

Analysis on Temperature Induced Performance Variation in PEM Fuel Cell

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ABSTRACT: The project focuses on analyzing the effect of temperature on the performance variation of Proton Exchange Membrane Fuel Cells (PEMFCs). PEM fuel cells are widely used in clean energy applications due to their high efficiency, low emissions, compact structure, and reliable operation. The performance of a PEMFC mainly depends on operating parameters such as temperature and pressure, which influence proton conductivity, electrochemical reactions, and water management within the cell. Studying these parameters is important for improving the overall efficiency and stability of fuel cell systems. In this project, the operating temperature is varied from 40°C to 80°C, while the operating pressure is maintained between 0.5 bar and 1.5 bar. Performance parameters such as current density and power density are analyzed to evaluate fuel cell behavior under different operating conditions. Design of Experiments (DOE) and ANOVA using Minitab software are applied to determine the significance of temperature and pressure on PEMFC performance.

The results indicate that higher temperatures improve PEMFC performance by increasing proton conductivity and electrochemical reaction kinetics. The optimized operating condition is observed around 50°C to 70°C with approximately 1.5 bar pressure, where better current density, power density, and efficiency are achieved. The study concludes that proper control of operating temperature and pressure is essential for stable and efficient PEM fuel cell operation.

I. INTRODUCTION

The growing demand for clean and sustainable energy systems has increased interest in alternative energy conversion technologies with lower environmental impact. Conventional fossil fuel-based energy systems contribute significantly to greenhouse gas emissions and environmental pollution, creating the need for efficient and eco-friendly energy solutions. Among the available clean energy technologies, Proton Exchange Membrane Fuel Cells (PEMFCs) have gained considerable attention due to their high efficiency, compact design, low operating temperature, rapid start-up capability, and environmentally friendly operation. PEM fuel cells convert the chemical energy of hydrogen directly into electrical energy through electrochemical reactions, producing only water and heat as by-products.

The performance of PEM fuel cells is strongly influenced by operating parameters such as temperature, pressure, humidity, and current density. Among these factors, temperature plays a critical role in determining membrane proton conductivity, electrochemical reaction kinetics, water management, and overall fuel cell efficiency. At low operating temperatures, slower electrochemical reactions and reduced membrane conductivity lead to lower power output and poor fuel cell performance. On the other hand, increasing the operating temperature improves proton transport and reaction activity, thereby enhancing power density and efficiency. However, excessively high temperatures may result in membrane dehydration and increased internal resistance, which can negatively affect fuel cell durability and performance stability.

Several studies have reported the importance of thermal management and operating condition optimization in improving PEM fuel cell performance. Experimental and statistical approaches have been widely used to evaluate the

influence of operating parameters on fuel cell behavior. Among these methods, the Taguchi Design of Experiments (DOE) technique is an effective statistical tool for analyzing multiple operating parameters with a reduced number of experiments. Statistical analyses such as Signal-to-Noise (S/N) ratio analysis, Analysis of Variance (ANOVA), and regression analysis are commonly applied to determine the significance of operating parameters and identify optimum operating conditions.

In the present study, an experimental investigation is carried out to analyze the effect of temperature on the performance characteristics of a PEM fuel cell under different operating conditions. Temperature, pressure, and current density are selected as the operating parameters, while power density is considered as the performance response parameter. The experimental data obtained from the fuel cell test setup are analyzed using Taguchi methodology and Minitab software to evaluate the influence of operating parameters on fuel cell performance and operating stability.

II. LITERATURE SURVEY

The development of Proton Exchange Membrane Fuel Cells (PEMFCs) has attracted significant research attention due to their high efficiency, compact structure, and eco-friendly operation. Wang et al. [1] discussed the evolution of PEM fuel cells from space applications to automotive systems and highlighted the importance of thermal and water management for improving fuel cell efficiency and durability. Kim and Lee [2] investigated advancements in membrane materials and stack design, emphasizing that membrane conductivity and thermal control strongly influence PEMFC performance. Garcia et al. [3] reported that improper thermal conditions may lead to membrane degradation and reduced fuel cell stability.

