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Performance Analysis of an Alkaline Fuel Cell with Ni/C on the Anode

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Abstract

Increasing global energy demand encourages the development of renewable energy, one of which is hydrogen-based energy through fuel cells. Alkaline fuel cells (AFC) are an attractive alternative because they can use non-noble metal catalysts. This research aims to develop an economical nickel-based catalyst material for the anode of an AFC. Experiments were conducted by mixing nickel and carbon black (Ni/C) as supporting materials, and polytetrafluoroethylene as a binder. The nickel concentration variations used were 0%, 10%, and 20% by weight. Results show that increasing nickel concentration is directly proportional to AFC performance. Cells with 20% nickel concentration produced the highest voltage, current, and efficiency. This research proves the potential of nickel as an effective and economical alternative catalyst in the development of AFCs, which can contribute to the advancement of renewable energy technology.

1. Introduction

Global energy demand continues to grow in tandem with population expansion, economic development, and technological advancement. Although fossil fuels remain the primary energy source, their non-renewable nature is prompting many countries to seek alternative solutions to ensure energy resilience [1]. Currently, people are really focused on switching to renewable energy sources to reduce their dependence on fossil fuels. One promising alternative is hydrogen-based energy, which is expected to support energy diversification and mitigate environmental impacts. Hydrogen is a carbon-free energy source that has the potential to replace fossil fuels. Its clean and environmentally friendly nature makes it a promising energy alternative [2]. The application of hydrogen in power generation systems is carried out through fuel cells, which convert hydrogen into electricity through an electrochemical process. Fuel cells will play a crucial role in driving the future transition towards a sustainable energy system that produces minimal carbon emissions [3]. The fuel cell comprises two electrodes, an anode and a cathode, which are positioned around the electrolyte. During operation, the cathode draws in air (or pure oxygen), while the anode receives fuel such as hydrogen. Inside the cell, a catalyst and a membrane, also known as an electrolyte membrane, work together to split hydrogen molecules into electrons and positive ions, facilitating the electrochemical reactions necessary for power generation. A flow of electricity is produced by electrons traveling in various directions to the cathode via an external circuit. To reach the cathode, the positive ions must move across the electrolyte membrane. Water is created when they reunite with oxygen and the electrons from the external circuit while a catalyst is present [4][5]. Fuel cells can be categorised into different

types based on the electrolyte used: alkaline fuel cells (AFCs), polymer electrolyte membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) [6].

The Alkaline Fuel Cell (AFC) functions on a mechanism similar to that of traditional fuel cells. In an AFC, the fuel undergoes a reaction at the anode while the oxidant reacts at the cathode, resulting in the generation of electrical energy and water [7]. Typically, AFCs use a liquid alkaline solution, most often potassium hydroxide (KOH), as the electrolyte. These fuel cells are considered low-temperature systems, with operational temperatures generally falling between 50°C and 100°C [8]. At the anode of an alkaline fuel cell, hydrogen oxidation occurs. In this reaction, hydrogen reacts with two OH^- ions from the electrolyte solution, producing two water molecules and two electrons. The redox reaction is $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$. On the cathode side, the reaction that occurs is the reduction of oxygen. In this reaction, oxygen molecules and two water molecules combine to form hydroxide (OH^-) ions. These ions then diffuse through the electrolyte solution toward the anode. The redox reaction that occurs is $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$. Oxidation and reduction reactions are combined to form a total reaction, which can be written as $O_2 + 2H_2 \rightarrow 2H_2O$ [9]. Based on existing literature, it is clear that most AFC developers have focused on electrode development to increase fuel cell power output by selecting the appropriate catalyst and electrode structures. Alkaline fuel cells operate without any moving components, which in theory allows for reduced manufacturing costs. However, the main contributors to the overall expense are the quality of materials, the catalysts used, and the effectiveness of the sealing system. These components are essential for attaining high efficiency, which makes the production of efficient alkaline fuel cells relatively expensive [10].

