

# Analysis of activation, ohmic, and concentration losses in hydrogen fuelled PEM fuel cell

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**Abstract.** This paper deals with the effects of design (active area, current density, membrane conductivity) and operating parameters (temperature, relative humidity) on the performance of hydrogen-fuelled proton exchange membrane (PEM) fuel cell. The design parameter of a PEM fuel cell with the active area of the single cell considered in this study is 25 cm<sup>2</sup> (5 x 5). The operating voltage and current density of the fuel cell were 0.7 V and 0.5 A/cm<sup>2</sup> respectively. The variations of activation voltage, ohmic voltage, and concentration voltage with respect to current density are analyzed in detail. The membrane conductivity with variable relative humidity is also analyzed. The results show that the maximum activation overpotential of the fuel cell was 0.4358 V at 0.21 A/cm<sup>2</sup> due to slow reaction kinetics. The calculated ohmic and concentrated overpotential in the fuel cell was 0.01395 V at 0.76 A/cm<sup>2</sup> and 0.027 V at 1.46 A/cm<sup>2</sup> respectively.

**Keywords:** activation; concentration; hydrogen; ohmic; PEM fuel cell

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## 1. Introduction

The Polymer electrolyte membrane (PEM) fuel cells are one of the viable options for portable power, and transportation. The PEM fuel cell is advantageous due to its higher power density, ease to start, fast dynamic response, etc. The operating parameters such as pressure, temperature, a stoichiometric ratio of fuel (hydrogen and oxygen), and humidity influence the performance of a PEM fuel cell. The relative humidity is one of the main important factors for the performance of the fuel cell. Improper humidification leads to a decrease in the performance of fuel cells. Hence, it is essential to understand the effects of different design and operating parameters on fuel cell performance.

Benmouiza and Cheknane (2018) analyzed the effect of various operating parameters on the performance of fuel cells. At higher current densities, the voltage in activation, ohmic, and mass transport decreased by 0.2 V, 0.8 V, and 1 V, respectively. The pressure effect on its performance was negligible at low and higher current density regions but in medium current density, pressure affects fuel cell performance significantly.

Hong *et al.* (2017) developed a model (one-dimensional) for the cathode catalyst layer to analyze voltage losses. The author analyzed that the inter-diffusion effects of gas constituents had

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a substantial influence on the fuel cell performance.

Gaia D'elia (2015) observed the effects of different conditions on the performance of fuel cells. In this work, the author developed a 2D (two-dimensional) model and observed the effect of exchange current density variation at the cathode while reducing oxygen concentration at the cathode catalyst. The results reveal that the hydrogen and air stoichiometry do not have any significant effect on activation and mass transport losses. If the operating temperature increases, activation overpotential decreases due to fast reaction kinetics. The ohmic losses can be controlled through optimization of membrane thickness and humidification.

Mulyazmi *et al.* (2018) found that the cathode relative humidity of 70-90% shows better performance for a single cell. The condition for maximum current density was at 70% RHA (relative humidity anode) and 90% RHC (relative humidity cathode) with an operating temperature of 353 K and at 1atm pressure. A mathematical model was developed for observing the effect of the respective relative humidity of cathode and anode on the performance of PEM fuel cells.

Haji, Shaker (2010) experimented with a 40W PEM fuel cell stack consisting of 10 cells in series with an active area of 25 cm<sup>2</sup> and analyzed the different losses that occur in fuel cells along with current losses. The linear regression optimization technique was used for analyzing the fitness of input parameters. It was found that activation losses were 95.8% at the current density of 0.02 A/cm<sup>2</sup> with sufficient air stoichiometry.

Amphlett *et al.* (1995) studied the effect of operating parameters on activation overpotential and the fitness of input variables was checked using the linear regression technique. It is reported that activation losses were significantly higher (0.272 to 0.445 V) in comparison to ohmic losses (0.105 to 0.011 V). The cathode kinetics are strongly dependent on oxygen/oxidizer composition, mass transport, and temperature of the fuel cell.

