

Performance Analysis of Alkaline Fuel Cell with Variation of Potassium Hydroxide Concentration in Electrolyte Solution

Mohammad Rifqy Alfariz¹, Nasrul Ilminnafik^{1*}, Dwi Djumhariyanto¹, Intan Hardiatama¹, Muhammad Khadafi Ibnu¹, Raafi Aditya Nugraha¹, Domingos de Sousa Freitas²

¹Department of Mechanical Engineering, Universitas Jember, Jember, 68121, Indonesia

²Department of Mechanical Engineering, National University of Timor Lorosa'e, Dili, Timor Leste

*Corresponding author: nasrul.teknik@unej.ac.id

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ABSTRACT

Alkaline Fuel Cell (AFC) is a green energy conversion tool that converts chemical energy into electrical energy through electrochemical reactions. This research aims to analyze the effect of potassium hydroxide (KOH) concentration variation in electrolyte solution on the AFC performance, using nickel and manganese catalysts. The research methods include experiments using various KOH concentrations to determine the optimal concentration to produce the best AFC performance. The voltage and current produced are measured, as well as the calculation of the electrical power and efficiency of the AFC. The results showed that KOH concentration has a significant influence on the performance of AFC. It was found that the optimal KOH concentration produces maximum electrical power and energy conversion efficiency. The highest alkaline fuel cell performance was found at 70% KOH concentration. In addition, the use of nickel and manganese catalysts was shown to improve the stability and efficiency of AFC. The result makes an important contribution to the development of AFC technology, supporting global efforts towards cleaner and more sustainable energy use. The findings also provide a basis for further innovations in AFC design and materials, as well as their potential in practical applications such as electric vehicles and portable power plants.

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Keywords: Alkaline fuel cell, efficiency, electrolyte, nickel, manganese catalyst, potassium hydroxide.

I. Introduction

The increase in global population has led to enhance in energy demand, and until now, fossil-based fuels were a major source of the global energy needs. The fossil fuels is non-renewable energy, it means will run out in due time. Fossil fuels also contain toxic substances that can damage the environment and endanger the lives of mankind, both individually and globally [1]. To reduce dependence on fossil energy sources and greenhouse gas emissions, various renewable and green energy technologies have been developed, including fuel cells. The fuel cell has capable to convert the chemical energy directly into electrical energy with high efficiency and minimal environmental impact [2]. Fuel cell requires reactants which usually use hydrogen on the anode and oxygen on the cathode. In fuel cells, hydrogen gas is decomposed into electrical energy through the reactions that separate electrons and protons from hydrogen gas and produce electrical energy [3]. Fuel cell contains an electrolyte that separates the cathode from the anode. Electrolyte has not function as conductor, so they can only conduct ions [4]. While fuel cell was first demonstrated by Sir William Robert Grove in 1839, the application of fuel cells in



practical was carried out in 1950. They applied as an electric power generator for welding equipment with a capacity of 5 kW by the National Aeronautics and Space Administration (NASA) in the United States [5].

Alkaline fuel cells (AFCs) are well known for their high power densities and long lifespans in specific applications. Despite their decline in popularity due to the introduction of Proton Exchange Membrane Fuel Cells (PEMFC), AFC still holds potential for specific applications, particularly when cost and CO₂ sensitivity can be well managed [6]. AFC has come a long way from its beginnings in the 1930s, especially in the areas of electrolyte chemistry, cell construction, and electrode materials. The performance of these cells is mostly influenced by the concentration of potassium hydroxide (KOH) in the electrolyte solution. Of all the available hydroxides (NaOH/LiOH/KOH), KOH is the most frequently used in alkaline electrolytes due to its rapid electrochemical kinetics, high solubility of zinc salts, and higher ionic conductivity afforded by the ions K⁺ [7]. The electrolyte solution's ionic conductivity is influenced by the presence of ions K⁺. Conductivity increases with a rise in ion K⁺ concentration. As OH⁻ ions travel throughout the electrochemical reaction, K⁺ ions contribute to maintaining charge balance in the solution [8].