Alkaline fuel cells represent an emerging area of development within fuel cell technology. One notable advantage of these cells is their ability to operate using non-precious metal catalysts, such as nickel [11]. Incorporating nickel can enhance the rate of the electrochemical reactions occurring within the cell, which in turn leads to improved overall performance and efficiency [12]. Nickel catalysts are widely used in fuel cell anodes because hydrogen oxidation reactions occur at the anode. This means that hydrogen molecules dissolve in the electrolyte solution and are reabsorbed onto the electrode surface during the reaction [13], [14]. Nickel exhibits a notable affinity for hydrogen, which promotes the effective adsorption of hydrogen molecules onto its surface. The deployment of nickel-based catalysts within alkaline fuel cells has become an important focus of ongoing research, aimed at improving the overall efficiency of these systems. This effort is motivated by the broader goal of assisting a transition toward a more sustainable and low-carbon energy infrastructure. Previous research has shown that nickel-based catalysts at the anode can improve AFC performance, offering a cost-effective alternative to platinum. A study by [15] reported good performance using 304 stainless steel electrodes. Additional studies by [16] and [17] demonstrated notable improvements in catalytic activity and current density through the integration of nickel catalysts with carbon support. This study aims to further explore these findings. Specifically, we propose to evaluate the performance of alkaline fuel cells, focusing on voltage, current, and efficiency while varying the concentration of nickel catalyst supported on carbon material (Ni/C). The primary objective of this study is to develop an alkaline fuel cell using cost-effective alternative non-noble metal catalysts, thereby contributing to the advancement of sustainable and environmentally friendly energy solutions.

2. Methodology

An experimental strategy utilizing modifications in an alkaline fuel cell's anode catalysts was the research method used in this study. Under carefully monitored laboratory conditions, direct observations and measurements were made to gather accurate performance data. The goal of the studies was to determine how various Ni/C ratios affected the cell's electrochemical performance, including output voltage, current, and overall efficiency.

In order to simulate realistic fuel cell operation, all experiments were conducted at room temperature and air pressure. The cell's current-voltage characteristics were measured over time as part of the performance evaluation, and power output and efficiency were then calculated using accepted electrochemical equations. This methodology was chosen because it minimizes external influences, ensures reproducibility, and permits direct comparison of catalyst variations under identical settings. The results obtained can more accurately represent the true performance potential of the suggested Ni/C catalysts in AFC systems by using an experimental approach as opposed to a merely theoretical or simulation-based one.

2.1 Materials and Equipment

The experimental setup in this study involved several key instruments and equipment to ensure the success of the experiment and the accuracy of the collected data. Several essential instruments and materials were employed in this study. The equipment was primarily used to support the measurement, control, and operation of the alkaline fuel cell system, while the selected materials were chosen based on their specific properties suitable for cell fabrication and testing. The detailed list of equipment and materials utilized in the experiment is presented in Tables 1 and 2.

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 320-330

Table 1 *Equipment for the experiment*

No	Equipment	Type	Source
1	Alkaline fuel cell stack	-	Universitas Jember, Indonesia
2	Data logger	Midi Logger GL200A	Graphtec Corp. Japan
3	Multimeter	CD800 A	Sanwa Electric, Japan
4	Stopwatch	Digital	One Med
5	Hydrogen gas cylinder	Standard	Karina Gas, Indonesia
6	Oxygen gas cylinder	Standard	Karina Gas, Indonesia
7	Gas regulator	Heavy duty	Muraku, Indonesia
8	Gas hose	Standard	Bridgestone, Indonesia

Table 2 *Material for the experiment*

No	Equipment	Type	Source
1	Carbon black	Vulcan N330, CABOT powder	Meraki Chemical
2	Nickel powder	Metal powder	Loba Chemie Pvt. Ltd.
3	Polytetrafluoroethylene	Powder	Commercially available
4	Isopropyl alcohol	Tecnical	Commercially available
5	Stainless steel 304 plates	Plate 0,5 mm	Commercially available
6	Stainless steel mesh	Mesh 100	Commercially available
7	High-purity oxygen and hydrogen gases	Industrial gas	Karina Gas, Indonesia
8	Potassium hydroxide	Tecnical	PT. Timuraya Tunggal, Indonesia
9	Cathode Catalyst (MnO_2/C)	Prototype	Universitas Jember