Guvelioglu *et al.* (2007) analyzed the effect of reactant flow rate (hydrogen and air) on the performance of the fuel cell for both 100 and 75% RH cases. When the hydrogen flow rate increases from 1 to 3, it increases the current density, while a slight drop in current density was observed with the increased air flow rate. It was observed that a more uniform current density was obtained with 75% RH compared to 100% RH. Water concentration increases proportionally as the hydrogen flow rate increases.

Chavan *et al.* (2017) simulated a PEM fuel cell consisting of an active area of 25 cm<sup>2</sup> through MATLAB SIMULINK. It was found that as the hydrogen flow rate increases, it increases the cell temperature due to more collision of hydrogen molecules. As the number of collisions between hydrogen molecules increases, the performance of the fuel cell improved.

Liu *et al.* (2020) analyzed the effect of humidification on the performance of fuel cells using thermodynamic and heat and transfer models. The better results were obtained with a relative humidity of (RH) 75 % and 100% respectively. The author analyzed the effects of asymmetric humidification on the performance of PEM fuel cells. The maximum system efficiency was 17 % using the anode relative humidity (RHA) of 75%, and cathode relative humidity (RHC) of 50%. The effective fuel cell performance was achieved with relative humidity at 75% and 100% compared to 50%.

D.N Ozen *et al.* (2016) studied the influence of input parameters (temperature and relative humidity) on the power density of fuel cells. The results depicted that membrane and electrode resistance decreased from 0.407 to 0.092  $\Omega$  cm<sup>2</sup>, and 0.203 to 0.041  $\Omega$  cm<sup>2</sup> respectively while increasing humidity from 20 to 100%. If cathode humidifier temperature decreases from 80 to 350°C, membrane resistance increases by 3.4 m $\Omega$ . This paper depicts the effect of operating parameters on the various losses which include activation, ohmic, and concentration overpotential.

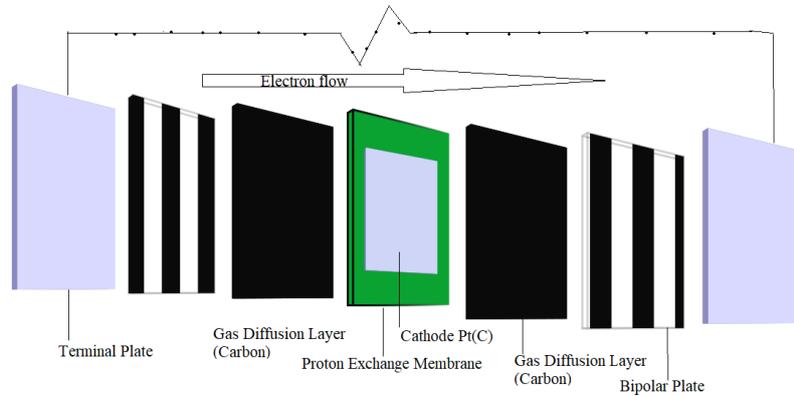
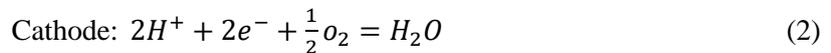


Fig. 1 Exploded View of PEM fuel cell components

Most of the studies have been carried out on the influence of the variable parameters on the performance of the fuel cell. However, the information on the effects of operating parameters such as operating temperature on different types of losses in the fuel cell is not provided in detail. In addition to this, the individual effect of operating parameters on different losses has not been explored. Hence an attempt is tried to study the effect of operating temperature and relative humidity on the various losses that occur in the fuel cell. The effect of relative humidity on membrane conductivity is also analyzed in this paper.

## 2. Methodology

The operating parameters were taken as temperature (333 -353 K with the step increment of 1 K) and relative humidity (30% to 90% in a step increment of 10%). The active area of the fuel cell was 25 cm<sup>2</sup> and NAFION 117 membrane is used for analysis. The fuel cell stack was restricted to operating below 600C. The mathematical modelling of the operating parameters (relative humidity and temperature) has been done to analyze the losses. The respective reactions on anode and cathode are given in Eqs. (1)-(3) (O'hayre *et al.* 2016)



## 3. Mathematical model

A mathematical model available in the literature was used to analyze the effect of various operating parameters on fuel cell losses. Empirical relations were used to analyze the effects of various parameters on the performance of fuel cells. The potential of the fuel cell system to

perform electrical work is measured in terms of voltage. The electrical work, and charge  $Q$  through electrical potential are given in Eq. (4) (O'hayre *et al.* 2016).

$$W_{elec} = E \cdot Q \quad (4)$$

Where  $W_{elec}$  is the electrical work,  $E$  is the potential difference in volt and  $Q$  is charges in coulomb.

