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# Temperature Uniformity Improvement in Proton Exchange Membrane Fuel Cell: A Review

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## Abstract

The proton exchange membrane fuel cell emerging as a clean power generating system with high power density. The chemical energy of the fuel supplied to the system is directly converted to electrical energy irrespective to the energy conversion in conventional IC engine. Though PEMFC can be a potential alternative to IC engines, it needs much attention in research and development in view of commercialization. Thermal management is one of the key issue which need to be addressed to achieve the desired performance and prolong the life of fuel cell components. For optimum performance and better efficiency, the PEMFC operating temperature is limited from 60$^{o}$C to 70$^{o}$C. The thermal performance of PEMFC can be improved by enhancing the temperature uniformity within the cell or stack. This paper reviewed various research articles, addressed the methods applied to improve the temperature uniformity in PEMFC. The flow field configurations, flow channel dimensions, flow arrangements & flow field orientation, operating and other miscellaneous parameters are considered as potential scope and reviewed. Enhanced reactant distribution, better membrane hydration, uniform current density distribution, reduced cathode humidity and different fuel cell resistances are the factors identified which are helping to improve the temperature distribution in the fuel cell. Among the different methods reported the strategy associated with reactant and coolant flow channels are the most viable and cost effective approaches to achieve the desired temperature uniformity. However, the change of bipolar material like metal foam and metallic flow fields with spacers can give better thermal performance with reduced system weight. The operating parameters like stoichiometric ratio and anode humidity doesn't impact the temperature distribution much.

**Keywords:** temperature uniformity, flow channel configurations, flow channel dimensions, enhanced reactant distribution reduced system weight

## Introduction

The use of gasoline powered internal combustion engines in automotive sector increases the greenhouse gas emission and thereby increases global warming. The emission standards are approaching towards the zero tail pipe pollutants the Hydrogen powered PEMFC can be a suitable alternative for gasoline [1]. The PEMFC has some superior advantages for automotive application like low noble metal catalyst loading, high power density, quick start up, low operating temperature and facile hydrogen oxidation reaction [2]. Along with electricity an equal amount of heat energy is generated in the cell and the major sources for heat generation are entropic heat of reaction, electrochemical irreversible heat and Joule heating [3]. It is very important to maintain the operating temperature of PEMFC in an optimum range to prevent performance loss due to water flooding and to protect fuel cell components from degradation due to excess heat generation over long run [4]. The total amount of heat generated in PEMFC stack accounts for about 60% of hydrogen consumption and about 35% of heat is removed through various components of fuel cell by different modes of heat transfer and remaining heat energy will be removed from the stack using dedicative cooling system like air cooling, liquid cooling, passive cooling and phase change cooling [5] . The actual working of PEMFC is not isothermal in nature and every fuel cell is operating with some spatial temperature gradient which causes non uniform temperature distribution in the catalyst layer and bipolar plates [6,7]. The larger temperature gradient in the cell leads to membrane dehydration and reduces the ionic conductivity of the membrane thereby altering the output power and reduces the system performance [8]. The non-uniform reactant flow in the cell causes non uniform temperature distribution which in turn creates non uniformity in electrochemical reaction at different locations and results in formation of localized hot spots [9]. The mechanical degradation of the membrane due to hot spot formation is mainly associated with non-uniform reactant supply in poorly designed bipolar plates [10]. The parameters like current density, reactant mass flow rate, GDL permeability and cooling flow channels design have significant influence on temperature distribution. This paper discusses the various methods reported in literature to improve the temperature uniformity in the PEMFC. At first, heat generation and heat transfer in fuel cell will be discussed followed by the discussion on effects of different temperature uniformity improvement approaches like reactant and coolant flow channel configurations, bi-polar plate materials, flow channel dimensions, reactant flow arrangements and flow channel orientations, operating and other miscellaneous parameters will be done.

