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Original Article

Enhancement of Proton Exchange Membrane Fuel Cell (PEMFC) Design Parameters and Diagnostics Using Taguchi Method

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Abstract *- In this paper, we focus mainly on the designs and operational characteristics of the Fuel Cell (FC), including its temperature, pressure, stoichiometric flows at the anode and cathode, and humidification temperature at the anode and cathode, and its output responses, including voltage, current, and electric power. In addition to discussing design optimization and materials development for the proton exchange membrane, electrolyte, anode and cathode catalysts, testing, and analysis of a single PEM fuel cell, the author focused on diagnostics that increased PEM fuel cell performance. Furthermore, this study introduces the Taguchi design optimization method. The Nafion 212 cs membrane with an active area of 32 cm2 and a Membrane Electrode Assembly (MEA) were used for this study. A PEM fuel cell was analyzed and tested at the Advanced Materials Research Laboratory, Rashtrasant Tukdoji Maharaj Nagpur University. Electrical power output, voltage, and current were monitored.*

Keywords *- PEMFC design, Taguchi Voltage, Current, Power.*

1. Introduction

Figure 1 shows the excellent efficiency, small size, and large capacity of PEM fuel cells. They use a rigid polymer as the electrolyte and porous carbon electrodes catalyzed with platinum or platinum alloy catalysts. All they need to run on is water, hydrogen, and oxygen from the air. Fuels are usually pure hydrogen coming from storage tanks or converters. They have quicker start-up times, and longer life spans because they operate at far lower temperatures. However, a platinum catalyst is needed to distinguish between the protons and electrons in hydrogen, raising the device's price. PEM FCs are mostly found in stationary and portable uses, especially in automobiles, buses, and tractor-trailers. They can also be employed to generate power, both fixed and transportable. [1]. The polymer electrolyte membrane (PEM), a treated material similar to kitchen plastic wrap, is vital in FC methods as it only permits positive ions to pass among the anode and cathode, preventing disruptions caused by other substances.

1.1. Reversible Fuel Cells

Reversible FCs use hydrogen and oxygen to produce power; as impurities, they also produce water and heat. They can also use electrolysis to split water into hydrogen and oxygen using power derived from solar energy or wind power. These FCs have the capability to supply energy on demand but simultaneously store excess energy in the form of hydrogen during periods of peak power production that may, as a matter of fact, make intermittent RE plants practical as well [2].

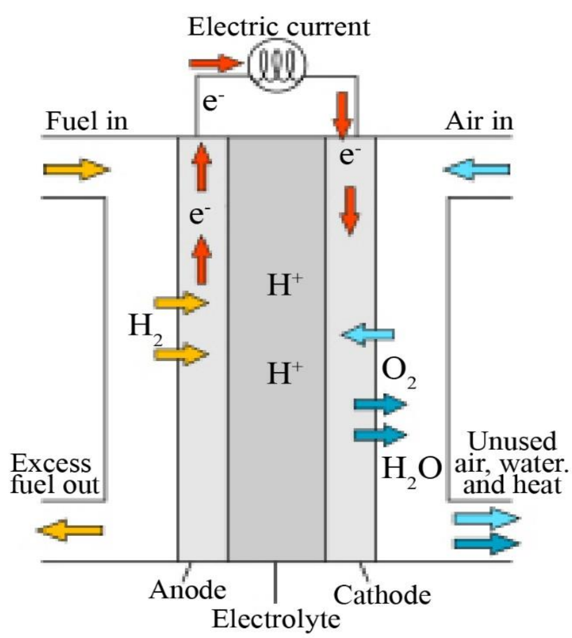

Fig. 1 PEM fuel cell

1.2. Applications of Fuel Cell

There are several uses for the FCs technique. A wide quantity of investigation has been underway to harvest an FC-powered automobile that is reasonable.

- Compared to cars with gasoline or diesel engines, FC electric automobiles, or FCEVs, are considered more beneficial to the atmosphere because they run on renewable fuels.
- They have been the energy source for numerous space missions, such as the Appolo satellite mission.
- Both water and heat are characteristically the harvests that these cells produce.
- Certain FCs are quite reasonable in the armed forces because of their versatility.
- Many electrical gadgets can also be driven by these electrochemical batteries.
- FCs are additionally applied in many remote spaces as main or prime power supplies [3, 4].

