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A Review on Temperature Reduction Management and Heat Management System to be Implemented in High Temperature Proton Exchange Membrane Fuel Cell

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Abstract: *Commercialization of technology of PEMFC (proton electron membrane fuel cells) remains a big obstacle regardless of the broad research on PEM and other fuel cells.High temperature proton exchange fuel cell has found its wide application now days and it is very important to manage the Heat and apply cooling arrangement for the fuel cell stack as durability is at stake when exposed for the longer duration. Considering the heat sources HT-PEM has three heat sources: 1) irreversible joule heating caused by the charge transport in the solid electrolyte or the conductor 2) Reversible heating due to the charge entropy change and 3) irreversible heating of the reaction caused due to the over potential. Considering all the aspect it is found that the optimum temperature for HT PEM Fuel cell is 170℃ to 180℃ though it is observed that at 200℃ the efficiency has shown positive effect. The enormous heat generated by the electrochemical reaction of the fuel cell as a by-product and when it reaches to the extreme limit of the recommended temperature which makes cooling necessary and based on the FC power the cooling strategy is to be implemented accordingly, Even though there are many methods for cooling but the medium through which the cooling takes place is restricted to 2 i.e. Air and Liquid..*

Keywords: Proton Exchange Membrane Fuel Cell, Irreversible Joule Heating, Reversible Heating, Irreversible Heating, Cooling, Heating

I. INTRODUCTION

In today's society, renewable energy is critical. It was a big issue in both the November 2016 US election and the recently ended French election (May 2017). This is due to the need for a cleaner environment as well as a reduction in the ever-increasing cost of energy as the world's population grows. PEM fuel cells are seen as a viable option because they produce near-zero emissions while also being highly efficient. The fuel cell has been in development since 1839. After more than a century, the first PEM fuel cell was developed. If correctly studied, fuel cell development can be ascribed to the discovery of materials with features that improve the product's durability. Regardless of effective progress made in the growth of the PEM fuel cell, commercialization remains a serious challenge.

Fuel cell can be prominently defined as an electrochemical device that does the constant alteration of chemical energy into electrical energy (can be considered as a fuel) during the Redox reaction (oxidising-reducing reaction) though the reaction is exothermic. The construction is simple in case of fuel cell it comprises the negative electrode and positive electrode separated by the electrolyte. The functional components of fuel cells consist of the membrane that ensures separation of basic reactants of the cell that are responsible for the generation of the electricity (hydrogen and oxygen, porous electrodes and bipolar plates or current collectors) for joint control of supply and distribution of reactants with subsequent delivery of electric current. The area of contact between electrodes and membrane forms a three-phase interface - electrode, electrolyte and reagents produced by oxidising of fuel or reduction of the oxidising agent; that enables the actual functioning of fuel cell and the performance of key electrochemical processes. The reaction that takes in the fuel cell. These reactions are exothermic and when combined with 2 half-cell potential for electrochemical reaction the output is a positive cell potential. [1,2].

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Following are the Chemical reactions that occur in the Fuel Cell:

$H_2 + ½ O_2 \rightarrow H_2O$ (Full reaction)
$H_2 \rightarrow 2 H^+ + 2e-$ (Reaction taking place at Anode half)
$O_2 + 4e- + 4H^+ \rightarrow 2H_2O$ (Reaction taking at Cathode half)

This future sustainable energy system has the potential to become the prominent energy providing alternative solutions to the world. Proton exchange membrane fuel cell is also known as polymer electrolyte membrane.

