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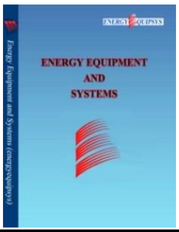

Finite element analysis of electrical conduction in additively manufactured SS316L bipolar plates for PEM fuel cells

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ABSTRACT

This study presents a numerical simulation-based analysis of the electrical conductivity of SS316L bipolar plates against the most widely used graphite plates for Proton Exchange Membrane Fuel Cells (PEMFCs) using ANSYS Electric. A well-defined three-dimensional model of a bipolar plate with a serpentine channel has been made with some customization to improve the flow, as serpentine channels are often utilized in fuel cell stacks. The serpentine flow channel design was chosen for its capacity to encourage equal current distribution and reduce localized resistance, consequently solving fundamental limitations that have long held back the commercial viability of PEMFC bipolar plates, as they are known to be one of the best for flow distribution, with few issues of pressure drop, which can be solved with modifications in the design. The simulation evaluated voltage potential and surface current density across bipolar plates of SS316L and graphite. SS316L exhibited a significantly lower effective resistance (2.29×10^{-7} Ω) compared to graphite (3.32×10^{-5} Ω), under identical conditions. The comparison indicates that SS316L possesses much lower effective resistance compared to graphite, making it a cost-effective and long-lasting alternative for the production of a bipolar plate. This paper comprehensively explores the relationship between conduction performance, geometric design, and material properties, thereby contributing towards the optimal design of bipolar plates aimed at enhancing fuel cell efficiency.

Keywords: Fuel cell; Energy Storage; Additive Manufacturing; Automobiles; Electric Vehicles.

1. Introduction

Fuel cells are clean and efficient energy sources well-suited for efficiency- and emissions-sensitive low-emission applications. PEMFCs have been of special interest due to the rapid start-up, high power density, and range of transportation and stationary power applications (1–4). The bipolar plates perform a number of important functions in PEMFCs and contribute significantly to a fuel cell's weight, volume and cost (5). These plates provide mechanical rigidity, electrical conduction in a stack, and channels for cooling water and/or gases used in the reaction. These flow field patterns vary, and certain types have advantages over other, and some 3D printed patterns with modifications have been shown to enhance the process (6,7).

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Static electric conduction analysis of bipolar plates is the subject matter of this project, and it is a comparison between two materials, SS316L stainless steel and graphite. Since bipolar plates provide cell-to-cell contact as well as protection for the bulk of ohmic losses of the system, these are significantly large fuel cell stack components. Hence, lowering overall efficiency results in lowering the electrical resistance of the plates. Electrical conductivity, heat management, lifespan, and manufacturing depend heavily upon the selection of the material of the bipolar plate and its design, and over 100 designs have been studied by researchers around the globe (8,9). Because of excellent electrical and thermal properties, lightness, and chemical inertness, it makes graphite an excellent first-choice material in any design; it has long controlled all designs. Its only limitations are that it is brittle, more costly, and poor in machining complex flow fields. Although with relatively lower thermal conductivity than that of graphite, SS316L stainless steel is an appropriate alternative owing to superior mechanical strength, workability, and low cost (10). The extent of this current work is to use ANSYS Electric as a computational solver in an attempt to conduct an exhaustive static electrical conduction simulation of bipolar plates. FEA and CFD have been used in the past for simulations of auto parts before manufacturing, fuel cell parts, plates, and flow channels, and the results have often proved to be in line with actual results, considering careful selection of input parameters and the setup. It enables the improvement of design and verification of design parameters (11,12). The aim of the investigation is to contrast and compare SS316L and graphite bipolar plate performance under identical geometrical conditions and boundary conditions. The comparison will be against the reference plate geometry of 95×95×2.5mm for duplicating the flow field patterns usually found in PEMFC stacks using serpentine channel geometries. Bipolar plate is the most important part of Proton Exchange Membrane Fuel Cells (PEMFCs) as it not only serves as a current collector and gas distributor but also as a mechanical support, reactant separation, and bulk management of current in the cell. It affects the electric circuit efficiency of the fuel cell stack as well. Different studies have examined the type of bipolar plates, e.g., different materials and geometries, to minimize ohmic losses and enhance performance. Graphite has traditionally been used as the primary material for bipolar plates because it has high electrical and thermal conductivities, chemical inertness, and low mass. Several studies indicate that high-quality graphite could have in-plane electrical resistivity down to 9×10^{-6} Ω•m, although its anisotropic nature often requires the adoption of an average isotropic value when applying it to simulation calculations. In most modelling schemes, graphite is modelled as an isotropic material with resistivity between 1×10^{-4} Ω•m. This is accepted for preliminary comparative studies but might not be completely representative of the directionally dependent conductivity of graphite. It has been noted in the literature study that while high in-plane conductivity of graphite is promising for proper current distribution if utilized as a bipolar plate, it is not suitable for use because it is brittle and cannot be easily made into intricate flow field shapes.