1.2.1. Parts of a Fuel Cell

The electrochemical reaction that turns fuel into energy is facilitated by the cooperation of multiple parts in a fuel cell. One fuel cell's primary components are as follows:

1.3. Electrodes (Anode, Cathode)

- Anode: In a Hydrogen fuel cell, the electrode is a place where hydrogen molecules are oxidized and split into protons and electrons.
- Cathode: The cathodic reaction occurring at the cathode electrode is actually the result of protons and electrons from the anode working with airborne oxygen molecules to create water [5].

1.4. Electrolyte

The electrolyte is a material that facilitates ion movement between the anode and cathode, preventing fuel and oxidizer mixing. Different types of electrolytes, such as PEM and solid oxide electrolytes, are utilized in fuel cell technologies [6].

1.5. Catalyst Layers

Hydrogen molecules can have their protons and electrons separated from them by placing a platinum catalyst layer on both sides of a membrane. The platinum catalyst is a mixed ionomer applied to a portion of the carbon substrate, all encapsulated by the membrane and GDLs. Protons can pass between layers due to the ionomer, facilitating effective water synthesis and hydrogen reduction. This conventional compound coat shows a serious role in generating effective hydrogen [7].

1.6. Gas Diffusion Layers (GDL)

GDLs are exterior layers of catalysts that help move reactants and remove water from products. They are made of polytetrafluoroethylene (PTFE)-coated paper with carbon that has holes that permit gasses to spread quickly. Because PTFE keeps these small pores open, too much water cannot accumulate. The interior of the GDL is commonly coated with a microporous layer, which is made up of a tiny quantity of PTFE and high-surface-area carbon. This layer ensures membrane conductance, balances retained water and discharge, and permits hydrogen and oxygen flow into electrodes. [8].

1.7. Bipolar Plates

To create a usable voltage source, many MEAs are joined in parallel by piling them over each other. Two bipolar plates that provide the stack with both structural integrity and potential for electricity are positioned across every single cell. A "flow field" of channels is usually present on the plates to allow gasses to pass through the MEA; extra channels can be employed to move coolants around. Usually composed of carbon, metal, or blended substances, such as plates [9].

1.8. Gaskets

Each MEA in an FC stack is positioned among bipolar plates, but gaskets—usually made of elastic polymers—are placed across the periphery to provide a leak-proof sealing [10].

1.9. Stack

A Fuel Cell stack is a system made up of several cells linked in either sequence or parallel format to boost the generation of electricity. Each cell's voltage contributes to the device's overall electricity output [11].

1.10. Balance of Plant (BOP)

According to the particular FC design and utilization, the balance of the plant consists of necessary parts in accumulation to the core FC stack, such as motors, air conditioners, coolers, and other supplementary parts [12].

1.11. Gas Supply and Distribution

Fuel and oxidant supply and allocation systems for the anode and cathode, respectively [13].

1.12. Fuel Cell Systems

FC systems can have quite different and intricate designs depending on the FC type and usage. Yet, many FC structures share a few important fragments,

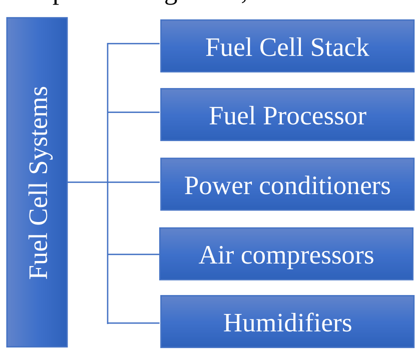

Fig. 2 Fuel cell systems

1.13. FC Stack

The core component of an FC power structure is the FC stack, which uses chemical processes to produce Direct Current (DC). A maximum of 1 V is produced by just one FC, which is inadequate for many applications. Single FCs are linked in sequence to create FC stacks, which might have many FCs to optimize energy. FC output is contingent upon various elements, including dimensions, operational temperature, and air pressure.

Fig. 3 Fuel cell stack

1.13.1. Fuel Cell Stack Size

The initial stage in FC stack manufacturing involves determining power requirements, which are then calculated to encounter these necessities, often involving known Full power, voltage, and electricity. The energy outcome of an Energy and stack voltage combine to form the FC stack.

$$w_{FC} = V_{st}.I$$

Designers need to be aware of the application-specific power levels and current specifications for an FC stack to design the right stack. Determined from the generated electricity, stack electricity, productivity, quantity, and mass constraints, electricity and power efficiency are critical.

$$I = i * a_{cell}$$

The separation curve connects the current concentration with the cell potential.

$$v_{cell} = f(i)$$

Figure 4 depicts a polarization curve illustration. The FC stack can be originally designed with the inclusion of the polarization curve.

