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Comparative study of materials for proton exchange membrane fuel cells bipolar plates: electrical performance, durability, and automotive compatibility

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Abstract. Bipolar plates are essential components of proton exchange membrane fuel cells because they contribute to current transport, reactant flow distribution, heat dissipation, and overall stack durability. The present study compares metallic, graphite, and composite bipolar plate materials in terms of conductivity, corrosion resistance, mechanical behavior, and suitability for automotive applications. Metallic bipolar plates provide excellent electrical conductivity and allow compact fuel cell stack configurations, although corrosion and surface degradation may progressively increase interfacial contact resistance during operation. Composite materials reinforced with conductive nanofillers, including carbon nanotubes, demonstrate improved chemical stability, reduced interfacial resistance, and favorable weight-to-strength characteristics. Graphite-based plates remain attractive because of their high corrosion resistance and stable electrochemical properties; however, their brittle structure limits their use under severe mechanical and vibrational conditions. This work highlights the importance of balancing durability, electrical efficiency, manufacturing feasibility, and cost in the development of next-generation PEMFC bipolar plates for hydrogen transportation systems.

Introduction

The transition toward sustainable mobility has positioned Proton Exchange Membrane Fuel Cells (PEMFCs) as a primary energy conversion solution, owing to their superior efficiency and minimal environmental footprint [1,2]. Within the PEMFC stack architecture, bipolar plates perform several vital functions: they facilitate electron conduction, ensure uniform reactant distribution, regulate heat, and provide structural separation between cells [3]. Consequently, the intrinsic properties of the materials used for these plates significantly dictate the overall stack performance, service life, and suitability for the rigorous demands of the automotive industry [3].

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In the early stages of development, graphite was the standard choice for plate manufacturing due to its exceptional chemical stability and consistent electrical conductivity in acidic environments. However, its implementation in transportation remains hindered by mechanical brittleness, high machining expenses, and limited durability when subjected to automotive vibrations and thermal cycling [5,10].

Consequently, metallic bipolar plates have emerged as a compelling alternative, offering high electrical conductivity, reduced volumetric footprint, and feasibility for mass production [9]. Despite these benefits, metals are prone to electrochemical oxidation in the fuel cell's operating environment. This phenomenon leads to the development of a passive layer that increases interfacial contact resistance (ICR), ultimately compromising long-term efficiency [8,11].

To address these challenges, composite bipolar plates have been developed as a lightweight, corrosion-resistant alternative [5,7]. The integration of conductive fillers, such as carbon nanotubes, has been instrumental in enhancing both the electrical network and the structural integrity of these materials [7,10]. Furthermore, advanced surface engineering and protective coatings are now essential strategies to mitigate corrosion and stabilize contact resistance during extended operation [8].

The integration of PEMFCs into vehicles requires meeting strict criteria for power density, mechanical resilience, and reliability under dynamic conditions [14,15]. Optimizing bipolar plate materials is therefore a fundamental requirement for the industrial success of hydrogen technology. This study provides a comparative assessment of metallic, composite, and graphite-based solutions, evaluating their electrical behavior, thermal management, and durability to identify the most effective configurations for future automotive applications [3, 11,15].

1 Materials for bipolar plates (metal – graphite – composites)

Bipolar plates must integrate a complex set of electrical, thermal, and mechanical properties to function effectively within a PEMFC stack. High electronic conductivity is essential for minimizing resistive losses during current transport, while superior thermal conductivity is required for efficient heat management across the assembly. Furthermore, these components must possess robust mechanical integrity and negligible gas crossover to maintain structural stability and prevent the mixing of reactants [3,6].

Given that the internal environment of a PEMFC is characterized by high humidity, acidity, and elevated temperatures, the chosen materials must exhibit exceptional chemical inertness. It is critical that they resist corrosion to prevent the release of metallic ions, which could poison the membrane electrode assembly and degrade electrochemical performance over time. From a manufacturing standpoint, the ideal material should allow for ultra-thin designs and be compatible with high-volume, cost-efficient production techniques [9,10].

Currently, bipolar plate technologies are classified into three major groups based on their chemical composition and processing methods: graphite-based, metallic, and composite materials. [5,10].

