

ANALYSIS OF CURRENT FLUX DENSITY MAGNITUDE (CFDM) OF A SINGLE CHANNEL NAFION BASED PEM FUEL CELL

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Abstract

The need for energy is growing day by day and scientists as well as engineers are rolling up their sleeves for developing several methods for countering this deficiency in energy. Fuel cells are a good remedy for dealing with this energy deficiency. Proton exchange membrane (PEMFC) is the most popular and commonly used one among the different kinds of fuel cells (FC) due to its high efficiency. In this paper a 3D model of a simple nafion based PEMFC is designed and studied for its current density under varying mass fraction of hydrogen. This study helps in determining the optimum mass fraction of inlet fuel such that both overhydration and dehydration of Nafion in the cell can be avoided and it also helps to regulate the cell temperature below the glass transition temperature of the Nafion membrane.

Keywords: PEM FUEL CELL, CFDM, NAFION.

INTRODUCTION

A typical FC is an electrochemical unit that converts the chemical energy of the reactant species in to electricity. Among all FC's the PEMFC is the most commonly used cell due to its high efficiency [1-2]. The Bi-product of a typical PEMFC is H₂O, which makes it a more suitable choice in the modern era [3-5]. Nafion is the most commonly used membrane in a PEMFC due to its high proton permeability and optimum glass transition temperature [4]. The hydrogen is used as fuel in the PEMFC and the catalytic splitting of hydrogen takes place at the Anode catalytic layer (ACL) and the chemical expression of catalytic splitting is given in Eq (1a). The electrons formed due to the anode reactions travels through the external circuit and reaches the Cathode catalytic layer (CCL), while the protons travel through the selective permeable membrane and reaches the cathode. At the cathode side oxygen is fed as the oxidiser and at the CCL the oxygen molecules chemically interact with H⁺ ions and electrons to produce electrical energy.



The electro-chemical reactions produce H₂O as bi-product and it also releases heat energy along with energy production. Proper thermal management of PEMFC is an important thing to be considered while designing the cell. More than 40% of the chemical energy from the species are wasted as heat loss; If proper mechanisms or methods are designed and implemented for recovering this waste heat, the efficiency of a PEM cell can be made to rally further. One important thing while designing the heat mitigation methods is that uniform temperature have to be maintained distribution across the cell to maintain higher permeability of H⁺ ions and high chemical kinetics at the active area of the nafion membrane [5-11]. In order to cool a single PEM cell or a complete cell stack, different types of coolants can be used. In this work water have been used as the coolant for the sake of simplicity.

The governing laws and equations used in fuel cell study are conservation of mass, momentum, charge, species and energy. Eq (2), Eq (3), Eq (4), Eq (5), Eq (6) represents conservation of mass, conservation of momentum, conservation of species, conservation of charge, conservation of energy.

$$\frac{\partial \varepsilon \rho}{\partial t} + \nabla \rho u = s_m \quad (2)$$

$$\frac{1}{\varepsilon} \left[\frac{\partial \rho u}{\partial t} + \frac{1}{\varepsilon \nabla \rho u u} \right] = -\nabla \rho + \nabla t + S_u \quad (3)$$

$$\frac{\partial(\varepsilon C_k)}{\partial t} + \nabla(u C_k) = \nabla(D_k^{eff} \nabla C_k) + S_k \quad (4)$$

$$\nabla(k^{eff} \nabla \phi_e) + s_\phi = 0 \quad (5a)$$

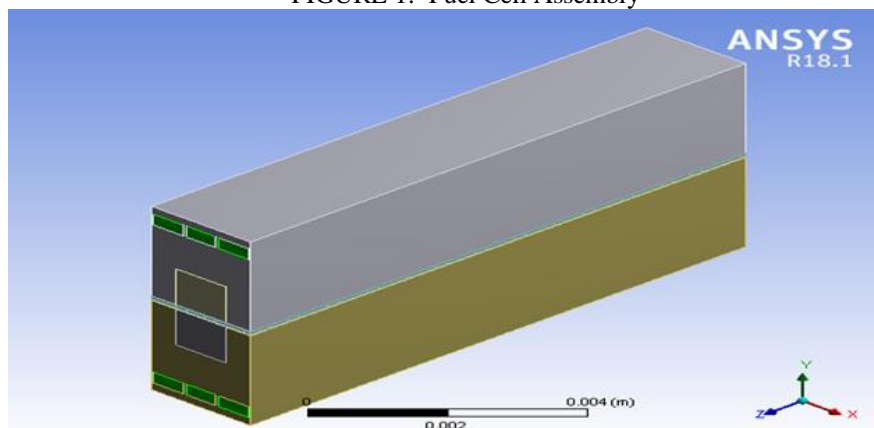
$$\nabla(\sigma^{eff} \nabla \phi_e) + s_\phi = 0 \quad (5b)$$

$$\frac{\partial}{\partial t} [(\rho C_p)_m T] + \nabla(\rho C_p U T) = \nabla(k^{eff} \nabla T) + S_T \quad (6)$$