With the optimum combination of plant, electronics, operating conditions, and other variables, FC system designers can construct systems at an output of 0.8 V per cell or higher. Usually, they work in the range between 0.6 and 0.7 V at nominal power. The main performance measures used for efficiency are temperature, pressure, and humidity-all those that could be increased while the other variables are optimized. However, depending on the application, the capability to improve these factors is constrained by system considerations, size, and costs [14].

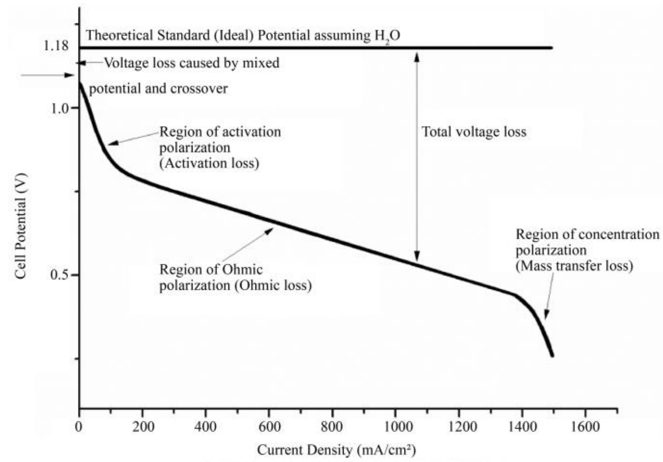

Fig. 4 Typical PEM fuel cell stack polarization curve

1.13.2. Number of Cells

To compute the general stack voltage, multiply the mean cell power by the quantity of cells in the load or the total stack energy.

$$V_{st} = \sum_{i=1}^{N_{cell}} V_i = \bar{V}_{cell} * N_{cell}$$

The plan of fuel cell stacks encompasses designing the cell area to achieve the required current and maximum power requirement. Fuel cell stacks can be constructed analogously to enhance yield current; however, most stacks are connected in series. Avoid using cells with massive or tiny activity regions to maintain consistent temp, humidity, and water management while preventing resistant inefficiencies. The operational characteristics at maximum energy consumption are the cell voltage and current intensity; stack dimension and productivity can be strongly impacted by the mean voltage and matching current density. Improved efficiency is the result of higher cell voltage, which may be attained by optimizing chemical flows, overall temperature, heat, humidity, pressure, and flow channel structure using MEA components. The following equation can be used to estimate the FC stack productivity:

$$\eta_{stack} = \frac{V_{cell}}{1.482}$$

1.13.3. Stack Configuration

In the typical bipolar stack structure, bipolar plates with power lines, end plates, Membrane Electrode Assemblies (MEAs), and gaskets connect many fuel cell stacks. To ensure effective and dependable energy production, the stack is fastened collectively utilizing bolts, rods, or different methods that lock the cells collectively. The most important idea is to consider the following when designing the appropriate fuel cell:

- It is important to consistently spread fuel and oxidants throughout every cell's outer region.
- The stack as a whole has to be the same degree.
- The membrane of an FC made with a polymer electrolyte cannot be washed out or filled with water.
- Restrictions on impedance inefficiencies ought to be avoided.
- To guarantee no gas spill, the stack needs to be adequately covered.
- The stack needs to be resilient and strong to the required circumstances.

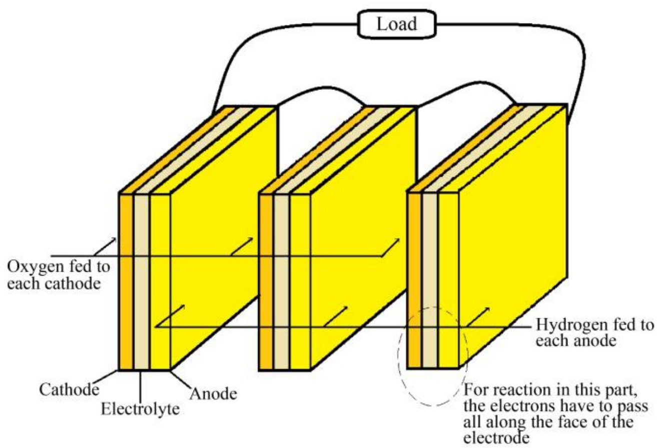

Fig. 5 Fuel cells connected in series (fuel cell stack)

Vertical or bipolar plate stacking is the standard method of connecting fuel cells, as seen in Figure 5. The bipolar plate gets its name from the fact that it acts as both the cathode and the anode in consecutive cells. Bipolar stacking bears a resemblance to the process of stacking batteries in a flashlight. Because of its comparatively high electrical contact surface, bipolar stacks benefit from simple electric connections between their cells and very low ohmic loss. Robust fuel cell stacks are produced by the bipolar plate architecture.

