidant pressure, fuel flow rate, and oxidant flow rate corresponding to max power. The obtained results demonstrated corresponding the values are 0.017 as well as 0.0262 respectively for treating and testing phases. The coefficient of determination values is 0.9921 as well as 0.9622 respectively for treating coupled with testing phases. The optimal parameters are 1.0 bar, 0.8 bar, 117.03 mL/min, 150.0 mL/min respectively fuel pressure, oxidant pressure, fuel flow rate, and oxidant flow rate with max power. The output power of PEMFC has been increased from 0.587 W using experimental works to 0.92 W [14].

2. Analysis method

The PEMFC investigate under three dimensional steady states model. The mass, momentum, energy and species equations are used to finding the solution of electrochemical and membrane equation.

2.1 Model assumption

The computational studies of PEM fuel cells are based on following assumptions:

- The pin type flow field of thickness 0.054 mm are used to investigate the PEM fuel cell.
- The PEM fuel cells are investigated under 333K and 353K temperature.
- Under this study the value of water transport coefficient for fuel cells is taken1.15 cm^2/sec.
- The limiting current are used in this configuration is 1.2A.

2.2 Computational model

Three dimensional computational models are used to theoretically analysis the PEM fuel cells and enhance its performance after simulate it, the CFD tool are used to design the cell components and statically running conditions are analysed from CFD software [15]. There are three subcategories of 3D computational models: (i) Flow or Transport model, (ii) Membrane model and (iii) Electrochemical model.

2.2.1 Transport or Flow Sub-model

The transport equations in term of mass, momentum, energy and species can be written as follows [16]:

Continuity:

$$\nabla.(\rho v) = S_m \quad (1)$$

Momentum:

$$\frac{1}{\varepsilon^2}\nabla.(\rho vv) = -\nabla p + \frac{1}{\varepsilon}\nabla.(\mu\nabla v) + \rho g + S_{mom} \quad (2)$$

Species:

$$\nabla.(\rho v Y_i) = -\nabla.J_i + S_i \quad (3)$$

Energy:

$$\nabla.\left(\rho c_p v T\right) = \nabla.(k_{eff}\nabla T) + S_h \quad (4)$$

The detail descriptions about transport/flow sub model must see ref. [17].

2.2.2 Membrane Sub-model

The water transport of a membrane is depended on two important phenomena such as, (i) electro-osmotic drug and (ii) back diffusion. In detailed information about the phenomenon must see ref. [17, 18]. The net water transport across flow field/membrane can be written as:

$$\alpha = n_d - F.D_w.\frac{(C_{w,c} - C_{w,a})}{I.t_{cat}.t_{mem}} \quad (5)$$

2.2.2.1 Water content

The electro-osmotic drag and diffusion coefficients are calculated form activities of the gas, the gas transport from anode to cathode side are written as [19]:

$$a = \frac{P_{H_2O}}{P_{sat}} \quad (6)$$

The membrane conductivity is written as:

$$\lambda = \begin{cases} 0.043 + 17.81a - 39.85a^2 + 36a^3, 0 < a \leq 1 \\ 14 + 1.4(a-1), \ \ 1 < a \leq 3 \end{cases} \quad (7)$$

2.2.2.2 Proton conductivity

The proton conductivity of membrane is also the function of water content and cell temperature are written as [20]:

$$\sigma_{mem} = [0.5139\lambda - 0.326] \exp\left[1268\left(\frac{1}{303} - \frac{1}{T}\right)\right] \quad (8)$$

2.2.3 Electrochemical Sub-model

The identical cell voltage of fuel cells can be described from Nernst flow field equation as follows [21]:

$$E = E_0 + \frac{RT}{2F}\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right) \quad (9)$$

The cell voltage also knows as output voltage. In a PEM fuel cell, there are few losses such as, activation, ohmic and concentration losses due to inherent voltage losses (internal currents and cross-over losses). Therefore open circuit voltage V_{OC} is also less than reversible voltage. So the cell voltage can be written as follows [22]:

Cell voltage

$$V_{cell} = V_{oc} - V_{act} - V_{ohm} - V_{conc} \quad (10)$$

Activation losses

$$V_{act} = \frac{RT}{\alpha_c F}\ln\left(\frac{i}{i_{o,c}}\right) \quad (11)$$

Ohmic losses

$$V_{ohm} = \left(R_{cell} + \frac{t_{mem}}{\sigma_{mem}}\right) \quad (12)$$

Concentration losses

$$V_{conc} = \frac{RT}{nF}\ln\left(1 - \frac{i}{i_{lim}}\right) \quad (13)$$

3. Results and Discussion

The pin-type membrane is used to investigate the designing of PEM fuel cell under different operating condition. The three dimensional steady state models are used to compute the data based on the given geometrical and operating parameters are listed in ***table 1***.The three dimensional steady state models are used to investigate the PEM fuel cell according to data using from ***table 1***. The ***equations 9 to 13 are*** used to calculate the data and the calculated data are used to draw the figure**.** In overall study, the water transport coefficients taken into account 1.15cm^2/sec and the pin-type flow field are used. The thickness of pin-type membrane is taken 0.054 mm and the cell is operated at 333K and 353K thermal temperature. The ***fig. 1***illustrates the polarization curve and power density under 300K operating temperature using with pin-type membrane of 0.054 mm thickness and calculated data are compared with experimental data. The results show great agreement with experimental data. The ***fig. 2*** also same as the ***fig. 1***thatshow the polarization curve and power density with membrane thickness 0.054 mm but here comparison show between 333K and 353K operating temperature and with corresponding experimental data [22, 23].

The computational data are calculated from three dimensional steady state equation for the parallel and p-type membrane under 300K and compared with experimental data. The ***fig. 3*** show better justification between polarization and power density curve and provide great agreement with experimental data (show from dots) [21]. In this configuration the max current and power density are found 0.858A/cm^2 and 0.715W/cm^2 at 333K temperature. Similar at, 353K temperature the max current and power density are calculated 0.849A/cm^2 and 0.676W/cm^2. The ***fig. 4*** shows the polarization curve and power density using limiting current 1.2A, and with water transport coefficient 0.5 and 1.15 cm^2/sec at room temperature. The overall investigations are much useful to collect the more information under several operating mode. The collect information about a PEM fuel cell is used to enhance the performance of cell.