The electron charge is calculated by Eq. (5) (O'hayre *et al.* 2016).

$$Q = nF \quad (5)$$

Where  $n$  is the number of moles of electron and  $F$  is faradays constant

The Gibbs free energy ( $\Delta g$ ) is calculated from Eq. (6) (O'hayre *et al.* 2016).

$$\Delta g = -nFE \quad (6)$$

Thus, Gibbs free energy sets the magnitude of reversible voltage for an electrochemical reaction. The reversible voltage generated from the hydrogen-oxygen fuel cell in standard state conditions is given in Eq. (7) (O'hayre *et al.* 2016).

$$\begin{aligned} E^0 &= -\frac{\Delta g_{rxn}^0}{nF} \\ &= -\frac{237000}{2 * 96485} \\ &= +1.23 \text{ V} \end{aligned} \quad (7)$$

### 3.1 Ideal fuel cell efficiency

The efficiency of the fuel cell is given by Eq. (8) (O'hayre *et al.* 2016).

$$\eta = \frac{\text{Useful Energy}}{\text{Total Energy}} \quad (8)$$

If extraction of work from a chemical reaction, the efficiency can be calculated using Eq. (9) (O'hayre *et al.*).

$$\eta = \frac{\text{work}}{\Delta h} \quad (9)$$

The *fuel cell* reversible efficiency is given by Eq. (10) (O'hayre *et al.* 2016).

$$\eta_{thermo,fc} = \frac{\Delta g}{\Delta h} \quad (10)$$

At room temperature and pressure, the  $H_2-O_2$  fuel cell has  $\Delta g = -237.17$  kJ/mol and  $\Delta h_{HHV} = -285.83$  kJ/mol.

$$\begin{aligned} \eta_{thermo,fc} &= \frac{-237.17}{-285.83} \\ \eta_{thermo,fc} &= 0.83 \end{aligned}$$

The maximum theoretical hydrogen-oxygen fuel cell efficiency is 83%.

### 3.2 Reversible cell voltage

Reversible cell voltage is defined as the Voltage obtained from the fuel cell at standard pressure and temperature condition. For fuel cell, standard pressure and temperature condition are 1 atm. and 25°C. The Standard voltage obtained from the fuel cell is 1.229 V. The actual voltage obtained from the fuel cell considering losses is given by Eq. (11) (O'hayre *et al.* 2016).

$$V_{actual} = E_{nerst} - V_{act} - V_{ohmic} - V_{conc} \quad (11)$$

### 3.3 Activation losses

The activation losses are defined as losses that take place due to slow chemical kinetics. The activation losses are calculated based on the Tafel equation which is given in Eq. (12) (O'hayre *et al.* 2016).

$$V_{act} = b \ln\left(\frac{i}{i_l}\right) \quad (12)$$

where  $V_{act}$  is activation overpotential,  $b$  is known as Tafel slope and  $i$  is applied current density and  $i_l$  is limited current density,  $\ln$  is the natural logarithm. The value of the Tafel slope is calculated using Eq. (13) (O'hayre *et al.* 2016).

$$b = \frac{RT}{\alpha.n.F} \quad (13)$$

where  $R$  is the universal gas constant,  $T$  is the operating temperature,  $n$  is the number of electron transfers,  $\alpha$  is the transfer coefficient and  $F$  is the faraday's constant.

The activation losses are calculated by Eq. (14) (O'hayre *et al.* 2016).

$$V_{act} = \frac{RT}{\alpha.n.F} \ln\left(\frac{i}{i_l}\right) \quad (14)$$

$i_l$  is dependent upon the pressure, temperature, and loading of catalysts on the surface. The typical value is  $i_l 10^{-2}$  to  $10^{-6}$  A/cm<sup>2</sup>.