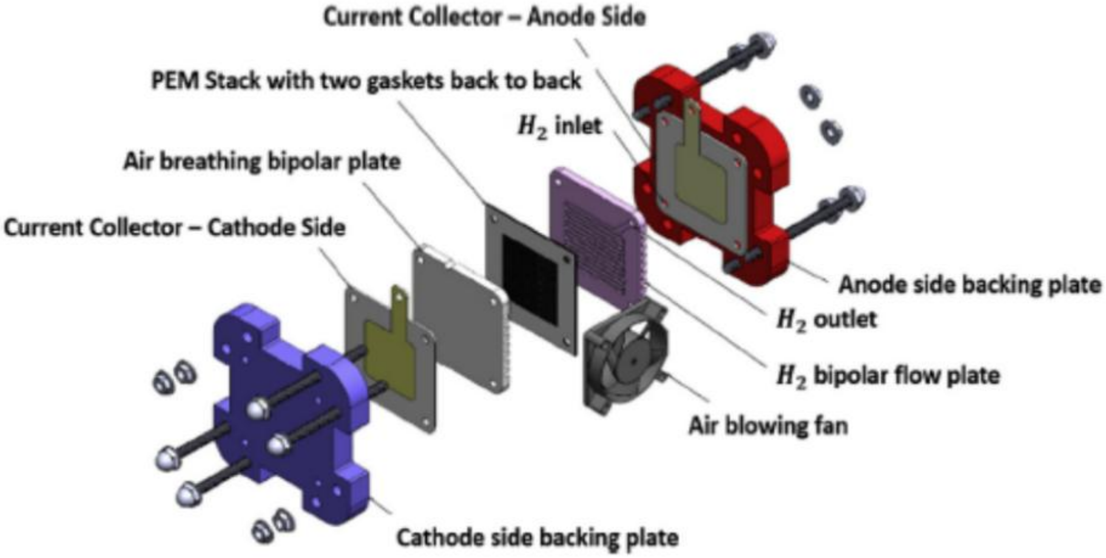

Figure 1: Schematic modelling of Proton exchange membrane fuel cell. [12]

II. WORKING OF THE FUEL CELL

Considering the 3 division of the of the proton exchange membrane fuel cell one being the anode other being the cathode region and the middle part which separates the anode and cathode is the proton exchange membrane. Hydrogen gas flows in the anode region and travel through the diffusion to the porous gas diffusion layer and reaches the reaction site, where it gets electrochemically oxidized. The membrane then allows the transfer of proton and water. Air flows inside the cathode layer and transports to the cathode layer. Where the reaction of protons coming from the anode through the membrane and the oxygen takes place also electron transports from the external circuit to form water [12].

III. NATURE OF THE REACTION TAKING PLACE IN FUEL CELL

The reaction taking place in the Proton exchange membrane fuel cell is exothermic in nature, it is the spontaneous redox reaction that generates the power for the fuel cell. The heat generated after certain extent is the major concern to the fuel cell, the heat generated with the reaction can cause the damage to the low temperature proton exchange membrane fuel cell, as we know the low temperature proton exchange membrane fuel cell membrane typically uses perfluorosulfonic acid i.e. Nafion. It has a hydrophobic phase which acts as a base for structural integrity of the membrane and sulphonic acid acts as a hydrophilic phase for the water reservoir [3]. Water acts a charge carrier and allows the conductivity of the proton inside membrane therefore it is always expected that membrane has to be in the hydrated state for the proton conduction and heat may hinder the process by dehydrating membrane and cathode flooding. Dehydration of the membrane will decrease the proton conductivity of the membrane thus the resistance of the cell will significantly increase, but excessive water at the cathode end of the electro-catalyst will cause flooding and there will be significant impact on the movement of the oxygen through the porous gas diffusion electrode will be restricted [4][5]. Perfluorosulfonic acid often suffers from degradation near 80℃ at low humidity condition [6]. Approximately 60% of the energy of the total energy produced during the reaction is converted in to the electricity and rest 40% is waste in the MEA of the fuel cell [7].