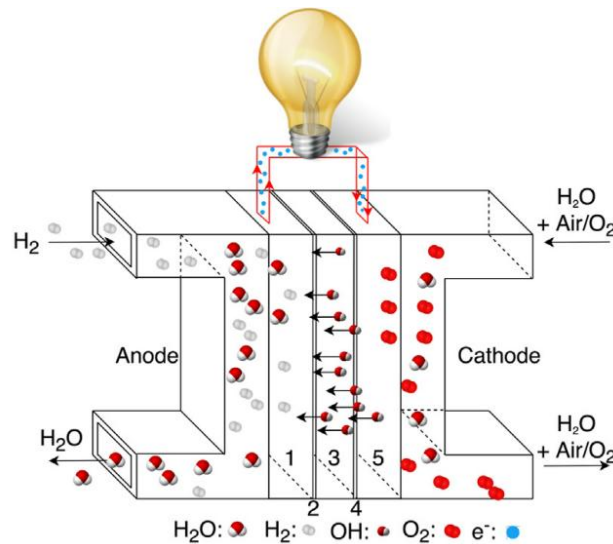
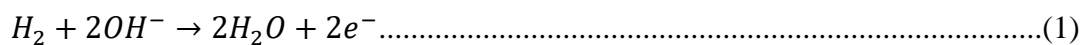
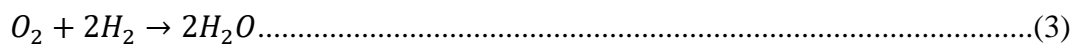
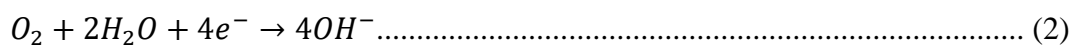


Fig. 1. Working principle of alkaline fuel cell [8]

Based on Figure 1, the reaction that occurs in the alkaline fuel cell is, first, hydrogen gas is supplied to the anode, which will react with hydroxide ions in the electrolyte to produce water and electrons after penetrating the gas diffusion layer and reaching the catalyst layer, as shown in Eq. (1).



Furthermore, the oxygen source usually comes from purified air/oxygen supplied to the cathode along with water. The oxygen gas, dissolved in water, is reduced in the cathode catalyst layer to form hydroxide ions, which diffuse through the electrolyte to enter the hydrogen oxidation reaction occurring at the anode. The idealized oxygen reduction reaction is shown in Eq. (2).



The redox reactions in Eq. (1) and (2) are combined to form the overall mechanism given in Eq. (3).

The concentration of KOH in the electrolyte solution plays an important role in the reaction and determining the performance of AFCs, as it affects the ionic conductivity and speed of electrochemical reactions. Research has demonstrated that KOH concentration and catalyst type can significantly affect AFC performance. For example, research by Suardamana (2014) [9] showed that an AFC having an electrolyte volume of 180,000 mm³ with an electrolyte solution concentration of 70% KOH produced the highest voltage at a level of about 63.9 mV without load, while when using a load, the result was about 25 mV. A catalyst is not used in the alkaline fuel cell, which uses electrodes made of 304 stainless steel plates [10].

Direct hydrazine fuel cells (DHFCs) and zinc-air batteries are two fuel cell variants that have used KOH-doped membranes. Under ideal conditions, KOH-doped polybenzimidazole membranes have shown encouraging results in DHFCs, reaching a peak power density of 0.708 W cm⁻² [11]. It was discovered that the best solution for increasing discharge duration and enhancing performance in zinc-air batteries was 40% KOH [12].

While higher KOH concentrations generally improve performance, they can also lead to increased internal resistance and potential degradation of cell components. Therefore, finding the optimal concentration is crucial for balancing performance and longevity. Additionally, the presence of impurities in commercial KOH can alter catalyst performance, as seen in studies on cobalt oxide catalysts for oxygen evolution reactions [13].