1.1 Metal bipolar plate

Metallic substrates are extensively researched for PEMFC applications due to their superior electronic conductivity, thermal diffusivity, and mechanical robustness. Their high fracture toughness and structural stiffness provide essential resilience against the mechanical stresses and vibrations inherent in transport environments. Furthermore, the inherent strength of metals allows for the production of ultra-thin plates—often reaching thicknesses under 0.1 mm—which facilitates the design of lightweight and high-density fuel cell stacks [9,15].

A variety of metals, such as titanium alloys, noble metals, and stainless steel, have been evaluated for plate construction. Stainless steel, in particular, is a leading candidate because it offers an optimal compromise between cost-efficiency, mechanical integrity, and ease of mass production [4,9]. Nevertheless, the harsh, acidic, and humid conditions inside a PEMFC stack trigger corrosion processes. These phenomena can lead to the leaching of metallic cations, which may contaminate the membrane electrode assembly and accelerate its degradation. Moreover, the spontaneous development of resistive oxide layers on the metal surface elevates the interfacial contact resistance (ICR), detrimental to the stack's overall electrical output [8,11].

To mitigate these degradation mechanisms, surface engineering strategies, such as the application of conductive and anti-corrosive coatings, have become indispensable. While these treatments effectively stabilize the surface and enhance durability, the selection of coating techniques must balance manufacturing expenses with the need for high conductivity. Additionally, ensuring the long-term adhesion of these protective barriers under dynamic operating conditions remains a critical hurdle for large-scale commercialization [8,9].

1.2 Graphite bipolar plate

Due to their remarkable chemical inertness and consistent electronic conductivity, graphite-based materials were among the earliest solutions implemented for PEMFC bipolar plates. The traditional fabrication of these components involves complex blending and graphitization cycles, followed by precise mechanical machining to engrave the necessary reactant flow channels [5,10].

Despite their proven electrochemical durability, several drawbacks hinder the widespread adoption of pure graphite plates. Achieving the required gas impermeability and structural robustness during stack compression typically necessitates relatively thick designs, which penalizes the overall power density. Furthermore, the specialized machining of flow fields is a labor-intensive process that limits throughput. The high-temperature graphitization phase also demands significant energy and long processing times, leading to substantial manufacturing costs [10].

A major technical obstacle remains the inherent brittleness of graphite, which makes it susceptible to fracturing under the mechanical shocks and vibratory stresses typical of automotive environments. These mechanical limitations, combined with the volume and weight constraints of modern vehicles, restrict the use of conventional graphite plates in the pursuit of more resilient and compact fuel cell architectures [5,15].

1.3 Composite graphite bipolar plate

To bridge the gap between the chemical stability of graphite and the manufacturability of metals, composite bipolar plates have emerged as a versatile alternative. These components are typically fabricated by integrating conductive carbon-based fillers into a polymer matrix, such as epoxy or vinyl ester resins. By utilizing injection or compression molding, these materials allow for the rapid production of complex flow-field geometries, significantly enhancing manufacturing throughput compared to traditional machining [5,10].

A primary advantage of composite plates lies in their exceptional corrosion resistance and substantial weight reduction, which are critical for mobile PEMFC applications. The inclusion of advanced carbon fillers, particularly carbon nanotubes or graphene, has been shown to drastically improve the bulk electrical conductivity and lower the interfacial contact resistance (ICR) [7]. This reinforcement not only optimizes the electron transport network but also enhances the mechanical toughness of the plate, addressing the brittleness issues associated with pure graphite [5,7].

However, achieving an ideal balance between high filler loading for conductivity and maintaining the fluidity required for molding remains a technical challenge. Despite this, the ability to tailor the material properties through nanomaterial reinforcement makes composites a highly promising solution for durable and cost-effective automotive fuel cell stacks [10, 15].

2 Performance and durability of bipolar plate materials

2.1 Polarization curves and electrical performance

To evaluate the electrochemical efficacy of the PEMFC stack, polarization behavior was analyzed, as it provides a standard benchmark for assessing energy conversion performance [6, 11]. The numerical data generated for aluminum, graphite composite, and pure graphite plates are presented through voltage–current and power density–current density relationships in Fig. 1(a) and 1(b) [11].