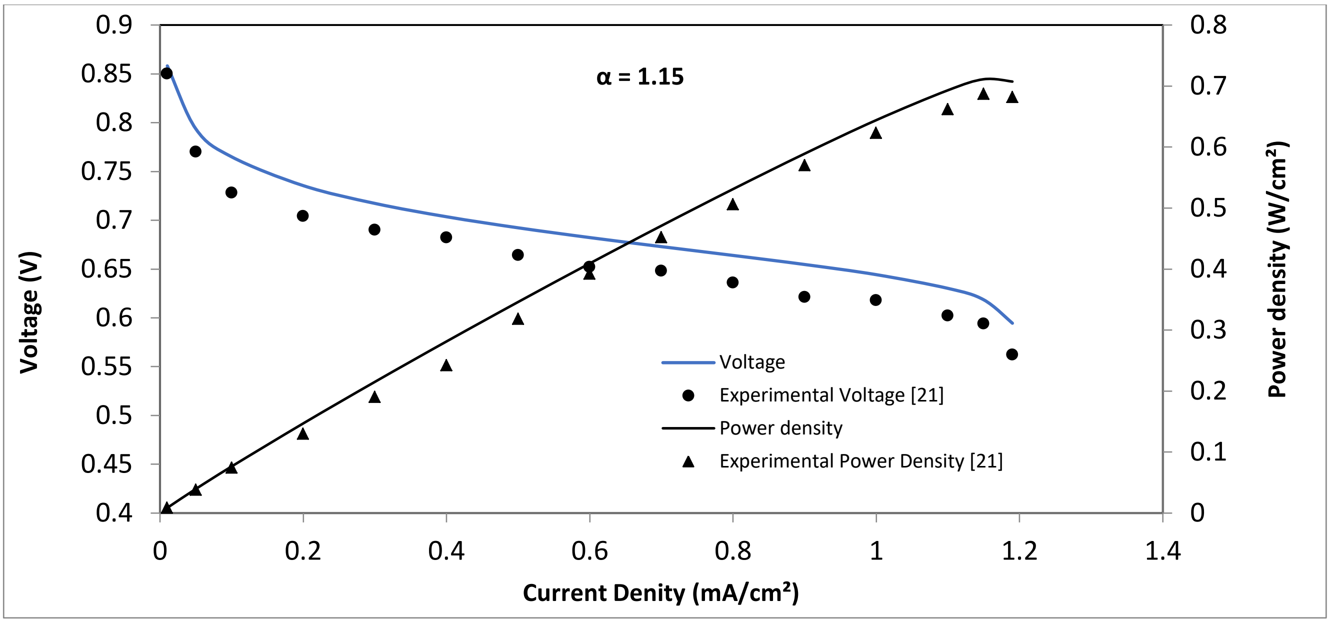

Figure 1 Show the polarization curve and power density under membrane thickness 0.054mm at room temperature and compared with experimental data [21].

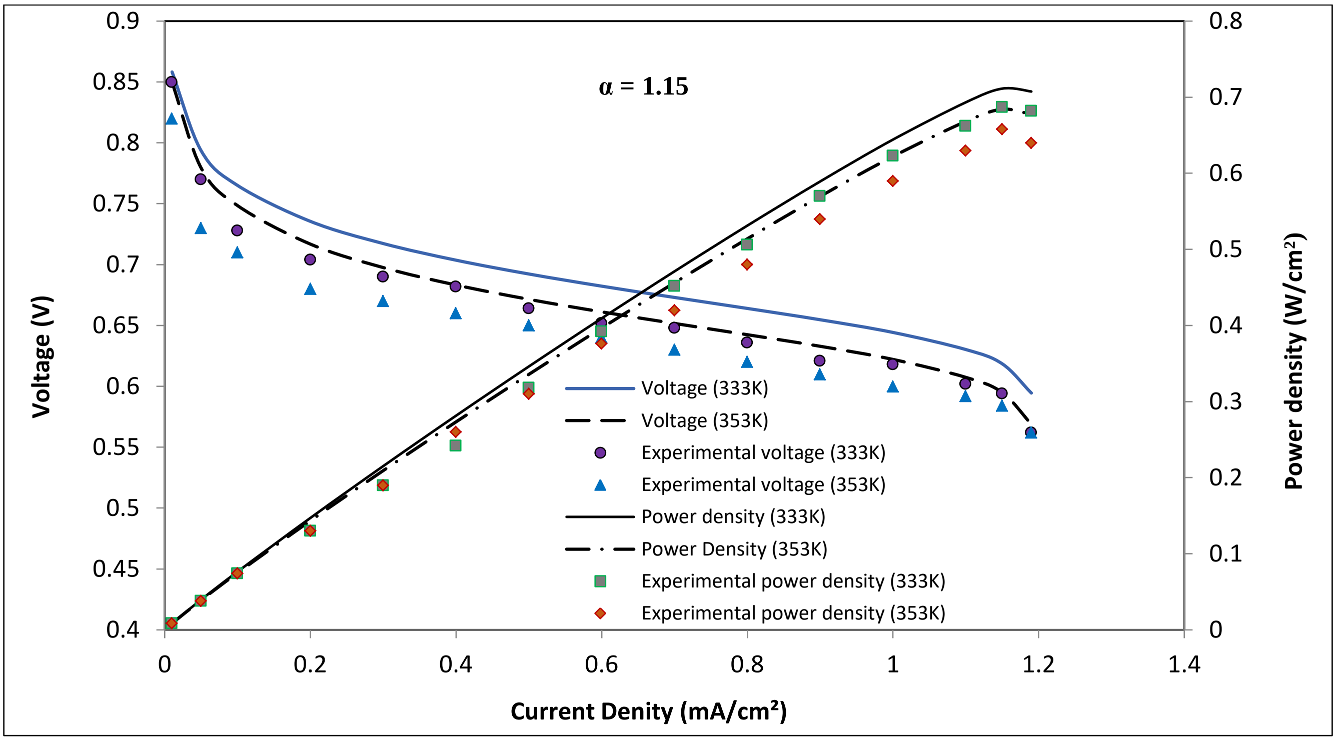

Figure 2 Show the polarization curve and power density under membrane thickness 0.054 mm at 333K and 353K temperature and compared with experimental data [18, 19].

