Steady State Thermal and Structural Simulation of SS 316L Bipolar Plates used in 250 Watt PEMFC

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Abstract: Design and optimisation of bipolar plates play a crucial role in determining the overall efficiency of the PEM (proton exchange membrane) fuel cell. These plates are designed in such a way that the PEM fuel cell achieves the best water and thermal management capability. The conventionally used graphite-based bipolar plates are getting replaced by metallic plates for powering space applications and portable devices due to its good mechanical and electrical properties. In this paper, we present the thermal and structural simulation of the stainless-steel type 316L bipolar plates used in 250W PEM fuel cell after the preheating process but before the supply of the fuel into the stack.

Keywords: PEM fuel cell, SS 316 L, Bipolar plates

1. Introduction
In a proton exchange membrane fuel cell (PEMFC), bipolar plates (BP) play a crucial role. BP has several functions in a typical cell stack like maintaining uniform conveyance of hydrogen and oxygen across the active surface area of the membrane electrode assembly, conducting the electrical output from one cell to the other, supporting thin membranes and electrodes to form the perfect fuel cell stack, etc. The flow channels for the fuel, air and coolant are either milled, stamped or wire cut (EDM) on it [1,2]. A typical BP must be designed, optimised and manufactured to obtain the best water management and thermal management within the cell. Water and thermal management are crucial in a PEMFC stack because only in the optimum hydrated state the, cell gives the best performance and during flooding and dry-out the cell gives poor output [3]. Graphite and graphite-based composites are the commonly used materials for manufacturing BP, since graphite have reasonable electrical conductivity and high thermal conductivity. The graphite-based BP lacks good machinability and mechanical strength. Hence, they cannot be reduced in size beyond a limit, thereby making them bulkier in volume [4]. In the recent trend of technology, fuel cells are used in space applications and portable devices; so, the size of the cell stack is a major issue. In order to solve this problem, researchers came up with the concept of metallic BP as a good alternative for graphite [5]. BP made of metals have good thermal conductivity, electrical conductivity, good mechanical strength, easy machinability and high-speed mass production is possible [6,7]. Due to the high machinability of metals, we can reduce the thickness of the BP & this will help us to reduce the overall size of the fuel cell stack. The most widely preferred metal for BP is stainless steel (SS). The type 316L SS is recommended by many researchers and engineers due to its good thermal, electrical and mechanical...
properties [6]. The BP plays a crucial role in heat management of the cell stack. The coolant flow channels on a BP are designed in a way to evenly cool the MEA of the cell. The most commonly used membrane in a PEMFC is NAFION and the best performance of the cell occurs within a temperature range of 80°C to 100°C [8,9]. The fuel H₂ is delivered to the anode side of the MEA and catalytic splitting of H₂ into protons and electrons takes place at anode. The newly formed protons travel through the membrane and reach the cathode side where O₂ is fed. At cathode, O₂ combines with both protons and electrons to produce water. This overall reaction produces both electrical and heat energy. A schematic representation of a PEMFC is shown in Figure 1.

![Schematic of PEMFC](image)

**Figure 1:** Parts of a PEM Fuel cell

Since the optimum temperature range of PEMFC is nearer to 80°C, we have to preheat the fuel cell stack before supplying the fuel [10–12]. This can be achieved by many ways like solar preheating, circulating hot gases or water through the flow channels and manifolds in the BP, or by the usage of heater rods [13,14]. We took the case of preheating with metallic rods for our study. This preheating gives rise to thermal stresses in BP and in our work, we are focusing to simulate the induced thermal stress and temperature distribution of a simple BP made of SS 316L using COMSOL Multiphysics 5.6.

### 2. Problem and Model Description

As mentioned above the BP is preheated to achieve the optimal operating temperature range. Only after attaining this temperature range, we will start supplying fuel to the cell stack; this helps to reduce fuel wastage and to attain the best efficiency. This preheating induces thermal stresses on the metallic plate and in this paper; we try to simulate the induced thermal stresses and temperature distribution of the preheated SS 316L BP after attaining steady state and before the actual supply of the fuel into the stack. To simplify the problem, we chose a simple symmetrical BP. The geometry of the plate is given in Figure 2. Our BP has an outer dimension of 24 x 20 cm² with an active area of 49.5 cm² and the thickness of the plate is 1 cm.
To reduce the computational requirements and computing time we chose to reduce the size of the plate into one in eighth of its actual size. This action is justifiable because of the symmetry of the BP we considered. This reduction in size is summarised in the Figure 3.