This study aims to analyze the effect of varying potassium hydroxide concentration in the electrolyte solution on the performance of AFC using nickel and manganese catalysts. The catalyst used in AFC is also a factor that affects the efficiency and stability of the fuel cell [14]. The combination of nickel and manganese catalysts attracts attention due to their abundant availability, relatively affordable price, and potential to increase catalytic activity in AFC [15], [16]. It is anticipated that the research will be able to determine the ideal KOH concentration to attain the greatest AFC performance and comprehend how the usage of nickel and manganese catalysts impacts fuel cell stability and efficiency through tests and in-depth analysis. In addition to assisting efforts toward a cleaner and more sustainable energy future, the results are anticipated to have a substantial impact on the development and optimization of AFC technology. They will also be in line with global trends in fuel cell and hydrogen technology as components of future energy solutions.

II. Material and Methods

The research variables consisted of independent variables, dependent variables, and control variables. Independent variables are factors that influence or cause changes, namely the concentration of KOH in the electrolyte solution, with variations in concentration of 10%, 30%, 50%, and 70% on a mass basis. Meanwhile, the dependent variable was the result or response observed due to changes in the independent variable, namely, electric current and voltage, which was then calculated as efficiency and electrical power. The calculation results were analyzed using two-way ANOVA (Analysis of variance with two factors) with an alpha value of 0.05. In addition, to ensure the validity and reliability of the research results, several control variables such as electrolyte volume, gas diffusion electrode (GDL) with the catalyst MnO₂/C on the cathode, GDL with the catalyst Ni/C on the anode, oxygen inlet pressure of 0.5 bar, and hydrogen inlet pressure of 1 bar. These variables were kept constant throughout the research process.

1. Alkaline Fuel Cell Design and Manufacturing Process

An alkaline fuel cell was designed with an electrolyte volume of 160,000 and a reaction surface area of 3,000. The electrode in the alkaline fuel cell uses a GDL type with the catalyst on the cathode is (MnO_2/C), and the catalyst on the anode is (Ni/C), which we produce at the University of Jember Manufacturing Process Laboratory. The alkaline fuel cell uses a single-stack model as shown in Figure 2. The hydrogen and oxygen supplies are set at a pressure of 1 bar and 0.5 bar, respectively. The equipment and materials used in the experiment are shown in Tables 1 and 2.

Table 1. Equipment for the experiment

No	Equipment	Type	Source
1	Alkaline Fuel Cell	-	Universitas Jember, Indonesia
2	Oxygen gas cylinder	Standard	Karina Gas, Indonesia
3	Hydrogen gas cylinder	Standard	Karina Gas, Indonesia
4	Data logger	Midi LOGGER GL200A	Graphtec Corporation, Japan
5	Regulator	Heavy duty	Muraku, Indonesia
6	Multimeter	CD800A	Sanwa Electric, Japan
7	Scales	Digital	Nankai Tools, Indonesia
8	Beaker Glass	Standard	Herma, Indonesia
9	Gas hose	Standard	Bridgestone, Indonesia
10	Stop watch	Digital	OneMed, Indonesia

Table 2. Materials for the experiment

No	Materials	Type	Source
1	Potassium Hydroxide	Technical	PT. Timuraya Tunggal, Indonesia
2	Aquades	Aqua	SMART-LAB, Indonesia
3	Hydrogen gas	Industrial Gas	Karina Gas, Indonesia
4	Oxygen gas	Industrial Gas	Karina Gas, Indonesia
5	Cathode Catalyst (MnO_2/C)	Prototype	Universitas Jember, Indonesia
6	Anode Catalyst (Ni/C)	Prototype	Universitas Jember, Indonesia