The simulation results reveal that aluminum bipolar plates deliver the highest electrochemical output across the tested range. Composite-based plates exhibit intermediate performance, while traditional graphite configurations show the most limited power density. Specifically, the peak power densities were recorded at 482.5 mW/cm² for aluminum, followed by 445 mW/cm² for the composite material, and 414 mW/cm² for the graphite plates. These power peaks were achieved at operating voltages of approximately 0.48 V, 0.45 V, and 0.46 V, respectively. Such variations highlight the decisive role of the plate's material composition in determining the overall electrical efficiency of the fuel cell [11,13].

The superior performance of the aluminum-based system is primarily linked to its high electronic conductivity, which optimizes current collection and reduces ohmic losses. Similarly, the composite plates benefit from an efficient charge-transfer network established by the conductive carbon fillers within the polymer matrix [5,7]. On the other hand, the higher internal resistance characteristic of conventional graphite contributes to the observed reduction in power output under identical test conditions [10,11].

Furthermore, the fluctuations in cell voltage and power output are governed by a complex interplay between membrane ionic transport, localized thermal gradients, and reactant diffusion [12,15]. Because PEMFC performance relies on coupled electrochemical and thermodynamic processes, any change in the bipolar plate material simultaneously shifts the equilibrium of current distribution and heat management within the stack [11,12].

2.2 Current collection performance

The efficiency and operational lifespan of PEMFCs are heavily dictated by the interaction between bipolar plate material characteristics and their architectural design, which directly govern ohmic losses and mass transport dynamics [13,14]. Consequently, analyzing the local current distribution is vital for understanding stack durability. Any heterogeneity in current density can trigger adverse effects such as localized thermal spikes, uneven reactant depletion, or electrode flooding, all of which contribute to the premature degradation of the catalyst layer [13].

The in-plane electronic distribution across the cell's mid-section is illustrated in Fig. 2. While the distribution patterns appear similar across the three materials due to the shared flow-field geometry, distinct variations in magnitude are evident [11]. The simulations confirm that electron transport is predominantly concentrated within the rib areas of the plates. Conversely, the peripheral zones exhibit significantly lower current densities, a result of reduced reactant accessibility in those regions.

Among the evaluated candidates, the aluminum-based plates achieved the peak current density at the collector interface, recorded at 1000.5 mA/cm². The graphite composite plates followed closely with values near 990 mA/cm², while the conventional graphite plates showed the most substantial reduction, dropping to approximately 900 mA/cm². These findings validate that the intrinsic conductivity of the bipolar plate material is a primary determinant of current collection efficiency and, by extension, the overall electrochemical output of the PEMFC system [11,13].

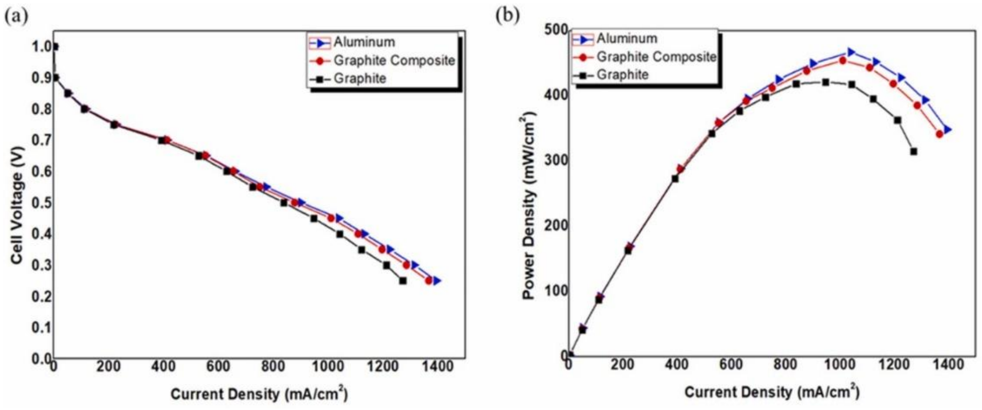

Fig. 1.Electrochemical performance comparison of PEMFCs using different bipolar plate materials.