The reduced model is divided into three zones, active zone where the MEA comes into contact with the metal plate, heat source zone which comprises the aluminium rod, and finally the outer zone where manifold of the gas and fuel are built. In our problem, we took a fuel cell stack consisting of 25 BPs. The electrical heat input was given to the BP through the two aluminium rods placed at the mid axis of the plate. The input heat was 200 W for the entire stack assembly. The plate is made of stainless steel 316L which comprises both active and outer zone and the heat source zone is made of aluminium. The heat transfer through the gas manifold was taken to be 50 W/m²K and to the surrounding as 5 W/m²K. The material properties of aluminium were directly taken from the material library of COMSOL and the properties of SS 316L was manually provided.
Table 1: Basic properties of BP materials

| Material               | Density (g/cc) | Modulus of elasticity (GPa) | Coefficient of thermal expansion (1/K) | Thermal conductivity (W/m.K) | Specific heat (kJ/kg K) | Electrical Resistivity (nΩ·m) | Poisson ratio |
|------------------------|----------------|----------------------------|---------------------------------------|-----------------------------|-------------------------|-------------------------------|--------------|
| SS 316 L              | 7.99           | 193                        | 16*10^-6                             | 16.2                        | 0.5                     | 740                           | 0.27         |
| Aluminium alloy       | 2.7            | 70                         | 23*10^-6                             | 237                         | 0.9                     | 26.5                          | 0.35         |
| Graphite (with binder) | 2.2            | 12                         | 4.7*10^-6                             | 250                         | 0.8                     | 18*10^3                       | 0.28         |

Table 2: Parameters for the stack assembly

| Parameter                                    | Value                  |
|----------------------------------------------|------------------------|
| Input heat to 25 plates                      | 200 Watt               |
| Heat transfer coefficient to the surrounding | 5 W/m²K                |
| Heat transfer coefficient to the manifold    | 500 W/m²K              |
| Pressure at the Active zone (P₁)            | 10^6 N/m²              |
| Pressure at the Outer zone (P₂)             | 7.99x10^6 N/m²         |

3. Thermal and Structural Analysis

Our study focusses on thermal & structural analysis of SS 316L BP. We assume that the heat input (200W) was equally distributed among all plates in the stack through the aluminium rods and we assume that the power from the heat source is uniformly distributed across the heat source zone. The active zone and outer zone do not have any heating element in them so the heat generated from those zones is zero.

\[ \nabla \cdot (-k \nabla T) + Q_{\text{source}} = 0 \quad (1) \]

Eq(1) represents the steady-state heat equation (Fourier’s law). \( Q_{\text{source}} \) and \( K \) represent heat source and thermal conductivity. Since we are studying the case of the BP when it attained steady state and prior to starting of the fuel cell, the losses that are caused by the power generation and other losses are absent. In our problem, symmetric and convective conditions are the only boundary conditions for the heat analysis. The convective and symmetric boundaries are illustrated in figure 5 & figure 6.
The symmetric boundary conditions imply that the flux through the boundary is zero.

\[ (-k \cdot \nabla T) \cdot n = 0 \]  

(2)

The convective boundary conditions set the heat flux proportional to the temperature difference between the fluid outside and the temperature at the boundary. Thus, we can express this convective boundary condition as:

\[ (-k \cdot \nabla T) \cdot n = h(T_{\text{ext}} - T_{\text{fluid}}) \]  

(3)

Where, \( h \) denotes the convective heat transfer coefficient.

Figure 5: Symmetry boundaries

Figure 6: Convective boundaries

When the plate is heated, the plate thermally expands causing thermal induced structural stress to develop. The thermally induced loads are proportional to the temperature difference between the actual and reference temperature. The displacement perpendicular to the symmetric planes are set to zero as we apply the constraints over them as shown in Figure 7 and Figure 8

Figure 7: No displacement through symmetric boundaries
In the manifold and in the active part of the BP, the load applied by the tie rods on the stack is applied as can be seen in Figure 9. The constraints and load on every other boundary are assumed to be negligible. The only questionable assumption in this sense is the possible loads and restrictions that the tie rods impose on the holes in the BP. It would be possible to pair a model for the tie rods with a detailed model of the BP in a more detailed analysis. The strain on these distinct parts would probably show different gradients. These assumptions are made to simplify the problem.