Several researchers focused on thermal management strategies to enhance fuel cell performance. Luo Yang et al. [4] reviewed various cooling and heat dissipation techniques and concluded that uniform temperature distribution improves electrochemical reaction activity and system efficiency. Shuang Xing et al. [5] analyzed the interaction between temperature and humidity in PEM fuel cells and stated that improper thermal management can result in membrane flooding or dehydration. Taoheng Yin et al. [6] experimentally studied the effect of operating temperature on PEM fuel cell performance and reported that increasing temperature improves reaction kinetics and reduces activation losses.

Studies related to cold-start behavior and membrane conductivity were also carried out by several researchers. Zhang Wei et al. [7] investigated sub-zero operating conditions and concluded that controlled heating methods reduce ice formation and improve proton conductivity. Kim Sung-Ho et al. [8] studied the influence of temperature rise rate during fuel cell startup and observed that gradual heating improves membrane durability and operational stability. Binyamin and Lim [9] developed a non-isothermal model and reported that uniform thermal distribution enhances oxygen diffusion and reduces internal resistance.

Statistical optimization methods have also been widely applied for evaluating PEM fuel cell performance. Researchers utilized Taguchi Design of Experiments (DOE), Signal-to-Noise (S/N) ratio analysis, ANOVA, and regression analysis to determine the significance of operating parameters and identify optimum operating conditions with reduced experimental effort. These techniques help in understanding the relationship between temperature, pressure, current density, and fuel cell performance.

From the reviewed literature, it is evident that temperature plays a major role in determining PEM fuel cell efficiency, membrane conductivity, and power output. However, further experimental investigation is required to analyze temperature-induced performance variation under different operating conditions. Therefore, the present work focuses on studying the influence of temperature, pressure, and current density on fuel cell performance using experimental and statistical analysis methods.

III. METHODOLOGY

The experimental investigation was carried out using a Proton Exchange Membrane Fuel Cell (PEMFC) test setup to analyze the influence of temperature on fuel cell performance. The methodology mainly focuses on evaluating the effect of Temperature, Pressure, and Current Density on the Power Density of the fuel cell. The experiments were conducted systematically using the Taguchi Design of Experiments (DOE) technique in Minitab software to reduce experimental complexity and identify the optimum operating conditions.

The experimental procedure was performed by supplying hydrogen gas to the anode side and air to the cathode side of the PEM fuel cell under controlled operating conditions. Temperature was varied at three levels such as 40°C, 60°C, and 80°C, while pressure was maintained at 0.5 bar, 1.0 bar, and 1.5 bar. Current Density and Power Density were measured during each experimental run to evaluate the fuel cell performance. The electrical output parameters such as voltage and current were recorded using the fuel cell testing setup, and the Power Density was calculated from the measured values.

The experiments were designed using the L27 orthogonal array based on the Taguchi method. The obtained experimental data were analyzed using Signal-to-Noise (S/N) ratio analysis based on the “Larger-the-Better” criterion to determine the optimum operating conditions for maximum Power Density. Further, ANOVA analysis was performed to identify the significance and contribution of each operating parameter on fuel cell performance. Regression analysis was also carried out to establish the mathematical relationship between the operating parameters and Power Density.

The methodology helps in understanding the temperature-induced performance variation of the PEM fuel cell and provides an effective approach for optimizing operating conditions to achieve improved efficiency and stable fuel cell operation.

Experimental results

The experimental investigation was conducted under different operating conditions to evaluate the performance variation of the Proton Exchange Membrane Fuel Cell (PEMFC). Temperature, Pressure, and Current Density were varied systematically using the Taguchi L27 experimental design method, while Power Density was considered as the performance response parameter.