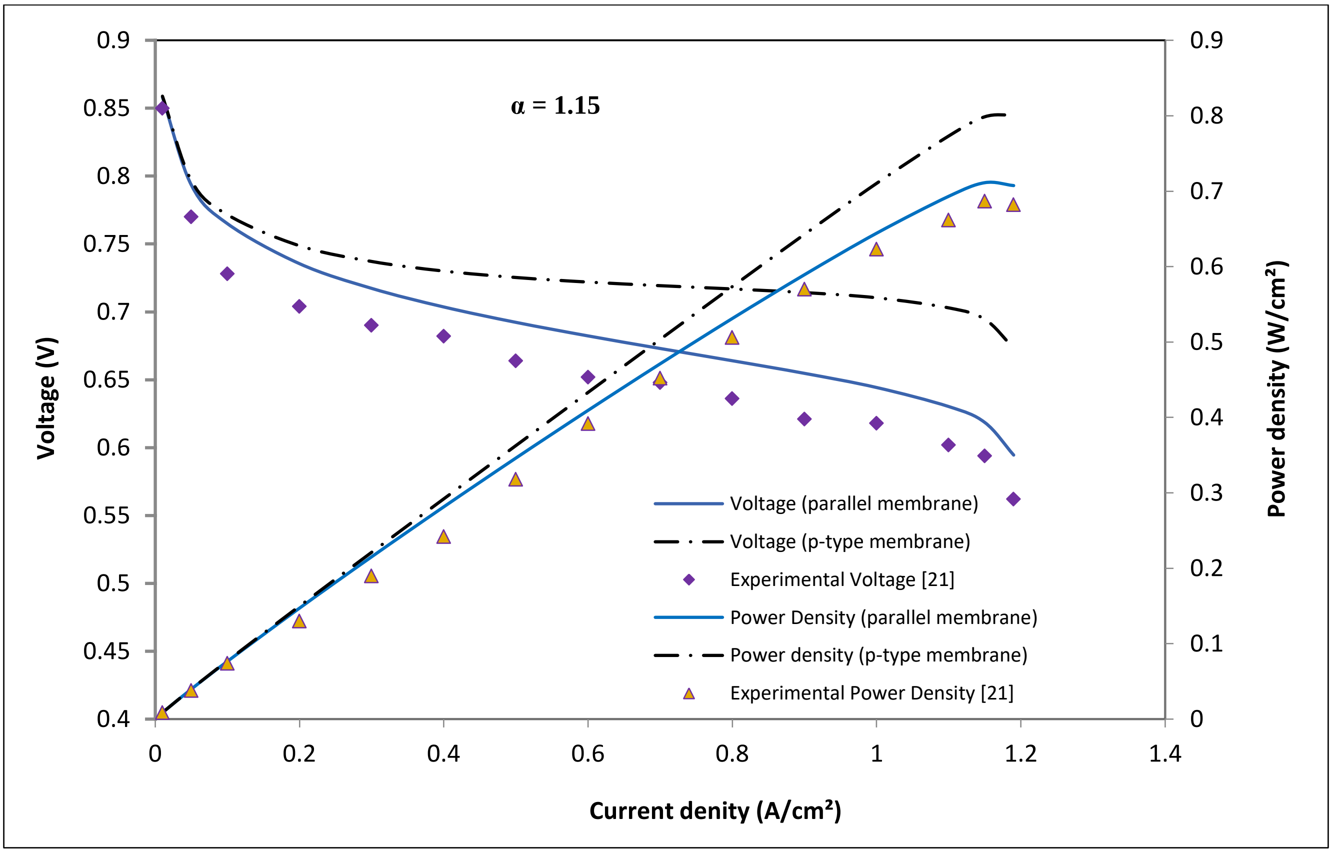

Figure 3 Show the polarization curve and power density under parallel (thickness 0.054 mm) and serpentine membrane (thickness 0.0254 mm) at room temperature and compared with experimental data [21].