## Heat generation and transfer

The heat generation in fuel cell is proportional to the current density and cell operating voltage departure from ideal thermal voltage. The equation (3) gives generalized heat generation which is the summation of reversible and irreversible heat generation equation given in equation (1) and (2) respectively. The reversible heat generation is mainly due to the entropy change of reactant and irreversible heat generation is associated with activation, ohmic and concentration polarization. These polarization is also responsible for the loss in cell operating voltage.

$$q''_{rev} = i\,(E_{th} - E^0) \tag{1}$$

$$q''_{irrev} = i\,(E^0 - E_{cell}) \tag{2}$$

$$q''_{total} = i\,(E_{th} - E_{cell}) \tag{3}$$

where,
$q''$ = heat flux (W/cm$^2$)
$i$ = current density (A/cm$^2$)
$E_{th}$ = thermal voltage (V)
$E^0$ = Nernst voltage (V)
$E_{cell}$ = cell operating voltage (V)

The typical polarization of PEMFC is shown in figure. 1. The change in voltage in and power density is the function of current density. At low current density the voltage is high due to minimum cell polarization. The heat generation also less due to low rate of electro chemical reaction. Upon increasing the current density, the temperature of the cell rises up and affects the cell performance once the cell temperature is not controlled effectively [2].

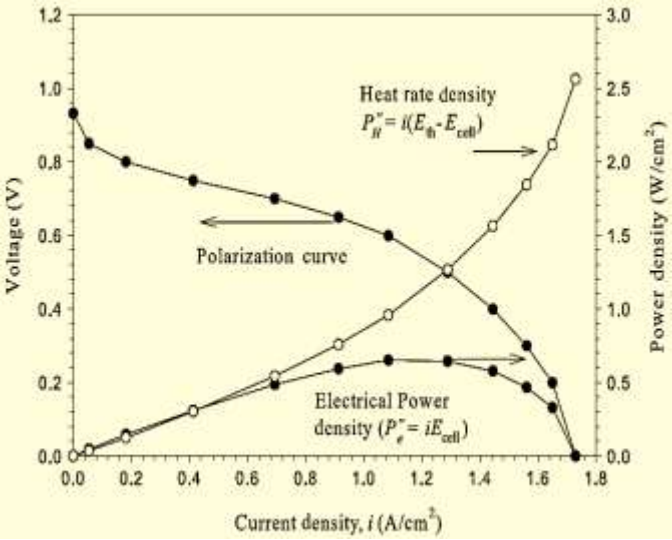

Figure. 1 Typical PEMFC polarization curve with heat generation [2]

The percentage of total heat generation due to reversible, irreversible and ohmic polarization are 35%, 55% and 10% respectively. Nearly one third of generated heat is transferred from the fuel cell naturally and remaining irreversibly heat generated from electrochemical reaction causes temperature non uniformity in fuel cell and a separate cooling medium is need to be provided to maintain the cell temperature in optimum range [11]. The cathode side of the fuel cell accounts for more heat generation because of the electrochemical reaction takes place at cathode catalyst layer. Most of the generated heat transferred through GDL is dissipated outside the fuel cell through channel shoulders. The abundant availability of oxygen near the cathode inlet leads to higher rate of electrochemical reaction and produces more heat. Along the flow channel due to the consumption of oxygen the rate of electrochemical reaction decreases which in turn reduces the temperature along the flow [12].