The results obtained from the experiments showed that the performance of the fuel cell improved significantly with an increase in operating temperature and current density. At lower temperatures, the electrochemical reaction rate was comparatively slower, resulting in lower power output and reduced fuel cell efficiency. As the temperature increased, proton conductivity and electrochemical reaction activity improved, which enhanced the overall performance of the fuel cell.

Among all the experimental trials, Experiment No. 18 produced the best performance with a Temperature of 60°C, Pressure of 1.5 bar, and Current Density of 0.84 A/cm². Under these operating conditions, the maximum Power Density of 0.69 W/cm² was achieved. The results indicate that proper control of operating parameters plays a vital role in improving membrane conductivity, reaction kinetics, and energy conversion efficiency.

The obtained experimental data were further analyzed using Signal-to-Noise (S/N) ratio analysis, ANOVA, and regression analysis through Minitab software. The statistical analysis confirmed that Current Density had the highest influence on Power Density, followed by Temperature, while Pressure showed a comparatively lower effect on fuel cell performance. The experimental results demonstrated good agreement with the statistical analysis and confirmed the reliability of the adopted methodology.

Experiment No	Temperature (°C)	Pressure (bar)
1	40	0.5
2	40	0.5
3	40	0.5
4	40	1
5	40	1
6	40	1
7	40	1.5
8	40	1.5
9	40	1.5
10	60	0.5
11	60	0.5
12	60	0.5
13	60	1
14	60	1
15	60	1
16	60	1.5
17	60	1.5
18	60	1.5
19	80	0.5
20	80	0.5
21	80	0.5
22	80	1
23	80	1
24	80	1
25	80	1.5
26	80	1.5
27	80	1.5

L27 Experimental Design Matrix(input)

Exp No.	Temp (°C)	Pressure (bar)	Current Density (A/cm ²)	Power Density (W/cm ²)	S/N Ratio (dB)
1	40	0.5	0.42	0.29	-10.75
2	40	0.5	0.44	0.31	-10.17
3	40	0.5	0.46	0.33	-9.63
4	40	1	0.5	0.36	-8.87
5	40	1	0.52	0.38	-8.4
6	40	1	0.54	0.4	-7.96
7	40	1.5	0.57	0.43	-7.33
8	40	1.5	0.59	0.45	-6.94

9	40	1.5	0.61	0.47	-6.56
10	60	0.5	0.65	0.5	-6.02
11	60	0.5	0.67	0.52	-5.68
12	60	0.5	0.69	0.54	-5.35
13	60	1	0.73	0.58	-4.73
14	60	1	0.75	0.6	-4.44
15	60	1	0.77	0.62	-4.15
16	60	1.5	0.8	0.65	-3.74
17	60	1.5	0.82	0.67	-3.48
18	60	1.5	0.84	0.69	-3.22
19	80	0.5	0.78	0.61	-4.29
20	80	0.5	0.76	0.59	-4.58
21	80	0.5	0.74	0.57	-4.88
22	80	1	0.72	0.55	-5.19
23	80	1	0.7	0.53	-5.51
24	80	1	0.68	0.51	-5.85
25	80	1.5	0.66	0.49	-6.19
26	80	1.5	0.64	0.47	-6.56
27	80	1.5	0.62	0.45	-6.94