Sealing a bipolar arrangement can be challenging. Think about the fuel cell assembly seen in the illustration in Figure 5. The edge gaskets enclose each cell in a gastight seal when compressed. This stack will undoubtedly leak if edge seals are not added to each cell. As far as we are aware, fuel cells normally only have an electrical efficiency of between 30 and 60% and an operating power density. The fuel cell stack's exhaust gases and residual energy can be used as heat. This energy cannot be transformed into electricity. The fuel cell stack may overheat if the rate at which heat is generated is too great. Thermal gradients can be avoided, and the stack can function within its ideal temperature range with cooling help. One of the key elements affecting the overall effectiveness of a fuel cell system is the reusing of heat internally within the system. The heat generated by fuel cell systems should be recovered and utilised for warming purposes outside of the system. This can eliminate the need for fuel in other devices that generate heat.

Expertise in solar system installation is needed to be profitable in comparison to traditional power generation on a large scale. Introducing solar energy technology for electricity generation was a big worry because of the significant unpredictability of weather patterns and power generation. An assessment of hydrogen fuel cell technology's applications in the areas of transportation, industry, heat, and electricity generation was given by Iain Staffell et al. In this cutthroat environment, there are still obstacles to overcome in terms of cost, performance, and significant advancements before hydrogen can be considered a clean energy source. [15]. S. A. Sherif and colleagues studied the technologies for producing, storing, and deploying hydrogen. The several processes for generating hydrogen, such as electrolysis, thermolysis, photolysis, thermochemical cycles, and generation from biomass, were all covered in this paper [16]. Daniel Real et al. gave a study on renewable energy sources up to non-concentrating solar collectors for hydrogen generation using a solar-powered methanol-reforming process [17]. Anand Singh et al. suggested a study for an integrated hydrogen fuel cell system academic research building in India. The hydrogen fuel-powered fuel cell and the electrolysis procedure for producing hydrogen were completed. The author believed that the greatest choice for producing power in a sustainable manner would be renewable hybrid energy systems. The hybrid system's economic viability and feasibility analysis were presented [18]. Quan Zhuang et al. used natural gas decarbonization to investigate the modeling of an integrated power cycle system that includes HFC and CFC. Nonetheless, the author disclosed that the current advancement in CFCs is restricted because there aren't many examples. The CFC needs further research and development. The development of carbon fuel cells will accelerate by utilizing pure carbon from the natural gas decarbonization feed. Applying HFC advancements to CFC will solve a few chemical, mechanical, and engineering problems [19]. The design of a single PEM fuel cell assembly includes a two-dimensional view, as shown in Figure 6, an exploded view (Figure 7), and a Schematic 3 D View of the PEM Fuel Cell (Figure 8)

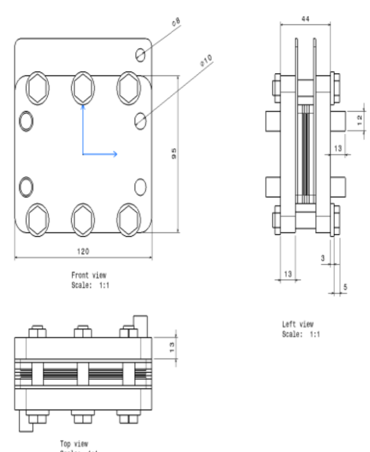

Fig. 6 2D View of PEM fuel cell (front view, top view and side view)