### Effect of reactant and cooling flow channel configuration

The role of reactant flow field configuration is inevitable in performance of PEMFC. Along with reactant transport it also acts both as an electric and thermal energy transfer medium. The flow field design should ensure low pressure drop in both anode and cathode side, no water flooding and uniform temperature distribution across the active area to achieve better performance [13]. New innovative leaf veins structured flow field design distributes the current and temperature more uniformly across the active area of the cell compared to the conventional serpentine flow field. The performance improvement obtained was around 42.1% at 0.4 V in the new flow field [14]. Due to the non-uniform reactant distribution in the conventional parallel flow field, the modified parallel flow field with multiple inlet and outlet in both anode and cathode is considered. The modified flow field enhanced the reactant distribution to GDL and evenly distributes the current density across the cell and there by reduces the hot spot formation at some specified location which improves the temperature uniformity in the cell [15]. In the new chaotic flow channels with 1 and 2 datum surfaces, the temperature uniformity measured at the membrane mid surface resulted that flow channels with 2 datum surfaces shows better improvement in temperature uniformity than flow channels with 1 datum surface. As the flow channel datum surfaces are at different height in 2 datum flow channels the reactant concentration decreases and improves the heat transfer. In addition, the number of flow channel bends and angle of flow channel corner have significant impact on the temperature uniformity. The 2 datum flow channel with 90$^0$ corner angle and less number of bends dominates in temperature uniformity compared to other designs. The schematic shown in figure. 2 (a) and figure. 2(b) indicates temperature distribution at mid surface of membrane in 1 datum flow channel is and 2 datum flow channel with 90$^0$ bends [16].

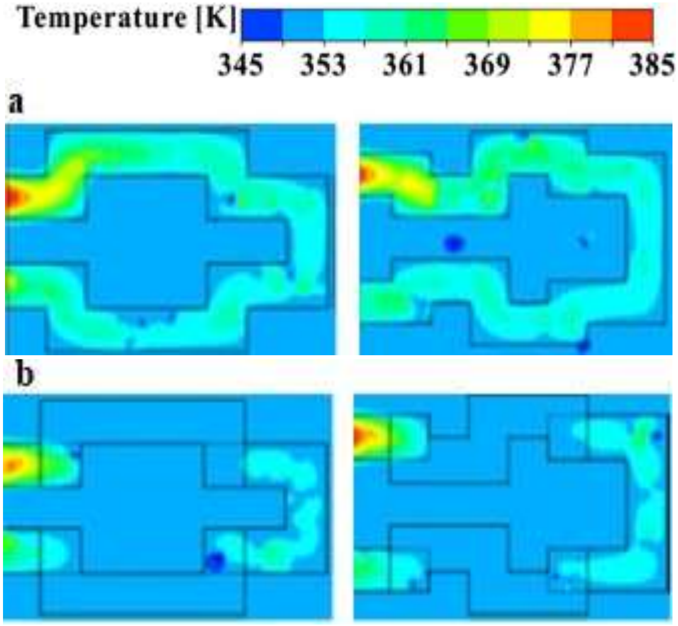

Figure. 2 temperature distribution at membrane mid surface in 1 datum flow channel (a) and 2 datum flow channel (b) [16]

Like reactant flow channel, the design of coolant flow channels also equally important to keep the fuel cell temperature in a tolerable range. Based on the amount and location of heat generated in the fuel cell appropriate cooling strategy can be used. From conventional serpentine to various modified flow fields will be served as cooling channel designs. Considering the temperature gradient and Index of uniform temperature the conventional spiral will be the best flow field design [11]. The metallic bipolar plate with spacer plate is used as novel cooling plate in order to reduce the total weight of PEMFC and to distribute the temperature contour uniformly. The spacer plate acts as mid layer and distributes the coolant through the grooves provided [17]. The maximum temperature of a PEMFC will be reduced using metal foam as reactant flow field and it render more uniform current density and temperature distribution due to absence of shoulders which exists in the conventional flow field. Metal foam with good thermal conductivity assists for better heat transfer from the fuel cell compared to conventional flow channels where more amount of heat is accumulated under the channels which cannot be transferred outside the cell effectively. Better performance can be achieved even at low and medium current densities because at low temperature the metal foam offers less resistance [12]. Along with good electrical conductivity, metal foam exhibits various advantages like low cost, easy manufacturing, high mechanical strength and low activation, Ohmic and concentration resistances compare to conventional PEMFC [18]. Metal foam inserts in cooling flow field is another approach to improve the cooling performance in PEMFC. At low porosity the metal foam insert ensures better heat transfer due to good fluid contact with solid material and fluid momentum. The increase in porosity percentage affects the fluid momentum and eventually brought down the heat transfer rate [19].