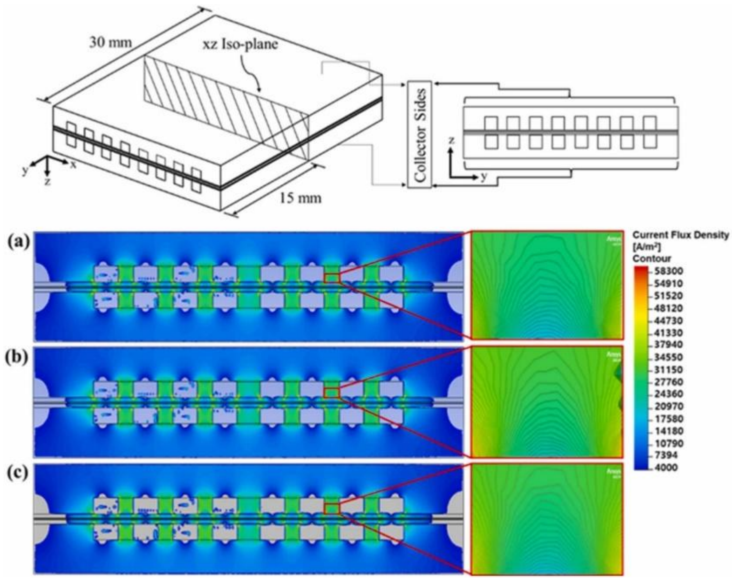

Fig. 2. Simulated current density distribution for different bipolar plate materials.

The current collection performance and local current density distribution were evaluated using COMSOL Multiphysics.
Musse, D., & Lee, D. (2024)

The distribution of current density at the collector interface and its evolution along the through-plane direction (Z-axis) are illustrated in Fig. 3(a) and Fig. 3(b). The data indicate that aluminum and graphite composite plates exhibit more significant current density gradients than the pure graphite version. This behavior is primarily linked to their superior electronic conductivity and the higher operational current levels these materials can sustain [11,13].

Electrical conductivity remains a fundamental metric for determining the efficiency of bipolar plates. Generally, materials with high conductivity minimize internal resistive losses. This reduction is critical as it limits ohmic drops and decreases energy dissipation through Joule heating [14]. Consequently, optimizing this parameter enhances the overall effectiveness of charge transport throughout the PEMFC stack [10,11].

While graphite is recognized for its adequate intrinsic conductivity, its higher operating voltage under the studied conditions can paradoxically restrict its current collection efficiency. Conversely, the graphite composite architecture operates at a marginally lower cell voltage. This shift in the operating point facilitates more effective current extraction, leading to superior collection behavior compared to standard graphite plates [11].

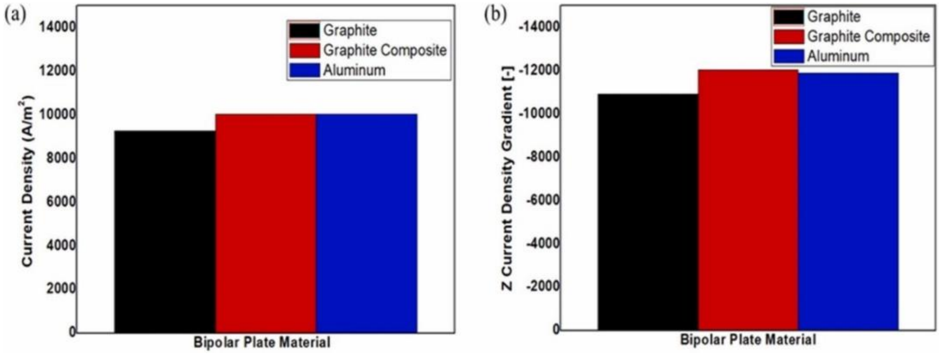

Fig. 3. Current collection performances of the bipolar plate materials: (a) Current density at the collector sides, (b) Z current density gradient magnitudes.

The current density at the bipolar plate collector side and the through-plane (z-direction) current density gradients were extracted using COMSOL Multiphysics.
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2.3 Heat generation and wall heat flux

Within a PEMFC, thermal energy is predominantly produced in the catalyst layers, where the core electrochemical processes occur. This total heat output is the sum of reversible and irreversible components. Reversible heat is generated by entropic changes and phase transitions, whereas irreversible heat is a byproduct of electrochemical overpotentials during the redox reactions [12,14].