The Tafel slope or activation loss constant ( $b$ ) can also be calculated using the empirical relation given in Eq. (15) (O'hayre *et al.* 2016).

$$b = 0.1937e^{-2.1917(\alpha)} \quad (15)$$

where  $\alpha$  is the transfer coefficient whose value is obtained from Eq. (16) (O'hayre *et al.* 2016).

$$\alpha = (0.001552RH_{c,inlet} + 0.000139)T \quad (16)$$

$RH_{C, the inlet}$  is cathode relative humidity (RH).

### 3.4 Ohmic losses

Ohmic voltage is calculated using Eq. (17) (O'hayre *et al.* 2016).

$$V_{ohm} = I * R_{ohm} \quad (17)$$

where  $V_{ohm}$  is the ohmic overpotential,  $I$  is current flowing through the circuit obstructing ionic resistance of  $R_{ohm}$ . The ohmic resistance is calculated through the given Eq. (18) (O'hayre *et al.* 2016).

$$R_{ohm} = \frac{t_m}{\sigma} \quad (18)$$

where  $t_m$  is membrane thickness and  $\sigma$  is the membrane conductivity which is material dependent property. The membrane conductivity is calculated by Eq. (19) (O'hayre *et al.* 2016).

$$\sigma_m = (0.005139\lambda_m - 0.003260)exp(1268(\frac{1}{303} - \frac{1}{T})) \quad (19)$$

where  $\sigma_m$  is the membrane conductivity function of membrane water content and temperature,  $\lambda_m$  is membrane water content and T is operating temperature in K.

The membrane water content is calculated through an empirical equation which is the function of relative humidity given in Eq. (20) (O'hayre *et al.* 2016).

$$\lambda_m = 0.048 + 17.81RH - 39.83RH^2 + 39.85RH^3 \quad (20)$$

$\lambda_m$  represents membrane water content, RH represents the membrane relative humidity.

### 3.5 Concentration voltage losses

The concentration voltage losses are dominant in the higher current density region of the fuel cell. The empirical relation for concentration overpotential is given by Eq. (21) (O'hayre *et al.* 2016).

$$V_{conc} = c \cdot \ln(\frac{i_l}{i_l - i}) \quad (21)$$

$V_{conc}$  is known as concentration overpotential, and c is concentration loss constant. The loss constant is calculated from Eq. (22) (O'hayre *et al.* 2016).

$$c = \frac{RT}{nF} \quad (22)$$

R is the universal gas constant, T is the operating temperature in K, n is the number of charges transferred and F is the Faraday constant.

The concentration losses are calculated by Eq. ( $V_{conc} = \frac{RT}{nF} \ln(\frac{i_l}{i_l - i})$ ) 23) (O'hayre *et al.* 2016).

$$V_{conc} = \frac{RT}{nF} \ln(\frac{i_l}{i_l - i}) \quad (23)$$

$i_l$  is the maximum current density generated by the PEM fuel cell. The maximum permissible amount of current density is calculated by Eq. (24) (O'hayre *et al.* 2016).

$$i_l = nFh_m \left( \frac{c_{o_2,in} - c_{o_2,out}}{\ln(\frac{c_{o_2,in}}{c_{o_2,out}})} \right) \quad (24)$$

where  $i_l$  is the maximum current density drawn from the fuel cell, n is the number of charge transfer,  $h_m$  is convective heat mass transfer coefficient,  $c_{o_2}$ , in and out represent the concentration of oxygen flowing in and out from the fuel cell.