Although in this current research work, electrical conductivity behaviour also would be properly considered, channels such as these are needed for even reactant distribution and efficient heat evacuation, and 1mm deep channels with 2mm width at the plate surface have been employed (13,14). The one bipolar plate is maintained at 1 V and the other at 0 V, the voltage boundary condition used in this work. Such a configuration provides an electrical potential gradient across the plate, and the voltage contour and current density distribution will be simpler. Integration of the current density over the concerned boundary surface yields the effective electrical resistance of the plate. The simulation compares the net conduction character of graphite and SS316L with the aid of such summated values of the current. SS316L is simulated with isotropic resistivity 6.9×10^{-7} Ω•m, and the graphite is simulated with isotropic resistivity 1×10^{-4} Ω-m. Such simulation material parameters within the calculation are of utmost significance when utilized in the calculation. These plain comparisons to SS316L and generic information in the sense of entire conduction plate are obtained by utilization of such a method. But in practice, the response of graphite may be regulated from that at which its anisotropy is completely balanced out. ANSYS Electric has been used in this work to get the contours of voltage and the current density of the bipolar plates. Equi-drop electrical potential of the bipolar plate has been simulated from the above contours. These profiles show uniform contours of the plate from 1 V to 0 V. The idea behind this work is to do comparison of both the materials: Graphite, Stainless steel and general electrical characterization of bipolar plates using ANSYS Electric. Our objective is to investigate the effective resistance of bipolar plates and identify the ideal material to reduce conduction losses of PEMFCs through accurate calculation of the distribution of current density and imposition of a controlled voltage gradient. The total current as the integral of the directional current density over the surface, is done and Ohm's law is used to calculate the effective resistance. For bipolar plate design in PEMFC stacks, the conclusions of such electrical studies are of great importance. Enhanced fuel cell performance is achieved with efficient low effective resistance and minimal ohmic loss. This prepares for the outcome in utilization, paving the way for material selection and design optimization to future-proof continuously improving fuel cell systems.

Several studies have been conducted for metal bipolar plates to be used as an alternative due to the drawbacks related to graphite (15,16). Stainless steel and, more significantly, SS316L have proven to be effective alternatives in the manufacture of bipolar plates. SS316L is used because it has a high mechanical quality, ease of manufacture, and cost-effectiveness (17,18). The plate model has been designed with AM techniques in mind, for several advantages (19). The material's electrical resistivity is of the order 6.9×10^{-7} Ω•m, which is less than the isotropic value conventionally employed for graphite. Because of its low resistivity, under the same boundary conditions, SS316L will carry electrical current with lesser ohmic losses. Different research articles have discovered that metal bipolar plates provide better electrical contact and durability, although they typically exhibit lower thermal conductivity than graphite. In most instances, stainless steel's higher manufacturability and mechanical strength have offset its relatively higher thermal resistance, thereby improving overall fuel cell performance. Static electrical conduction analysis was used in some research to assess bipolar plate performance. These kinds of analysis typically consist of applying a specified voltage boundary condition to the plate and simulating the resulting voltage distribution and current density by means of numerical simulation software. Effective resistance of the plate is subsequently determined by integrating over the relevant boundary surface and through Ohm's law. Such integration is feasible in such a way that direct comparison for materials under identical geometrical and boundary conditions can be carried out. Simulation tools, for example, ANSYS Electric, can be used to simulate the electrochemical performance of bipolar plates and assess the impact of different design parameters, for example, channel geometry and material properties.

The analysis adopts an isotropic resistivity of 1×10^{-4} Ω•m for graphite and 6.9×10^{-7} Ω•m for SS316L based on documented literature values of the materials. Besides, the bipolar plate's geometric structure also plays an important part in deciding the electrical performance. The serpentine channel pattern, widely used in PEMFCs, is beneficial in dispersing the reactant gases and coolant uniformly over the active region of the membrane electrode assembly (20,21). Although the major concern of the static electrical analysis is conduction via the material of the plate, the existence of these channels affects the effective path of conduction and might result in localized density fluctuations of current. Numerical integration methods have been used in several analyses to calculate the net current through specific boundaries and, hence, determine the effective resistance of the plate. This technique creates worthwhile information regarding geometric form and material effects on overall performance.

For manufacturing AM can help with many issues in Fuel cells like dimensions, design iterations, complex geometries of flow channels and for metals, also AM have proven to be very effective, modern AM techniques have evolved to improve the production rates and considering the nature and stage of Bipolar plate and fuel cell development AM can help with manufacturing and thus it has been adapted here (22–24). AM is used extensively in the energy sector, from Fuel cells to lithium-ion, and by many others, especially in the research field (25). Unlike traditional processes, AM is an additive process that reduces material wastage, which contributes to long-term sustainable goals (26). Stainless steel and graphite trade-offs in terms of utilization are well characterized, with increased conductivity and heat performance for the graphite at a cost of reduced mechanical strength and manufacturing ease, while stainless steel exhibits low electrical resistivity and wearability at the cost of diminished thermal conductivity. Static electrical conduction analysis, for example, in ANSYS Electric, is a valuable means of quantifying differences and material choice guidance in fuel cell design as material affects the conductivity performance. This paper extends research in this field by making a comprehensive comparison between SS316L and graphite under controlled simulated conditions and thus to the knowledge of how such materials will behave for electrical conduction. Plate design, thickness, and channels have been optimized for stackability and better thermals.