2.2 Design and Manufacturing of Alkaline Fuel Cell

To provide a more comprehensive understanding of the structural design of the alkaline fuel cell employed in this investigation, the schematic diagram along with its primary components is illustrated in Fig. 1. The diagram elucidates the sequential layering and the specific function of each part in ensuring the optimal operation of the single-stack AFC. The outermost element, designated as (1) the end plate, functions both as a mechanical cover and as a pressure-bearing support, thereby preserving the structural stability of the stack. The (2) monopolar plate acts as a separator and simultaneously provides a conductive pathway for electric current. The (3) current collector is tasked with capturing and assisting the flow of electrical current generated within the cell. To prevent gas or liquid leaks, a (4) gasket is incorporated between layers, also serving as an electrical insulator. Lastly, the (5) gas diffusion electrode ensures uniform distribution of reactant gases and hosts the active sites where electrochemical reactions transpire. In Fig. 1(b), the fully assembled single-stack AFC is depicted, displaying the compact configuration characteristic of the prototype used in this study. This design was deliberately maintained in a simplified form, excluding bipolar plates, with the primary aim of reducing complexity and concentrating on the evaluation of Ni/C variations in catalytic activity and their effect on overall cell performance.

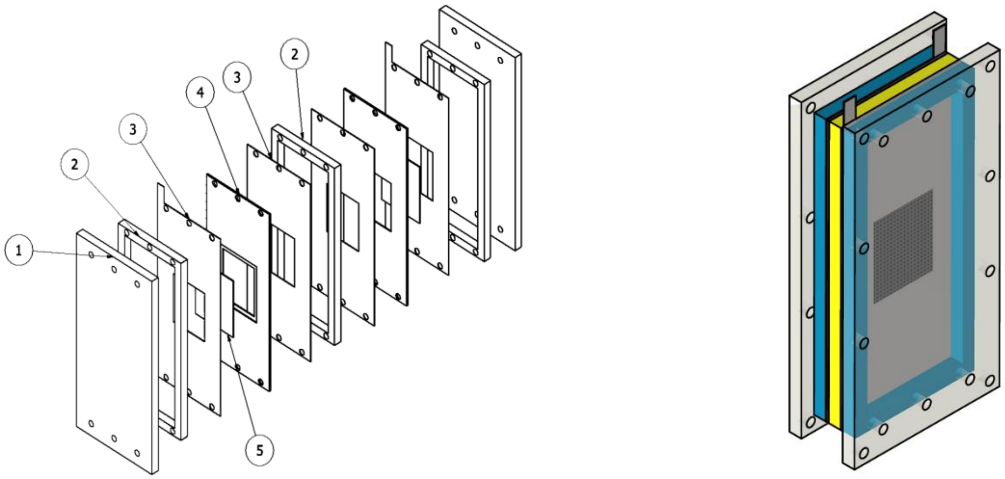

Fig. *1 Schematic diagram of alkaline fuel cell (AFC) (a) Main components and layer arrangement; (b) Assembled single-stack AFC*