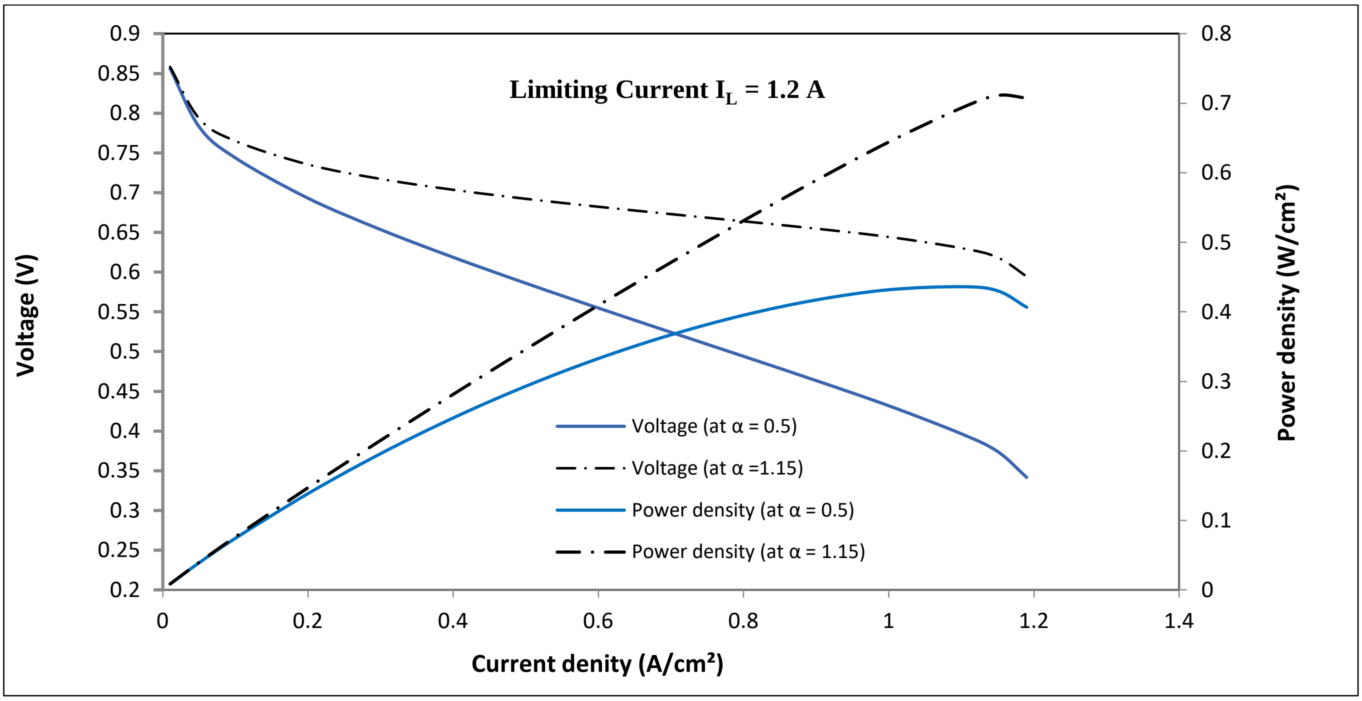

Figure 4 Show the polarization curve and power density under limiting current 1.2 A with taking water transport coefficient 0.5 and 1.15 cm^2/sec at room temperature.

Table 1 Geometric and operating parameters of fuel cells.