## 4. Results and discussion

This section explained the influence of the various operating parameters on the performance of

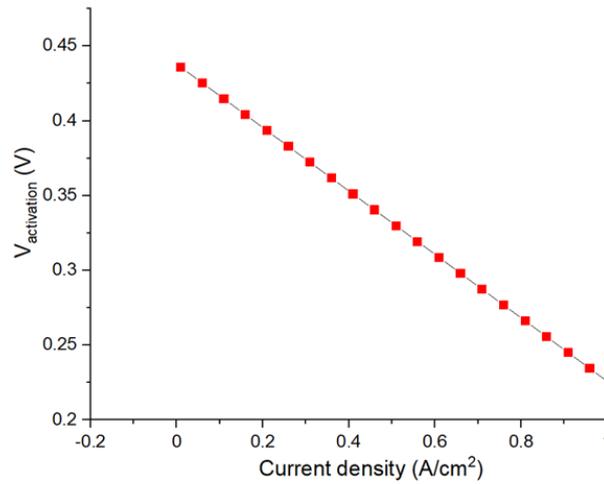


Fig. 2 Variation of activation voltage concerning current density

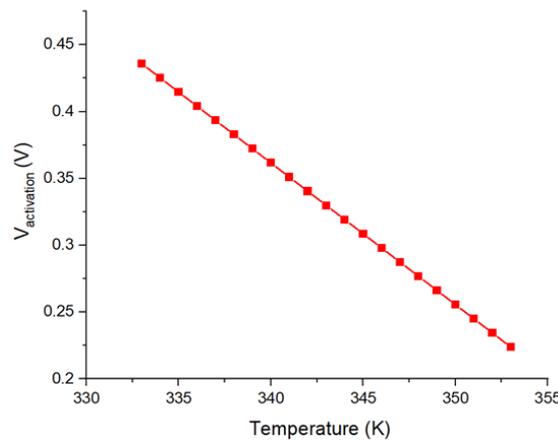


Fig. 3 Variation of activation voltage vs temperature

the fuel cell. The input process parameters were taken as the operating temperature and relative humidity. This result depicts the influence of input process parameters on the performance of the proton exchange membrane fuel cell.

#### 4.1 Effect of temperature on activation overpotential

Fig. 2 depicts the variation of activation voltage with respect to the current density. It shows a linearly decreasing trend with increasing current density. Activation voltage is dominated in the lower current density region due to the slow kinetics of the chemical reaction. At the low exchange current density, the chemical kinetics become slow. The slow reactions occur due to the catalyst activation barrier to convert the product into reactants. Activation overpotential can be enhanced by increasing the hydrogen absorption rate over the surface of the electrode. The effects of

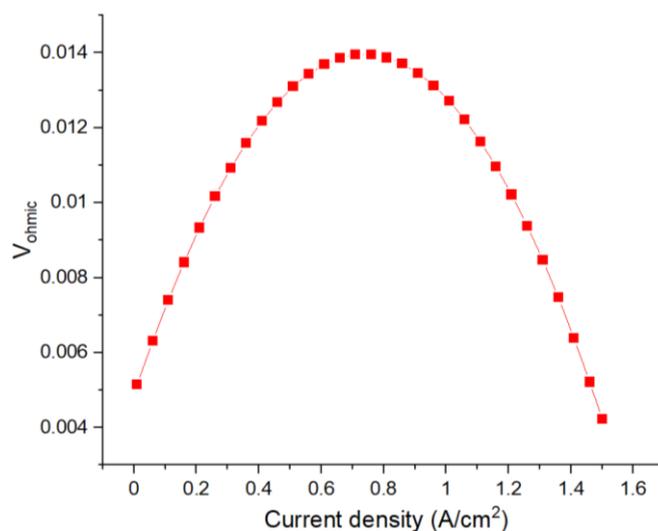


Fig. 4 Variation of ohmic voltage vs current density

temperature on activation voltage (overpotential) are shown in Fig. 3. It is observed from the results that activation overpotential is dominated at lower temperatures and decreases with the rise in temperature. The sluggish chemical kinetics could be enhanced in two ways, either by increasing the operating temperature or by coating the catalyst over the surface of GDL (Gas diffusion layer). The maximum activation overpotential fuel cell was 0.4358 V at 0.01 A/cm<sup>2</sup>. As the size of the PEM fuel cell increases the flow kinetics decreases due to non-uniformity inflow and it reduces the kinetics of the fuel cell.