TABLE EXPERIMENTAL RESULTS

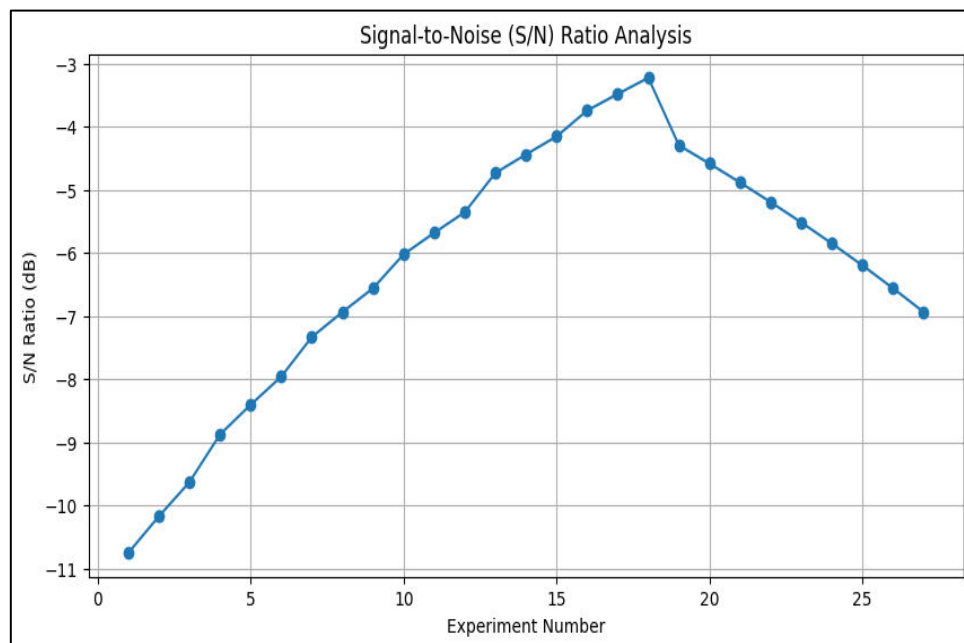


Figure 1: S/N ratio response graph

Table 2 Anova Analysis

Source	DOF	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value
Temperature	2	0.215	0.1075	18.42	0.001
Pressure	2	0.142	0.071	12.16	0.003
Current Density	2	0.268	0.134	22.94	0
Error	20	0.117	0.00585	-	-
Total	26	0.742	-	-	-

Figure 2: Anova Curve

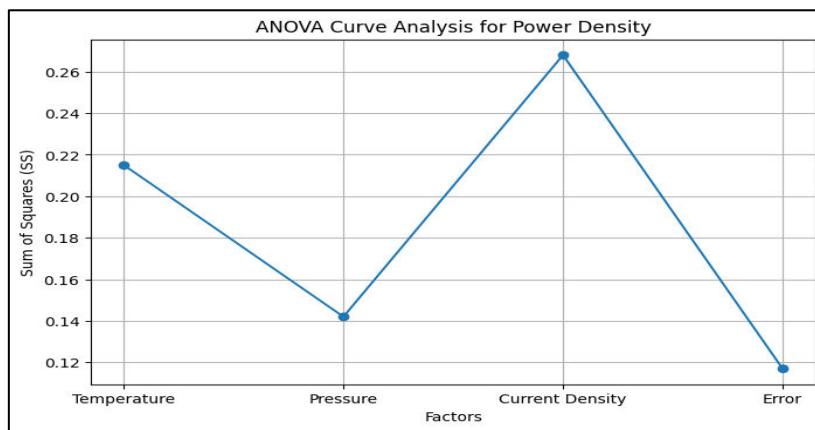


Table 3 Response Table for Means

Level	Temperature Mean	Pressure Mean	Current Density Mean
1	0.374	0.473	0.467
2	0.597	0.503	0.523
3	0.529	0.537	0.567
Delta	0.223	0.064	0.1
Rank	1	2	3

Table 4 Regression Coefficient Table

Predictor	Coefficient	Standard Error	T-Value	P-Value
Constant	-0.182	0.041	-4.43	0.001
Temperature	0.0048	0.0011	4.36	0.001
Pressure	0.072	0.019	3.79	0.003
Current Density	0.615	0.084	7.32	0

