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A Brief Review of Current Advancements in the Proton Exchange Membrane Fuel Cell

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A B S T R A C T

The high efficiency, quick startup time, and zero local emissions of proton exchange membrane fuel cells (PEMFCs) have made them a potential sustainable energy conversion technology. This review focusses on membrane electrolytes, catalyst layers, and bipolar plate advances while critically analysing the basic working principles, important material components, and recent developments in PEMFC design. As noted in current literature, performance optimisation techniques, durability enhancement, and cost-cutting measures are prioritised. Both stationary and transportation applications are examined in relation to the difficulties of water and temperature management, catalyst degradation, and system integration. To offer a forward-looking view of commercialisation prospects, trends in hybridisation, the incorporation of renewable hydrogen, and the recycling of essential materials are also examined. In order to achieve sustainable, widespread deployment of PEM fuel cell technology, this study summarises the most recent advancements, points out research gaps, and suggests future paths.

Keywords: PEM fuel cell, proton exchange membrane, hydrogen energy, catalyst degradation, water management, fuel cell durability, cleans energy.

1. Introduction

The Proton Exchange Membrane Fuel Cell (PEMFC) has become a viable option for clean power generation because of its low operating temperature, high energy efficiency, quick startup time, and almost negligible emissions of pollutants. In PEMFCs, hydrogen and oxygen undergo an electrochemical reaction that directly transforms their chemical energy into electrical energy, with the only waste being heat and water. A solid polymer electrolyte membrane that promotes proton transfer from the anode to the cathode while blocking electron crossover makes up the core of a PEMFC. Compact system design, high power density, and scalability are made possible by this special arrangement for a variety of applications, including fixed power systems, vehicle propulsion, and portable electronics. Notwithstanding these benefits, obstacles to PEMFC technology commercialisation include membrane durability, catalyst cost (particularly platinum), water management, and system integration.

2. Reviews on Proton Exchange Membrane Fuel Cell

[1] Tayfun Ozgur, Ali Cem Yakaryılmaz, et al (2018) examined a PEM fuel cell based CHP system to improve energy efficiency by raising the operating pressure. Along with higher operating pressure, a larger pressure differential between the anode and cathode electrodes improves system exergy efficiency. Electroosmotic drag is produced by the pressure differential between the two electrodes. As a result, a large pressure differential increases this drag and raises the system's energy efficiency. Better performance is correlated with increased exergy efficiency, which can also be attained by skilfully regulating the air stoichiometry between 2 and 4. Though it has been found that large increments might result in a loss in performance, increasing current density does improve exergy efficiency. This is because, mostly as a result of parasitic loads, the difference between the gross stack power and the net system power increases as current density increases. About 1.0 A/cm2 is the ideal number for optimising exergy efficiency.

[2] N. Matulic a, G. Radica a,*, F. Barbir a,S.Nizetic b et al (2019) examined into a simulation carried out on a realistic blend of urban and city road cycles is what makes this methodology novel. The main goal was to simulate a typical truck driving cycle in order to precisely predict fuel and emission reductions. A simplified model of the Proton Exchange Membrane Fuel Cell (PEMFC) was used because the early research was predicated on a continuous load demand for the fuel cell. In order to meet the needs of auxiliary consumers, the PEM fuel cell stack was designed. An expected daily driving time of eight hours was used to determine the hydrogen consumption and the hydrogen tank's dimensions. Finally, switching from internal combustion engines to auxiliary units in commercial vehicles showed the potential for up to 9% decrease in CO_2 emissions and fuel savings throughout the designated test cycle. Auxiliary loads, like cooling chambers in commercial vehicles, increase fuel consumption and, as a result, internal

combustion engine emissions of pollutants. A PEM fuel cell system was created especially for this use in order to reduce the additional pollution produced by these auxiliary loads. The cooling chamber requires a maximum additional power requirement of 5 kW, which the PEM fuel cell was designed to meet. Weight measurements: 32.5 kg, 65 35 21.2 cm, 8e12 A 40% @72 V, 24 V.