IV. HEAT TRANSFER AND HEAT MANAGEMENT SYSTEM

4.1 Heat Transfer

HT-PEM has three heat sources: 1) irreversible joule heating caused by the charge transport in the solid electrolyte or the conductor (refer Eq. c), 2) Reversible heating due to the charge entropy change (refer Eq. d), second term on right side) and 3) irreversible heating of the reaction caused due to the overpotential (refer Eq. d). Correspondingly, the following are the equation that are used to calculate the heat transfer in the solid and fluid materials respectively. [8,10,13]

$$\rho C_P \frac{\partial T}{\partial t} = \nabla . (k \nabla T) + Q_h \qquad \text{(a)}$$

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u . \nabla T = \nabla . (k \nabla T) + Q_h \qquad \text{(b)}$$

Above equations are based on the first law of thermodynamics. On left hand side is the internal energy. the next term after the first term in (Eq. b) describes heat transfer in a velocity field. Velocity is kept zero for the heat transfer in equation in velocity field (Eq. a). according to the fourier's law both the right-hand side terms of the (Eq. a) and (Eq. b) describes the heat flux vector and is proportional to temperature gradient, and the very next term is the source of heat, which includes three heat sources mentioned above. [8,9,13]

$$Q_{h,j} = -(i_s . \nabla \emptyset_s + i_1 . \nabla \emptyset_1) \qquad \text{(c)}$$

$$Q_{h,m} = (\emptyset_s - \emptyset_l - E_{eq,m}) i_m + T \frac{\partial E_{eq,m}}{\partial T} i_m \qquad \text{(d)}$$

Where, ρ = Density (kg.m^{-3})
C_P = Heat Capacity (J.kg^{-1}.°C^{-1})
T = Temperature (℃)
t = Time (s)
k = Thermal conductivity (W.m^{-1}. ℃$^{-1}$)
Q_h = Heat source or sink (W.m^{-3})
u = Velocity (m.s^{-1})
$Q_{h,m}$ = Heat source or sink electrode reaction on anode or cathode (W.m^{-3})
$\emptyset_s$ = Potential of electrode (V)
$E_{eq,m}$ = Equilibrium potential of electrode reactiom on anode or cathode (V)
i_m = Current density (A.m^{-2})
$\emptyset_l$ = Potential of electrolyte (V)

4.2 Heat Management

Heat management is an extremely important for the fuel cell for the best performance and the high efficiency. High temperature proton exchange membrane requires heat to improve the kinetics of the electrochemical reaction since High temperature proton exchange membrane fuel cell uses the high temperature for the operation. as it offers very less resistance at the elevated temperature i.e above 200℃. The kinetics improves the current density due to the less resistance in the membrane and higher oxygen consumption at the same time at the cathode. Also, the activation energy and various transport properties all depends on the temperature to some extent. Fig. 1 shows the simulation data (taking 433 K as an example) with the help of comparison with the experimental data [12].

Acid leaching due to various mechanism used for the production of power can occur due to the temperature rise and durability of the fuel cell will decrease. Therefore, stack temperature level must be maintained to certain level so that the temperature overshoot will not be the cause for the destruction of the stack and its components. Operating the fuel cell within its prescribed temperature range is always advice able and for a short period especially in the start-up mode. Therefore, it is equally important to operate the proton exchange membrane fuel cell at a proper operating temperature therefore heat management is an important aspect for the proton exchange membrane fuel cell. [14]

While operating the High temperature proton exchange membrane fuel cell it must be ensured that the temperature of air fuel inlet, hydrogen and the stack should be determined based on the expected power density and durability. The temperature is a key variable which needs to be continuously checked and controlled precisely for a dependable operation. The uniform distribution of the heat by heating the stacks or gas lines in temperature precise environment to balance the performance of the stack. [15-17]

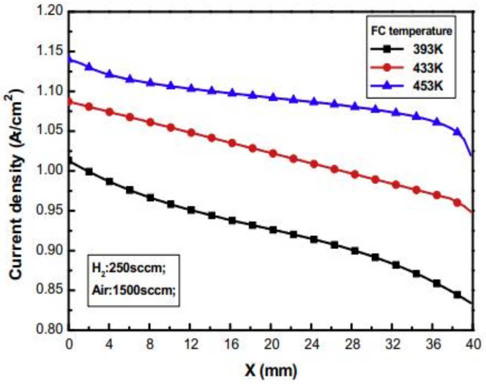

Figure 2: Current density with the fuel cell temperature. [12]

