

Performance Analysis of a PEM Fuel Cell Stack Having 150 cm² Active Layer by Using Design of Experiments (DOE)

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Abstract. In this study, the effects of operating parameters on power density of a 3-cell PEMFC (Polymer Electrolyte Membrane Fuel Cell) stack with serpentine flow channels having 150 cm² total active layer have been examined experimentally. Desing Expert, which is the experimental design program (trial version) was used, and the data obtained as a result of the experiments were analyzed by entering this program. A total of 25 experiments were carried out according to the design created with the data entered into the program within the specified operating conditions range. The independent variables were entered which are cell temperature, humidification temperature, H₂ flow rate and O₂ flow rate, and the response is the power density. In this study, the hydrophobic cell stack which has the highest cell performance of which was previous studies results was used. In the optimization study, keeping the power density and maximum H₂ flow to a minimum, the most suitable values are cell temperature 57.826°C, humidification temperature 56.151°C, O₂ flow 1.587 L/min. Finally 432.398 mW/cm² power density value was obtained under these operating conditions.

1 Introduction

It is accepted by many scientists that hydrogen energy system is the most advanced technology that can continuously meet the increasing energy needs of the world without polluting the environment. One of the most economical and efficient technologies using hydrogen energy is fuel cell technology. Fuel cells are the systems that convert the energy of the oxidizer (air or oxygen) which is continuously fed to the cathode side into electrical energy as a result of the electrochemical reactions [1]. As a result of this transformation, only water and heat are released as combustion products. When hydrogen is used as a fuel, only water is produced as an emission shows that it is an environmentally friendly energy source and the ability to work and produce electricity as long as the fuel is supplied shows that it is a continuous energy source. High efficiency, low operating temperature (below 100°C) depending on fuel cell type, no moving parts and therefore vibration-free operation, fast response time, low mechanical parts and low emissions are counted as the main advantages of automotive and battery has been proposed as an ideal power source for a variety of applications such as industry.

In recent years, studies conducted by researchers show that there has been much progress in optimization theories and techniques through the application of numerical analysis and engineering. Especially with the increase of software using the response surface methodology and optimization studies on fuel cells have increased as well as in other science fields.

San et al. [2] in the study of investigated how the contact angle, surface roughness and hydrogen flow rate arguments of PEM fuel cells affect the cell power as output by using a response surface method with an active area of 50 cm². Silva and Rouboa [3] studied the effect of these variables on power density directly by entering methanol concentration, air and methanol flow rate, temperature and relative humidity values as independent variables in operating parameters of methanol fuel cells. Similarly, Kanani et al. [4] developed a model that optimizes anode and cathode stoichiometry ratios, relative humidity values and inlet gas temperatures from operating parameters to achieve maximum fuel cell performance. Wahdame et al. [5] examined the pressure and gas flow variables using the experimental design in a 20-cell and 500 W PEM fuel cell stack. Another common study for PEM fuel cells is the effect of pressing time, temperature and pressure on battery performance, which is one of the hot pressing parameters in the production of MEA (Membrane Electrolyte Assembly) [6,7]

Desing Expert, which is the experimental design program (trial version) was used, and the data obtained as a result of the experiments were analyzed by entering this program.

The main objective of this investigation is to find optimal operating conditions of PEM fuel cell by using response surface methodology (RSM) with defined variables of cell and humidification temperatures, H₂ and O₂ flow rates. Power density was used as response. At the end of experiments and analysis of DOE maximum power density was obtained under the condition of

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minimum H₂ flow rate with the minimum number of experiments intended for using DOE.

2 Experimental study

2.1 Desing of Experiments

The statistical design, known as experimental design, is the methodology of how to plan and conduct experiments to obtain maximum information with the least number of experiments [5].

Response surface methodology is a combination of statistical and mathematical techniques necessary for the development and optimization of processes [8]. The aim of the response surface is to estimate the optimum point of the multiple parameters which have an effect on the result obtained in the experimental study. At the same time, the experimental design allows the planning of a small number of experiments and the determination of these optimum points. In addition to the use of the response surface methodology for optimization purposes, it is also used to determine the effects of interactions of independent variables on the desired response. Response surface methodology consists of 3 stages;

- Experimental design
- Mathematical modeling
- Model validation

The design of the experiment begins with the determination of the variables and the desired response from these variables. During this determination, it is taken into account that fewer and more efficient experiments are performed.