[3] Sara Luciani 1,2,* and Andrea Tonoli 1,2 et al (2022) in order to maximise the PEM fuel cell system's efficiency and reduce fuel consumption, the study explores a number of control algorithms targeted at maximising the power distribution between the battery and the fuel cell. First, the vehicle and fuel cell system models are described. The vehicle dynamics are represented using a forward modelling technique, while the PEM fuel cell is represented by a semi-empirical and quasi-static model. In order to maximise the fuel cell system's efficiency while preserving the battery's stable state of charge (SOC), an examination of several rule-based control schemes is then carried out. A forward method was used to model a passenger FCEV. A semi-empirical model was used to simulate the fuel cell system, accounting for the effects of different auxiliary systems as well as the system's water and temperature management features. Three different control systems were investigated in order to guarantee a suitable distribution of power and energy between the fuel cell and the battery. While the other two strategies used rule-based control techniques, the first strategy mandated a steady power output from the fuel cell. The results showed that in both high-load cycles (US06 and WLTP) and low-load cycles (FTP, NEDC, and UDDS). During low-load and high-load driving cycles, the most efficient control method reduced fuel consumption by 30% and 20%, respectively, compared to the baseline control strategy, resulting in a fuel cell system efficiency of 33% or higher.

[4] Attia A. El-Fergany et al (2018) proposes a groundbreaking application of a very modern heuristic-based technique, notably the Salp Swarm Optimizer (SSO), to identify the optimal values of unknown parameters in the PEMFC model. The goal function is the total square deviations (TSD) between the calculated and actual results. In order to ensure precise modelling, simulation, and control, the SSO-based approach was developed to determine the ideal values of the unknown parameters in PEMFCs. To demonstrate how well the SSO performs, two test cases have been run. When the ideal values of the unknown parameters are used, it is clear that there is a good correlation between the estimated and measured voltage points. The effectiveness and resilience of the suggested SSO-based process are confirmed by the parametric performance tests that were carried out. Compared to other approaches, the method shows fast convergence, produces respectable results, and involves less work to tune the SSO control settings. Additionally, it is proposed that the SSO might be a useful instrument for dealing with additional intricate engineering optimisation problems.

[5] L. Xing, Y. Wang, P.K. Das, K. Scott, W. Shi et al (2018) found that platinum loading and GDL porosity had a significant impact on performance, indicating that GDL porosity had a significant impact on the ideal platinum gradients. This is explained by the connections between the transit rate of species and the electrochemical reaction rate. Merely raising the platinum loading close to the exit does not improve cell performance or current density uniformity when both the initial platinum loading and GDL porosity are increased at the cathode intake. GDL porosity and graded platinum loading have both been studied using numerical and experimental techniques. The homogeneity of current density is strongly affected by their longitudinal distributions. This homogeneity is not enhanced by merely increasing platinum loading at the cathode exit. Consequently, it is essential to systematically engineer the gradients in GDL porosity and platinum loading.

[6] Abdelghani Harrag a,b,*, Sabir Messalti c et al (2017) The fuzzy logic approach is first used to automatically modify the Incremental Conductance (IC) Maximum Power Point Tracking (MPPT) controller's variable step size. The output power of the Proton Exchange Membrane (PEM) fuel cell system, which is composed of a 7kW fuel cell supplying power to a 50Ω resistive load via a DC-DC boost converter controlled by the proposed MPPT, is then monitored using the proposed variable step size fuzzy-based MPPT controller. This study introduces a fuzzy-based MPPT controller with variable step size to adjust the maximum power point on the Power-Voltage (P-V) curve. making certain that the load receives the best possible transfer of the maximum amount of electricity. A 7kW PEM fuel cell that supplies a 50Ω resistive load via a DC-DC boost converter operated by the proposed MPPT has been successfully used to analyse the effectiveness and performance of the suggested variable step size fuzzy-based MPPT controller.

[7] Gamze Karanfil (2019) investigates the main advantages of applying several Design of Experiments (DOE) and optimisation methodologies to the parts, design, operating conditions, and model parameters of PEM fuel cells. The Taguchi approach and Response Surface Methodology (RSM), which are frequently used in PEM fuel cell research, are first highlighted. A summary of the results is given, and further experimental design and optimisation methods pertinent to PEM fuel cells are investigated. By finding ideal conditions through fewer experimental trials in PEM fuel cells, DOE and optimisation techniques are successful in improving performance and lowering costs. To fine-tune PEM Fuel Cell (PEMFC) characteristics and circumstances, assess experimental results, and identify important parameters and conditions, a range of design and optimisation techniques are used. A review of the literature indicates that experimental studies employing DOE and optimisation techniques like Taguchi and RSM are significant improvements in their final performance over studies carried out with conventional techniques.

