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Core Analysis of Low-Temperature Fuel Cell Technologies: Principles, Classification, Status, and Outlook

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Abstract. This study conducts an in-depth analysis of low-temperature fuel cell (LTFC) technologies to address the practical demand for efficient, low-emission energy conversion in the global pursuit of carbon neutrality. It first elaborates on the electrochemical reaction principles of LTFCs, which enable direct conversion of chemical energy from fuels (e.g., hydrogen, methanol, ammonia) into electricity while minimizing heat loss and pollutant emissions—avoiding the energy waste associated with heat-to-mechanical energy transitions in traditional combustion systems. The study then classifies mainstream LTFC technical routes, including proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells (DMFCs), direct ammonia fuel cells (DAFCs), and microbial fuel cells (MFCs), and compares their unique characteristics: PEMFCs stand out for rapid start-up and high electrical efficiency, making them ideal for transportation; DMFCs use liquid methanol-water mixtures to eliminate high-pressure hydrogen storage, suiting portable electronics; DAFCs leverage ammonia's favorable storage properties to solve hydrogen transport issues; MFCs uniquely integrate wastewater treatment with power generation. By reviewing relevant literature, the paper summarizes the current research status in key areas such as non-platinum-group metal (non-PGM) catalyst development, membrane performance optimization, and system-level hybrid design. The corresponding outlook on future development trends—such as scaled production of low-cost non-PGM materials and expanded application in heavy-duty maritime/road transport—is presented, providing a systematic cognitive framework for academia and industry to advance LTFC commercialization and support energy system decarbonization.

Keywords: low-temperature fuel cells, cell performance, future development

1. Introduction

Against the backdrop of global fossil fuel depletion and escalating greenhouse gas emissions, low-temperature fuel cells (LTFCs)—operating at temperatures below 300°C—have emerged as a pivotal technology for sustainable energy transition. Their core advantage lies in converting chemical energy from fuels such as hydrogen and methanol into electricity with high efficiency and minimal pollution, effectively addressing the dual challenges of traditional energy systems. Osman et al. [1] comprehensively reviewed LTFCs technology, defining its core structure consisting of an anode (for fuel oxidation), a cathode (for oxidant reduction), and an electrolyte (for charge transport), while

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classifying it into major subtypes including proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells (DMFCs), and alkaline fuel cells (AFCs). They also pointed out main problems that LTFCs try to solve. These include the high price of key materials such as Nafion membranes. Another problem is the low efficiency of internal combustion engines. These issues have long restricted how sustainable transportation and shipping can be.

Recent studies build on the basic design of PEMFCs. They work to make electrode parts better to improve performance. Special focus is on gas diffusion layers (GDLs). Research on new GDL structures [2] has led to big gains in moving gas and water inside the cell. This solves problems like "water flooding" found in older PEMFC designs. So, the technology becomes more reliable for real-world use.

A big hurdle for wider use of LTFCs is storing hydrogen. Direct ammonia fuel cells (DAFCs) have come up as a good answer. Ammonia is easier to store and move than hydrogen. Work on NiCu alloy catalysts for DAFCs has moved this type forward. It cuts down the need for rare, costly platinum-group metals (PGMs). At the same time, it keeps high efficiency in turning ammonia into energy. This progress helps with two big problems: storage limits and high costs. These problems have made it hard to scale up.

Looking beyond single cell technology, system-level improvements have expanded LTFC uses. This is especially true for heavy-duty work like shipping. Fuel cell-battery hybrid systems adjusted with particle swarm optimization (PSO) methods [3] have been shown to lower fuel use in ferries. Trial projects demonstrate good round-trip efficiency. This use case does two things. This proves LTFCs are good for large transport jobs. It also shows they can cut emissions in areas where normal battery technology does not work well.

This paper studies main technical progress and possible future uses for low-temperature fuel cells (LTFCs). It aims to describe LTFCs features and their practical worth in different technical fields. These cover making core materials better, improving how subtypes work, and creating new system plans. It also looks at how these technical choices shape wider LTFC adoption and cleaner energy setups. The paper will go over key research areas in the LTFC field. These include making better gas diffusion layer structures for proton exchange membrane fuel cells (PEMFCs), creating non-platinum-group metal (non-PGM) catalysts for direct ammonia fuel cells (DAFCs), and designing fuel cell-battery hybrid systems for ship use. The paper will carefully study the technical strengths and current limits of each area. It will also give ideas for future technical paths to solve present problems LTFCs face. These problems are high material costs, not enough infrastructure, and the need for longer life. Suggestions include pushing forward large-scale production of non-PGM catalysts and speeding up building of ammonia and hydrogen fuel supply infrastructure. The aim is to create a foundation for LTFC systems that work well, cost less, and suit various uses. This would support carbon neutrality goals in difficult fields like transport and shipping.