Description	Symbol	Value
Cell/electrode height (mm)	L	80, 90, 120
Cell/electrode width (mm)	W	10, 12, 14
Gas channel height (mm)	l	60, 80, 120
Gas channel width (mm)	w	2
Gas channel depth (mm)	d	1.2
Rib width (mm)	s	1
GDL porosity	ε_{GDL}	0.5
Catalyst porosity	ε_{CL}	0.5
Membrane thickness (mm)	δ_{MEM}	0.054
Open-circuit voltage (V)	V_{oc}	0.95
Operating temperature (K)	T_{cell}	333, 353
Anode mass flow (kg/s)	$q_{m,a}$	6×10^{-7}
Limiting current (A/cm^2)	i_{lim}	1.2

4. Conclusions

The main goals of those studies are enhance the performance of PEM fuel cells. Also increasing its efficiency and decreasing cost. This is necessary to make the fuel cell more sustainable power sources in nearly future. The computational studies of PEM fuel cells are much useful for finding its statically performance data for analysis the PEMFCs under different operation. When experimental data do not available because the experimental setup of such large enough modes are not possible. Here the mathematical analysis of PEM fuel cells are used to enhance the performance of cell and also it can be used for designing a fuel cell after monitoring its statically performed from CFD software according to our requirement. Therefore the methods provide good approach to design a PEM fuel cell for new require application.

Declarations

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Conflicts of Interest
The authors declare that there are no competing interests.

References

[1] C.Y. Jung, W.J. Kim, S.C. Yi, "Computational analysis of polarizations in membrane-electrode-assembly for proton exchange membrane fuel cells," *Journal of Membrane Science,* Vol. **341**, Issue **1-2**, pp. **5-10**, **2009**. https://doi.org/10.1016/j.memsci.2009.06.006

[2] P. Ahmadi, E. Kjeang, "Realistic simulation of fuel economy and life cycle metrics for hydrogen fuel cell vehicles," *International Journal of Energy Research,* Vol. **41**, Issue **5**, pp.**714-727, 2017**. https://doi.org/10.1002/er.3672

[3] J.D. Morse, "Micro fuel cell power sources," *International Journal of Energy Research,* Vol. **31**, pp. **576-602, 2007**. https://doi.org/10.1002/er.1281

[4] F. Barbir, S. Yazici, "Status and development of PEM fuel cell technology," *International Journal of Energy Research, Vol.* **32**, Issue **5**,pp. **369-378**, **2008**. https://doi.org/10.1002/er.1371

[5] S. Endoo, K. Pruksathorn, P. Piumsomboon, "Identification of the key variables in membrane electrode preparation for PEM fuel cells by a factorial design," *Renewable Energy,* Vol. **35**, Issue **4**, pp. **807-813**, **2010.** https://doi.org/10.1016/j.renene.2009.10.013

[6] A.S.M. Al-Obaidi, T. Nguyen Huynh, "Renewable vs. conventional energy: which wins the race to sustainable development?," *IOP Conference Series: Materials Science and Engineering,* Vol.**434**, Issue **3**, pp. **012310**, **2018**. https://doi.org/10.1088/1757-899X/434/1/012310

[7] B.S. Machado, M. Mamlouk, N. Chakraborty, "Three-dimensional agglomerate model of an anion exchange membrane fuel cell using air at the cathode- A parametric study," *Journal Power Sources,* Vol. **412**, pp. **105-117**, **2019**. https://doi.org/10.1016/j.jpowsour.2018.11.022

[8] H.A. Dhahad, W.H. Alawee, A.K. Hassan, "Experimental study of the effect of flow field design to PEM fuel cells performance," *Renewable Energy Focus,* Vol. **30**, pp. **71-77**, **2019**. https://doi.org/10.1016/j.ref.2019.05.002

[9] C. Suarez, A. Iranzo, B. Toharias, F. Rosa, "Experimental and numerical Investigation on the design of a bio inspired PEM fuel cell," *Energy,* Vol. **257**, pp. **124799**, **2022**. https://doi.org/10.1016/j.energy.2022.124799

[10] A.R. Vijay Babu, P.M. Kumar, G.S. Rao, "Parametric study of the proton exchange membrane fuel cell for investigation of enhanced performance used in fuel cell vehicles,"*Alexandria Engineering Journal,* Vol.**57**, Issue **4**, pp. **3953-3958**, **2018**. https://doi.org/10.1016/j.aej.2018.03.010

[11] M.M. Ibrahim Salem, R. Ali, H. Zhang, "Simplified mathematical model of proton exchange membrane fuel cell based on horizon fuel cell stack,"*Journal Modified Power System Clean Energy,* Vol. **4**, Issue **4**, pp. **668-679**, **2016**. https://doi.org/10.1007/s40565-016-0196-5