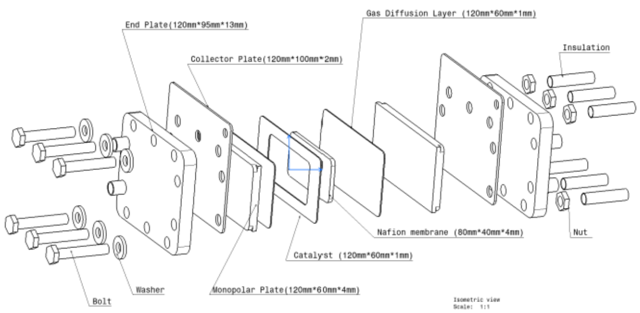

Fig. 7 Exploded view

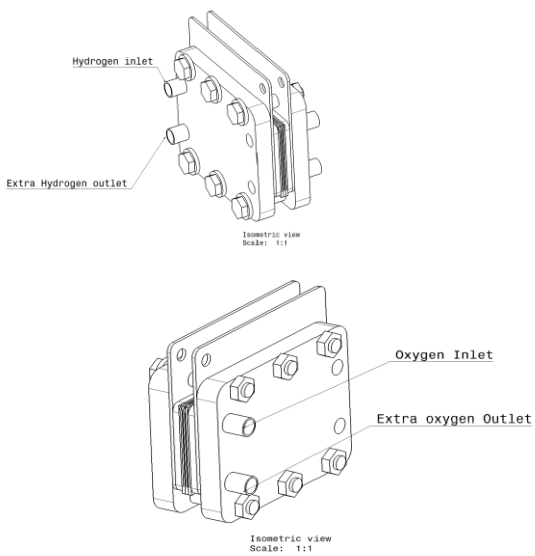

Fig. 8 Schematic 3D views

2. Testing of PEM Fuel Cell Using Test Station

The fuel cell investigation station for testing the sole PEM fuel cell assembly, as shown in Figure 9, was used for the experimentation. As exemplified in Figure 9, the test system of the experimental apparatus consists of an electronic load system, a humidifying system, a temperature control system, a flow rate control system, and a gas supply system. Reactant gases enter the humidifiers through the channels under the supervision of the mass flow controller. As the reactant gas arrives energy cell, saturated vapor begins to react with it; a temperature controller controls the operating temperature of the fuel cell, and a back pressure regulator adjusts the back pressure. An electronic load bank attached to the fuel cell regulates and modifies its output voltage and current.

Software is used in this experiment to control the gas mass flow rates. Furthermore, the computer automatically creates, stores, and records the Tafel and long-term test data in addition to the voltage, current, and power data recorded over time.

The experiment is carried out using the following procedure:

- Switch on the computer and modify the gas discharge pressures of the nitrogen, oxygen, and hydrogen cylinders.
- Turn on the test and verify that there is enough water in the humidifiers.
- To ensure that any lingering hydrogen and oxygen are removed from the fuel cell.
- Fire up the apparatus for testing fuel cells.
- The fuel cell polarization data configuration should have an active surface area, fuel cell number, reactant gas flow rates, maximum, minimum, voltage increment step, and the time interval between each consecutive pair of voltage versus current data points.
- Lastly, the fuel cell's reactant gases are given. Modify the back pressure, humidification temperature, and fuel cell temperature.
- Launch the computer program that will manage and gather data for the experiments automatically. Turn off the unit after testing and repeat the 15–20-minute nitrogen purge. Utilize the postprocess software to get the experimental results.

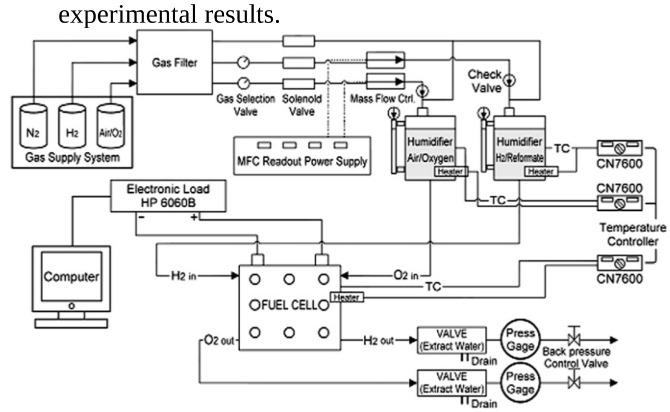

Fig. 9 Schematic view of fuel cell test station for testing of PEM fuel cell [20] (source: Wu 2009)