The design types used in the design and optimization of experimental studies have become easier to understand in a suitable software. Various response surface methods are available within these software. Some of these are factorial design, D-optimal design, Box-Behnken design, hybrid design, central composite design, pentagonal design and hexagonal design. In mathematical modeling, the data required to construct response models are usually complete factorial, D-optimal design or central composite design. The most common type of design is the central composite design. This design is often used in the design of a second order polynomial model where mathematically linear models are not suitable. After the selected method, the number of experiments with the determined variables emerges.

Model validation, after creating the model, this equation ,for example in this study it was chosen a quadratic model Eq. (1) ,explains the relationship to what extent and predictions to be made using this equation should be investigated. One of the assumptions made is that the mathematical form of the selected model is appropriate, and therefore can represent the true average response. For this purpose, calculation of variation coefficient (CV), application of hypothesis tests to regression analysis, application of hypothesis tests to individual regression coefficients, calculation of regression coefficient (R²) and corrected regression coefficient (R²adj), estimated residual error squares sum (PRESS) (adequite precision) value calculation, model

of non-conformity test (lack of fit test) and different analysis methods such as residue analysis are applied [9]

The total number of experiments with four variables is 25. In addition to analyzing the effects of these variables, a quadratic model Eq. (1) was chosen in terms of independent variables for this experimental methodology.

$$Y = \beta_0 + \sum_{i=1}^4 \beta_i X_i + \sum_{i=1}^4 \beta_{ii} X_i^2 + \sum_{i=1}^4 \sum_{j=1+i}^4 \beta_{ij} X_i X_j + e \quad (1)$$

where Y is predicted response (power density), X_i term is the main factor, β₀ term is coefficient of intercept, β_i term is the coefficients of linear effect, β_{ii} term is the coefficients of quadratic effect, β_{ij} term is the linear coefficients for the interaction between variables i and j, e is the residual of ith experiment.

2.2 Material and method

Membrane electrode unit for fuel cell was prepared in TUBITAK MAM laboratories. Vulcan (20%) Pt catalyst was used as catalyst, SIGRACET 29BC coded commercial carbon paper was used as gas diffusion layer and Nafion XL was used as membrane. The anode and cathode sides of the membrane were coated with the same catalyst. The catalyst load of the MEAs is constant and is 0.6 mg/cm².

For performance tests, a 3-cell stack (Figure 1) was assembled in the TUBITAK MAM Fuel Cell Group Laboratories and the existing test setup was used. The device can measure up to about 2 kW in the form of a single cell or stack. In the test system, hydrogen, oxygen and air can be used as the reactant gas, and these gases can be sent to the cell in humid conditions by passing through the humidifier, which can be temperature controlled. On the main screen anode and cathode humidity, anode and cathode line temperature and cell temperature control panel, at the same time the input gas flow rate panel, electronic load and test data collection system that collects the current system is collected in.

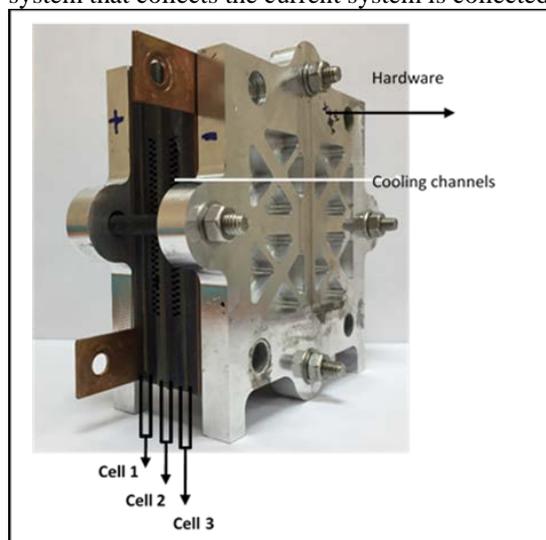


Fig. 1. Experimental 3-cell PEMFC stack

Table 1. Experimental operating conditions of fuel cell.

| | |
|-----------------------------|--------------|
| Humidification temperature | 45°C~60°C |
| Cell temperature | 50°C~60°C |
| Flow rate of O ₂ | 1~1.6 L/min. |
| Flow rate of H ₂ | 1~1.6 L/min. |
| Operation pressure | 1 bar |

