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# Effect of Temperature on the Performance Factors and Durability of Proton Exchange Membrane of Hydrogen Fuel Cell: A Narrative Review

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### Abstract

Hydrogen fuel cell technology is now being extensively researched around the world to find a reliable renewable energy source. Global warming, national calamities, fossil-fuel shortages have drawn global attention to environment friendly and renewable energy source. The hydrogen fuel cell technology most certainly fits those requisites. New researches facilitate improving performance, endurance, cost-efficiency, and overcoming limitations of the fuel cells. The various factors affecting the features and the efficiency of a fuel cell must be explored in the course of advancement in a specific manner. Temperature is one of the most critical performance-changing parameters of Proton Exchange Membrane Fuel Cells (PEMFC). In this review paper, we have discussed the impact of temperature on the efficiency and durability of the hydrogen fuel cell, more precisely, on a Proton Exchange Membrane Fuel Cell (PEMFC). We found that increase in temperature increases the performance and efficiency, power production, voltage, leakage current, but decreases mass crossover and durability. But we concluded with the findings that an optimum temperature is required for the best performance.



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Temperature.

### Introduction

In the face of global warming, carbon pollution, fossil fuel decline hydrogen fuel cell is an exciting new

platform to cope up with both fuel and environmental issues.<sup>1,2</sup> In the modern world, there is a huge demand for hydrogen fuel in the industries. Hydrogen

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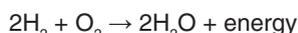
gas can be produced from fossil fuel (coal, gas, petroleum etc.) or renewable energy sources (solar, wind, geothermal energy, biogas, biomass, etc.).<sup>3,4</sup> This hydrogen gas can be a universal fuel that can be produced using all existing fuel sources and can be stored for any time of future use. In a fuel cell, electricity is produced with a chemical reaction between hydrogen and oxygen where hydrogen gives an electron by oxidation reaction to the anode and becomes an electron less hydrogen ion called proton.<sup>4,6</sup> This proton passes through the proton exchange membrane and reacts with oxygen by a reduction reaction with the formation of water and heat. In the external circuit, the electron flow gives the output current load. We can get electricity from an electrochemical reaction with zero emission of harmful chemicals and gases. That's why the fuel cell technology is considered to be sustainable and emission-free fuel solution for future demand.<sup>7-10</sup> The fuel cell has a wide range of applications. Because it operates with less start-up-time, zero knocking, no carbon emission and modern electricity production technology. It can be a source of energy for vehicles, industries, electricity demand, and even household chores. A fuel cell can meet MW level power demand in the grid. The power of the fuel cell may remain side by side of the grid. When the grid power becomes low then the fuel cell power can be a good alternative source of power with kW level.

In the electrochemical reaction in a fuel cell, there is a generation of heat along with the electricity and water.<sup>4,8,11</sup> This heat can be used in the water boiling system with 90% efficiency. Fuel cells are being used in vehicles as a mobile battery.<sup>12-14</sup> Without polluting the environment, electricity can be produced along with heat and water from hydrogen and oxygen gas fed into the PEMFC. In this reaction process, there are a lot of parameters to be considered to make the reaction process continue for a long duration without interruption. The different factors affecting the architecture and the performance of a fuel cell must be explored in a precise manner in the way of progress.<sup>12-19</sup> Among all the parameters, the temperature of a fuel cell is a significant performance changing factor.<sup>7-9,14</sup> In this review paper we will focus on the effects of temperature on the performance and durability of hydrogen fuel cell and more specifically, a Proton Exchange Membrane Fuel Cell (PEMFC).

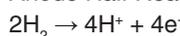
### Mechanism of Hydrogen Fuel Cell

The main theme of a PEMFC is to produce electricity from the electrochemical reaction between hydrogen and oxygen reactant.<sup>1,2</sup> In this reaction electricity, heat, and water are produced. This electrochemical reaction happens with two electrodes separate with a proton exchange membrane. In the anode side, a hydrogen oxidation reaction occurs and in the cathode side, an oxygen reduction reaction occurs.<sup>8</sup> For uniform reaction over the surface of the electrode, there is a gas diffusion layer. This gas diffusion layer will drive the gas all over the electrode to control the optimum performance of the reaction. Oxidation and reduction reactions are a slow process without any catalyst. For better and continuous operation, we need to introduce catalyst in the electrode. In the anode side, hydrogen gas is changed into hydrogen atom (proton, H<sup>+</sup>) and the electron goes through the outer circuit.<sup>14</sup> Now only proton can pass through the proton exchange membrane. Hydrogen or oxygen gas is not permitted to pass through the proton exchange membrane. On the cathode side, oxygen gas comes from the air and passes through the gas diffusion layer, and with the help of the oxygen reduction reaction electricity, water, and heat are produced.<sup>14,17</sup> Figure 1 shows the mechanism of the PEMFC.