2. Fundamental working principles of low-temperature fuel cells

To see why LTFCs matter technically, start with how they basically work. Regular combustion engines face Carnot cycle limits. LTFCs are different. They function as open thermodynamic systems. They turn fuel's chemical energy directly into electricity through natural electrochemical reactions. This direct change removes energy losses linked to heat-to-mechanical energy shifts, and this builds the base for high efficiency. All LTFCs have three main parts: an anode, a cathode, and an electrolyte layer between them. Let's take hydrogen-based LTFCs (like PEMFCs) as an example. Hydrogen gas (H_2) breaks into protons (H^+) and electrons (e^-) at the anode, with the help of a catalyst. The electrons move through an external circuit to make electricity—this is the cell's direct

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electrical output. At the same time, protons move through the electrolyte to the cathode. At the cathode, oxygen from the air reacts with the protons and electrons to form water (H_2O). Water is the main byproduct of most LTFCs. This reaction path makes almost no pollutant emissions, and this is a key plus over traditional combustion technologies.

A key difference between LTFCs and high-temperature fuel cells (>500°C) is reaction speed. LTFCs usually work at temperatures below 100°C. This lowers heat loss but slows down electrochemical reactions. To fix this, they need catalysts that work better to speed up reaction rates. This balance between temperature, catalyst performance, and system complexity is why LTFCs are good for mobile, portable, and decentralized uses—places where starting quickly and having a small design are needed. Also, the type of charge carrier (like protons in PEMFCs, hydroxide ions in AFCs) decides what the electrolyte does and how the cell works overall. This gives each LTFC subtype its own special features [4].

2.1. Proton Exchange Membrane Fuel Cells (PEMFCs)

Proton exchange membrane fuel cells (PEMFCs) are the LTFC subtype that people study and use the most. They use solid polymeric proton exchange membranes (such as Nafion) as electrolytes. Catalysts are coated on porous gas diffusion layers (GDLs) at both the anode and cathode. Recent improvements in GDL design—like hierarchical porous structures—have made mass transport and mechanical durability better. This helps PEMFCs have high electrical efficiency (up to 60%) and start quickly (5–10 minutes). These features make them perfect for transportation (like FCEVs) and stationary backup power (like data center emergency power). But the high cost of membrane materials and platinum catalysts is still a big problem for using them on a large scale [5].

2.2. Direct Methanol Fuel Cells (DMFCs)

Direct methanol fuel cells (DMFCs) share the same polymer electrolyte as PEMFCs but differ in fuel type: they use a liquid mixture of methanol and water, eliminating the need for high-pressure hydrogen storage. A Pt-Ru alloy catalyst at the anode mitigates methanol crossover (a common issue where methanol diffuses to the cathode and reduces efficiency). Flexible DMFCs, optimized with homogeneous anode GDLs, have thin, bendable structures that enable 10–50 W output—perfect for portable electronics like wearable devices or medical equipment [6]. Their main limitations are low efficiency (capped at 40%, due to slow anode kinetics and methanol crossover) and the need for safe handling of toxic methanol.

2.3. Alkaline Fuel Cells (AFCs)

Alkaline fuel cells (AFCs) use aqueous potassium hydroxide (KOH, 30–50% concentration) or alkaline membranes as electrolytes, with Ni-based catalysts replacing expensive platinum. Alkaline conditions accelerate cathode reactions, allowing AFCs to achieve high power density at 40–60°C, and they tolerate CO_2 in fuel when paired with alkaline membranes. However, the corrosive nature of aqueous KOH requires complex management systems to prevent leakage, and CO_2 in the air reacts with KOH to form K_2CO_3 precipitates—these precipitates block electrolyte channels and shorten the cell's lifespan [7].

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2.4. Direct Ammonia Fuel Cells (DAFCs)

DDirect ammonia fuel cells (DAFCs), a specialized LTFC subtype operating at 25–80°C, use alkaline electrolytes or anion exchange membranes. Their key advantage lies in ammonia's favorable storage properties: liquid at ambient temperature and low pressure (0.86 MPa) with a high hydrogen content. NiCu alloy catalysts further reduce costs by replacing PGMs, making DAFCs suitable for long-distance transportation (e.g., AHFCEVs). Yet ammonia crossover degrades cathode performance, and its oxidation kinetics are slower than hydrogen, limiting overall efficiency [8].

