

The Relative Humidity Effect Of The Reactants Flows Into The Cell To Increase PEM Fuel Cell Performance

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Abstract. Design of the Proton Exchange Membrane (PEM) fuel cell system is still developed and improved to achieve performance and efficiency optimal. Improvement of PEM fuel cell performance can be achieved by knowing the effect of system parameters based on thermodynamics on voltage and current density. Many parameters affect the performance of PEM fuel cell, one of which is the relative humidity of the reactants that flow in on the anode and cathode sides. The results of this study show that the increase in relative humidity value on the cathode side (RHC) causes a significant increase in current density value when compared to the increase of relative humidity value on the anode side (RHA). The performance of single cells with high values is found in RHC is from 70% to 90%. The maximum current density generated at RHA is 70% and RHC is 90% with PEM operating temperature of 363 K and pressure of 1 atm

1 Introduction

Fuel cells are electro chemical devices that convert chemical energy from fuel (hydrogen) and oxidant (oxygen or air) directly into electrical energy and thermal energy, producing water as a by product [1-3]. One type of fuel cell is the PEM fuel cell, which can be operated at low temperatures to produce electrical energy. Developing the system performance of PEM fuel cells requires a suitable design and appropriate technology. The main purpose is to achieve optimal performance and obtain a low-cost PEM fuel cell system.

Many parameters in the PEM fuel cell system are associated with other parameters in the system. These parameters consist of the operating conditions, the design of the membrane electrolyte assembly (MEA) and the stack PEM fuel cell system [4-5]. In the case of the PEM fuel cells, the system is defined as a group of objects or materials that are integrated and operated together. The performance of the PEM fuel cells is evaluated in the form of the voltage generated, the power density and the efficiency. The optimal performance of the cells is influenced by many internal and external factors, such as the fuel cell design and assembly, the degradation of materials, the operating conditions and the impurities or the contaminants [6]. The design and optimization of a PEMFC system are very complex

because they are related to the use of the system, the selection of appropriate components, and the functions of each variable. The purpose of studies on PEM fuel cell systems is to consider the capital and operational costs, efficiency, fuel consumption, flexibility and fuel cell life [7-10]. Other parameters such as the pressure, temperature, composition and utilization of the fuel, and composition and the utilization of oxidant can be varied simultaneously to achieve the desired operating point.

The main challenges facing the commercialization of PEM fuel cells include cost and reliability PEM fuel cell characteristics are highly influenced by the design of an optimal PEMFC system. The PEM fuel cell central system must be supported by providing an oxidant supply (oxygen or air), a fuel supply (hydrogen), heat and water management, process control, equipment and supervision [11-12]. The many failures in PEM fuel cell systems include flooding, the diffusion of water from the cathode side to the anode side and poor of integration heat and mass management during the operation of the system [13-15]. The focus of this research was to develop a fundamental thermodynamic basis for developing a modeling system to optimize the performance of PEM fuel cell systems. The next focus was to determine the relative humidity of the reactants entering the PEM fuel cell stack on the voltage and the current density that was produced by the resulting fuel cell system.

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2 RESEARCH DESIGN

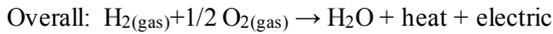
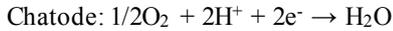
This research design is to determine the performance of a single cell PEM fuel cell based on the process performed by mulyaznmi 2013 [16]. Single cell Of PEM fuel cell performance produced using an assumed reactant has passed the external humidifier. The determination of single cell of PEM fuel cell performance was determined by varying relative humidity on the anode and cathode sides, as well as validating results obtained from other studies. The operating parameters used as the basis for the modeling case are listed in Table 1.

Table 1. Basic modeling operation parameters

Parameters	Value
Cell Temperature	353
Thick dry membrane	0.0051 cm for Nafion 112
Catalyst load	0.0002 g cm ⁻²
Thick catalyst	0.0005 cm
Faraday Constant	96,485 C/mol elektron
Stoichiometric ratio for hydrogen	1.2
Stoichiometric ratio for oxygen	2
Universal gas constant	8.314 J/mol K

3 Mathematics Models

The reaction that occurs in the PEM fuel cell system is:



3.1 Water Liquid in the reactant

The water vapor component with hydrogen as a reactant flowing in the PEM fuel cell is (Barbier, F. 2005):

$$\mathcal{N}_{\text{H}_2\text{O in H}_2} = \frac{\delta_{\text{H}_2} \cdot I}{2F} \cdot \eta_{\text{cell}} \cdot \psi \quad (1)$$

The molar humidity ratio of ψ , y is as follows::

$$\psi = \frac{N_v}{N_a} = \frac{\text{mol of water vapor}}{\text{mol of dry gas}} \quad (2)$$

The mass and molar relation of humidity is

$$\psi \frac{M_v}{M_a} = x \quad (3)$$

Mole fraction of water vapor can be interpreted as follows[17]:

$$y = \varphi \frac{P_{\text{sat}}}{P} \quad (4)$$

φ is relative humidity, P_{sat} is saturated vapor pressure (atm), and P is total pressure (atm).

The saturated vapor pressure $p_{\text{H}_2\text{O}}$ is as follows[18]:

$$\begin{aligned} P_{\text{H}_2\text{O}}^o(T) = & 6.02724 \times 10^{-3} \\ & + 4.38484 \times 10^{-4}(T - 273.15) \\ & + 1.39844 \times 10^{-5}(T - 273.25)^2 \\ & + 2.71166 \times 10^{-7}(T - 273.15)^3 \\ & + 2.57731 \times 10^{-9}(T - 273.15)^4 \\ & + 2.82254 \times 10^{-11}(T - 273.15)^5 \end{aligned}$$

(5)

The molar ratio relationship ψ with partial pressure is::

$$\psi = \frac{P_v}{P_a} = \frac{P_v}{P - P_v} \quad (6)$$

P_v is partial pressure of water vapor (atm), P_a is partial pressure gas (atm), P is total pressure.

Based on equation (6), then:

$$\psi = \frac{x \cdot M_a}{M_w} \quad (7)$$

Then the equation becomes

$$\frac{P_v}{P - P_v} = \frac{x \cdot M_a}{M_w} \quad (8)$$

Consequently:

$$\psi = \frac{\varphi \cdot P_{V_s}}{P - \varphi \cdot P_{V_s}} \quad (9)$$

So the amount of moles of water vapor in hydrogen is:

$$\mathcal{N}_{\text{H}_2\text{O in H}_2} = \frac{\delta_{\text{H}_2} \cdot I}{2F} \cdot \eta_{\text{cell}} \cdot \frac{\varphi \cdot P_{V_s}}{P - \varphi \cdot P_{V_s}} \quad (10)$$

where: P_a is the steam flow pressure in the hydrogen flowing into the anode. While the amount of water vapor in oxygen flowing in PEM fuel cell is:

$$\mathcal{N}_{\text{H}_2\text{O in O}_2} = \delta_{\text{O}_2} \cdot \mathcal{N}_{\text{O}_2} \cdot \eta_{\text{cell}} \cdot \frac{\varphi \cdot P_{V_s}}{P_c - \varphi \cdot P_{V_s}} \quad (11)$$

Where P_c is the pressure of the water vapor flow in oxygen flows into the anode. The amount of water vapor in the air flowing in PEM fuel cell is:

$$\mathcal{N}_{\text{H}_2\text{O in air}} = \delta_{\text{O}_2} \cdot n_{\text{cell}} \cdot \frac{N_{\text{O}_2}}{X_{\text{O}_2}} \cdot \frac{\varphi \cdot P_{V_s}}{P_c - \varphi \cdot P_{V_s}} \quad (12)$$

The mass of air flowing out of PEM fuel cell is:

$$\mathcal{N}_{\text{air, out stack}} = \left[\left(\delta_{\text{O}_2} \frac{1 - X_{\text{mol O}_2}}{X_{\text{mol O}_2}} \right) + (\delta_{\text{O}_2} - 1) \right] \frac{I}{4F} n_{\text{cell}} \quad (13)$$

3.2 EOD and Back Diffusion

The number of protons that move from the anode to the cathode of the PEM fuel cell ($\mathcal{N}_{\text{drag}}$) on the EOD phenomenon can be calculated based on the following equations [19-21]:

$$\mathcal{N}_{\text{drag}} = \frac{n_d}{F} I \quad (14)$$

EOD coefficient value (n_d) can be defined based on the following equation:

$$n_d = \frac{2.5 \lambda p_{em}}{22} \quad (15)$$

Where λp_{em} is the membrane water content that can be calculated based on the following equation [22-24]:

$$\begin{aligned} \lambda = & 0.043 + 17.81 a_{\text{H}_2\text{O}} - 39.85 a_{\text{H}_2\text{O}}^2 \\ & + 36 \cdot a_{\text{H}_2\text{O}}^3 \quad 0 < a_{\text{H}_2\text{O}} \leq 1 \end{aligned} \quad (16)$$