The novelty of this work includes:

- First simulation-based electrical characterization of AM-compatible SS316L bipolar plates for PEMFC applications, focusing on conduction behaviour under realistic boundary conditions.
- Comparative evaluation against isotropically modelled graphite, providing a material selection basis rooted in conduction efficiency and manufacturability.
- Customized serpentine geometry designed for additive manufacturing, integrating both electrical performance and buildability considerations, a combination rarely emphasized in previous studies.
- Development of a simulation methodology in ANSYS Electric tailored to bipolar plates, including directional current density extraction and resistance quantification through boundary integration, extending beyond simplified analytical or purely thermal models found in earlier literature.

2. Materials and Methods

The simulation was conducted with ANSYS Electric to simulate and model a static electrical conduction analysis of bipolar plates for application in Proton Exchange Membrane Fuel Cells (PEMFCs). The aim of this study was to investigate and compare the conduction performance of bipolar plates made of two different materials: SS316L stainless steel and graphite using the Finite Element Method tool. The geometry model, meshing strategy, material property assignment, boundary conditions, and the method applied to calculate effective electrical resistance are all illustrated in this section.

2.1. SS316L as material for Bipolar plates

In PEMFC applications, the choice of material has a significant impact on the longevity and performance of bipolar plates. Because it combined mechanical strength, corrosion resistance, electrical conductivity, and AM manufacturing capability, SS316L was chosen for this project. Although it has been used historically for bipolar plates, graphite has a number of drawbacks, such as brittleness, high machining costs, and reduced mechanical strength. Its delicate nature renders it unsuitable for applications needing high durability and mechanical resilience, despite its exceptional corrosion resistance and strong electrical conductivity. Because of its improved mechanical qualities and ease of production, austenitic stainless steel, or SS316L, offers an alluring substitute. It resists the acidic conditions inside the fuel cell and offers a compromise between structural integrity and electrical conductivity.

2.2. Geometric Model

Bipolar plate geometry was simulated as a three-dimensional solid of $95 \times 95 \times 2.5$ mm in size. To simulate the real configuration adopted in fuel cell stacks, the plate was simulated with serpentine channels on two faces. Even though the real active membrane area is confined to a

50×50 mm central area, in the spirit of being overly cautious, a constant voltage was assigned to one face so the entire plate was subjected to a static electric field. The serpentine channel structure was utilized because of its prevalent use in PEMFCs, as it provides a distinct path for current collection and also minimizes the resistance caused by non-uniform current distribution, and fuel cells' performance is also affected by the aspect ratio of the channels (27,28). These are known to have some issues with pressure drop and thus the model has been modified with curved channels, improving the flow and reducing pressure issues (29). The structure was initially designed in a CAD environment and then transferred to ANSYS Workbench. It was ensured that the imported structure had all the details, such as the channel, to accurately simulate conduction phenomena. The model was also saved as a solid body so that the top and bottom faces could be kept free for future assignment of boundary conditions. The geometry of the bipolar plate was designed with additive manufacturing (AM) limitations in mind for successful printing and optimal performance, and thus the actual process selection affects the quality of plate as per the geometry (30,31). The 1 mm depth and 1 mm width of the groove used were selected keeping in view AM's limitation in resolving details. A 0.3 mm fillet radius at the groove bottom was included to remove sharp corners, with improved build stability and stress concentration minimization during printing. For minimal risk of deformation and ensured feature precision, the wall thickness of the channel was maintained greater than the minimum printable value commonly recommended for AM of stainless steel. Serpentine flow pattern was also minimized to a minimum overhang, which minimizes the amount of support structures required during fabrication. In addition, the design was to improve build stability and enable precise layer deposition, particularly in regions significant to existing flow.

2.3. Meshing Strategy

Meshing is a highly critical step in attaining valid simulation outcomes. An organized meshing approach was employed to represent the fine details of the serpentine channels with as much computational cost as possible to be avoided. ANSYS Workbench had global mesh parameters established with a baseline element size that was a compromise between solution accuracy and computing resources available. Local sizing controls were also employed on top of that to even more carefully tailor mesh areas with high geometric curvature, particularly in the channels.

In indicating the action of conduction over the significant boundaries, element skewness quality criteria, aspect ratio, and global density were checked for the mesh. The mesh was created in a conform shape so that it would guarantee the boundaries—over which voltages were being applied—were properly modelled. The mesh was then input to the ANSYS Electric module with boundary surfaces well tagged and recognizable. This process ensured integration of future current density over specific boundary faces with reliability in solving the mesh.