Table 2. Results of ANOVA (Analysis of Variance)

| Source | Sum of Squares | df | Mean Square | F-value | p-value | Source |
|------------------------------|----------------|----|--------------------------------|---------|---------|-------------|
| Model | 58122.09 | 22 | 2641.91 | 29.52 | 0.0333 | significant |
| A-cell temperature | 816.08 | 1 | 816.08 | 9.12 | 0.0944 | |
| B-Humidification temperature | 3052.93 | 1 | 3052.93 | 34.11 | 0.0281 | |
| C-H ₂ flow rate | 212.18 | 1 | 212.18 | 2.37 | 0.2635 | |
| D-O ₂ flow rate | 1073.70 | 1 | 1073.70 | 12.00 | 0.0742 | |
| AB | 562.52 | 1 | 562.52 | 6.29 | 0.1290 | |
| AC | 5.35 | 1 | 5.35 | 0.0598 | 0.8297 | |
| AD | 256.72 | 1 | 256.72 | 2.87 | 0.2324 | |
| BC | 470.13 | 1 | 470.13 | 5.25 | 0.1490 | |
| BD | 2229.49 | 1 | 2229.49 | 24.91 | 0.0379 | |
| CD | 481.91 | 1 | 481.91 | 5.38 | 0.1461 | |
| A ² | 1133.05 | 1 | 1133.05 | 12.66 | 0.0707 | |
| B ² | 1915.17 | 1 | 1915.17 | 21.40 | 0.0437 | |
| C ² | 170.94 | 1 | 170.94 | 1.91 | 0.3011 | |
| D ² | 7.56 | 1 | 7.56 | 0.0844 | 0.7987 | |
| Residual | 178.99 | 2 | 89.50 | | | |
| Cor Total | 58301.08 | 24 | | | | |
| Std. Dev. | 9.46 | | R² | 0.9969 | | |
| Mean | 359.11 | | Adjusted R² | 0.9632 | | |
| C.V. % | 2.63 | | Predicted R² | 0.8390 | | |
| | | | Adeq | 18.4846 | | |
| | | | Precision | | | |

3 Results and discussions

It was used the optimization tab of Design Expert 11.0 (trial version) software to determine the maximum power density under ambient conditions. While the criteria for the operating environment was determining, the power density was selected as the maximum degree of importance due to the goal is to achieve the maximum power density. An analysis of variance (ANOVA) was performed to verify the significance of this quadratic model.

The model regression coefficient, R² is 0.9969 indicating that almost all the data variance can be described by the empirical model. The Model F-value of 29.52 implies the model is significant. Values of "Prob >

F" less than 0.0500 indicate model terms are significant. In this case A, B, D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Pred R Squared" of 0.8390 is as close to the "Adj R-Squared" of 0.9632 as one might normally expect. A ratio greater than 4 is desirable. Based on regression analysis, the following quadratic equation Eq. (2) has been suggested a mathematical model for the data. Power density = 333.042 - 10.057*A + 6.771*B - 0.059*C + 4.875*D + 5.46187*AB - 3.408*AC - 1.728*AD - 0.723*BC + 2.679*BD - 1.098*CD - 1.072*A² - 17.972*B² - 13.892*C² + 1.887*D² (2)

Figure 2 and Figure 3 show the surface curves of the power density that give the variation of the cell temperature and H₂-O₂ flow rates selected as independent parameters. Either way, the increase in the cell temperature at low flow rates did not create a significant

increase in performance, but with the increase in flow rates, the performance increased up to 56°C, and then the increase in the cell temperature decreased the power density. The reasons for this can be said that the membrane dries at high cell temperature, sweeping the water formed as a result of reactions with high flow rates and not effecting the membrane moistening.