The cathodic side is the primary source of thermal energy, accounting for nearly 50% of the stack's total heat generation [11,14]. This concentration of heat at the cathode is fundamentally tied to the oxygen reduction reaction (ORR), which is more exothermic and less kinetically efficient than the hydrogen oxidation reaction (HOR) at the anode [11].

The simulation data in Fig. 4 highlight how the choice of bipolar plate material influences thermal output. Graphite composite plates demonstrate the highest rate of heat generation, followed by aluminum, while the lowest thermal production is observed with pure graphite plates. These fluctuations are directly related to the interplay between the material's electronic conductivity, the resulting current density profiles, and the overall electrochemical intensity within the system [11,12].

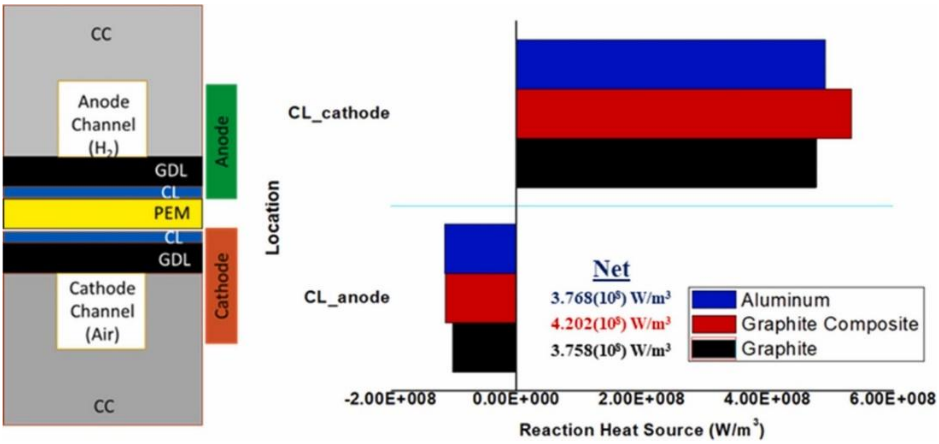

Fig. 4. Reaction heat sources in the PEMFCs depending on bipolar plate materials of graphite, graphite composite and aluminum.

The heat generation resulting from electrochemical reactions was numerically evaluated using COMSOL Multiphysics.
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Thermal management is a decisive factor for the operational efficiency of PEMFC systems [14]. Effective heat dissipation must be achieved through two primary pathways: convective heat loss across the bipolar plate boundaries and the enthalpy associated with the water vapor exiting the stack. As the central cooling interface, bipolar plates are required to possess a high degree of electronic conductivity coupled with efficient thermal diffusivity to effectively reject waste heat [11].

The intensity of electrochemical activity within the stack is a primary driver for the rate of thermal generation. Specifically, as current densities increase alongside a reduction in operating voltage, the accelerated reaction kinetics inevitably lead to a higher thermal load [11,12]. Based on the simulation findings, the graphite composite configuration demonstrates the most significant heat production and expulsion. Aluminum follows as an intermediate solution, whereas the pure graphite plates are characterized by the minimum thermal flux density observed in this study [11,14].

Analysis of the heat flux contours in Fig. 5 reveals that thermal transfer reaches its peak intensity in the active regions surrounding the catalyst layers. While all evaluated materials follow a comparable distribution pattern due to the identical flow-field geometry, the intensity is notably higher for the graphite composite. This trend is a direct result of the more demanding heat generation and dissipation requirements associated with its specific electrochemical operating conditions [11,14].