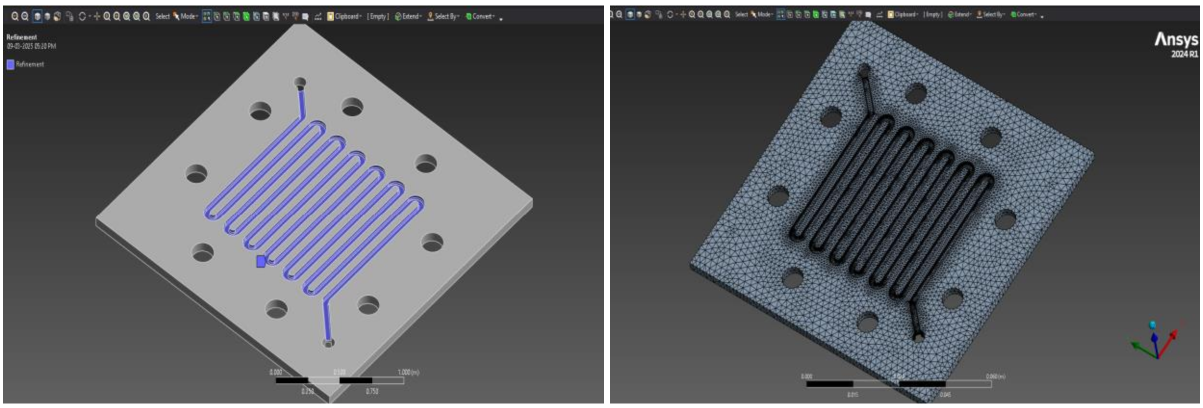

Fig. 1. Meshing with local refinement for the channel section

The bipolar plate's intricate serpentine form was resolved using a structured meshing approach. To guarantee precise current density capture in high-gradient zones, a global mesh control was used in conjunction with local refinement in the serpentine flow channel sections. In situations where conduction routes are extremely sensitive to geometry, this helps preserve solution fidelity. 319,474 nodes and 166,642 elements made up the final mesh, which had an average surface area of 8.14×10^{-5} m² and a minimum element edge length of 2.42×10^{-4} m. ANSYS mesh quality evaluation tools were used to measure aspect ratio metrics and element skewness (kept < 0.75). No serious problems with mesh quality were found. Three distinct mesh densities were used for simulations in order to guarantee grid independence. Throughout these runs, the computed resistance values and the resultant total current were compared. The mesh was considered grid-independent when the total current change between iterations was less than 1%. The final mesh utilised in this study provided the best balance between accuracy of results and computational expense.

2.4. Material Properties

Two of the materials that were the subject of discussion in the research were SS316L stainless steel and graphite. Their conductivity properties were of paramount importance in the forecasting of conduction performance. These properties were defined in the global Engineering Data in ANSYS Workbench and were thereafter verified and, if necessary, manually entered into the ANSYS Electric domain. Consistency of units was maintained during the simulation so that integrated figures resulting from current density were in SI units.

- **SS316L**: SS316L was simulated with an isotropic electrical resistivity of 6.9×10^{-7} Ω•m. This corresponds to literature values for SS316L upon conversion to micro-ohm-meters (~0.69 μΩ•m). Other suitable properties, such as thermal conductivity and density, were taken from standard sources, although for the static electrical conduction analysis, the point of focus was on electrical resistivity.
- **Graphite**: Graphite was simulated as isotropic material with electrical resistivity 1×10^{-4} Ω•m. Although naturally, graphite has anisotropic conductivity, with significantly lower in-plane resistivity, the material was assumed isotropic to facilitate direct comparison with SS316L. Such an assumption is common in initial studies where one cares less about relative conduction performance comparison and less about trying to simulate exact anisotropic behavior.

2.5. Boundary Conditions

One of the more important aspects of the simulation was the application of proper electrical boundary conditions to stimulate conduction along the bipolar plate. The simulation was started with a voltage boundary condition on one of the larger faces of the plate, at 1 V and the other face at 0 V. This gave a clear potential gradient in the plate so that current density distribution and effective resistance could be calculated. The choice of these boundary conditions is made according to the need to simulate the current collection process in a real fuel cell stack. Although in an actual operation the central active membrane area of around 50 × 50 mm supplies most of the current, in the simulation, conservatively the voltage difference across the whole face is used. This process provides a worst-case scenario conduction analysis and reveals any potential hotspots or high-resistance areas.

2.6. Simulation Procedure

The simulation of static electrical conduction was conducted using ANSYS Electric. The following is the procedure:

2.6.1. Initialization

Simulation was started with nominal properties for the material, utilizing the content of graphite on plates and considering a constant starting potential distribution to the entire domain. The solitary face was given a voltage of 1 V and the other a voltage of 0 V to supply a positive potential gradient. The type of initialization used was a very good one so that the convergence for the solution by iteration.