4. Grid Independence
The meshing was carried out using the in-built meshing tool of COMSOL Multiphysics 5.6. We used free triangular mesh on the top surface and swept it across the remaining portion. The maximum element size of 0.0024 m, maximum element growth rate 1.3, curvature factor 0.2 and resolution of narrow regions equals 1, was given. We compared the results obtained from various mesh sizes and we chose an inbuilt mesh size of extremely fine in the COMSOL mesh tool as it gave correct results. The skewness value of the mesh was in the desirable range. Hence, this meshing was enough for doing the computational analysis of our symmetric BP. The Extremely fine mesh is shown in Figure 10 and the grid independence test is illustrated in Fig 11.
5. Results and Discussion
Using COMSOL Multiphysics 5.6, the thermal and structural simulation of a simple BP made of SS 316L was carried out. The reference temperature and pressure were set to be 293 K and 101.325 KPa. Usually, BP has manifolds for gases and coolant but in our case, we provided only gas manifolds to make the problem less complex. The geometry of the BP was symmetric. Hence, we could scale down the size of the plate to one in eighth of its actual size. Few input parameters were directly given to the system to avoid extra computing requirements and no initial values were given to the computation. The properties of SS 316 L were manually fed to the solver and all other material properties were taken from the material library. The temperature distribution across the plate was plotted and we can see a good temperature distribution across the active zone where the MEA comes into contact with the BP and the temperature drop towards the end of the active zone was only about 10 degree Celsius. This helps the MEA to function efficiently due to the efficient temperature distribution in metal plates. The button channel is larger in size than the side channel hence the temperature is lesser in the button channel due to more convective heat dissipation. The temperature distribution of the plate is provided in Figure 12.
The maximum temperature gradient was observed at the interface between the active zone and the outer zone. This leads to the fact that more thermal induced stress gradient is at this interface and we can also see that the magnitude of stresses nearer to the button channel is lower than the magnitude of stress at the side channel as shown in Figure 13.

![Figure 13: von Mises stress in (a) SS316L and (b) Graphite](image)

Using von Mises stress, we can determine whether a material will yield or fail for the given conditions. Under loaded condition, if the von Mises stress of the given material is equivalent or predominant than the yield stress under simple tension, the material will yield or fail. The yield strength and other mechanical properties of the graphite is poor compared to metals like SS 316L. Hence, from the mechanical strength and stress handling point of view, the metallic BP have significant upper hand compared to conventional graphite-based plates. As shown in the Figure 13 (a), the stress nearer to the heat source zone and the outer zone are higher than that of the stress at the active zone. By turning off the thermal expansion in the solver, we can calculate the external pressure loads and it is found that the thermally induced loads are greater in magnitude than that of external pressure loads.

The results we obtained shows that the loads acting on the plates are far long away from the critical values. However, the thermal expansion can be considerably more significant. Hence, these expansions cannot be neglected. The expansion along the Z- direction is given in Figure 14. The whole plate attained an average temperature of 368.58 K and active area attained 391.57 K. The SS 316L plates have more thermal expansion than the graphite plates. The thermal expansions near the heat zone were higher than other areas. Even though these expansions are in μm range, they can significantly damage the MEA of the PEMFC.

![Figure 14: Expansion in the Z- direction (a) SS 316L (b) Graphite](image)
While designing a BP we must keep these displacements to the minimum such that there is no hindrance or halt in the membrane process of separating the hydrogen and oxygen at the cell compartments. If the thermal expansion is very large it can significantly damage the MPL (microporous layer) and to the extreme, the entire MEA itself can get damaged.

6. Conclusion
Fuel cells are a promising area in the field of alternative fuels for powering portable devices, space application as well as power-plants. Among fuel cells, the most widely used cell is the PEM fuel cell because of its low temperature operations and higher efficiency. The heat and water management of the PEMFC must be optimised to get the best performance. Hence, the design and optimisation of the BP is crucial. The conventionally used graphite-based BP does not hold good mechanical strength and machinability. The lack of these properties makes the graphite-based BP bulkier in size. For portable devices and space application, we prefer compact designs with good mechanical and electrical properties. The stainless steel is the best alternative for graphite as it has got all the desirable properties required for a good BP. In our work, we provided a thermal and structural simulation of a stainless-steel type 316L used in 250 W PEMFC and the results obtained are discussed. The thermal expansion of the metallic plates is higher than that of graphite, so we must design the plates precisely such that this thermal expansion does not damage the MPL and the whole MEA of the PEM fuel cell. The SS BP is a good alternative for graphite-based BP, but the thermal expansion of metals raises issues regarding the durability and performance of the MEA. So we must focus on developing materials with good mechanical and electrical properties whose thermal expansion can be regulated to the minimum even at elevated temperatures.

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