Many researchers have shown their interest to study the performance of the fuel cell based on the temperature. Zhang et al [18] studied the performance based on the temperature of the fuel cell Wannek et al. studied for a temperature range of 120℃ - 180℃. While Wannek et al. [19] prepared research for the temperature range of 140℃ - 200℃ and observed the performance of the cell under various operating temperature and according to their research with the rise in temperature the current density will increase but membrane resistance will decrease which is shown below (fig. 3).

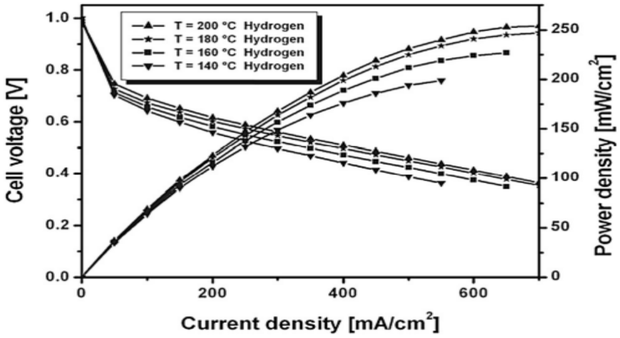

Figure 3: HT-PEM fuel cell performance at various operating temperature using hydrogen and air at ambient pressure [19].

Similarly, other researchers have shown various optimum temperature ranges for the high temperature proton exchange fuel cell, Parrondo et al. [20] suggests that that 180℃ is the optimum range of temperature for the operation of High temperature fuel cell, whereas Ong et al. [21] says 170℃ was the optimum temperature for their fuel cell. Moreover Onno et al. [24] had a long-term observation on various operating temperature 150℃, 170℃, 190℃ to study the durability of the fuel cell, and concluded that high temperature yields better performance but durability of the cell is compromised at higher temperature.

High temperature proton exchange membrane requires some amount of heat for the good start-up. Heating of the stack takes place inside the chamber thus making it tough or eliminate heat form the stack. According to Zhang et al. [18] the heat can be removed at a higher rate via cathode air flow, thus streamlining or simplifying the design of the stack arrangement which would also reduce the cost and at same way improve the power density. Also, the components can be kept in ambient environment where they are heated separately. This will offer a controlled and fast means by which unwanted heat is rejected at much higher rate due to high temperature difference between the fuel cell components and ambient surroundings. Time required for heating of the thermal mass can be determined by heat transfer, mass and thermal losses shown in the equation below (Eq. e),

$$t = \frac{c_{p,s} m_s \Delta T}{Q_{in}} \qquad \text{(e)}$$

Where, $c_{p,s}$ is the specific heat, $\Delta T$is the heat difference and $Q_{in}$is the input energy.

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There are many researchers who published their study on the different ways to raise the temperature for the start-up of the high temperature proton exchange membrane fuel cell. Wang et al. [13] proposed that HT- PEMFC consists the gas channel heating, cooling channel heating, combined gas cannel and reaction heating. To heat the cooling channel preheated air around 160℃ is blown over the stacks into the cooling channel while Gas channel heating is conducted by heating the channel and blowing preheated air along with preheated Nitrogen gas at 160℃ into anode gas channel. Best configuration was found to be combination of reaction heating methods and cooling channels (fig. 4), shows that heating is done at a faster rate when compared with other heating methods.