[12] L. Placca, R. Kouta, "Fault tree analysis for PEM fuel cell degradation process modelling," *International Journal of Hydrogen Energy,* Vol. **36**, Issue **19**, pp. **12393-12405**, **2011**. https://doi.org/10.1016/j.ijhydene.2011.06.093

[13] M. Chandran, K. Palaniswamy, N.B. KarthikBabu, O. Das, "A study of the influence of current ramp rate on the performance of polymer electrolyte membrane fuel cell," Scientific Reports, Vol. **12**, pp. **21888**, **2022**. https://doi.org/10.1038/s41598-022-25037-0

[14] H. Rezk, T. Wilberforce, E.T. Sayed, Ahmed N.M. Alahmadid, A.G. Olabi, "Finding best operational conditions of PEM fuel cell using adaptive neuro-fuzzy inference system and metaheuristic," *Energy Reports,* Vol. **8**, pp. **6181-6190**, **2022**. https://doi.org/10.1016/j.egyr.2022.04.061

[15] E. Afshari, "Computational analysis of heat transfer in a PEM fuel cell with metal foam as a flow field," *Journal of Thermal Analysis and Calorimetry,* Vol. **139**, pp. **2423-2434**, **2020**. https://doi.org/10.1007/s10973-019-08354-x

[16] A. Sagar, S. Chugh, K. Sonkar, A. Sharma, E. Kjeang, "A computational analysis on the operational behaviour of open cathode polymer electrolyte membrane fuel cells,"*International Journal of Hydrogen Energy,* Vol. **45**, pp. **34125-34138**, **2020**. https://doi.org/10.1016/j.ijhydene.2020.09.133

[17] T.E. Springer, T.A. Zawodzinski, S. Gottesfeld, "Polymer Electrolyte Fuel Cell Model," *Journal of Electrochemical Society,* Vol. **138**, pp. **2334-2342**, **1991**. http://dx.doi.org/10.1149/1.2085971

[18] P.M. Kumar, A.K. Kolar, "Effect of cathode channel dimensions on the performance of an air-breathing PEM fuel cell," *International Journal of Thermal Science*, Vol. **49**, pp. **844-857**, **2010**. https://doi:10.1016/j.ijthermalsci.2009.12.002

[19] W. Pen, P. Wang, X. Chen, F. Wang, G. Dai, "Combined effects of flow channel configuration and operating conditions on PEM fuel cell performance," *Energy Conversion and Management,* Vol. **220**, pp. **113046**, **2020**. https://doi.org/10.1016/j.enconman.2020.113046

[20] Y.M. Ferng, A. Su, "A three-dimensional full cell CFD model used to investigate the effects of different flow channel designs on PEMFC performance," *International Journal of Hydrogen Energy*, Vol. **32**, pp. **4466–4476**, **2007**. https://doi.org/10.1016/j.ijhydene.2007.05.012

[21] C. Mahjoubi, J.C. Olivier, S. Skander-mustapha, M. Machmoum, I. Slama-belkhodja, "An improved thermal control of open cathode proton exchange membrane fuel cell," *International Journal of Hydrogen Energy,*Vol. **44**, Issue **22**, pp. **11332–11345**, **2019**. https://doi.org/10.1016/j.ijhydene.2018.11.055

[22] Z. Hu, L. Xu, J. Li, Q. Gan, X. Xu, M. Ouyang, Z. Song, J. Kim, "A multipoint voltage-monitoring method for fuel cell inconsistency analysis," *Energy Conversion and Management,* Vol. **177**, pp. **572-581**, **2018**. https://doi.org/10.1016/j.enconman.2018.09.077

[23] T. Reshetenko, A. Kulikovsky, "On the distribution of local current density along a PEM fuel cell cathode channel," *Electrochemistry Communications*, Vol. **101**, pp. **35-38**, **2019**. https://doi.org/10.1016/j.elecom.2019.02.005

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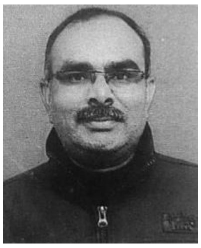

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