Membrane water activity $a_{\text{H}_2\text{O}}$ is calculated based on the following equation

$$a_{\text{H}_2\text{O}} = \frac{a_{\text{H}_2\text{O},a} + a_{\text{H}_2\text{O},k}}{2} \quad (17)$$

Water diffusion from the cathode side to the anode side PEM fuel cell $\mathcal{N}_{\text{diff,H}_2\text{O}}$ is defined as follows [20, 22, 25]:

$$\mathcal{N}_{\text{diff,H}_2\text{O}} = D_w \frac{(C_{K,v} - C_{A,v})}{x_m} \quad (18)$$

According to [17] that the water diffusion from the anode side to the cathode side of the PEM fuel cell system is as follows:

$$J_w = k_g (y_a - y_c) \quad (19)$$

J_w is humidity flux across the membrane

3.3 PEM Fuel Cell Performance

The value of cell voltage at PEMFC system is [26]

$$V_{operasi} = V_{rev} - V_{irrev} \quad (20)$$

$$V_{irrev} = V_{act} - V_{ohm} - V_{con} \quad (21)$$

3.3.1 Reversible Cell Voltage (V_{rev})

At standard state the value of PEM fuel cell electric power is [27]:

$$E = \frac{-\Delta G_f^0}{nF} = \frac{237.340}{2 \text{ mol} \times 96,485} \frac{\text{Kj mol}^{-1}}{\text{C mol}^{-1}} = 1.229V \quad \text{At } 25^{\circ}\text{C and pressure 1 atm}$$

The potential of electricity as a function of temperature (E_T) is:

$$E_T = E^0 + \frac{\Delta S}{nF} (T - T_0) \quad (22)$$

The reversible voltage for PEM fuel cell is [27-29]:

$$V_{rev} = E_T + \frac{RT}{nF} \ln \left(\frac{P_{H_2} x(P_{O_2}^{0.5})}{P_{H_2O}} \right) \quad (23)$$

So the value of PEM fuel cell electric power based on equation (22) is:

$$E_T = 1.229V - 0.85 \times 10^{-3} (T - T_0) V/K \quad (24)$$

Assuming that the partial pressure is 1 atm because the water is in the liquid phase, then:

$$V_{rev} = 1.229V - 0.85 \times 10^{-3} (T - T_0) + 4.31 \times 10^{-5} \times T \times \ln(P_{H_2} x(P_{O_2}^{0.5})) \quad (25)$$

3.3.2 Voltage Activation (V_{act})

In the equilibrium state, the net current (zero down stream) is zero, although the PEMFC response system occurs simultaneously. The consequences are:

$$r = k_f C_{O_2} - k_b C_{H_2} = \frac{i_c}{nF} - \frac{i_a}{nF} \quad (26)$$

The value is expressed as a change in the current density. This condition can be stated as follows:

$$i_c = i_a \text{ dan } r_f = r_b$$

Can be simplified to be the first form:

$$\frac{RT}{F} \left[\frac{d}{dE} \ln(k_b) - \frac{d}{dE} \ln \left(\frac{1}{k_f} \right) \right] = 1 \quad (27)$$

For the reductive symmetry factor expressed by α , then

$$\frac{RT}{F} \frac{d}{dE} \ln \left(\frac{1}{k_f} \right) = \alpha \quad (28)$$

With oxidative symmetry is: $1 - \alpha$

$$\frac{RT}{F} \frac{d}{dE} \ln(k_b) = 1 - \alpha \quad (29)$$

Can be simplified to:

$$\ln(k_b) = \frac{(1-\alpha)FE}{RT} + c \quad (30)$$

k_f value for standard condition is $k_f = k_{f,0}$, $k_b = k_{b,0}$ and $E = E_0$

Can be changed to:

$$k_f = k_{f,0} \exp \left(\frac{-\alpha FE}{RT} \right) \quad (31)$$

$$\text{And } k_b = k_{b,0} \exp \left(\frac{(1-\alpha)FE}{RT} \right) \quad (32)$$