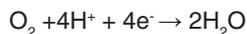
The full reaction is mentioned below.<sup>17-21, 24,25</sup>



Anode Half Reaction:



Cathode Half Reaction:



Among fuel cells, the proton exchange membrane fuel cell (PEMFC) gather much attention because of some unique criteria such as low thermal condition of operation, greater efficiency, shorter in size.<sup>10</sup> The proton exchange membrane has hydrophilic and hydrophobic characteristics at the same time. Table 1 shows the types of PEMFC and their features. The design of the membrane remains durable for the hydrophobic part of the membrane, on the other hand, the hydrophilic part helps the membrane to remain hydrated for the optimum operation of the

PEMFC,<sup>22,24-30</sup> Water in the hydrated membrane helps proton to dissociate from the sulfonic acid part of the membrane material and the hydrogen ion (Proton)

transfer from the anode side to the cathode side through the membrane. The input hydrogen gas must be pure up to 99.99%.

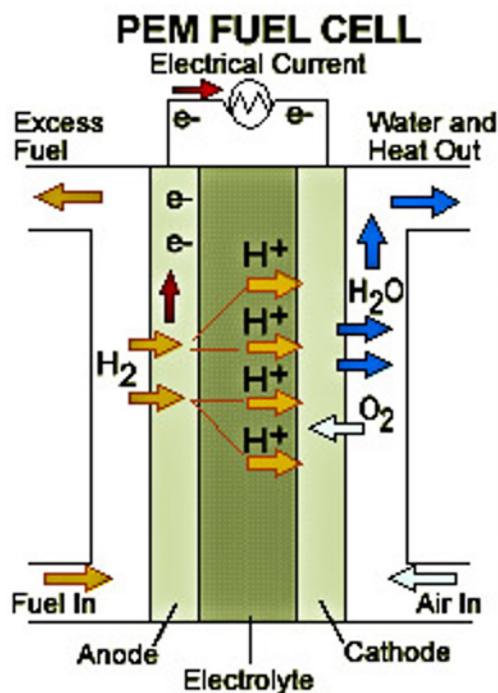


Fig. 1: Mechanism of PEMFC ( Source: <https://publish.illinois.edu/fuel-cells/2012/11/11/pemfc/>)

Table 1: Types of Proton Exchange Membrane Fuel Cell.

PEMFC Type	Operating Temperature	Features
High Temperature-PEMFC	Above 100°C	I. Durable in high CO condition II. Well heat releasing system III. Humidification not required
Low Temperature-PEMFC	60°C to 80°C	I. Gas permeability resistance is high. II. Cost effective technology

### Factors Affecting the Performance of Hydrogen Fuel Cell

The performance of a PEMFC can be affected by many reasons. The load current, temperature, relative humidity, membrane thickness, membrane-active area, electrode active area, corrosion, purity, pressure, and concentration of hydrogen fuel, maintenance of water inside the cell, pressure in the electrode particularly on both side of the membrane etc. are the factors.<sup>12-19, 22,28</sup>

Activation, ohmic and concentration losses make the fuel cell voltage less than before.<sup>29</sup> Humid condition and thermal condition are two significant factors for PEMFC operation. The change in the temperature of a fuel cell affects the electrochemical reaction, proton exchange, and water production. The bipolar plate has two sides.<sup>30,31</sup> On one side there is a gas flow path and on the other side, external water flow is used for temperature maintenance in the fuel cell. Rising current density accelerates the reaction

process.<sup>17-19</sup> Besides, the heat production in the fuel cell is proportional to the rate of the reaction process. In the outer part of the plate, the proton exchange membrane becomes dried because of the rising temperature. Additionally, the density of the electron flow rate becomes lower over time in the fuel cell.<sup>19,28</sup> The density of the electron flow is higher when the supplied gas is enough. The current distribution is also an important factor and it is inversely proportional to the density of electron flow rate. The rising reactant flow rate creates a uniform current flow. Inappropriate thermal energy will decrease the performance of the proton exchange membrane.<sup>12, 23-28</sup>

### Effect of Temperature on PEMFC

Though several factors such as operating temperature, electrolytes used, humidity, catalyst, produced heat etc. have vital effects on the performance of Hydrogen Fuel Cell, in this paper, we will discuss the effects of temperature elaborately. The effects of temperature on different parameters are shown in Table 2 and discussed elaborately below:

### Performance and Efficiency

Heat generates during the PEMFC operation. For better efficiency and consistence output there must be a cooling process either by air or fluid to get rid

of the cell generated heat.<sup>10</sup> The proton exchange membrane fuel cell shows better performance with the rise in temperature and pressure. Because the entropy change is small during the rise in temperature and pressure. A less chance of entropy indicates better and stable performance in a fuel cell. As the thermal energy is improved, the overall performance like current, current density, voltage, electricity production of a proton exchange membrane fuel cell improves.<sup>24</sup> It has been observed in another study that fuel cell performance increased when the temperature increased to 120°C.<sup>32,33,37</sup>

Normally it is considered that the efficiency of the PEMFC is increased in terms of the increase in temperature.<sup>22,36-40</sup> A hydrated proton exchange membrane normally works in a range of temperatures below 100°C and if we include some new elements in the PEMFC then the FC will operate in the temperature range higher than 100°C.<sup>36,37</sup> A new technology has been found for high-temperature fuel cells with a temperature range from 90°C to 200°C.<sup>40,44-46</sup> At this high-temperature range from 90 to 200°C, the rate of proton exchange through the membrane becomes high and that's why there is a rapid rise in reaction mechanism in anode and cathode.<sup>40-46</sup> The transfer of mass positively rises with the rise of the temperature.

**Table 2: Effect of Temperature on PEMFC parameters**

Parameters	Effect on the parameters	References
Performance and efficiency	Increases with the increase in temperature	22,32,36,37
Humidity	Optimum temperature maintains the required humidity	32,36,45-50
Power Production	Increases with the increase in temperature	18,32, 55,56
Voltage	Increases with the increase in temperature	47, 58-60
Leakage Current	Increases with the increase in temperature	61,62
Catalyst Tolerance	Increases with the increase in temperature	26,29,36, 40,66,67
Mass cross-over	Decreases with the increase in temperature	32,44-46
Durability	Decreases with the increase in temperature	40,48,71-76

### Humidity

The proton exchange quality of the membrane depends on the humid condition of the membrane.<sup>47-53</sup> The presence of water in the membrane maintains the optimum humid condition. Adequate water is required for the membrane to be hydrated and the

rest of the water needs to come out of the fuel cell for better performance. Otherwise, the extra water will create additional complications inside the fuel cell. At the same time, the temperature rise is one of the reasons for water loss in the membrane.<sup>22,32,36</sup> When the temperature of hydrogen fuel remains high, the

membrane becomes dehydrated. As a result, less amount of proton can pass through the anode to the cathode side which will reduce the electron flow and efficiency of the PEMFC. In high temperature and high humidity, membrane crossover of the hydrogen gas rises. It is one of the reasons for PEMFC decay. After the exchange of protons through the membrane with electrochemical reaction, water is produced. Excess water production will make the membrane wet by the diffusion process.<sup>45</sup> Wet proton exchange membrane is very essential for proton exchange from anode to cathode. The electrochemical reaction would rapidly rise with the increase in temperature and would produce enough water. This water will make the membrane wet and again it will increase PEMFC efficiency.<sup>45,53,54</sup>

Without optimum humid conditions in the membrane, the resistance of the membrane to hydrogen ion will rise. As a result, this rise in resistance will increase the temperature. To maintain the good condition of the fuel cell operation, an optimum humid condition should be maintained either by *in-vitro* or *in-vivo* water maintenance in the fuel cell.<sup>47,48</sup> The ion exchange is the main parameter to be observed during less humid conditions. Humidity controls the hydrogen and oxygen flow in both of the electrodes in the fuel cell.<sup>48,49</sup> Particularly the humidity in the cathode side creates a condition for operating a fuel cell in lower temperatures. The performance and durability of the membrane directly depend on the humid condition. If the humidity in the proton exchange membrane is up to 100%, it can lead to catalyst decay from the surface of the membrane.<sup>47-50</sup> Besides, in less humidity, the polymer electrolyte membrane turns into more brittle form and degrades faster, particularly the acid group of the membrane degrades, and the catalyst is washed away from the surface of the membrane.<sup>32,36,47-50</sup>

### **The Efficiency of Power Production**

In a proton exchange membrane fuel cell, the density of power production rises by 16% for the operational temperature rise from 50°C to 80°C. The power production efficiency of a PEMFC is increased with the increase of operational temperature.<sup>18,32</sup> The value of dissipated power is reduced and the initiated over-potential become less due to the rising temperature which results in increased power production efficiency.<sup>55-56</sup>

### **Voltage**

According to the Nernst equation, the temperature is proportional to the output voltage.<sup>58</sup> Higher temperature leads to faster kinetics and as a result, the voltage is also increased. This increase in voltage surpasses the voltage loss from the negative thermodynamic correlation between the open-circuit voltage and temperature.<sup>58-60</sup> But in a study, the fuel cell was found to have worse performance due to unfortunate damage or hole in the proton exchange membrane at 70°C operating temperature.<sup>47</sup> In this case, the voltage dropped in the fuel cell as the hydrogen gas passes through the membrane. So, if the voltage does not increase with the temperature increase, there might be damage in the proton exchange membrane.