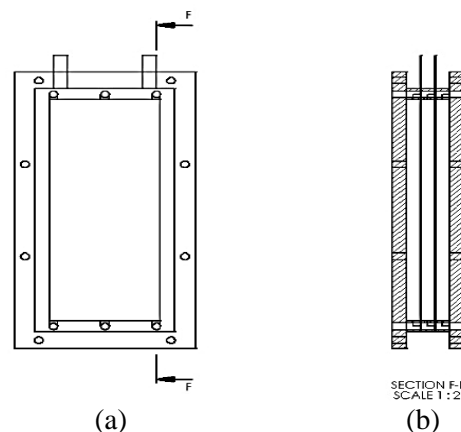
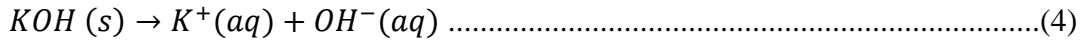


Fig. 2. (a) AFC design side view, (b) AFC design section view

2. Preparation of Variation of KOH Concentration in Electrolyte

The electrolyte in the AFC uses KOH solution, making the solution by mixing KOH powder with distilled water. Dissolved KOH will dissociate completely into its constituent ions as in Eq. (4).



This dissociation is the main source of ions in the solution. The concentration of ions is directly proportional to the amount of KOH dissolved, assuming there are no other compounds containing potassium. The electrolyte to be tested is a KOH solution with the composition as shown in Table 3.

Table 3. Composition data of various electrolyte solutions

Variation Name	KOH (%)	Distilled Water (%)
KOH 10%	10	90
KOH 30%	30	70
KOH 50%	50	50
KOH 70%	70	30

3. Alkaline Fuel Cell Testing

In testing alkaline fuel cells, what is measured and recorded is the voltage (V) and current (A). Recording measurements is done every two minutes for 10 minutes using a load in the form of a 3 mm LED at each concentration. The recorded voltage and current data will be calculated for electrical power and efficiency. Fuel cell efficiency is defined as the ratio between electricity generated and hydrogen consumed (Eq. (5)).

$$\eta = \frac{W_{el}}{W_{H2}} \dots\dots\dots(5)$$

The electric power generated is the product of voltage and current that expressed in Eq. (6).

$$W_{el} = I \times V \dots\dots\dots(6)$$

where I is the current in amperes and V is the voltage in volts. Hydrogen consumption according to Faraday's law is directly proportional to the current, as expressed in Eq. (7) and (8).

$$N_{H2} = \frac{I}{nF} \dots\dots\dots(7)$$

where in, and

$$W_{H2} = \Delta H \frac{I}{nF} \dots\dots\dots(8)$$

Description:

W_{H2} = hydrogen energy value consumed in Joules per second (Watts)

ΔH = hydrogen higher heating value (286)

n = number of electrons transferred (2 in this case)

F = Faraday's constant (96.485)

By combining Eq. (4) and (6), the fuel cell efficiency is directly proportional to the voltage:

$$\eta = \frac{V}{1.254} \dots\dots\dots(9)$$

4. Data Analysis

Data from the calculation of electrical power and efficiency are shown in the data tabulation. Furthermore, the analysis was carried out using two-way ANOVA (Analysis of variance with two factors) with an α value of 0.05. The results of the analysis that have been obtained in the form of ANOVA tables and decisions can be made respectively with the following rules:

- F value and p-value for factor A: Indicates whether factor A has a significant effect on the dependent variable.
- F-value and p-value for factor B: Indicates whether factor B has a significant influence on the dependent variable.
- F value and p-value for AB interaction: Indicates whether there is a significant interaction between factors A and B in influencing the dependent variable.

III. Results and Discussions

1. Alkaline Fuel Cell Manufacturing Process Results

Alkaline fuel cell is made to do performance testing in the form of voltage and current, then the test results are calculated for electrical power and efficiency. Electrolyte volume obtained 160,000 and reaction surface area 3,000 in accordance with the design. The final results of alkaline fuel cell manufacturing can be seen in Figure 3.