3. Research Methodology

To create an experiment using the Taguchi method, start with the orthogonal array. Initially, determine the total number of degrees of freedom required for all pertinent control variables and interference. The smallest array that satisfies the minimum number of degrees of freedom needed is chosen. Six three-level control factors are taken into account in this study. However, the impact of interaction between the components is not considered. For the six control factors, there are, therefore, twelve degrees of freedom. The DOF should be greater than or equal to the control factors. The L18(21_37) and L27(3 13) are the accessible three-level arrays. Since the L27(3 13), which has thirteen columns, has a higher resolution than the L18(21_37), which has eight columns, the L27(31 3) is used in this investigation. The orthogonal arrays produced from Latin squares are represented by the letter L. The variables a, b, and c in the La (b c) represent the number of trials (rows), levels, and factors (columns) in the array, respectively. Each factor combination experimental trial consists of four runs, denoted as y1, y2, y3, and y4. 108 measurement data points in total are analyzed.

Table 1. Design optimization parameters [20]

Factors	Lev 1	Lev 2	Lev 3
Operating Pressure (bar)	01	02	03
Operating Temperature (^{0}C)	50	65	80
Anode-Humidification Temperature (^{0}C)	50	70	85
Cathode-Humidification Temp (^{0}C)	50	70	85
Stoichiometric Flow Hydrogen	01	02	03
Stoichiometric Ratio Oxygen	01	02	03

Source: Wu 2009 [20]

Taguchi developed a technique for transforming repetitive data into a new value that indicates the variance at that time. The transformed SNR is utilized to indicate the superiority index. The most common quality characteristics can be classified into three categories: There are three categories of best: nominal, smaller, and larger. [20]. This study's larger-than-best feature, the fuel cell's highest electrical power, is the quality characteristic.

4. Results and Discussion

The SNRs for each trial's maximum electrical power are listed in Table 2. The orthogonal experimental design allows for separating the things of each mechanism component on the signal-to-noise at diverse levels. Table 3 shows the model summary. In addition, Figure 10 presents the slip bars of the independent features at various levels, along with the SNR response graph from Table 3.

Table 2. SN ratios coefficient

Item	Coeff.	SE Coefficient	T-Factor	P-Factor
Constant	17.7746	0.07663	231.942	0.000
Operating 50	-1.2875	0.10838	-11.880	0.000
Operating 65	0.2321	0.10838	2.141	0.050
Operating 1	-0.9359	0.10838	-8.635	0.000
Operating 2	0.3073	0.10838	2.836	0.013
Anode Hu 55	-0.0908	0.10838	-0.838	0.416
Anode Hu 70	-0.2239	0.10838	-2.066	0.058
Cathode Hu 50	0.0620	0.10838	0.572	0.577
Cathode Hu 70	-0.0408	0.10838	-0.377	0.712
Stoichio 1	0.2392	0.10838	2.207	0.045
Stoichio 2	-0.1118	0.10838	-1.031	0.320
Stoichio 1	-0.0332	0.10838	-0.306	0.764
Stoichio 2	0.0311	0.10838	0.287	0.778

Table 3. Summary

Sum	R-Square	Adjusted
0.3532	94.56 %	89.92 %

In summary, there is a high degree of positive correlation between the quality attribute and SNR size. The maximum levels of SNRs will be obtained. This research determines the appropriate variables that may influence fuel cell quality characteristics through ANOVA.

Fluctuations in the fuel cell operating process parameter can greatly impact the quality attributes, as reflected by the % contribution to the total sum of squared deviation. The statistical F-test is employed to identify fuel cell properties that significantly influence the quality attribute. Based on the ANOVA presented in Table 4, the variables that have a significant impact on the outcomes are the operating temperature and operating pressure.

The design presently has no trial run for the response of the anticipated optimum setting in a factorial experiment. In this paper's experiment, the Taguchi approach is applied to various PEMFC working conditions. As indicated in Figure 10, the Taguchi method initially selects suitable orthogonal arrays to determine the main optimum parameters and the interaction between the parameters and the responses. Then, SNRs from Table 6 are plotted in Figure 11.