### **Leakage Current**

The membrane of PEMFC is regarded as hydrogen impermeable and electrically insulated. But leakage current still occurs within the fuel cell. It is often supposed to be around 0.01 A.cm<sup>-2</sup> in PEM fuel cell simulation literature.<sup>61</sup> During the electrochemical reaction in the fuel cell, hydrogen gas, and electrons diffuse through the proton exchange membrane.<sup>62</sup> For the diffusion process of hydrogen gas and electrons through the proton exchange membrane, a minute amount of current is produced. This current is known as leakage current. With the rise in temperature, the leakage current also increases. If the temperature rises from 50°C to 80°C then the leakage current density change will be 6-12 mA/cm<sup>2</sup>. The value of leakage current density will be constant with the constant value of temperature.

### **Catalyst Tolerance**

The decay of the material of the components of the PEMFC is a very important factor in the performance of the PEMFC. The efficiency of catalyst decay over time depends on the hydrogen oxidation reaction, oxygen reduction reaction, high potential, and pH environment. Platinum catalyst plays a vital role in the performance of fuel cells. The oxygen reduction reaction in the cathode is a slow reaction process. To overcome the slowness, an effective catalyst can accelerate the oxygen reaction rate in the cathode which will improve the PEMFC efficiency rapidly. The energy conversion process in PEMFC is very efficient regarding the input hydrogen purity.<sup>37</sup> Otherwise less pure hydrogen will damage fuel

cell components and operation. To produce low-cost hydrogen fuel with required purity is a goal to achieve to make fuel cells more feasible to use. If the hydrogen is not pure then carbon mono oxide will be produced and associates with the surface of the catalyst. That's why the reaction hampered in the fuel cell.<sup>24-26</sup> However, in the HT-PEMFC this carbon mono-oxide dissociation in the catalyst surface can be solved. At high temperature accelerate the reaction kinetic in a fuel cell. In high-temperature PEM become dehydrated.<sup>26-29</sup> As a result catalyst decay decreases, proton passes through membrane rapidly, electrochemical reaction accelerates, reaction remains active for a long time. High temperature affects the lifetime of the FC. Besides leaching of reaction acid should be maintained in HT-PEMFC. Water is produced in the chemical reaction at the anode side. This water production falls at the rise in the operational temperature range from 80°C to 120°C. Rapid water production in the PEMFC will inundate the proton exchange membrane. A proton exchange membrane fuel cell has an efficiency of up to 60%.<sup>26</sup> The tolerance level of the catalyst to the contaminants in the membrane will rise significantly with temperature.<sup>40,65</sup> When PEMFC operates at a temperature below 100°C, CO covers the catalyst layer. As a result, the electrochemical reaction process becomes slower. The CO accumulation in the catalyst surface reduces the 50% lifetime of the fuel cell. To ameliorate the bad effect of CO, a certain type of catalyst should be selected which has no reactive mechanism to this harmful gas.<sup>40,67</sup>

#### **Mass Cross-Over and Concentration Over-Potential**

Mass cross-over and concentration over-potential are also related to the temperature of the PEMFC. If the temperature rises, the mass cross-over falls and concentration over-potential rises. The current density becomes high.<sup>32</sup> On the other hand, the activation over-potential remains static up to the 80°C. Then towards 100°C, the activation over-potential rises. It is considered that up to 80°C, the PEMFC efficiency remains in good condition. In anode and cathode, the activation over-potential decreases with the rise in temperature over 80°C. But in 120°C the anode activation over-potential value is higher than that was between in the 80 to 100°C range but in the cathode, the situation is opposite.<sup>44-46</sup>