#### 4.2 Effect of relative humidity on membrane conductivity

Fig. 4 shows the variation of membrane conductivity with respect to relative humidity. Membrane conductivity increases monotonically as the relative humidity increases. The conductivity of the membrane strongly depends on water content. As the membrane starts getting humidified, it allows more protonic ions to pass through it. The protons are being transported through the membrane by the grotthuss or vehicular mechanism (O'hayre *et al.* 2016). The minimum and maximum membrane conductivity were 0.003198 s/cm and 0.030282 s/cm at 30% and 90% relative humidity respectively. The better membrane conductivity is obtained at 90% relative humidity. Plenty amount of water content in the membrane activates the working sites of the membrane. The activated sites of the membrane result in enhanced protons transportation through the membrane. Membrane thickness has a significant effect on the charge transport because a thinner membrane kept the anode electrode saturated through the back diffusion of water from the cathode (Lin 1999).

#### 4.3 Variation of concentration overpotential with the current density

Fig. 5 indicates variation between concentration overpotential concerning the current density. The concentration overpotential shows increasing trends as current density increases and

dominates in higher current density regions. The insufficient reactant supply to the electrode results in concentration overpotential. The maximum concentration overpotential of the fuel cell was 0.027 V at 1.46 A/cm<sup>2</sup>. At lower current density, concentration losses are negligible and for higher current density concentration losses are dominated. At higher current densities, oxygen and hydrogen simply cannot diffuse through the electrode and ionize rapidly enough, and because products cannot be transported out at the required speed, mass transport results in a rapid reduction in voltage (Lin 1999). The concentration losses can be controlled with proper design of flow field on bipolar plate especially spiral flow field design because it will not allow accumulating the water on GDL so reactant could reach GDL effectively. If the production of water is controlled properly, more active sites will be available for reaction and mass transfer losses will decrease. Effective diffusion and migration of ions can enhance reactant flow over the surface of the electrode.