## Effect of flow channel dimensions

The fuel cell performance is greatly influenced by the reactant flow channel dimensions. Varying the channel aspect ratio produce changes in performance. Decreasing the channel width to land width ratio increases the channel numbers and improves the system power output at high current densities. Though power output increases, the heat generation also increases and it is not transferred effectively out of the fuel cell due to reduced land width [20]. The cathode reactant flow field with land to channel ratio greater than unity assist for more uniform temperature distribution on membrane surface. Figure. 3 shows the different land to channel ratio effects on membrane surface temperature distribution in a serpentine flow channel. The increase of land width dimension provides an additional surface area to transfer the heat effectively and keeps the cell operating temperature at optimum level. Apart from temperature distribution the electrical conductivity and current density distribution also improved [21]. The temperature performance of PEMFC improved by the obstacles provided in the reactant flow channel with different heights and widths.

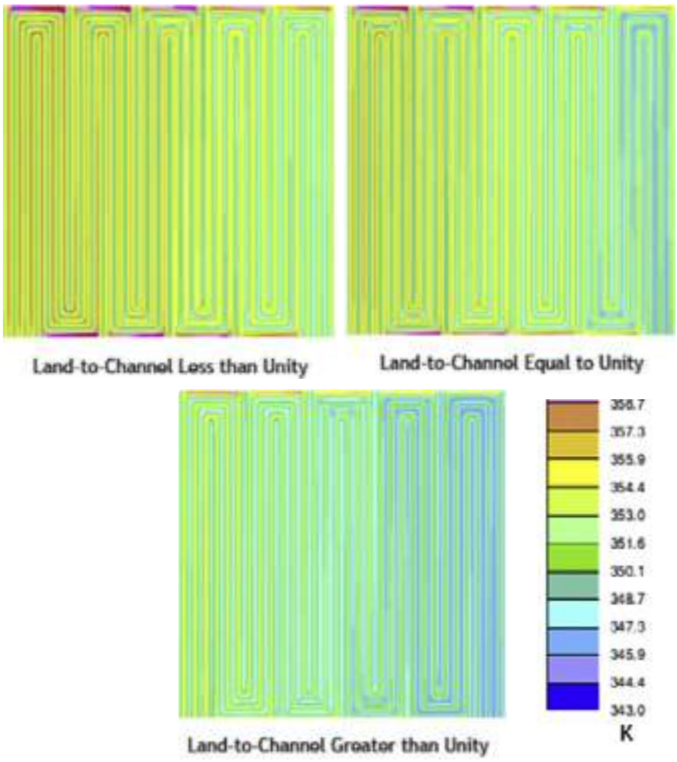

Figure. 3 temperature distribution on membrane surface with different land to channel ratio [21]

The obstacles with less height compare to width give better fuel cell performance. The zig-zag obstacles provided along the width of the flow channel leads to better temperature distribution on the membrane surface compare to the obstacles provided in regular pattern at 0.4V. Providing higher number of obstacles have little edge in temperature performance in zig-zag pattern [22]. The flow channel aspect ratio indicates the ratio of channel height and channel width has a significant impact on the temperature gradient in PEMFC. The channel aspect ratio is varied in both horizontal and vertical direction of the reactant flow channel by keeping the channel cross section and active area constant. At low channel aspect ratio, due to reduced water content in the membrane the local hot spots will be formed and increases the temperature gradient. On the other hand, the high channel aspect ratio narrows the flow channel and improves the membrane water content. The homogeneous water distribution in the membrane helps the temperature to distribute uniformly and reduces maximum cell temperature about 25% compare to the low channel aspect ratio design [23].