ANSYS 18.1 have been used fluent as the solver to study the simple one flow field channel type PEM fuel cell as depicted in figure 1. There are many researches that studies the improvement obtained in current flux density magnitude of a PEMFC by varying the mass flowrate of fuel (hydrogen) at the inlet [13]. The novelty of this work comes into picture as the mass flowrate is kept as a constant and the mass fraction of the inlet fuel at the anode is varied. Thus, in this work the CFDM of a single channel PEMFC at varying mass fraction of inlet fuel is studied and this study helped determining the optimum mass fraction of inlet fuel such that excess flooding can be avoided in cell and it also helps to regulate the cell temperature below the glass transition temperature of the Nafion membrane.

MODEL AND PROBLEM DESCRIPTION

FIGURE 1: Fuel Cell Assembly



A single channel fuel cell with anode catalytic layer, cathode catalytic layer and nafion as membrane was used for this study. Additional cooling channels are attached near to the current collector to carry away the waste heat and water is used as coolant in this problem. Water at 300 K flowing at 0.1m/s is passed through the channel carved in the current collector. The size specifications of the cell assembly are given in table 1. By keeping the mass flow rate as constant, CFDM of the cell at different mass fraction of inlet fuel has been studied

Table 1: PEMFC specifications

SL NO	Cell Parts	Value
1	ACL thickness	14 microns
2	CCL thickness	14 microns
3	Membrane Thickness	51 microns
4	Channel length	10 mm
5	Active area	20 mm ²

GRID INDEPENDENCY AND MODEL VALIDATION

Model validation and grid independency tests were carried out and the work done by Shaik et.al (2017) is used to validate the work [12]. The average error was found to be less than 1.5% and hence the present methodology using ANSYS Fluent is substantial to be resourceful and a proficient CFD tool for analysis of CFDM at varying mass fractions of inlet fuel. The Validation plot is depicted in figure 2. The grid independency test is illustrated in figure 3. The area of the cell is 0.2 sq.cm and the grid independence is carried out by parametric analysis. The element face area is varied from 0.3 mm to 0.0025 mm. The number of nodes is plotted against CFDM and minimum temperature of current collector. On plotting it was found that 134630 nodes gave optimized values between accuracy and computational time.

FIGURE 2: Model Validation

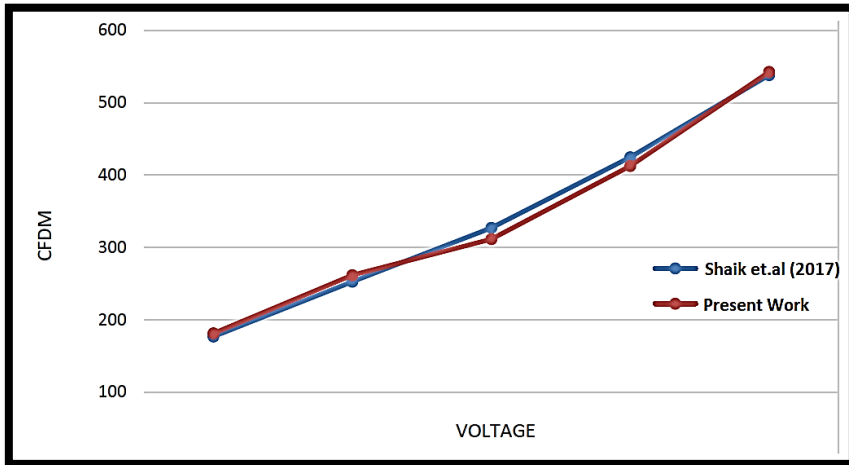
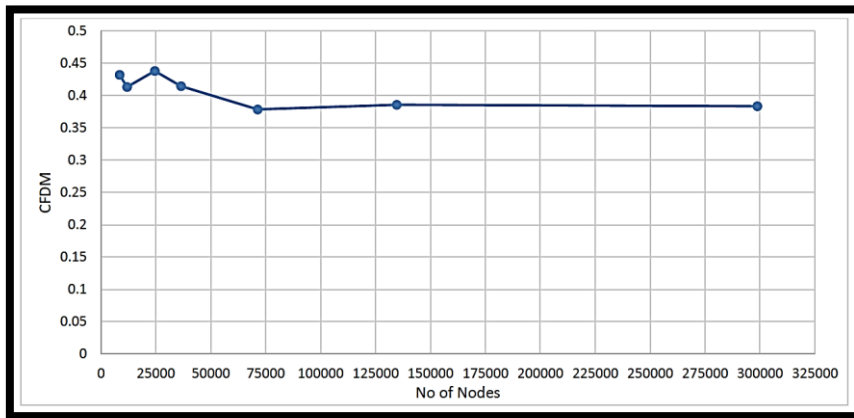