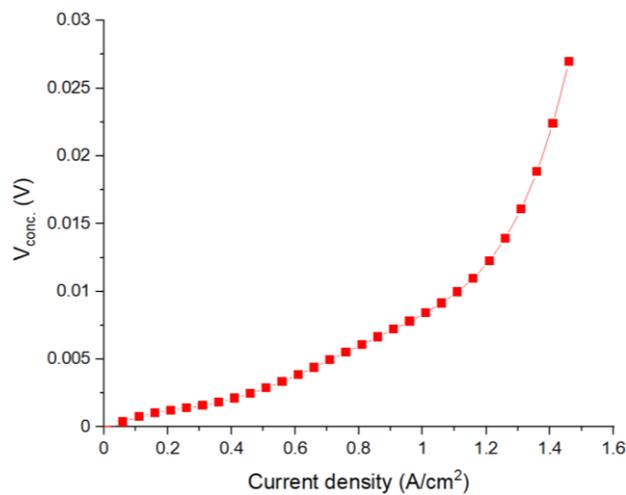


Fig. 5 Variation of Concentration overpotential vs current density

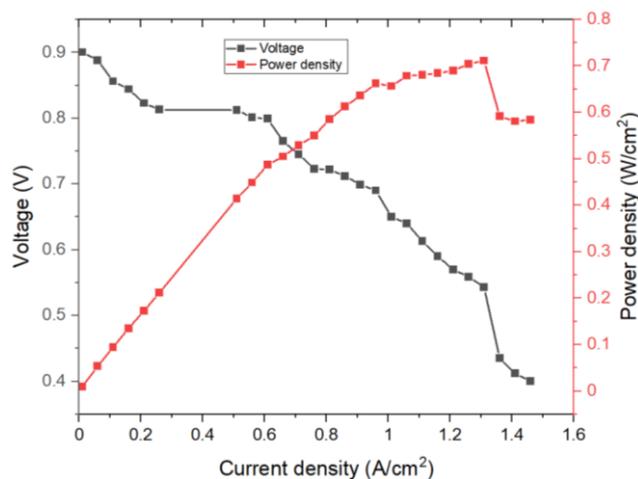


Fig. 6 Variation of Voltage with Current density

Table 1 Summary of various losses in fuel cell

Region	Parameters	Reasons	Remedies
Activation Overpotential	Temperature	<ol style="list-style-type: none"> <li>1. Low temperature is not enough to excite molecules from their low energy state to a higher energy state.</li> <li>2. Low-temperature results in slower chemical kinetics</li> </ol>	<ol style="list-style-type: none"> <li>1. Increasing the operating temperature of the Fuel cell</li> <li>2. Uniform platinum catalyst coating over the electrode surface</li> </ol>
Ohmic overpotential	Relative humidity	<ol style="list-style-type: none"> <li>1. Improper membrane humidification resists the flow of protons through itself. Through membrane.</li> <li>2. Excess humidification blocks the activated sites for ions transport which increases the ionic resistance of the membrane.</li> </ol>	Humidified membrane activates the sulphonate ions of the membrane which enhances the proton transport through the membrane.
Concentration Overpotential	Reactant flow over the electrode surface	<ol style="list-style-type: none"> <li>1. Pressure drop in a fuel cell as maximum flow rate to the membrane surface</li> <li>2. Due to insufficient reactant flow on the electrode surface</li> </ol>	<ol style="list-style-type: none"> <li>1. Effective flow design of flow channel</li> <li>2. Enhancement of convection transport of gases over the surface of the electrode</li> </ol>

#### 4.4 Voltage current density characteristics curve

Fig. 6 represents the variation of voltage generated from a single PEM fuel cell concerning current density. The voltage shows the decreasing trend and power shows the increasing trend concerning the current density. The decreasing characteristics of voltage take place due to various kinds of losses dominated in different current density regions. The three overpotential regions dominate as activation, ohmic, and concentration in the low, medium, and higher current density respectively. In lower current density regions (0-0.4 A/cm<sup>2</sup>), the activation losses are dominated due to slow chemical kinetics. Slow chemical kinetics take place as molecules do not get proper activation energy for the reaction. In the medium current density region (0.4-0.8 A/cm<sup>2</sup>), ohmic losses are dominated due to ionic resistance. The ionic losses occur due to improper humidification of the membrane. Excess humidification increases the charged sites but excessive charge sites increase the instability of the membrane (Spiegel 2011). In higher current density regions (0.8-1.5 A/cm<sup>2</sup>), concentration or mass transfer losses are dominated. The concentration losses occur as the reactant does not reach the electrode surface. The maximum power density was 0.711 W/cm<sup>2</sup> at 1.31 A/cm<sup>2</sup>.

#### 4.5 Summary

The maximum possible theoretical efficiency from the hydrogen-oxygen fuel cell is 83%. The actual efficiency of the fuel cell is about 45-50%. The reduction in fuel cell efficiency is due to different kinds of losses that take place in the fuel cell. Based on the study the reasons for overpotential are summarized in Table 1.

## 5. Conclusions

The following conclusions are drawn based on this study's results:

- Activation overpotential representing the reaction kinetics rate is calculated using Tafel slope and is found as 0.2238 V and maximum activation overpotential is found as 0.438 V.
- The ohmic overpotential was 0.01395 V at 0.76 A/cm<sup>2</sup>. The humid hydrogen and air increased the membrane conductivity resulting in more protonic ions transfer from anode to cathode and hence, lower ohmic resistance.
- The concentration overpotential occurs due to an insufficient supply of reactants. The maximum concentration overpotential was 0.027 V at 1.46 A/cm<sup>2</sup>. The reactant molecules are unable to reach at surface properly due to limited mass transport.
- The maximum power density obtained from the fuel cell was 0.711 W/cm<sup>2</sup> at 1.31 A/cm<sup>2</sup> and starts decreasing due to the dominance of the concentration losses.

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**Nomenclature**

$E_{\text{nernst}}$	Nernst Cell Voltage
$V_{\text{actual}}$	Actual fuel cell voltage
$V_{\text{act}}$	Activation Voltage
$V_{\text{ohm}}$	Ohmic Voltage
$V_{\text{conc.}}$	Concentration Voltage
RH	Relative humidity
RHA	Anode Relative humidity
RHC	Cathode Relative humidity
$\lambda_m$	Water vapor content in the membrane
R	Universal gas constant ( $\text{J.K}^{-1}\text{mol}^{-1}$ )
T	Operating temperature (K)
$i_l$	Limited current density