## Effect of reactant flow arrangements and flow channel orientations

The uniformity analysis is performed on four different flow configurations with cross flow and counter flow orientations for different current densities. At low current density the temperature profile is uniform in all flow configurations with small gradient decreasing from cathode inlet to outlet. However, at low-mid and high current densities the counter flow orientation with gravity assisted air flow produce more uniform temperature because the downward direction of air flow distributes the water and heat effectively. Conversely in cross flow orientation the removal of water gets difficult due to the upward flow of reactants which leads to temperature heterogeneity in the cell [24]. The orientation of the reactant flow channel is a must considering factor which contributes to temperature uniformity. Considering the channel overlapping and channel perpendicular orientations in serpentine flow channel the later have a good impact on the temperature distribution due to proper distribution of reactants. Figure. 4 indicates the orientation of channel at different assembled angle. The channel perpendicular orientation creates discontinuous channel cross section regions which enhances the local reactant concentration and aids to distribute the temperature more uniformly compared to the overlapping regions. In addition, the cathode flow field with fewer channels delivers better performs than more channels [25] .

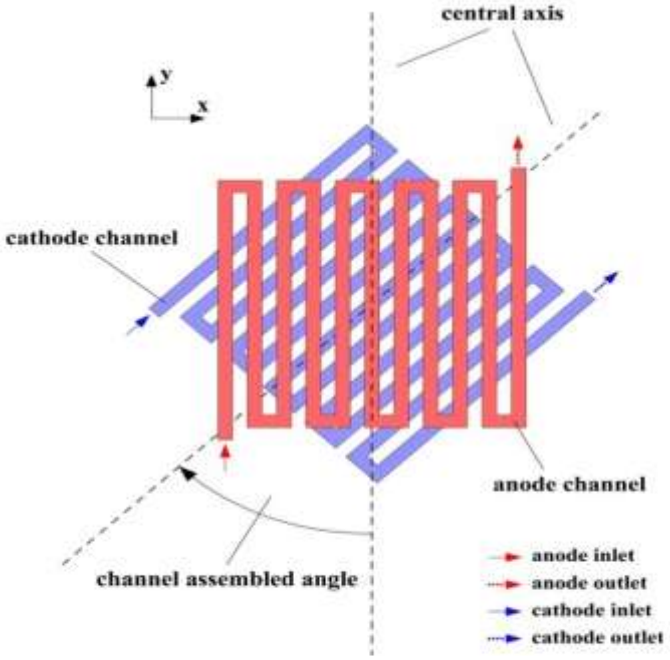

Figure. 4 flow channel assembly angle [25]

The in-plane temperature distribution in a PEMFC stack with FPHP at three inclination angles $+90^0$, $0^0$ and $-90^0$ is evaluated at different time intervals. At the beginning the in-plane temperature distribution of the stack is same in all the cases but when time increases the stack with $+90^0$ angle shows superior thermal performance with the help of FPHP. The FPHP pushes the temperature to mid of the cell in all configurations and eventually distributes the temperature more uniformly in $+90^0$ stack orientation because the gravity assists even in-plane distribution of water in the membrane which in turn reduces the cell temperature. The temperature distribution in $-90^0$ inclination angle is not so impressive because the reactant flow is against the gravity and FPHP operates pretty normal which requires higher time to make the temperature uniform [26].

**Effect of operating and other miscellaneous parameters**

The current density and relative humidity plays an important role in temperature uniformity in PEMFC. At high current density due to higher rate of electrochemical reaction large amount of heat will be generated and this heat must be removed from the cell to keep the performance of the cell under desired range. At high current density the cathode relative humidity significantly affects the temperature distribution and the relative humidity on cathode side should be controlled during the operation particularly at higher current densities [27]. Conversely the increase in anode inlet humidity decreases the hydrogen partial pressure and improves the membrane water content. This in turn enhances the membrane conductivity which reduces the ohmic potential and heat generated in the cell. The higher gas inlet temperature affects the cell performance at low current densities and subsequently the performance improves with increase in current density. Considering the stoichiometric ratio, the anode stoichiometry had slight impact on the fuel cell performance whereas the effect of cathode stoichiometry is negligible. From temperature distribution point of view, the impact of stoichiometric ratio is insignificant [28]. The impact of MPL and membrane thickness on temperature distribution is need to be considered. The cell temperature with MPL is slightly low because the MPL regulates moisture transfer in order improve the temperature distribution. The higher cathode humidity without MPL increases the reaction heat and reduces the cell performance in terms of output voltage. The minimum membrane thickness coupled with MPL promotes the water transport and proton conductivity which enhances the temperature distribution of the PEMFC. On the other hand, the effect of MPL in thick membrane is not realized good due to poor water transfer performance [29]. Upon developing the commercial size PEMFC stack, larger active area will be considered rather than laboratory level small active area. Hence, evaluating the temperature distribution in larger active area PEMFC is inevitable. Unlike small active area the temperature distribution in large size active area is not uniform in the reaction surface. This is because the cathode temperature field is affected by cooling effect of outer environment. Figure. 5 (a) shows the schematic of cathode flow channel with location of embedded sensors and figure. 5(b) indicates the temperature increases along the gas flow direction and reaches the maximum value in middle of the flow channel compare to the area near cathode inlet and outlet due to radiation. Due to uneven reactant flow in the cathode channel the humidity in the flow channel is not same and it increases from inlet to outlet which impacts the temperature uniformity. The supply of dry reactant in large size active area cell will be viable option to reduce the disparity in temperature distribution [30].