#### **Durability**

Despite the immense evolution of the proton exchange membrane, the longevity is still a concern.<sup>76</sup> The durability of the catalyst, electrode plate, gas diffusion layer, the gasket is directly related to the longevity of the proton exchange membrane.<sup>40-48</sup> Electrochemical erosion, component erosion, and thermal effect are the leading factors for the longevity of the proton exchange membrane.<sup>71,76</sup> The proton exchange membrane loses its water and becomes dehydrated with the rise of the temperature.<sup>40-46</sup> As a result, the hydrogen gas crossing the dehydrated membrane will reach on the cathode side. Hydrogen in the cathode side will then damage the bipolar plate, catalyst, and gaskets. If it continues to operate at high temperatures, then over time the durability of the PEMFC will decrease.<sup>28</sup> A fluid dynamic model was proposed in research with an operating temperature range from 80°C to 120°C and pressure range at 200000Pa. In this model, a high-temperature fuel cell showed better performance with better current density at 80°C rather than 120°C. The water production in the anode side was found to be better than that of in cathode side. A change in temperature from 120°C to 80°C was found to give smooth water production. But it can directly harm the fuel cell and the durability of the fuel cell will decrease.<sup>69</sup> At low thermal conditions around 100°C, there is a minute amount of water accumulation in the surface of the proton exchange membrane.<sup>24</sup> The sulfonate part of the Nafion membrane decays at high-temperature range around 200°C which will permit the hydrogen gas to pass through the proton exchange membrane and reaches in cathode area.<sup>24,68</sup>

#### **Effect of Input Hydrogen Gas Temperature**

PEMFC has unique criteria such as low operating temperature & pressure, longevity, mobility and small size.<sup>1-8</sup> The start-stop mechanism and output load stability are the major issues of PEMFC. Lack of enough input gas supply results in a rise in temperature in PEMFC.<sup>44-46</sup> Inadequate input gas supply creates a potential pressure in the anode. As a result, the temperature of PEMFC rises and creates decay in the membrane which makes a decay path.<sup>24</sup> In vehicle operation, the fuel cell temperature range is 80°C. But the stability of the PEMFC will be affected by this temperature. At changing operating

temperatures such as 25°C, 40°C, 60°C and 80°C the fuel cell efficiency increased with the increasing temperature. The fuel cell efficiency increases when the start-stop round was in on mode and the stack efficiency decreased when the start-stop round was in off mode. But regardless the start-stop round was on or off with rising temperature the fuel cell can run with better efficiency.<sup>45</sup>

### Effect of Internally Produced Heat

If the hydrogen and oxygen flow is not enough then there will be a rise in temperature in PEMFC. As a result, the overall performance of the fuel cell will fall.<sup>24</sup> Produced heat in the fuel cell during chemical reaction affects all the components (anode, cathode, gas diffusion layer, gasket, electron collector, membrane electrode assembly) and the operating condition (temperature, the humidity of the membrane, voltage, current) of the PEMFC.<sup>46-50,70-74</sup>

Lu *et al.*, in 2016 demonstrated that the Platinum palladium-based fuel cell reaction catalyst increases performance and output energy due to enhanced ion exchange during the reaction phase. If the resistance to ion exchange is lower, then the loss would be lower and the longevity would improve. Therefore, the extra heat production due to the resistance of the ion exchange would be lower.<sup>73</sup>

### New Technology for Enduring High Temperature

In the rising market, there is a huge demand for polymer electrolyte membrane temperature range from 120°C to 140°C. Because the water drainage system and heat processing are very easy in high-temperature PEMFC.<sup>23</sup> A new type of non-perfluorosulfonic acid membrane other than nafion or perfluorosulfonic acid is a good choice for cost-effective and durable in high-temperature condition with better performance.<sup>23,75</sup> It facilitates the use of high temperature.<sup>45</sup> By modifying different parameters and design constructions, high temperature can be used to have greater efficiency.

### Conclusion

Hydrogen fuel cell is a promising source of renewable energy in upcoming days. But the system is still not economically feasible as the cost of construction is high, the relatively inexpensive catalyst is yet to be discovered, durability is not up to the mark,

the cost of producing hydrogen gas is high, and so on. Fuel cell performance will vary depending on architectural design, component design, the chemical composition of components, atmospheric specifications, the parameters within the fuel cell, the best operating condition, the ability to generate energy. A continuous performance can be observed through a fuel cell test station setup. In this paper, we can conclude that temperature has significant effects on almost all ambient parameters and design components. So, considering all these effects, the optimum temperature should be used. As the higher temperature has been found to be beneficial in most cases, design variations are required to facilitate it. We have also discussed the design variations that can be useful for using high temperature. This review paper can lead to a proper combination and specification of the design components and factors to develop purpose-specific Hydrogen fuel cells.

### Highlights

- Different factors have effects on the performance and durability of Hydrogen fuel cell.
- The effects of Temperature on the performance and durability of PEMFC have been discussed.

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### Conflict of Interest

The authors do not have any conflict of interest.

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