Then known as the Butler Volmer equation, then the rate of reaction in the cell is:

$$i = nF \left(k_{f,0} \exp \left(\frac{-\alpha FE}{RT} \right) C_{O_2} - k_{b,0} \exp \left(\frac{(1-\alpha)FE}{RT} \right) C_{H_2} \right) \quad (33)$$

In equilibrium condition it is assumed that $k_{f,0} = k_{b,0} = k_0$

$$i_0 = nF k_0 C_{O_2}^{(1-\alpha)} C_{H_2}^{\alpha} \quad (34)$$

If this equation is compared to the reference current density ($i_{0,ref}$) is:

$$i_0 = i_{0,ref} \left(\frac{P_R}{P_{R,ref}} \right)^{\gamma} \exp \frac{E_c}{RT} \left(1 - \frac{T}{T_{ref}} \right) \quad (35)$$

The i_0 value is detected by the ideal surface reaction area per unit volume of the catalyst layer (a) [30-32]

The equation becomes:

$$i_0 = a i_{0,ref} \left(\frac{P_R}{P_{R,ref}} \right)^{\gamma} \exp \frac{E_c}{RT} \left(1 - \frac{T}{T_{ref}} \right) \quad (36)$$

$E_c = 76.5$ Kj/mol [33]

According to [31] that the value of a is:

$$a = a_0 \frac{m_{pt}}{L}$$

$$\text{According to [34] the value of } a_0 \text{ is:}$$

$$a_0 = 10^8 (4.4198Y^9 - 27.691Y^8 + 74.206Y^7 - 111.06Y^6 + 101.43Y^5 - 57.841Y^4 + 20.231Y^3 - 4.089Y^2 + 0.39451Y) \quad (37)$$

With $Y = \% \text{ Pt catalysts}$ having value in the range 0 to 100%.

$$a_0 = 10^8 (4.4198Y^9 - 27.691Y^8 + 74.206Y^7 - 111.06Y^6 + 101.43Y^5 - 57.841Y^4 + 20.231Y^3 - 4.089Y^2 + 0.39451Y) \quad (38)$$

According to [35] and [31] the reference current density value is:

$$i_{0,ref} = 10^{(3.057 - \frac{4001}{T})}$$

The value of the current density based on equation is::

$$i = nF k_0 \left(C_{O_2} \exp \left(\frac{-\alpha FE}{RT} \right) - C_{H_2} \exp \left(\frac{(1-\alpha)FE}{RT} \right) \right) \quad (39)$$

If the value i compared i_0 to the equation (35) is:

$$\frac{i}{i_0} = \frac{nF k_0 (C_{O_2} \exp \left(\frac{-\alpha FE}{RT} \right) - C_{H_2} \exp \left(\frac{(1-\alpha)FE}{RT} \right))}{nF k_0 (C_{O_2} \exp \left(\frac{-\alpha FE}{RT} \right))} \quad (40)$$

Nilai $E - E_r = \eta_{act}$, maka nilai $\frac{i}{i_0}$ menjadi:

$$V_{act} = \frac{RT}{2\alpha F} \sin h^{-1} \left(\frac{i}{i_0} \right) \quad (41)$$

The activation voltage value is [36-37]:

$$V_{act} = \frac{RT}{n\alpha F} \ln \left(\frac{i}{i_0} \right) \text{ where } i > i_0 \quad (42)$$

According to [36] the value of i_0 depends on temperature, pressure, type of catalyst used, specific surface area and loading. The value of i_0 is 10^{-2} A to 10^{-8} A. Based on the equation (42), the value of Tafel constant is::

$$b = \frac{RT}{n\alpha F} \quad (43)$$

In the PEMFC system model design, the Tafel constant value is based on research data conducted by [38] is:

$$b = 0.1937 e^{-2.197(\alpha)} \quad (44)$$

α is the exchange coefficient, whose value is [18]:

$$\alpha = (0.001552RH_{c,inlet} + 0.000139)T \quad (45)$$

$RH_{c,inlet}$ is the relative humidity that flows into the cathode of PEM fuel cell

3.3.3 Voltage Ohm (V_{ohm})

Loss caused by ohm resistance occurs in the membrane and catalyst layer and is a function of temperature and humidity [39]. Total voltage loss in PEM fuel cell is a linear function [40]. The total value of the ohm voltage according to [37] is:

$$V_{ohm} = iR_{ohm} \quad (46)$$

While the value of R_{ohm} :

$$R_{ohm} = \frac{t_m}{\sigma_m} \quad (47)$$

The value of the membrane conductivity is [32, 41]:

$$\sigma_m = (0.005139 \lambda_m - 0.003260) \exp \left[1268 \left(\frac{1}{303} - \frac{1}{T} \right) \right] \quad (48)$$

The value of the membrane water content is:

$$\lambda_m = 0.048 + 17.81RH - 39.83RH^2 + 39.85RH^3 \quad (49)$$

a is the average relative humidity in the PEM fuel cell stack.