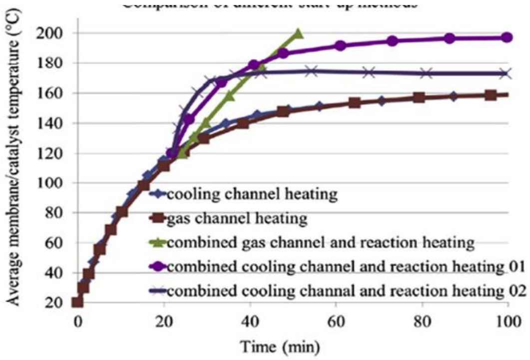

Figure 4: Comparison of different start-up methods [13]

Andreasen et al. [22] explains four different strategies for heating 400 W in-house stack construction, their work enlightens by the use of hot air (160℃) can be useful to rapidly reach the required temperature within 6 min. A homogeneous heat distribution and smaller start-up energy storage was used and applied throughout the entire stack compared to the direct heating strategy, where only outer parts were heated. Another heating method was suggested by Barreras et al. [23] where resistance wire was placed on every plate to heat the membrane electrode assembly by conduction. Temperature rises up evenly in the membrane electrode assembly with the help of this method.

Though the heat supplied while start-up is not only the major concern to manage the heat after certain extent and throughout operation is also the important step, as the reaction is going to take place more amount of heat is going to release and high degree of heat should be countered or removed. Though the excess unutilized heat should be used for other application. [14]

V. HEAT REDUCTION SYSTEM (COOLING MANAGEMENT SYSTEM)

The enormous heat generated by the electrochemical reaction of the fuel cell as a by-product and when it reaches to the extreme limit of the recommended temperature, it will be harmful for the stack components and in order to prevent it, a cooling system needs to be incorporated in the design of proton exchange membrane fuel cell [14]. Effectively removal of the heat has the positive impact on the durability of the device [33].

According to Collen Spiegel et al [25] There are several means to achieve cooling, some of the methods through which the cooling can take place are discussed below.

1. Cooling through free convection
2. Cooling through a condenser
3. Cooling using heat spreaders
4. Cooling using cooling plates

5.1 Cooling using Free Convection

Simplest of all for cooling a fuel cell stack is through free convection. No fancy design, no coolant and is also suitable for small or low power fuel cell stacks, heat dissipation can be achieved through fins or open cathode flow design. As the cooling depends on temperature and humidity of the environment therefore it does not have adequate temperature control over the proton exchange membrane fuel cell. Correspondingly, after cooling it becomes difficult to recover the waste heat for power using this method.

5.2 Cooling through Condenser

Unlike other cooling type condenser, it can be incorporated to cool the high temperature proton exchange membrane fuel cell. here water can be condensed from the exhaust and the same water can be reintroduced into stacks. To avoid losing water the condenser is kept water balance temperature. Therefore, the system accurate temperature control system to control the cooling.

5.3 Cooling using Heat Spreaders

Alternative option to cool the stack is using heat spreaders. Through the heat spreaders heat is more efficiently transferred outside the stack. Heat spreaders provides more surface area to spread the heat through conduction and then dissipate heat in the surrounding using natural or forced convection. For greater efficiency, high-performance heat spreaders must be used.

5.4 Cooling using Cooling Plates

To remove the heat from the stack thin plates are inserted into the fuel cell or additional channels are created in the bipolar plates to pass the water, air, or coolant to lower the heat from the stack. This cooling arrangement can provide precise temperature control, where accurate temperature is needed within the specified range.

Moreover, according to Bargal M. et al. [26] many such cooling methods are incorporated for the cooling of the stacks other methods including edge cooling, cooling with separate airflow, phase change cooling. These cooling have their own mode of application as per the usage and have their own advantages, disadvantages and challenges as given in (Table 1)

Table 1: Summary of cooling strategies for PEMFC stacks after adding and reproduced from Ref. [26]