[8] Lingchao Xia a,d, Caizhi Zhang a,*, Minghui Hu a, Shangfeng Jiang b,**, Cheng Siong Chin a,c, Zuchang Gao d, Quan Liao e et al (2018) Here, the influence of three parameters on the performance of HT-PEMFC is explored by a 3D model in COMSOL. The operating temperature, membrane thickness, and catalyst layer thickness are the characteristics that are being taken into account. The effect on performance is assessed using polarisation curves. The results show that raising the temperature can enhance the fuel cell's efficiency. To evaluate the impact of these parameters on performance within COMSOL, a three-dimensional model of a high-temperature proton exchange membrane fuel cell based on its working principles and reaction mechanisms is utilised. The thickness of the proton exchange membrane, the catalyst layer, and the operating temperature are the three main factors that are determined. Polarisation curves and power density curves demonstrate how these characteristics affect cell performance. The findings show that the HT PEMFC's performance is positively impacted by the operating temperature.

[9] Alexey Loskutov 1 , Andrey Kurkin 2,*, Andrey Shalukho 1, Ivan Lipuzhin 1 1 andRustamBedretdinov1 et al (2022) examined a hybrid energy complex (HEC) that operates as a reliable energy source by utilising lithium iron phosphate batteries with PEMFCs. Accurately determining the

PEMFC's properties is crucial for the creation of a prototype HEC that utilises PEMFC technology and related control algorithms. A 1 kW PEMFC's test results in both steady and dynamic operating modes are presented in this study. The average hydrogen consumption per minute, the amount of hydrogen needed to produce one kWh, and the PEMFC's efficiency in proportion to load current were all found to be related. Subsequently, these correlations are examined during stable operational modes. It is advised to switch the power source for consumers to batteries under low load circumstances because the PEMFC's continuous operation inside the activation loss region was characterised by an inflated hydrogen consumption for electricity generation and a low efficiency of not reaching 25%. In contrast, the PEMFC's performance in the concentration loss region was only around 35% efficient; thus, it is recommended to use the PEMFC and batteries together to increase the PEMFC's and the HEC's overall efficiency at high load currents.

[10] Yonghua Caia,b,c, Zhou Fanga,b,c, Ben Chena,b,c,*, Tianqi Yanga,b,c, Zhengkai Tud, * et al (2018) a PEMFC's (proton exchange membrane fuel cell) performance is greatly influenced by the flow field, and channel design is the focus of many research projects. In addition to proposing evaluation criteria to direct flow field design, this work presents a novel 3D cathode flow field including main and sub-channels as well as transition areas. The results show that the effective mass transfer coefficient and the performance assessment criterion can be used to evaluate a PEMFC's performance. Furthermore, a PEMFC's performance can be assessed using the new assessment criteria. The performance of a PEMFC could be improved using a novel 3D cathode flow field. Additionally, porous ribs help to enhance the performance of the 3D cathode flow field.

3. CONCLUSION

Recent developments in the study of proton exchange membrane fuel cells (PEMFCs) demonstrate the variety of strategies used to enhance performance, efficiency, and suitability for stationary, mobile, and hybrid systems. While high current densities can reduce net output because of parasitic loads, operating conditions like high pressure differentials and ideal air stoichiometry have been demonstrated to greatly increase exergy efficiency. While the best power management techniques between fuel cells and batteries in FCEVs result in significant fuel savings throughout a range of driving cycles, PEMFC integration for auxiliary power in commercial vehicles offers observable reductions in fuel consumption and CO_2 emissions in transportation applications. With heuristic algorithms like the Salp Swarm Optimiser (SSO) providing accurate PEMFC modelling and control through quick convergence and little parameter tuning, parameter optimisation is still crucial. Studies at the material level demonstrate how platinum loading and gas diffusion layer (GDL) porosity are interdependent, highlighting the necessity of methodical gradient design to guarantee consistent current density. In terms of control, variable step size MPPT controllers based on fuzzy logic improve maximum power extraction under dynamic load circumstances. Design of Experiments (DOE) and optimization techniques, such as Taguchi and Response Surface Methodology, enable performance enhancement with reduced experimental trials, while computational modeling has identified key operational factors—membrane thickness, catalyst layer thickness, and temperature—that positively influence high-temperature PEMFC performance. When properly maintained, hybrid energy complexes that combine PEMFCs with lithium iron phosphate batteries exhibit increased efficiency under a range of loads. Last but not least, novel 3D cathode flow field designs that include porous ribs and main-sub-channel transitions provide significant improvements in mass transfer and overall performance. Together, these studies demonstrate that PEMFC efficiency, durability, and practicality can be greatly increased through integrated optimisation, which spans system design, materials engineering, operational strategies, and intelligent control. This opens the door for wider adoption in the stationary energy and transportation sectors.

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