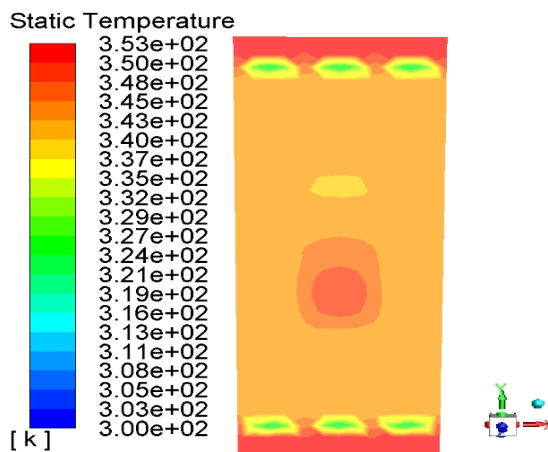
FIGURE 3: Grid Independency Test



RESULT AND DISCUSSION

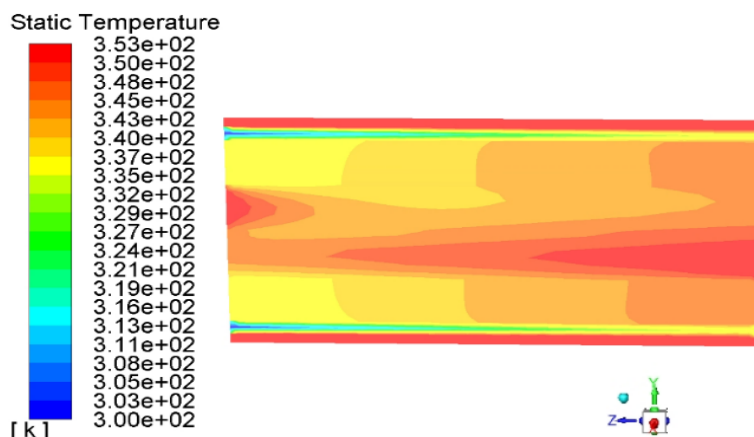
The static temperature contour of the front facing side and left-hand side of the PEMFC is shown in figure 4 and figure 5 respectively.

FIGURE 4: Static Temperature contour (XY plane)



It can be seen that the hydrogen and oxygen are reactants and water is product of the chemical reaction taking place in a PEM fuel cell. In addition to the reaction heat is liberated at the cathode side which proves the phenomenon of water formation from hydrogen and oxygen as exothermic reaction which involves liberation of heat during a chemical reaction, from figure 4 it can be clearly seen that the heat is produced at the cathode side. This confirms the process taking place inside the fuel cell proves the exothermic reaction phenomenon.

FIGURE 5: Static Temperature contour (YZ plane)



Water is used as a coolant flowing through the channels carved in the current collector the inlet water temperature is 300 K flowing at the velocity of 0.1m/s and the output temperature of the water at channel outlet is 337 K, which is evident from figure 5

The operating range of a low temperature PEM fuel cell is from 60-85°C It can be noted that the fuel cell working at the maximum of operating range has higher current flux density magnitude compared to that of one at lower temperature. This is because of because of faster chemical kinetics under higher temperatures which increases the permeability of H⁺ ions.