Cooling strategy	**FC power**	**Advantages**	**Limitations/Challenges**
Cooling with the help of Cathode air	<100 W	▪ Simple system ▪ No coolant loop ▪ Low cost	▪ Large volume and weight of the stack ▪ No control on temperature stack ▪ Free convection cannot be used for removing heat
Separate airflow cooling.	200–2000 W	▪ Simple system ▪ No coolant loop ▪ Slight parasitic power	▪ Unrealistic strategy ▪ An exchange between cooling performance and parasitic power
Cooling with heat spreaders (edge cooling)	~1000 W	▪ Lower system complication ▪ Developments in the complete system dependability ▪ low Parasitic power ▪ avoiding coolant sealing issue	▪ The limited heat transfer length ▪ cost effective materials are not easily available with decent mechanical properties and very high thermal conductivity
Cooling with the help of phase change		▪ Exclusion of coolant pump ▪ Reduces the coolant flow rate	▪ Two-phase flow instability
Cooling through boiling	~1000 W	▪ delivers a unvarying operating temperature ▪ Uses electronic devices and refrigeration fields and components	▪ Coolant boiling temperature must be lower stack operating temperature (Special coolant) ▪ Non-scalable to automotive powertrains
Evaporative cooling	500 W to 75 kW	▪ Simplifying the complete system ▪ Cold start capability ▪ Interior humidification	▪ Requires a special design ▪ Dynamic regulator of water evaporation rate ▪ The thermal mass of liquid water on cold start-up.

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Cooling strategy	**FC power**	**Advantages**	**Limitations/Challenges**
Cooling Liquid	>10 KW	▪ High cooling capability ▪ Flexible control of cooling capability ▪ Cooling improvement ability using diverse customs ▪ found its way in automotive applications	▪ Radiator size and weight ▪ Large parasitic power ▪ Requires additional tools

Though there are many methods to cool the fuel cell but infrastructure through which the cooling will take place are limited to two that is air and liquid cooling. For the air-cooling system, the air having higher stoichiometry is applied on the manifold the aim is to remove the heat generated by the stack and also keep the temperature with the required range. It is also accorded as the cheap and simple arrangement since it only need air pump to stream air to the cell and balance of plant (BOP). The blower power consumption is expected to be low so that minimum parasitic losses are expected from the system also the design should be such that a low-pressure drop is ensured in the manifold [14].

Barrers et al. [23] suggested the suction mode for the cooling their system design using compact axial air-fan to remove excessive heat. Based on the calculation of the amount of air needed to maintain the temperature the optimal number of cooling channel were used. Moreover, Andreasen et al. [27] used cathode air cooled structure, the cooling of the stack was done by the blower that supplied air needed for cathode reaction. Stack has the feed forward control mechanism that determines the minimum stoichiometry of air and temperature measured to maintain with the help of PI feedback controller as shown in (fig. 5)

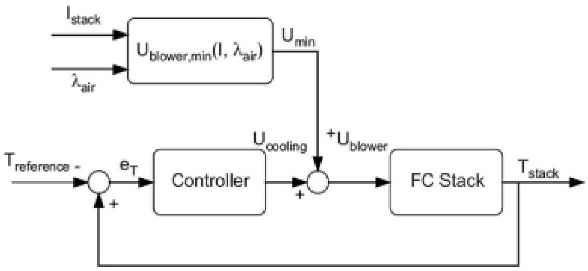

Figure 5: Block diagram showing the air flow strategy [27]

Reddy and Jayanti [28] in order to cool the stack temperature increased the cathode air flow by seven folds in excess of the stoichiometric ratio. The same heat which was removed was used to preheat the reactant to minimise the temperature variation of the stack.