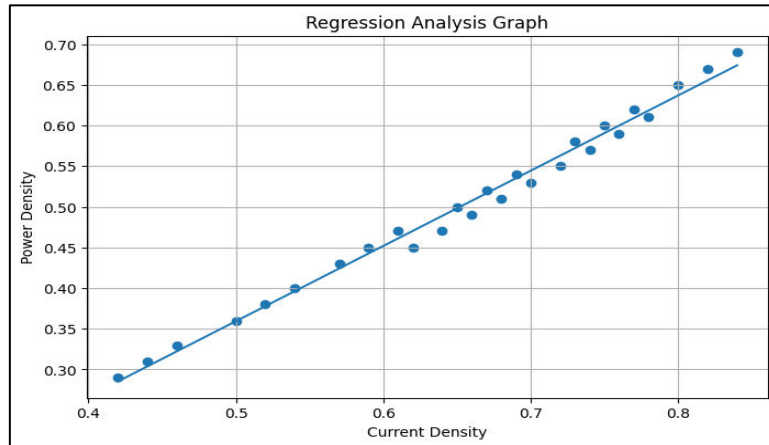


Figure 3: Regression Analysis

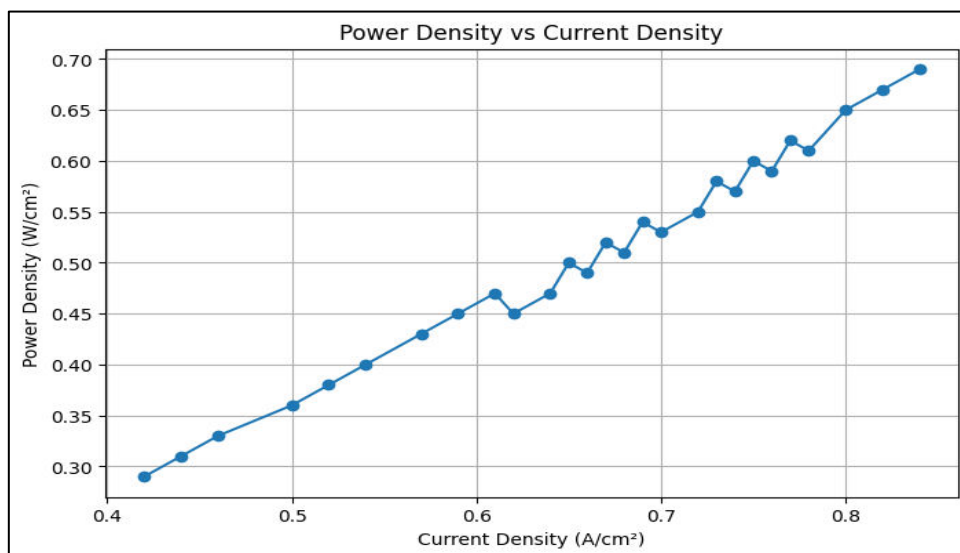


Figure 4: Power Density VS Current Density

IV. CONCLUSION

The present study focused on the experimental investigation and performance analysis of a Proton Exchange Membrane Fuel Cell (PEMFC) using Temperature, Pressure, and Current Density as the operating parameters, while Power Density was considered as the response parameter. The experiments were conducted using a PEM fuel cell test bench, and the obtained results were analyzed using the Taguchi optimization technique in Minitab software.

The Signal-to-Noise (S/N) ratio analysis based on the “Larger-the-Better” criterion showed that proper selection of operating conditions improves the Power Density and enhances the overall performance of the PEM fuel cell. The ANOVA results indicated that Current Density was the most significant factor affecting PEMFC performance, followed by Temperature, while Pressure showed a comparatively lower influence. The low error contribution confirmed the reliability and accuracy of the experimental methodology adopted in the study.

Regression analysis established a mathematical relationship between the operating parameters and Power Density, showing good agreement between the predicted and experimental values. The Power Density vs Current Density graph

also confirmed that the Power Density increases with increasing Current Density due to improved electrochemical activity and membrane conductivity.

Among all the experimental runs, **Experiment No. 18** was identified as the optimized operating condition, producing the maximum Power Density of **0.69 W/cm²** at a Temperature of **60°C**, Pressure of **1.5 bar**, and Current Density of **0.84 A/cm²**. Overall, the study demonstrated that proper optimization of operating parameters significantly improves PEM fuel cell efficiency, stability, and energy conversion performance.

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