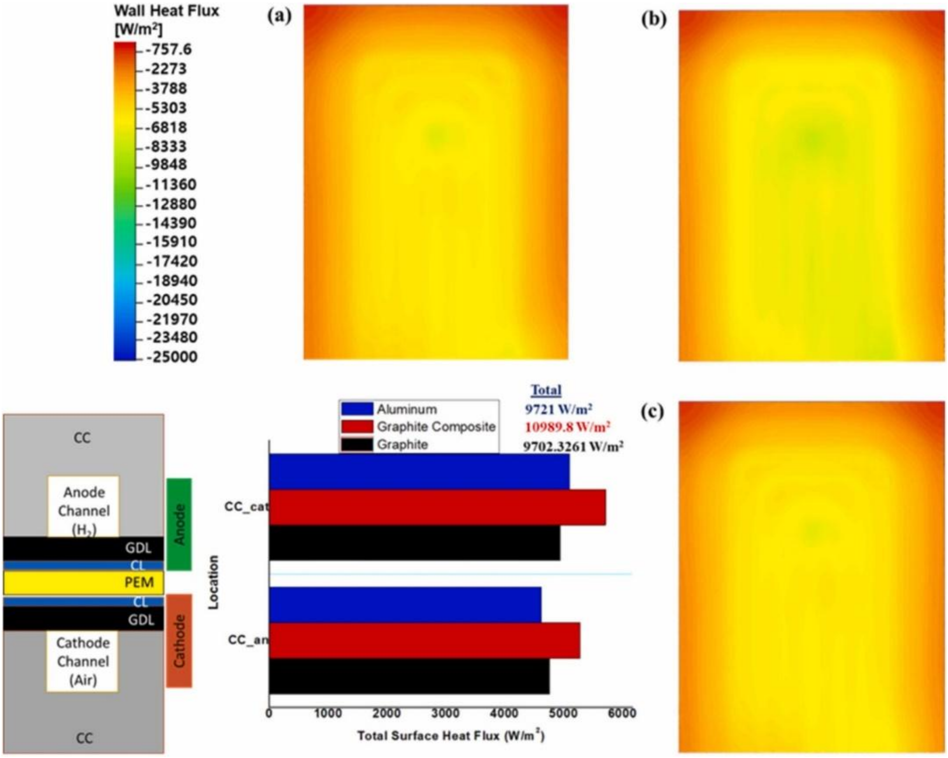

Fig. 5. Wall heat fluxes of the PEMFCs depending on bipolar plate materials; (a) Graphite bipolar plate (b) Graphite composite bipolar plate (c) Aluminum bipolar plate.

The wall heat flux and thermal distribution of the PEMFC were numerically evaluated using COMSOL Multiphysics.
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2.3.1 Impact of thermal gradients and heat flux on catalyst and membrane aging

Beyond influencing immediate electrochemical output, localized thermal gradients and intense heat fluxes significantly affect the long-term structural integrity of the membrane and catalyst layers [14]. Regions subjected to excessive temperatures and thermal non-uniformity are highly susceptible to accelerated aging, which manifests as membrane dehydration, chemical decomposition, and induced mechanical stress. Continuous thermal cycling, coupled with irregular temperature profiles, can lead to membrane thinning and the development of micro-cracks. These defects reduce protonic conductivity and increase ohmic resistance, progressively compromising the overall efficiency of the cell [11,12].

In a similar manner, concentrated heat fluxes adjacent to the catalyst layers can trigger degradation mechanisms such as the agglomeration of platinum nanoparticles and the corrosion of carbon supports. These phenomena result in a significant reduction of the electrochemically active surface area (ECSA). Such effects are particularly severe at the cathode, where the exothermic nature of the oxygen reduction reaction (ORR) generates the highest thermal loads. Over prolonged operation, these localized thermal stresses intensify performance decay and shorten the operational lifespan of the stack [11,14].

From a structural perspective, the bipolar plate material serves as a vital regulator of these aging processes through its inherent thermal conductivity and dissipation efficiency. Materials that facilitate a more homogeneous temperature distribution can effectively prevent the formation of "hot spots," thereby decelerating the degradation of the membrane and catalyst. Therefore, the thermal data presented in this study should be viewed not only as a measure of current performance but as a critical predictor of the system's reliability and durability under dynamic automotive conditions [13,15].

3 Automotive compatibility and application perspectives of bipolar plate materials

3.1 Automotive requirements for bipolar plate materials

Automotive PEMFC integration demands a rigorous balance between high power density, mechanical durability, and mass reduction. To function reliably under dynamic vehicle conditions, bipolar plates must ensure exceptional corrosion resistance and volumetric efficiency [13, 15].

Modern stack designs prioritize the reduction of plate thickness as a direct method to enhance specific power. Notably, the implementation of ultra-thin metallic plates (0.1 mm) has proven essential for developing the compact, high-performance systems required for the transportation sector [9,15]. This shift towards thinner, lighter materials is critical to overcoming the spatial and weight constraints of hydrogen-powered vehicles [5,7].