2.6.2. Solution Process

ANSYS Electric Modelled the voltage profile at steady-state and current density within the bipolar plate. The potential gradient was expressed by voltage contour plots across geometry. Special care was taken to ensure any peculiar jumps in voltage or abrupt changes in current density were not present, and such phenomena might demonstrate poor conducting regions, material inhomogeneities, or unwanted geometric flaws. The current density distribution was verified to ensure that flow paths were smooth, confirming uniform conduction characteristics and verifying average current normal to the application surface by using the direction current density outcomes. The calculation played a pivotal role in deciding the electrical performance of the plate as well as the estimation of its effective resistance. Since the analysis was static, the solution was taken to be complete when a stable voltage gradient between 1 V and 0 V was achieved.

2.6.3. Data Extraction

ANSYS Electric post-processing was employed to determine the voltage contour plots and current density distributions. Normal directional current density was used from the boundary face where voltage was applied to measure the conduction performance. Next, the mean current density was calculated and, knowing the surface area, the total current was calculated by multiplication. Finally, the effective resistance was calculated by Ohm's law (R = V/I), where V is 1 V. The procedure described for the ANSYS Electric simulation consists of a geometric representation of a bipolar plate with serpentine channels intentionally designed, a properly defined mesh (such as in Figure 1) capturing key details, and proper definitions of material properties for SS316L and graphite. The application of a 1 V to 0 V voltage boundary condition and integration of the direction current density over the corresponding boundary face, the plate resistance was calculated. This design, based on the process, provides a good foundation for comparing the two materials' electrical conductivity, one of the most significant factors in ensuring efficient and stable PEM fuel cells.

2.7. Additive Manufacturing Considerations

The bipolar plate geometry was designed keeping the limitations of AM in mind so that the design could be manufactured with ease. SS316L stainless steel material was used with its enhanced electric conductivity and corrosion resistance, over the capability of AM in producing high-complexity geometries. Serpentine flow field paths and dimensioned grooves (1 mm depth and width) were minimized to maintain tolerances offered by AM as well as minimize extreme deviation from design intent. Layer thickness, support material, and post-processing necessity were important parameters for AM. Overhangs were minimized through optimized serpentine pattern, and print quality was improved by minimizing excess support material. Geometrical smooth transitions among channels were also utilized to prevent sharp or abrupt corners that lead to decreased print precision or structural integrity. Future studies can encompass the optimization of such design parameters for improved manufacturability and exploration of other AM processes, such as Laser Powder Bed Fusion (LPBF) or Direct Energy Deposition (DED), for greater accuracy and material utilization. This integration of these AM methods further reduces the fabrication process complexity, reduces wastage of material, and improves overall component performance even further.

3. Results and Discussion

3.1. Voltage Contours and Potential Distribution

The static electrical conduction simulations presented voltage contours that give the potential distribution through the bipolar plate under a constant applied voltage boundary condition. For every test material—SS316L and graphite—a potential of 1 V was supplied to one of the faces, and the other face was set at 0 V. The contour plots resulting from this show a nearly linear gradient between the high-potential and low-potential faces, which is what would be expected and shows that the simulation could indeed create an even electric field throughout the plate. The contours of voltage for both SS316L and for graphite were devoid of any drastic discontinuities or local anomaly. This constancy shows that the paths for conduction remain intact and boundary conditions applied are being followed to the letter. This evenness is important in that it guarantees that there aren't any quantized pockets for excess resistance due to inadequate meshing or faults in the model. For both the materials, the voltage drop over the plate seems to be as would be expected from the provided geometry and boundary conditions. Figure 1 shows the voltage contour plots for SS316L and Graphite. The two figures confirm that the potential is uniform between 1 V and 0 V throughout the conduction domain demonstrating geometry uniformity. As both are similar, contours on SS316L are from the outer plate while graphite shows a cut section plane. Any minor differences observed between the two cases are primarily due to the differences in views – plate and section plane. Voltage contours shown in Fig. 2 display a uniform distribution, which indicates uniformity in the model, and this can also act as a step for model verification.