3.3.4 Concentric Voltage Kepekatan (V_{conc})

Loss of concentration capability because the reaction of the electrode is restricted by the reactant mass transfer within the PEM fuel cell [40]. The concentration capability value [29] is:

$$V_{conc} = c \ln \left(\frac{i_L}{i_L - i} \right) \quad (50)$$

c is the constant of loss by concentration. The value of c is:

$$c = \frac{RT}{nF} \quad (51)$$

$$V_{conc} = \frac{RT}{nF} \ln \left(\frac{i_L}{i_L - i} \right) \quad (52)$$

i_L is the maximum value of the current density generated by PEM fuel cell. The amount of current density limit value by the PEM fuel cell is [42]

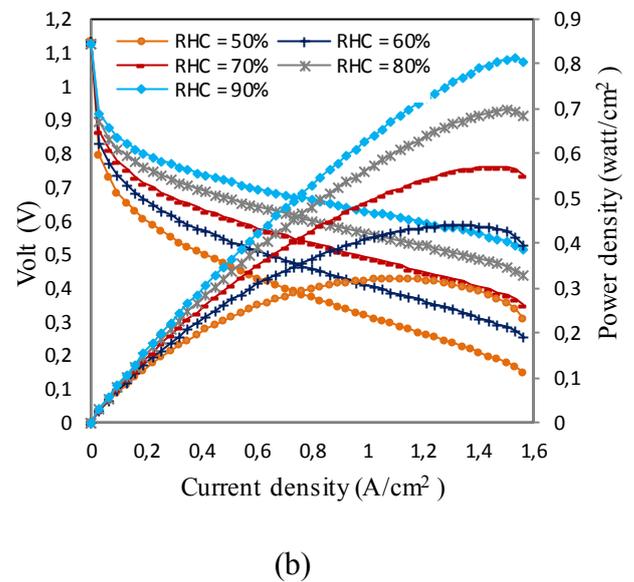
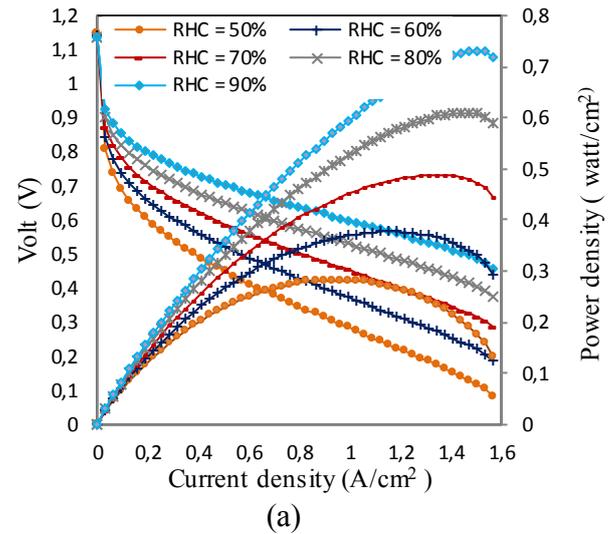
$$i_L = nFh_m \left(\frac{c_{O_2,in} - c_{O_2,out}}{\ln \frac{c_{O_2,in}}{c_{O_2,out}}} \right) \quad (53)$$

$c_{O_2,indanout}$ is the concentration of oxygen flowing in and out of PEM fuel cell (mol)

h_m is the convective mass transfer coefficient. The convective mass transfer coefficient value by [43]:

$$h_m = \frac{Sh_f D_{ij}}{H_c} \quad (54)$$

the cathode was 1atm. The hydrogen to oxygen stoichiometric ratio was 1.2 for hydrogen and 2 for oxygen. An increased RHA and an increased RHC value generally improve the single cell performance, as shown by the increases in the voltage and the power density that are produced. The single cell performance can be improved by increasing the relative humidity at the cathode, which increases the voltage and the power density that are produced. This result is reflected by the increased voltage and power density that are produced. Higher single cell performance can be achieved by increasing the RHC value.