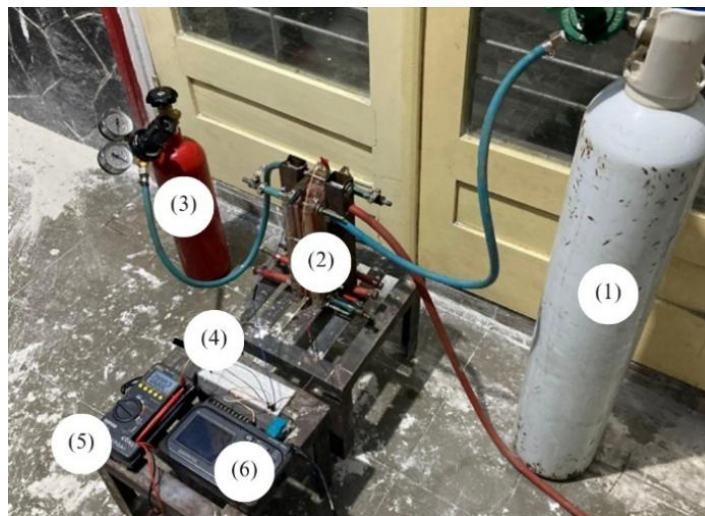


Fig. 3. Alkaline fuel cell: (1) Oxygen cylinder, (2) AFC, (3) Hydrogen cylinder, (4) Electric wiring, (5) Multimeter, (6) Data logger

2. Electrical Voltage

Based on Figure 4, it can be seen that the greater the concentration of KOH, the greater the voltage produced from the 0th minute to the 10th minute due to the increase in ionic conductivity as the KOH concentration increases. More effective ion transfer is made possible by high ionic conductivity, which boosts productivity and lowers operating heat. It can increase the stability and lifespan of the electrochemical device [10], [17]. However, as shown in a number of electrochemical systems, extremely high KOH concentrations can raise ionic strength, which lowers ionic conductivity and prevents ion movement because of increased solution viscosity [18].

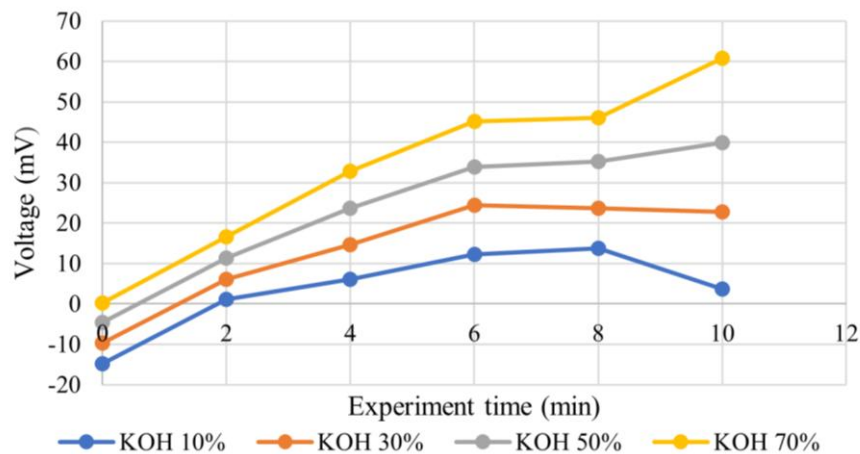


Fig. 4. Voltage of an alkaline fuel cell

3. Electric Current

According to Figure 5, it can be seen that the higher the KOH concentration, the greater the electric current produced, which is in line with the increase in voltage produced. The voltage affects the magnitude of the electric current. The higher the voltage, the greater the electric current that flows. This is in accordance with research by Yasu and Hadi (2021), which shows that increasing the voltage increases the magnitude of the electric current [19].