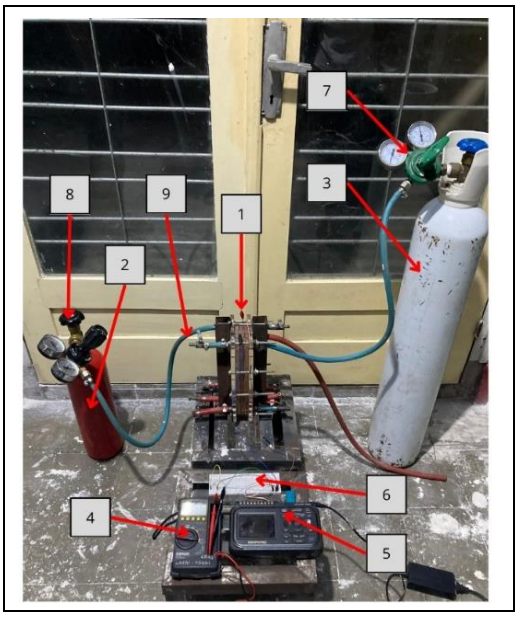

Fig. 2 *Real experimental setup of the alkaline fuel cell testing system*

In addition to the schematic design, the actual experimental setup used in this study is depicted in Fig. 2. This setup comprised a single-cell alkaline fuel cell stack (1), linked to a hydrogen cylinder (2) and an oxygen cylinder (3) serving as the fuel and oxidant sources, respectively. Gas flow was carefully regulated using a pressure regulator and gauge (7), complemented by valves (8) and flexible tubing (9) to ensure safe and precise delivery into the cell. The electrical output was monitored with a multimeter (4) and captured via a data logger (5), while a breadboard (6) assisted connections to the load through an auxiliary circuit interface. This arrangement enabled precise control of operating parameters and assisted dependable data collection throughout the experiment.

2.3 Electrode Preparation

The electrodes of alkaline fuel cells are composed of multiple layers of polytetrafluoroethylene (PTFE) bonded with carbon black. This three-layer structure serves several important functions and typically consists of an active layer, a gas diffusion layer, and a support material. Each layer contributes to the overall performance of the fuel cell by facilitating electron transfer, gas transport, and mechanical stability [18]. The double-layer electrode design is more commonly employed than the single-layer configuration, although more advanced designs may be utilized depending on the application's requirements. An effective double-layer electrode should feature a backing

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 320-330

material that permits efficient gas permeation, provides high electrical conductivity, and offers mechanical durability. In monopolar configurations, the backing material also functions as a current collector. Therefore, metal screens or meshes, typically composed of nickel, are often used to fulfill this dual role [19].

In this study, the catalyst layer was made using nickel powder (LOBA Chemie) as the active ingredient, carbon black (Vulcan N330, CABOT) as a conductive support, and polytetrafluoroethylene (PTFE) as a binder. Nickel was chosen because it is relatively less expensive than platinum-based catalysts, yet still exhibits adequate catalytic activity in alkaline media. Carbon black was used to increase surface area and enhance electron conductivity, while PTFE was added to provide mechanical integrity and hydrophobicity. The materials were mixed with isopropyl alcohol to produce a uniform slurry, which was then manually rolled onto a stainless steel mesh to form a sheet. The stainless steel mesh functions not only as a mechanical support but also as a current collector, owing to its excellent electrical conductivity. The active surface area of the electrode measures 50 × 60 mm. Catalyst electrodes were fabricated in three different formulations containing 0%, 10%, and 20% nickel by weight, to examine how varying the Ni/C ratio influences the electrochemical performance of AFC systems [20]. A concentration of 0% was chosen to determine whether nickel actually affects the performance of the AFC system, and 20% was chosen as the highest concentration only to determine whether an increase in concentration affects performance. Further research is needed to find the highest concentration that produces maximum performance and durability of the electrodes produced.

The gas diffusion layer, composed of a highly hydrophobic carbon material, plays an important role in assisting efficient gas transport, preventing electrolyte penetration, and offering structural support to the catalyst layer. This layer is fabricated by blending carbon black with PTFE in a weight ratio of 4 grams and incorporating isopropyl alcohol to achieve the desired consistency. To form the gas diffusion electrode (GDE), the catalyst layer and the GDE layer are carefully assembled onto a stainless steel mesh measuring 60 x 70 mm and 100 mesh. The assembly is subsequently pressed using a specialized press tool and heated at 320°C in a furnace for 30 minutes, imparting hydrophobic properties to the structure. A schematic illustration of the electrode configuration is provided in Fig. 3.