Table 4. ANOVA

Cause	DOF	Sequential Sum of Square	Adjusted	Mean Sum of Square	F-Factor	P- Factor
Operating Temp	2	19.3107	19.3107	9.65535	77.39	0.000
Operating Pressure	2	9.2684	9.2684	4.63420	37.14	0.000
Anode Humidification Temp	2	0.8379	0.8379	0.41897	3.36	0.064
Cathode Humidification Temp	2	0.1855	0.1855	0.09275	0.74	0.493
Stoichiometric flow Hydrogen	2	0.7824	0.7824	0.39118	3.14	0.075
Stoichiometric flow Oxygen	2	0.0344	0.0344	0.01720	0.14	0.872
Residual Error	14	1.7467	1.7467	0.12477		
Total	26	32.1660				

Table 5. Observations table of means

Statement	Avg	Fit	SE Fit	Residual	Standard Residule
7	8.163	7.636	0.245	0.527	2.07R
10	6.620	7.226	0.245	-0.606	-2.38R

Table 6. Response table for means

Level	Operating Temp	Operating Press	Anode Humidification Temp	Cathode Humidification Temp	Stoichio Metric Flow Hydrogen	Stoichio Metric flow Oxygen
1	16.49	16.84	17.68	17.84	18.01	17.74
2	18.01	18.08	17.55	17.73	17.66	17.81
3	18.83	18.40	18.09	17.75	17.65	17.78
Delta	2.34	1.56	0.54	0.10	0.37	0.06
Rank	1	2	3	5	4	6