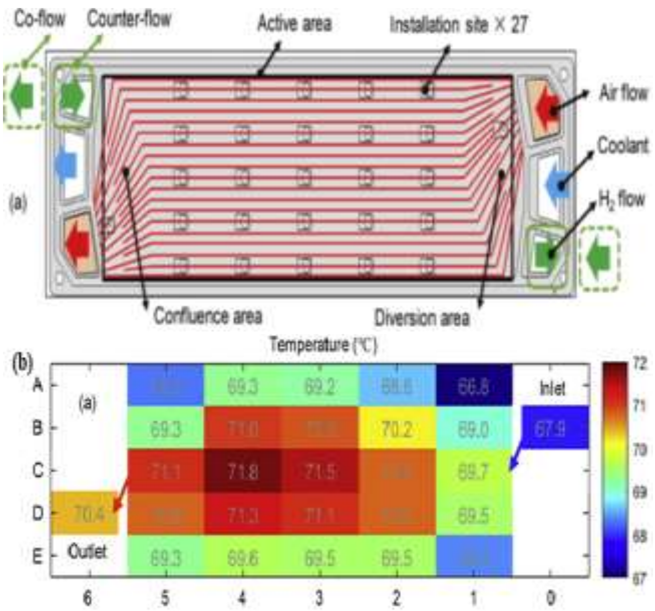

Figure. 5 cathode flow channel with embedded sensors (a) and corresponding temperature distribution (b) [30]

The supply of dry reactant can be achieved with the help of variable temperature flow field which enhances the membrane hydration throughout the active area by evaporating the internally generated water with the help of heat produced. Incorporating the variable temperature flow field could eliminate the external humidifier without affecting the system performance [31].

## Conclusion

Temperature distribution improvement PEMFC is paramount importance because it directly affects the fuel cell performance and life time of the components. The temperature uniformity inside the PEMFC stack will play a significant role when the system enters into commercialization particularly in automobile sectors. Several approaches have been reviewed and reported in this paper to achieve better temperature uniformity. The summary of these results as follows.

1. The modifications carried out in flow channel configurations provides exceptional outcome in temperature uniformity improvement by enhanced reactant distribution to GDL.
2. The metallic bipolar plate with spacer plates as cooling channel distributes the cell temperature uniformly and reduces the system weight marginally.
3. The high thermal conductivity metal foam used as reactant and coolant flow channels offers better thermal performance at low and medium current densities.
4. The flow channels with high land to channel width ratio, high channel height to width ratio and obstacles with less height to width ratio gives better temperature uniformity.
5. Considering the reactant flow orientations, the gravity assisted counter flow and channel perpendicular configurations exhibits good performance.
6. Considering the operating parameters, except current density other parameters like humidity, stoichiometric ratio didn't have much impact on temperature distribution. Thin membrane with MPL, supply of dry reactant in large active area cells are some other methods which helps to achieve better temperature distribution in PEMFC.

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