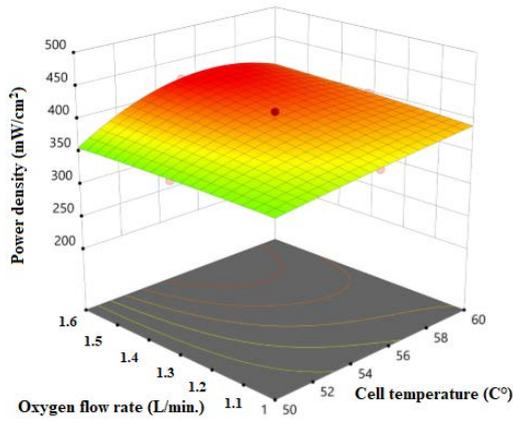


Fig. 2. Power density as functions of O₂ flow rate and cell temperature

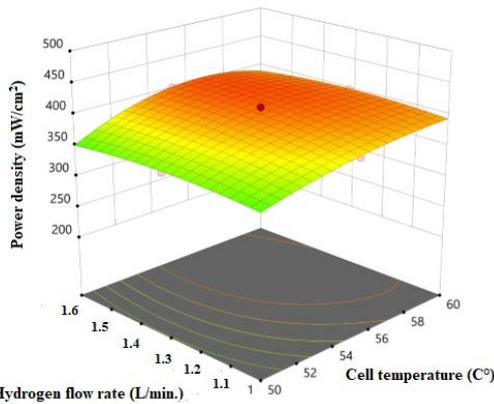


Fig. 3. Power density as functions of H₂ flow rate and cell temperature

When calculating the power density, the current values read according to the values between 1.3-2.5V entered into the test system interface are noted, then power is calculated with the results of current value obtained at 1.8 V from all the experiments completed (W), then 3-cell fuel The power density in mW/cm² was divided by dividing the cell stack into the active area. Figure 4 shows the effect of H₂ and O₂ flow rate on power density at constant cell and humidification temperature. If both flow rates are high, the power density has reached the highest value. However, as can be seen from the figure, O₂ flow rate is more effective in increasing the power density.

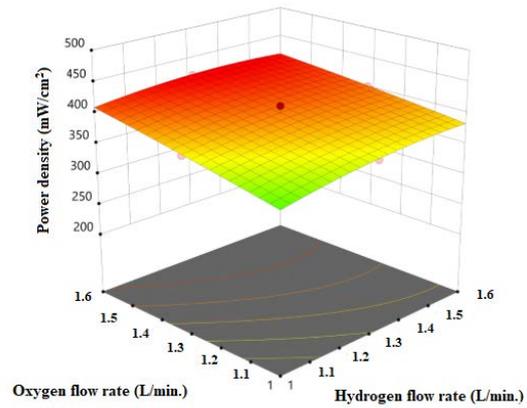


Fig. 4. Power density as functions of O₂ flow rate and H₂ flow rate

Figure 5 shows the curve giving the variation of power density with cell temperature and humidity temperature. Membrane drying is observed at cell temperatures higher than humidification temperatures. This results in poor performance. For example, at low humidity temperatures of up to 50°C, the increase in cell temperature has reduced the power density. At a low cell temperature, the performance improved as the humidification temperature increased from 45°C to 60°C. Maximum power density values have been reached at cell temperatures of 54°C and higher humidification temperatures. However, after the 60°C humidity temperature, increases after the cell temperature of 54°C reduced the power density. These decreases can be said that the high humidity value and the excess water formed due to the reaction rate at high temperature cause flooding in the channels.

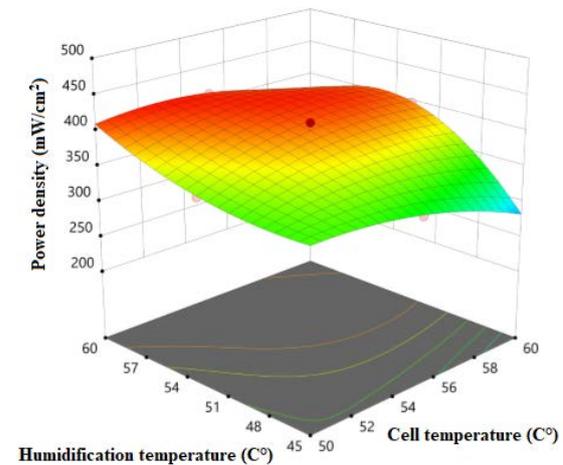


Fig. 5. Power density as functions of humidification and cell temperature

4 Conclusions

In the experimental design and optimization study, the hydrophobic cell stack with the highest cell performance obtained from the previous study was used. The effects of

cell temperature, humidification temperature, H₂ and O₂ flow rates on power density were investigated in a total of 25 experiments which were created by Design Expert 11.0 (trial version). In the optimization study, keeping the power density maximum and H₂ flow to a minimum, the most suitable values are cell temperature 57.826°C, humidification temperature 56.151°C and oxygen flow 1.587 L/min. 432.398 mW/cm² power density value was obtained under these operating conditions.

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