4 Results and Discussion

Figure 2 shows the effect that relative humidity has on the single cell performance. The operating temperature was maintained at 353 K. The pressure at the anode and

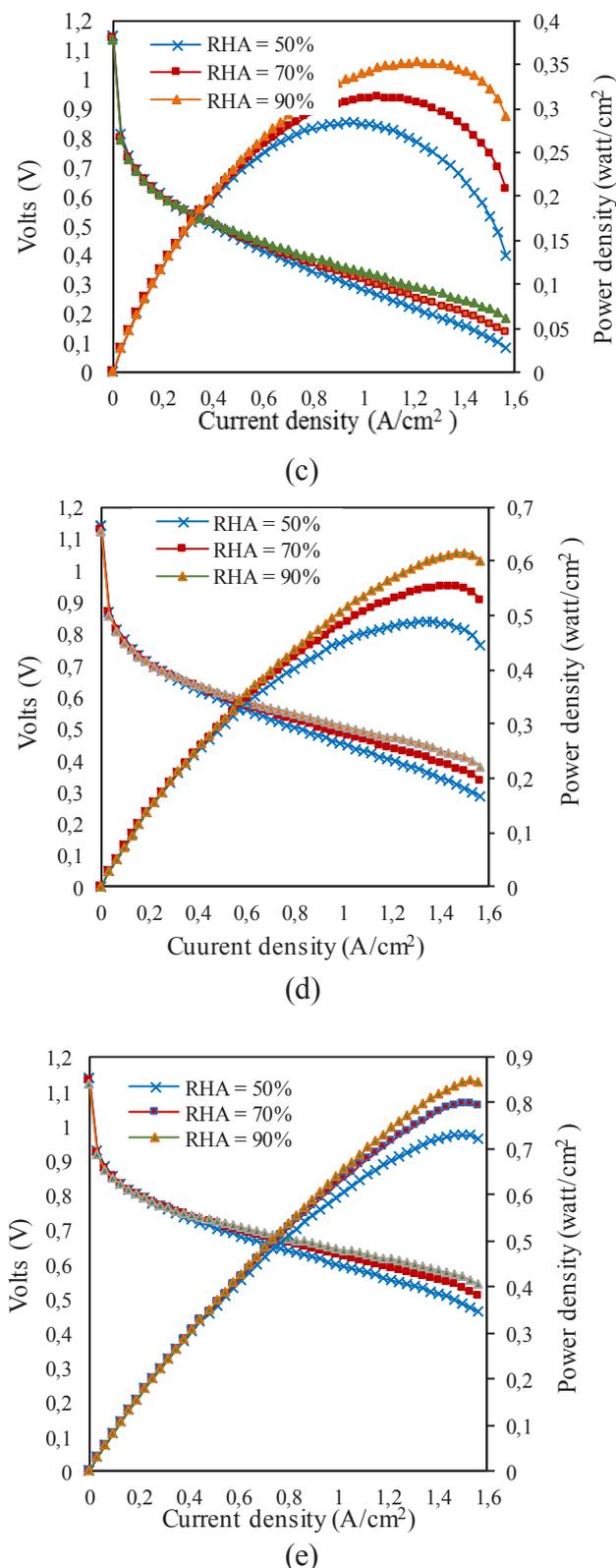


Fig 2. Effect of relative humidity on single cell performance of PEM fuel cells at temperatures of 353 K, the operating pressure of 1 atm, the stoichiometric ratio is 1.2 for H₂ and O₂ are 2: (a) RHA is 50% and RHC are 50%, 60%, 70%, 80% and 90%. (b) RHA is 75% and RHC are 50%, 60%, 70%, 80% and 90%. (c) RHA is 50%, 70% and 90%, RHC is 50%. (d) RHA are 50%, 70% and 90%, RHC is 70%. (e) RHA are 50%, 70% and 90%, RHC is 90%.