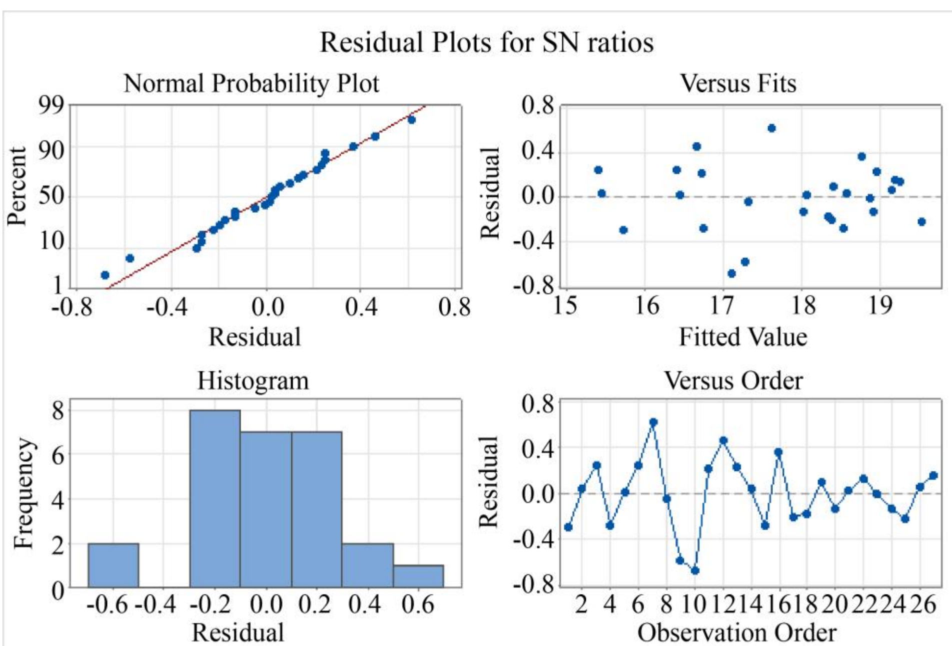

Fig. 10 Residual plots for SN ratios

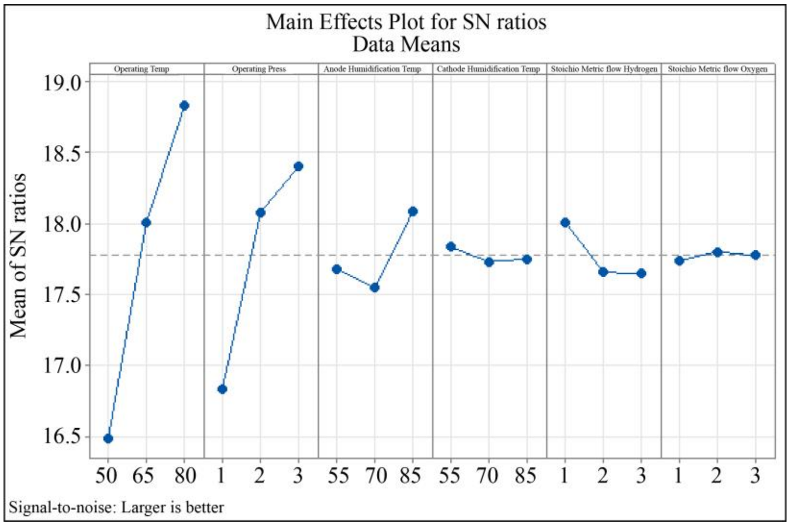

Fig. 11 Main effects plot for SN ratios

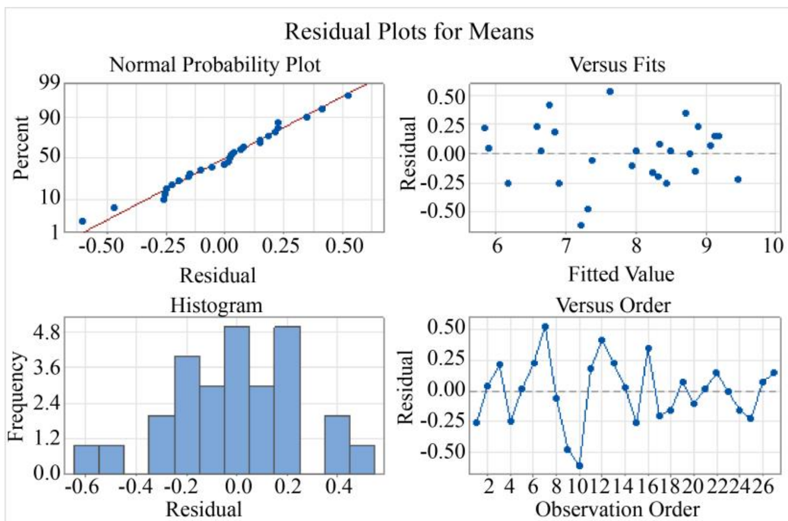

Fig. 12 Residual plots for means

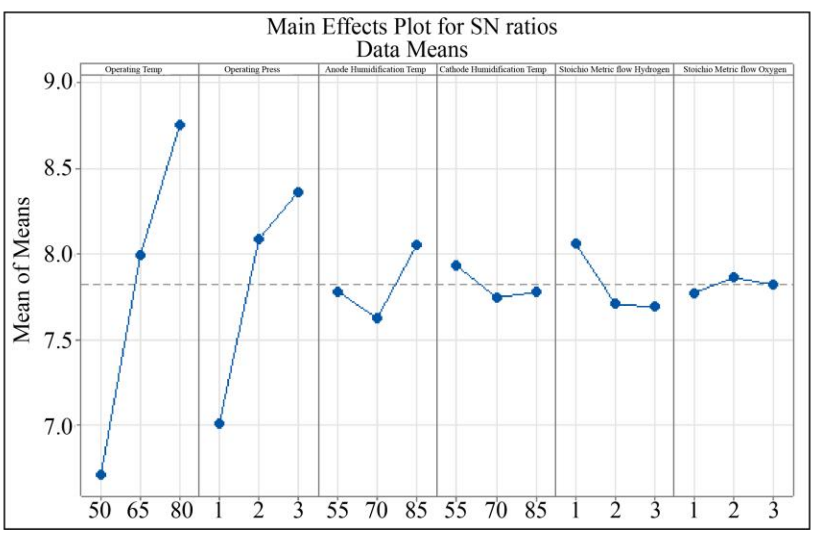

Fig. 13 Main effects plot for means

Figure 10 shows the result of residual plots for SN ratios corresponding to Table 4 and Table 5. Figure 12 shows the result of residual plots for means from Tables 4 and 5. Figure 13 shows the main effects plot for means. Therefore, to ensure consistency and reproducibility, a comparison should be made between the response of confirmation trials and the projected outcome.

5. Conclusion

The writers of this paper concentrated primarily on the diagnostic and design optimization parameters for proton exchange membranes. The discipline of design optimization relied heavily on the Taguchi approach. To get the right results, the low level, medium level, and high levels 1, 2, and 3 have been chosen for experiment design and optimization. The authors of this research discussed how PEMC performance could be enhanced through design optimization. The size of the membrane electrode assembly must be increased from 32 cm^2 to 50 cm2 or 100 cm2 to achieve better electrical power output and fuel cell efficiency. To make the fuel cell more effective, its active area has to be increased, say the scientists. The fuel cell has to be arranged in series to form the fuel cell stack, which is the focus of this work to satisfy the demand for electricity in terms of KW. Substitutes to Nafion membranes will become inevitable in the near future and reduce the fuel cell system's cost, which the authors of this research have described due to the existing need for a cost-effective and practical membrane material.

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