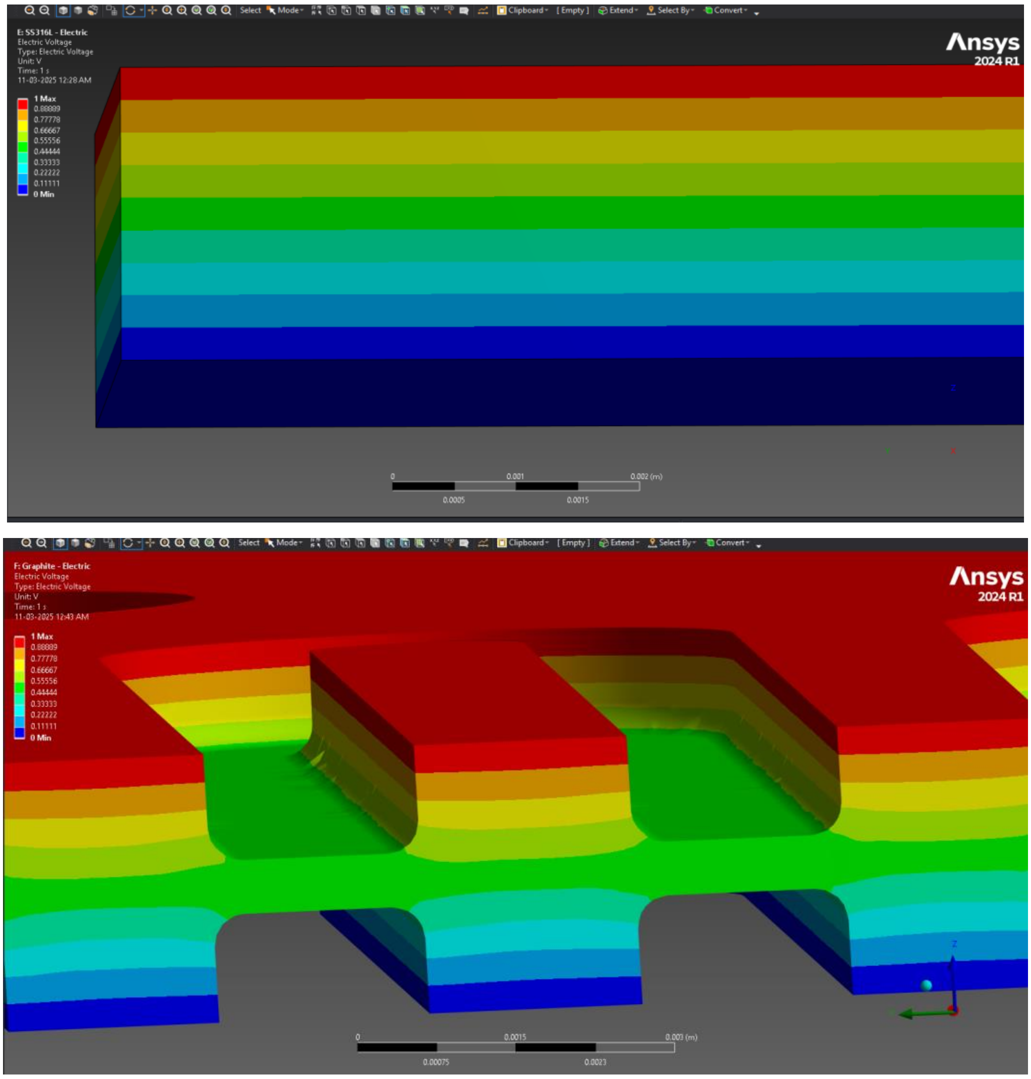

Fig. 2. Voltage contour plots for SS316L (top) and Graphite (bottom).

3.2. Current Density Distribution

The distribution of current density is an important parameter that gives information on the conduction behaviour of bipolar plates. Figure 3 shows the directional current density along the boundary normal on which the voltage was applied. For SS316L, the simulation provided a maximum current density of approximately 6.3652×10^{8} A/m², whereas the minimum observed value was around 5.7205×10^{8} A/m². And for the graphite model, peak current density was approximately 4.392×10^{6} A/m² and a minimum of around 3.9472×10^{6} A/m². These variations are mainly due to the input material properties. SS316L was given an isotropic resistivity of 6.9×10^{-7} Ω•m, whereas graphite was modelled with an isotropic resistivity of 1×10^{-4} Ω•m. While graphite has much greater in-plane conductivity, taking an isotropic average leads to a higher overall resistivity in the calculation. As a result, the SS316L plate has a greater local current density in certain areas since the lower resistivity of the material allows more current to pass through for the same voltage gradient.