Figures 2a and 2c show the effects of varying the relative humidity while all the other conditions are kept constant. The RHA in Figure 2a was maintained at 50% while the RHC was varied from 50% to 90%. In figure 2c, the RHC was maintained at 50% while the RHA was varied from 50% to 90%. Figure 2a shows the improvement in the single cell performance with an increase in the RHA. Figure 2c shows that the increase in RHA causes an insignificant improvement in the single-cell performance. Increasing the RHC was more effective than increasing the RHA with regard to improving the single cell performance. The increases in the RHA and the RHC resulted in an increased voltage and an increased power density. Specifically, an increased RHC significantly improved single cell performance. Figures 2c, 2d and 2e show the effect of RHA on the single cell performance; improved performance occurs beyond a voltage of 0.6 V. Figures 2a and 2b show the effect of maintaining the RHA at 50% and 70% while the value of RHC was kept constant from 50% to 90%.

The current density of a single PEM fuel cell at a voltage of 0.6V is shown in table 2.

Table 2. PEM fuel cell performance at 0.6V with different relative humidity at the cathode

Condition	Current density (A cm ⁻²) at 0.6V with different relative humidity at the cathode				
	RHC	RHC	RHC	RHC	RHC
	50%	60%	70%	80%	90%
Condition 1	0.193	0.289	0.449	0.673	0.961
Condition 2	0.193	0.321	0.513	0.801	1.185

Note:

Condition 4: RHA = 50%, PA and PC = 1 atm and T = 353 K

Condition 5: RHA = 75%, PA and PC = 1 atm and T = 353 K

Conditions 1 and 2 in table 2 show that the single PEM fuel cell was able to maintain the current density at the same value when the RHC was 50%, even though the RHA was increased from 50% to 70%. The current density increased when the RHC was increased from 60% to 90%. The same effect was observed when the RHA was increased from 50% to 70%, which resulted in an increased current density at a voltage of 0.6V.

Table 3. PEM fuel cell performance at 0.6V with different relative humidity at the anode

Condition	Current density (A cm ⁻²) at 0.6V with different relative humidity at the anode		
	RHA	RHA	RHA
	50%	70%	90%
Condition 3	0.193	0.193	0.193
Condition 4	0.449	0.513	0.545
Condition 5	0.961	1.121	1.281

Note:

Condition 3 : RHC = 50% , PA and PC = 1 atm and T = 353 K

Condition 4 : RHC = 75% , PA and PC = 1 atm and T = 353 K

Condition 5 : RHC = 90% , PA and PC = 1 atm and T = 353 K

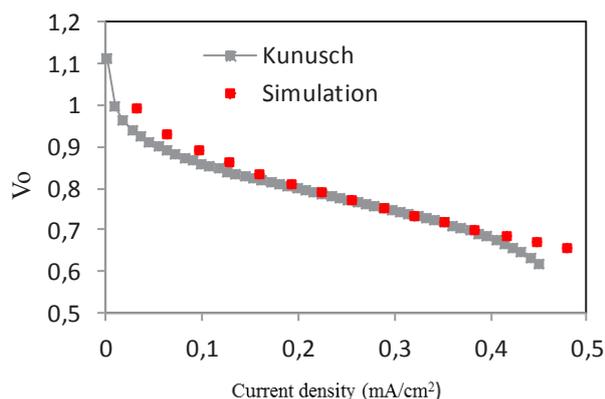


Fig 3. validation of simulation results

Table 3 shows the current density at a voltage of 0.6V when the RHA was varied. When the cell was operated at Condition 3, an increase in the RHA from 50% to 90% did not affect the value of current density at 0.193 A cm⁻². However, Conditions 7 and 8 show that an increase in the RHC and the RHA result in an increased current density in the single cell. Tables 3 and 3 show that when the RHC was 50% and the RHA was 50% in Conditions 1, 2 and 3, the current density remained unchanged at 0.193 Acm⁻². The increase in the RHA did not significantly increase the current density. However, an increase in the RHC significantly increased the current density. The performance of the single cell was highest at RHC values ranging from 70% to 90%.

The results of the simulation study in figure 3 showed similar trends in the performance of a single cell PEM fuel cell. However, the simulation results in this study did not show a significant decrease in voltage over the current density of 0.45 A cm², while the simulation results performed by Khunush showed a decrease in voltage value. The decrease in the value of this voltage is due to insufficient hydrogen and oxygen for the reaction

5 Conclusion

The conclusions that can be drawn from this study are as follows:

1. In the same relative humidity value at one side of the PEM Fuel Cell, the increase in single cell performance is influenced by the increase in RHC value compared to RHA value.
2. The highest single cell performance that occurs at 0.6V is indicated by the RHA value from 70% to 90% and RHC is 90%.

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