3.2 Metallic bipolar plates for automotive PEMFCs

Metallic plates, notably aluminum and stainless steel, are preferred for vehicles due to their high mechanical resilience and excellent formability. Their primary advantage lies in their minimal thickness, which drastically reduces the stack's total mass and volume [11,15].

Despite their benefits, metals are vulnerable to corrosion and high interfacial contact resistance (ICR) in acidic environments. To mitigate this, advanced surface treatments—such as zirconium carbide or conductive coatings—are applied. These protective layers can extend the fuel cell's operational life by over 30%, meeting the durability standards required for transportation [14,15]. Furthermore, the high thermal conductivity of metallic BPs ensures superior heat dissipation and temperature uniformity, which is vital for maintaining stability during variable driving cycles [11,13].

3.3 Graphite bipolar plates: limitations for automotive use

While graphite provides exceptional electrochemical stability and corrosion resistance, its inherent brittleness and poor mechanical toughness pose significant challenges for vehicle integration. To ensure structural integrity, graphite plates require a substantial thickness, which negatively impacts the stack's volumetric power density and conflicts with the compact design requirements of modern fuel cell electric vehicles (FCEVs) [5,15].

Due to these physical constraints and the high costs associated with complex machining, pure graphite BPs are primarily restricted to stationary power systems or laboratory-scale applications rather than mass-market automotive fuel cells [10,11].

3.4 Composite bipolar plates: a compromise solution

Composite bipolar plates, which integrate carbon fillers—such as graphite, fibers, or carbon black—into polymer matrices, serve as a middle ground between metallic and pure graphite options. These materials combine the corrosion resistance of graphite with improved mechanical durability, overcoming the inherent brittleness of traditional carbon plates [7,10].

From an automotive standpoint, composites offer significant benefits in terms of mass-production flexibility and chemical stability. However, their electrical conductivity and tensile strength generally fall below those of metallic alternatives. Consequently, while they provide a robust and cost-effective solution, their application in ultra-high-power automotive stacks is still balanced against the superior performance of thin-gauge metals [15,11].

3.5 Comparative assessment of bipolar plate materials for automotive PEMFCs

Table 1 provides a comparative summary of graphite, metallic, and composite bipolar plates based on essential automotive performance criteria [11,15]:

Table 1. Comparison of bipolar plate materials for automotive PEMFC applications

Candidate Material	**Electronic Conductivity**	**Structural Integrity**	**Resistance to Oxidation**	**Volumetric Efficiency**	**Transport Sector Viability**
Superior	Fragile (low impact resistance)	Exceptional	Suboptimal	Restricted	Superior
Intermediate	Balanced	Robust	Satisfactory	Moderate	Intermediate
Elevated	Outstanding	Enhanced (via protective layers)	Superior	High	Elevated

3.6 Application perspectives and future trends

The trajectory of automotive PEMFC engineering is increasingly focused on the evolution of ultra-lightweight and thin-gauge metallic bipolar plates. These components, protected by sophisticated anti-corrosion coatings, are essential for achieving long-term operational stability [14,15].

These material advancements are critical for meeting the ambitious 2040 performance benchmarks, which target a power density of approximately 9 $kW \cdot L^{-1}$ for next-generation fuel cell architectures. Furthermore, the convergence of automated manufacturing processes and innovative stack designs is expected to accelerate the mass-market adoption of metallic solutions in the transportation sector [9,15].

Conclusion

This study evaluated the performance and thermal characteristics of different bipolar plate materials—graphite, aluminum, and composites—for PEMFC applications. The numerical results indicate that coated aluminum plates deliver the highest peak power density (482.5mW/cm^2), making them the most viable option for compact automotive stacks due to their superior conductivity and reduced volume.

While graphite offers excellent chemical stability, its mechanical fragility and thickness limit its use in mobile systems. Conversely, composite materials provide a balanced alternative, offering high corrosion resistance and manufacturing flexibility, though with moderate electrical performance.

Furthermore, the thermal analysis highlights that managing localized heat flux and thermal gradients is essential to prevent membrane dehydration and catalyst degradation, ensuring the long-term reliability required for the transportation sector. Ultimately, the transition toward ultra-thin metallic plates and advanced coatings remains the key trajectory to meeting the 2040 power density targets for next-generation fuel cell electric vehicles.

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