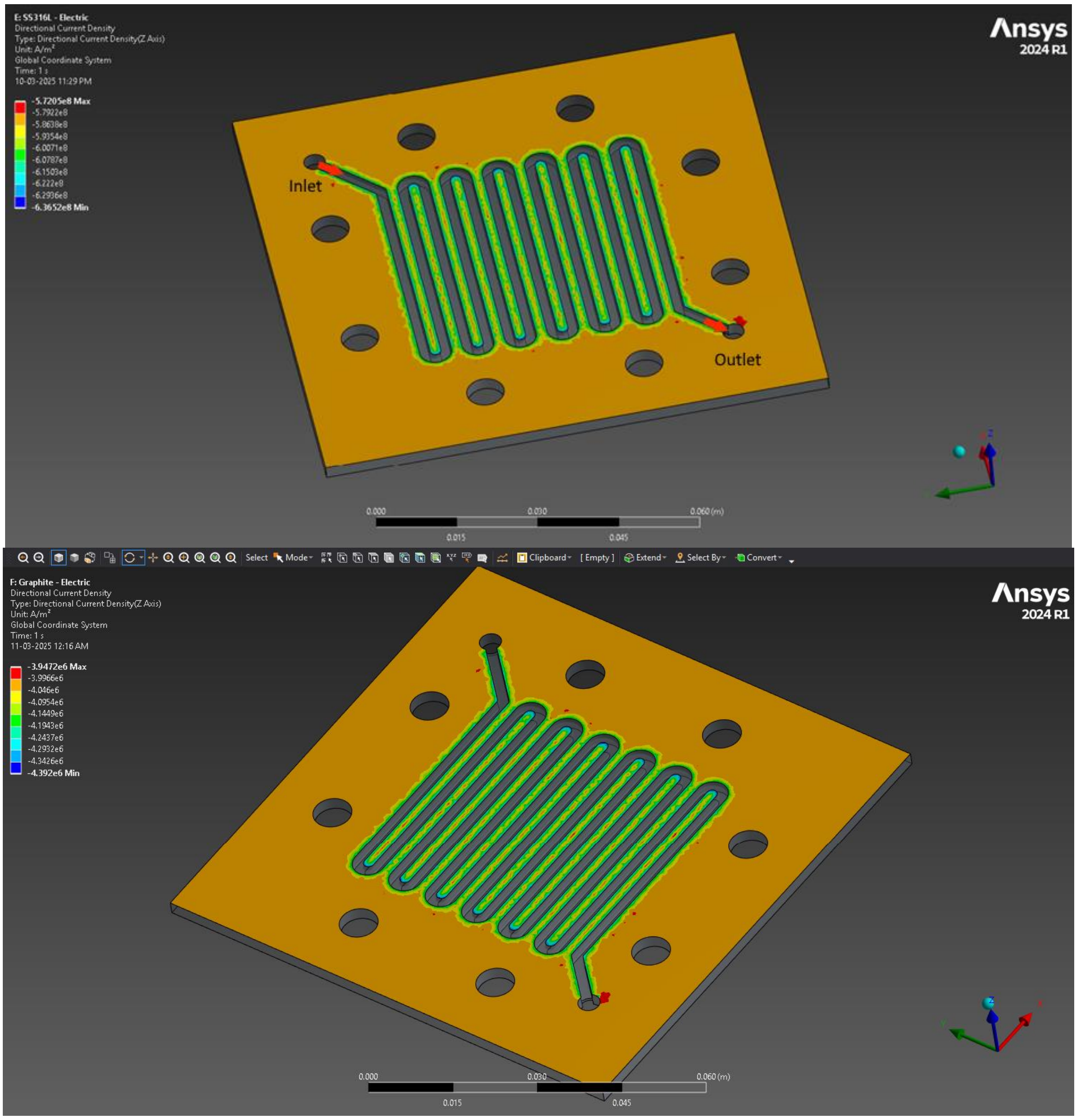

Fig. 3. Current density values in the direction normal to face of boundary (source), note the different values on left side of the figures.

The contour plots of current density reveal that SS316L has greater current density distribution whereas graphite shows lesser current density distribution. Negative sign denotes the direction of the current flow which is intended to flow from 1 V face to 0 V side. These plots also indicate the distribution, which appears to change around the channel geometry, which is typical for the case. The enhanced electrical performance realized in the stainless-steel bipolar plate can be explained in part by the accuracy and surface properties made possible by additive manufacturing. The AM process enabled the creation of complex serpentine channels with minimal dimensional deviation, with even channel width and depth throughout the plate. The dimensional accuracy aided in uniform current distribution by keeping localized resistance fluctuations to a minimum. In addition, the AM process created a surface finish that improved interfacial contact with surrounding fuel cell components. This better contact quality probably minimized contact resistance, further contributing to the observed decrease in effective resistance compared to traditional graphite plates. Although certain surface irregularities inherent to AM might still exist, their effect seemed negligible in this research, indicating that the selected process parameters adequately traded off build quality and electrical performance.

3.3. Effective Resistance Calculation

A key metric derived from the simulation is the effective electrical resistance of the bipolar plate. The effective resistance is determined by integrating the directional current density over the boundary face and applying Ohm's law, where R = V/I (with the applied voltage V = 1 V). For the SS316L model, the integrated current yielded an effective resistance on the order of 2.29×10^{-7} Ω. In contrast, the graphite model produced an effective resistance of approximately 3.32×10^{-5} Ω. These results indicate that, under the defined simulation conditions, SS316L conducts electrical current much more efficiently than the isotopically modelled graphite. The significantly lower effective resistance for SS316L is consistent with its much lower resistivity value. It is important to note that while graphite may exhibit superior in-plane conductivity in practice, the simulation employs an isotropic average that does not capture this anisotropy. As a result, the effective resistance of graphite appears higher than that of SS316L in the present analysis. The quantitative determination of effective resistance is critical because it directly impacts the overall performance of a fuel cell stack. Lower resistance implies reduced ohmic losses, which translates to higher overall efficiency. In the context of the simulation, the SS316L plate, with an effective resistance nearly two orders of magnitude lower than graphite, would theoretically contribute to lower conduction losses in the fuel cell.

3.4. Discussion of Material Performance

The static electrical conduction analysis gives useful information regarding the relative performance of SS316L and graphite as bipolar plate materials. The voltage contours, which in both instances are highly comparable, show that the global potential distribution is controlled by the applied boundary conditions and geometry instead of the material properties. But the variations in effective resistance and current density distribution are caused by the intrinsic electrical nature of the materials. For SS316L, the simulation calculates that its low isotropic resistivity (6.9×10^{-7} Ω•m) provides excellent ability in

Table 1. Overview of different properties of SS316L and Graphite plate and calculated resistance.