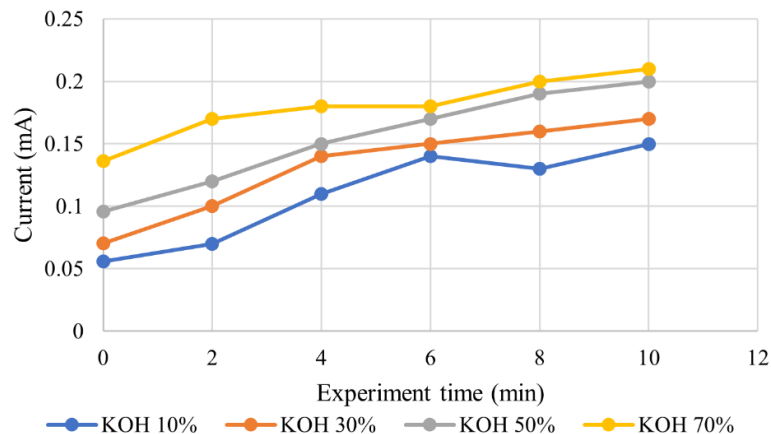


Fig. 5. Current of an alkaline fuel cell

4. Efficiency

Efficiency calculations are based on the assumption of complete conversion of oxygen and hydrogen fuels, referred to as voltage efficiency. The type of heating value used to calculate efficiency is the higher heating value. Based on Figure 6, the efficiency of the alkaline fuel cell increases with both higher KOH concentration and longer experiment duration. The highest efficiency, 4.1%, was recorded at a 70% KOH concentration at the 10th minute, compared to only 0.246% at the same time with a 10% concentration. These results demonstrate that increasing the concentration of KOH can significantly improve the efficiency of alkaline fuel cells. KOH is used as an electrolyte and affects cell performance. High KOH concentration can increase the electrolyte temperature and the performance of alkaline fuel cell [20].

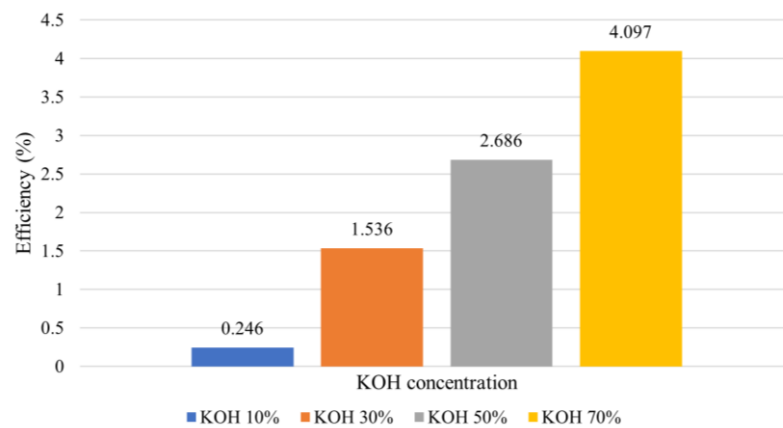


Fig. 6 Efficiency

5. Electrical Power

Electric power is the result of the multiplication between voltage and electric current, as in Eq. (6). Therefore, the results of the calculation of electric power have increased along with the increase in voltage and electric current. Based on Figure 7, the highest power output, 0.013 mW, was achieved at a 70% KOH concentration at 600 seconds. These results demonstrate that an optimal KOH electrolyte concentration can enhance ion conductivity and improve cell performance [21].

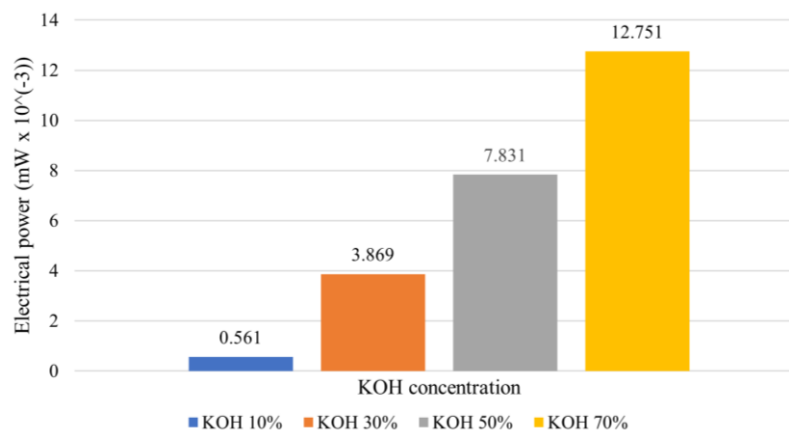


Fig. 7. Electric power

6. Analysis

From the alkaline fuel cell efficiency data, the results of the analysis using the two-way ANOVA feature with an alpha value of 0.05 are shown in Table 4. Based on the ANOVA table of electric power analysis results, the following decision is obtained:

- Because the p-value < 0.05 and $F > F\text{-Crit}$, then the factor variation of KOH concentration in the electrolyte solution has a significant effect on the efficiency of alkaline fuel cell.
- Because the p-value < 0.05 and $F > F\text{-Crit}$ then the length of time the experiment has a significant effect on the efficiency of alkaline fuel cell.
- Because the p-value < 0.05 and $F > F\text{-Crit}$, then the interaction factor variation of KOH concentration in the electrolyte solution with the length of time factor has a significant effect on the efficiency of alkaline fuel cell.

Table 4. Anova table of efficiency

Source of Variation	Ss	Df	Ms	F	P-value	F-Crit
Variation in electrolyte	34.8031	3	11.60103	5603.373	4.52E-61	2.798061
Trial time	74.31095	5	14.86219	7178.533	9.88E-68	2.408514
Interaction	12.73839	15	0.849226	410.1817	2.59E-45	1.880175
Error	0.099378	48	0.00207			
Total	121.9518	71				

Our results are slightly higher than previous research [9], in the field of prototype alkaline fuel cells, but still much lower when compared with precious metal catalyzed fuel cell. Some of the factors that influence these results are:

a. Type of KOH

KOH used in the research is of the technical type, while KOH with a better level is of the analytical type. Analytical KOH generally produces higher conductivity compared to technical KOH due to its purity. In his research on the conductivity of alkaline electrolytes for water electrolysis showed that electrolyte purity has a significant effect on conductivity, with pure electrolytes showing lower ionic resistance [22].

b. Fuel Cell Model

Our fuel cell is a simple model or prototype because the focus of this research is only on electrolyte solutions. A more complex form, for example, with the addition of a bipolar plate to hold the gas flow rate so as not to directly leave the alkaline fuel cell. The bipolar plate plays an important role in distributing reactant gases (hydrogen and oxygen) evenly throughout the electrode surface.

c. Cell Reversal

Negative voltage in fuel cells is an undesirable phenomenon and can cause component degradation and decreased fuel cell performance. Fuel starvation, inadequate air supply, water flooding, load changes, low catalyst performance, etc., can cause cell reversal and voltage to become negative. An in-depth understanding of these causes of negative voltage is important for the development of more reliable and durable fuel cell systems.

IV. Conclusions

The research aims to analyze the performance of Alkaline Fuel Cell (AFC) with various concentrations of Potassium Hydroxide (KOH) in the electrolyte solution. From the test results and data analysis carried out, it can be concluded: (1) Increasing the concentration of KOH in the electrolyte solution significantly increases the electrical power generated by the alkaline fuel cell. This is because the optimal concentration of KOH electrolyte can improve ion conductivity and cell performance. The highest alkaline fuel cell performance was found at 70% KOH concentration; (2) The efficiency of alkaline fuel cell increases with the increase of KOH concentration, caused by higher ionic conductivity at greater KOH concentrations, so that electrochemical reactions can take place more efficiently. The results of data analysis using ANOVA show that the F value is greater than F_{table} and the p-value is less than 0.05, which indicates a significant difference in the efficiency produced at various KOH concentrations.

The finding indicates that different concentrations of KOH greatly affect the performance of alkaline fuel cells, and the best performance is obtained at the highest concentration of 70%. Therefore, future research needs to focus on finding the highest concentration limit to improve the performance of alkaline fuel cells. In addition, molecular dynamics simulation-based approaches can be used to better understand the ion transport mechanism in concentrated KOH solution, in order to improve the overall efficiency of the alkaline fuel cell system.

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