Air cooling works for the low power generating fuel cell and becomes inefficient for the higher power generating fuel cell as the parasitic drain on the power becomes too high which makes it incompetent. Thus, liquid cooling system is preferred for a larger power or high operating temperature [29,30]. Liquid cooling optimizes the size and easier for the utility of the waste heat generated. In the liquid cooling system design a separate channel is designed through which the liquid flows to absorb the heat and stabilize it to the required amount. Subsequently a better method then the blower which required and consumed larger power to deliver the cooling. In this method the flow can be increased or decreased as per the required temperature profile. Also, many researches have been done to investigate the best cooling strategies for high temperature proton exchange membrane fuel cell stack [14]. Clement and Wang [31] they designed a system in which the liquid is pumped in the stack through the cooling plate channels and removed as the heat exchange occurs. Reddy et al. [32] applied an external cooling system to High temperature proton exchange membrane fuel cell stack and concentrated more towards local cell temperature, local over potential and local current density and restricted the temperature up to 10 K with the help of liquid cooling system.

VI. CONCLUSION

One of finest engineering inventions that is accorded as the future sustainable energy providing solution to the world. Unlike the other batteries which dries up, fuel cell produces power as long as oxidants are supplied. Fuel cell has the potential to be the replacement of the conventional fuel for the vehicle.

Managing Heat is one the important factor of the high temperature proton exchange membrane for the best performance and efficiency. Heat is required to boost the kinetics of the electrochemical reaction and the start-up of the high temperature proton exchange membrane fuel cell. For start-up of the high temperature proton exchange membrane fuel cell gas channel heating, cooling channel heating, combined gas channel and reactions heating is also used where 160℃ air is blown over the stacks. Though the temperature up to certain extent is found to be advantageous for the High temperature proton exchange membrane fuel cell, it improves the kinetics of the electrochemical reaction by offering less resistance at a high temperature above 200℃ The electrochemical reaction on the other hand generates high amount of heat during its operation. To manage the heat generated is priority in order to increase the efficiency and life of the high temperature proton exchange membrane fuel cell and to do so design should be such that the temperature distribution of the heat should be uniform to the overall stack of the High temperature proton exchange membrane. To manage the heat is to keep the temperature within the operating limit of the fuel cell though few positive outcomes are also observed at a slightly high temperature above the operating limit range like increase in the current density, slightly better performance is observed but the durability at the same time is compromised. High temperature is also responsible for the acid leaching of the cell and therefore stack temperature level must be maintained. Moreover, temperature of air fuel inlet, hydrogen and the stack should be determined based on the expected power density and durability. According to the researchers some suggests 170℃ is the optimum operating temperature whereas some suggest 180℃ and 190℃ as the optimum operating temperature range. To manage heat or to keep the required heat and reject the unwanted heat can be done by the means of cathode air flow and making the stack design more streamline and keeping the component in the ambient environment where they are heated separately which offers high rejection of the unwanted heat within the high temperature proton exchange membrane fuel cell. Time required for the heating is also determined in this paper by the heat transfer, mass and thermal losses.

The cooling management system is incorporated in the high temperature proton exchange membrane fuel cell to avoid the problems such as overheating of the stack and to improve the durability. There are several means to achieve cooling and some of the methods though which cooling can be achieved are, cooling through free convection where, cooling through a use od condenser, cooling with the help of heat spreaders and cooling using cooling plates can be achieved. Also, there are several strategies used for the fuel cell based on their power for example for the high temperature proton exchange membrane fuel cell having FC Power <100 W cooling with cathode air can be used, for FC Power 200-2000 W cooling with separate airflow can be used, for FC Power ~1000 W cooling with heat spreaders can be incorporated, for FC Power 500 W to 75 KW evaporative cooling method can be used, for FC Power >10 KW cooling liquid can be used for cooling. Though there are many methods to cool but medium is restricted to 2 i.e air cooling and water cooling. While using the air-cooling air having the high stoichiometry is blown on the manifold with the main aim to remove the heat in order to keep the temperature to the operating range. Liquid cooling the another medium to cool the high temperature proton exchange membrane where liquid absorbs the heat and drops down temperature to the required amount, generally liquid cooling system is preferred for the devices which uses large power or devices which have high operating temperature. Liquid cooling can be useful in dropping the temperature of the high proton exchange membrane upto 10 K.

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