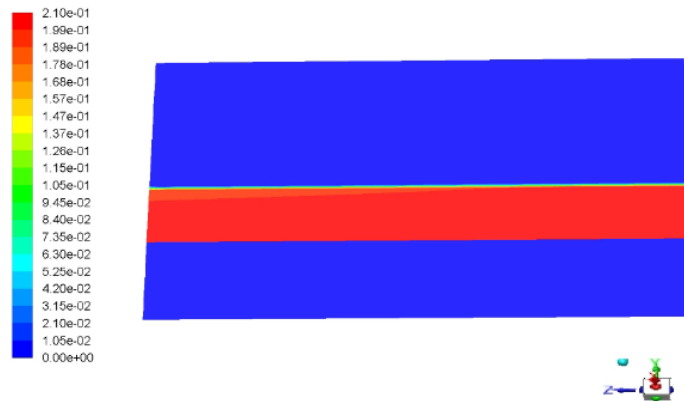
Humidified hydrogen is used as the reactant in anode side which is the mixture of hydrogen and water, similarly oxygen nitrogen mixture is used as reactant in cathode side. The mass fraction of oxygen at anode inlet is kept constant at 0.21 to match with that of ratio in atmosphere and remaining mass fraction is nitrogen which does not actually take part in a chemical reaction but prevents other unwanted reactions in the cell. The reason behind not using humidified reactant at cathode is water will be formed as product at the cathode side. The species contours of both Fuel and oxidizer are illustrated in figure 6 and figure 7. Species transport shows that the reactants diffuse completely through the membrane.

FIGURE 6: Species contour Hydrogen



From figure 6 it can be seen that the hydrogen species is found only in the region of anode gas channel and membrane and not beyond it. This ensures the proper working of fuel cell

FIGURE 7: Species contour Oxygen



Similarly, from figure 7 it can be seen that the hydrogen species is found only in the region of cathode gas channel and membrane and not beyond it. Presence of oxygen in anode side may result in formation of water at anode side which floods the membrane and blocks the permeability of H⁺ ions which reduces current flux produced throughout the cell.

FIGURE 8: Current Flux Density Magnitude (XY plane)

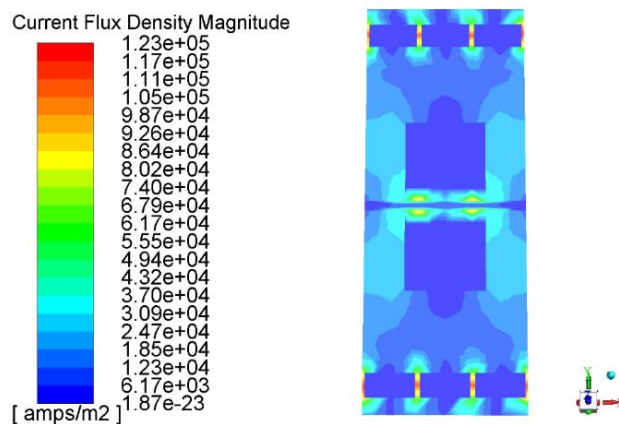


Figure 8 shows the cfdm throughout the cell, it can be seen that cfdm near membrane is higher due to permeability of ions across membrane and cfdm near coolant channels is higher because holes move towards the region of high temperature to low temperature in anode and electron move from the region of high temperature to low temperature in cathode.

FIGURE 9: CFDM V/S MASS FRACTION

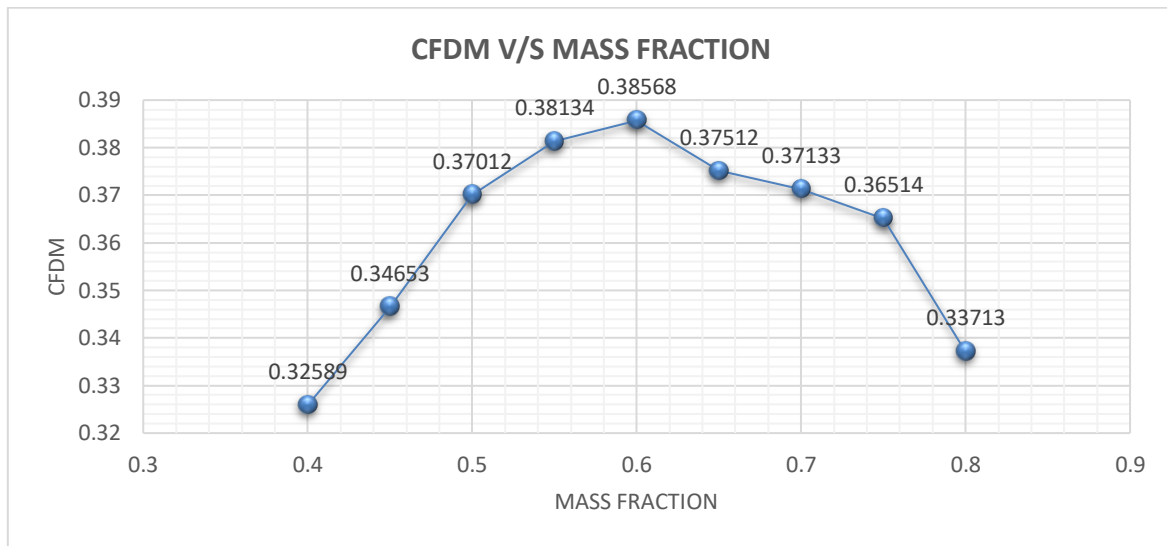


Figure 9 illustrates the CFDM versus mass fraction of hydrogen from which following inference can be made:

1. It is found that for a mass fraction of 0.6, the cell gave best output characteristics.
2. If the mass fraction of the hydrogen is less or small at the inlet then the mass fraction of H₂O will be high at inlet. This may lead to cell flooding which can significantly reduce the cell performance
3. If the mass fraction of the hydrogen is large at the inlet, then the mass fraction of H₂O will be less at inlet which may lead to membrane dry-out. This dry-out can be considered as the dead state of cell where ions doesn't dissociate.
4. These are due to the variation of membrane resistance at different water percentage which decides the ion movement through membrane.

FIGURE 10: CFDM V/S TEMPERATURE

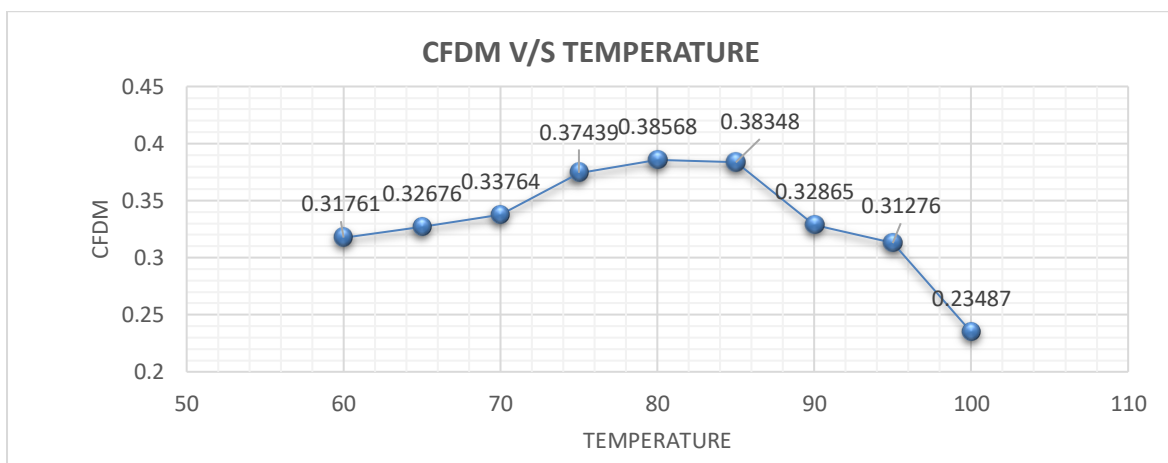


Figure 10 illustrates the CFDM versus cell temperature from which following inferences can be made:

1. By varying the operating temperature of the cell from 60°C to 100°C, it can be noted that CFDM increases to its peak value within a range of 85°C to 95°C and later it falls significantly.
2. The drop in CFDM occurs due to the rupture of Nafion membrane at elevated temperatures. This rupture of membrane can be prevented by developing a new efficient membrane with high glass transition temperature.

CONCLUSION

A 3D model of single channel PEMFC was modelled using ANSYS Fluent and the Current Flux Density Magnitude of the cell were calculated at various mass fractions of inlet fuel at constant mass flowrate.

- At lower mass fraction of H₂, the cell gets overhydrated which leads to flooding;
- On the other hand, at higher mass fraction of H₂ the cell gets dehydrated and the membrane crosses its Glass transition temperature which leads to the mechanical degradation of Nafion. Nafion is a solid polymer acidic membrane which dissociates H⁺ ions only when moisturized
- The optimum mass fractions of inlet fuel for best output characteristics comes around 0.6 of Hydrogen and remaining 0.4 moisture in this case.
- Higher CFDM is obtained at the operating temperature of around 75°C-85°C.

It can be concluded that mass fraction of inlet fuel and moisture is a crucial thing to be taken into consideration while designing a PEM fuel cell as its significantly affects the thermal management, water management, membrane performance and cell conductivity of a PEMFC.

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