2.5. Other fuel cells

Direct methane fuel cells operate below 200°C, using proton-exchange or alkaline membranes and Pt-ZrO_2/Ni-based catalysts for direct methane oxidation. They leverage abundant natural gas resources for stationary power (10–100 kW) in industrial facilities or rural areas with natural gas access, producing only CO_2 and water as byproducts. However, breaking methane's strong C-H bonds remains a challenge—slow C-H activation and catalyst deactivation from carbon deposition keep efficiency below 35% [9]. Phosphoric acid fuel cells (PAFCs) use liquid phosphoric acid immobilized in a porous matrix, operating at 150–200°C. Their high operating temperature allows them to tolerate up to 1% CO in fuel, simplifying fuel processing, and they excel in combined heat and power (CHP) systems with a total efficiency (electricity + heat) of 80%. With a lifespan exceeding 40,000 hours, they are well-suited for stationary applications like building or hospital power. Their large volume and slow start-up (1–2 hours) make them unsuitable for mobile use, though [10]. Microbial fuel cells (MFCs) stand out for their dual function: they treat wastewater while generating electricity. Microorganisms on biofilm-coated anodes (graphite or carbon felt) degrade organic pollutants in wastewater (which acts as both fuel and electrolyte), producing electrons that flow to the cathode. Operating at 25–35°C without external energy input, MFCs have a theoretical efficiency above 50% and low greenhouse gas emissions. Their main drawback is extremely low power density (10–100 mW/m^2), which restricts them to small-scale applications like wastewater treatment pilot projects or remote environmental sensors.

3. Future outlook for low-temperature fuel cell technology

The future advancement of low-temperature fuel cell (LTFC) technology will revolve around targeted innovations to address current bottlenecks and unlock broader applicability. In catalyst development, efforts will focus on optimizing non-platinum-group metal (non-PGM) options—enhancing their active-site efficiency and durability to match platinum-based catalysts while improving resistance to long-term degradation. For membrane technology, research will prioritize next-generation materials that resolve key limitations: boosting CO_2 tolerance for alkaline fuel cells (AFCs) to prevent channel blockage, reducing fuel crossover in direct methanol fuel cells (DMFCs), and balancing proton conductivity with mechanical stability across varied operating conditions. System integration will see wider adoption of hybrid setups (LTFCs + batteries + supercapacitors) to mitigate transient response issues, smooth load fluctuations, and extend overall system lifespan.

Cost reduction will be critical for commercialization, driven by scaled production of non-PGM catalysts and alternative membranes to leverage economies of scale, plus optimized manufacturing processes (e.g., modular assembly) to cut overhead. Extending LTFC lifespan via improved material durability and predictive maintenance will further lower total ownership costs by reducing replacements and downtime.

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In applications, LTFCs will deepen penetration into high-impact sectors: powering long-haul trucks and maritime vessels to decarbonize heavy-duty transport (addressing battery electric vehicles' cold-climate limits) and integrating into data centers, microgrids, and off-grid systems for reliable stationary power. Policy support aligned with carbon neutrality goals will accelerate this shift, while cross-disciplinary collaboration (materials science, microbiology, systems engineering) may yield hybrid technologies—such as LTFCs paired with wastewater treatment—to generate clean energy while addressing environmental needs.

Collectively, these steps will position LTFCs as a versatile cornerstone of the energy transition, bridging renewable generation and end use to reduce fossil fuel reliance and emissions.

4. Conclusion

This study presents a systematic analysis of low-temperature fuel cells (LTFCs)—a pivotal sustainable energy technology operating below 300°C—highlighting their core function of converting chemical energy from fuels (e.g., hydrogen, methanol, ammonia) into electricity with high efficiency and minimal emissions. It delineates the primary LTFC subtypes, each tailored to distinct applications: proton exchange membrane fuel cells (PEMFCs) excel in fast-start scenarios like transportation, direct methanol fuel cells (DMFCs) are well-suited for portable electronics, and direct ammonia fuel cells (DAFCs) address longstanding hydrogen storage challenges. Alkaline fuel cells (AFCs) and microbial fuel cells (MFCs) further broaden LTFC applicability, with MFCs uniquely offering dual benefits of power generation and wastewater treatment.

Current advancements in LTFCs focus on material innovations catalysts, enhanced gas diffusion layers) and system optimization (e.g., fuel cell-battery hybrid configurations for maritime use). However, key bottlenecks remain: high costs driven by platinum dependence and expensive membrane materials, limited durability of cell components, and insufficient infrastructure for hydrogen and ammonia refueling.

To overcome these barriers, future LTFC development must prioritize three core areas: strengthening fundamental research to clarify the relationship between material structure and performance, promoting industry-academia-research collaboration to accelerate the translation of lab-scale breakthroughs to practical applications, and addressing the gap in comprehensive lifecycle assessments for LTFC materials and systems. These measures will enhance LTFCs' cost-competitiveness and sustainability, enabling them to drive decarbonization in hard-to-electrify sectors (e.g., heavy-duty transport, stationary power) and support global carbon neutrality goals.

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