	SS316L	Graphite
Average Current Density	$-5.93\text{x}10^{8}$ A/m²	$-4.09\text{x}10^{6}$ A/m²
Face Area (Voltage application boundary)	$7.35\text{x}10^{-3}$ m²	$7.35\text{x}10^{-3}$ m²
Total current I (I= Average Current Density × Face Area)	$-43.64\text{x}10^{5}$ A	$-30.11\text{x}10^{3}$ A
Resistance (R= Voltage/ |Total current|)	$2.29\text{x}10^{-7}$ Ω	$3.32\text{x}10^{-5}$ Ω

sustaining high current flow and possesses extremely low effective resistance. It is a performance that is good in maintaining low ohmic losses in a fuel cell and enhancing efficiency. On the other hand, although graphite is very famous for its large conductivity in particular directions, with an isotropic resistivity of 1×10^{-4} Ω•m employed in the simulation, a higher effective resistance is achieved. This discrepancy also emphasizes the need to correctly simulate anisotropic behaviour in materials such as graphite if a more realistic comparison is to be achieved.

The effect of channel geometry on local current density is another controversial issue. Curved channels of bipolar plates are actually intended to evenly distribute electrical current and provide fluid flow for cooling. Nevertheless, based on simulation, channel corners and edges preferentially suffer local current density peaks. Although peaks like these are unavoidable, the peaks must be examined in depth so that they do not contribute to localized overheating and mechanical stress in reality. Additionally, it should be remembered that the stationary electric analysis performed in this work is a conservative estimation of the conduction behaviour. In a real fuel cell stack, only the active area corresponding to the membrane electrode assembly (usually around 50×50 mm) would be contributing substantial current. The simulation, applying the voltage across the whole plate, may be overestimating the conduction paths and respective current distribution. However, the method yields a worst-case estimation that is desirable for purposes of robust design.

3.5. Design Implications in Fuel Cells

The static electric conduction outcomes have direct design implications for bipolar plates and the choice of material for PEMFCs. The very low effective resistance that has been observed for SS316L indicates that, from the point of view of electrical conductivity, SS316L is an excellent choice as a bipolar plate. This benefit, combined with its higher mechanical strength and the simplicity of production, makes SS316L favourable for real fuel cell applications. The heightened effective resistance of graphite, nonetheless, as simulated herein, suggests that although graphite might provide advantages in mass and thermal conductivity, its conduction characteristics are not so appealing when isotropically minimized. The results highlight the fact that the choice of material for bipolar plates needs to compromise on several requirements, such as electrical conductivity, thermal management, corrosion resistance, and manufacturability.

4. Conclusion

The static electrical conduction analysis in ANSYS Electric provided insights into the performance of SS316L and graphite bipolar plates in PEM fuel cells under identical boundary conditions and geometries. Voltage contour plots confirmed smooth conduction paths, with both materials exhibiting linear voltage profiles, indicating that performance differences are primarily due to their intrinsic electrical properties, thus validating the model. SS316L demonstrated higher local current densities and lower effective resistance (2.29×10^{-7} Ω) compared to graphite (3.32×10^{-5} Ω), suggesting it is a suitable material for reducing ohmic losses. While graphite's anisotropic conductivity is not fully captured by the isotropic model used, the results still favor SS316L. The employed methodology, which includes detailed meshing, boundary condition application, and current density integration, provides a robust framework for assessing bipolar plate performance. Future work can include heat transfer simulations to evaluate thermal management and investigate the impact of additive manufacturing parameters, such as laser power and layer thickness, on electrical and surface properties. Optimization of these parameters could enhance surface finish, geometric accuracy, and electrical performance, further improving bipolar plate efficiency in PEMFC applications.

To summarize, Static electrical conduction analysis has proved that:

- SS316L and graphite exhibit a uniform voltage gradient between 1 V to 0 V over the bipolar plate, as per the model.
- SS316L possess much higher local current density and a much smaller effective resistance (approximately

2.29×10^{-7} Ω) compared to that of graphite (approximately 3.32×10^{-5} Ω).

- These are more or less properties of the input material, SS316L of which was simulated with an extremely low resistivity (6.9×10^{-7} Ω•m) when compared to higher isotropic resistivity in graphite (1×10^{-4} Ω•m).

The findings are in agreement with the application of SS316L to minimize conduction losses in bipolar plates, but thermal management and actual operating conditions also play significant roles. The results show that SS316L plates can be a good alternative and issues can be addressed with further methods of coatings, design optimization, and adapting different manufacturing technologies and this can help in improving the market penetration of the fuel cells. Although experimental validation was not conducted within the scope of this simulation-focused study, the observed trends in current density and effective resistance align with reported literature values. Future work can include experimental validation through actual fabrication of SS316L bipolar plates via AM and measurement of contact resistance using a four-point probe or PEMFC stack integration.

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