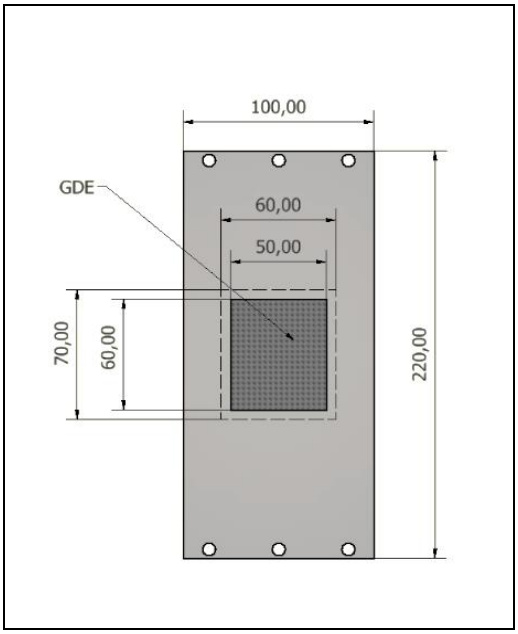

Fig. 3 *Electrode scheme*

2.4 Experimental Procedure and Data Collection

In this study, data collection was carried out indoors in an enclosed room between 7:00 PM and 12:00 AM (WIB) to maintain consistent environmental conditions throughout the experiment. A 30% potassium hydroxide (KOH) solution was used as the electrolyte, while gas diffusion electrodes (GDE) with an active surface area of 3000 mm^2 were employed. The cathode catalyst consisted of a 10% concentration of manganese dioxide/carbon (MnO_2/C). The experiment began when hydrogen and oxygen gases were supplied to the alkaline fuel cell, with an electrical load. Output data in the form of electric current (mA) and voltage (mV) were recorded at 2-minute intervals over 10 minutes. Each variation of the catalyst sample was tested three times to ensure data reliability and reproducibility, with all measurements conducted under controlled environmental conditions. The experimental procedure began with the preparation of the Ni/C catalyst and electrode assembly as described in Section 2.2.

After electrode fabrication, the alkaline fuel cell stack was assembled with stainless steel plates and gaskets to prevent leakage. The electrolyte solution was prepared by dissolving 30% potassium hydroxide (KOH) and subsequently introduced into the cell compartment. Hydrogen and oxygen gases were supplied from high-purity cylinders via regulators and pressure gauges, with valves regulating the flow into the anode and cathode chambers.

During operation, hydrogen was introduced to the anode and oxygen to the cathode at ambient pressure. A multimeter and data logger were connected to monitor voltage and current continuously. A breadboard and LED load were used to complete the external circuit. Each experiment was conducted for 10 minutes, with measurements recorded every 2 minutes to evaluate the voltage, current, and efficiency under different catalyst compositions. To ensure reliability, each variation of the catalyst sample was tested three times under controlled indoor conditions.

2.5 Equations

Electrical power (W_{el}) is the product of current and voltage generated by fuel cells as stated in equation (1) [21].

$$W_{el} = V \times I \tag{1}$$

In Equation (1), (W_{el}) represents the electrical power output generated by the fuel cell, measured in Watts. The symbol V denotes the electrical voltage in Volts (V), while I refers to the electric current flowing through the circuit, measured in Amperes(A).

Fuel cell efficiency is defined as the ratio of the electrical energy produced to the amount of hydrogen consumed. To calculate the fuel cell efficiency, Equation (2) can be used.

$$\eta = \frac{W_{el}}{W_{H2}} \tag{2}$$

Hydrogen consumption according to Faraday's law is directly proportional to the current generated. Therefore, it can be written in equations (3) and (4).

$$N_{H2} = \frac{I}{nF} \tag{3}$$

$$W_{H2} = \Delta H \frac{I}{nF} \tag{4}$$

According to [21], $\frac{\Delta H}{nF}$ has dimensions of volts, and the value ΔH = 286 kJ mol^{-1} has a value of 1.482 V in HHV (Higher Heating Value), which is referred to as thermoneutral potential. By combining equations (1) to (4), fuel cell efficiency is directly proportional to electrical voltage. This can be written in equation (4).

$$\eta = \frac{V}{1{,}482} \tag{5}$$

Where η denotes the efficiency of the fuel cell (%) and represents the fraction of chemical energy from hydrogen converted into electrical energy. W_{H2} is the energy rate of hydrogen consumption, expressed in Joules per second (J/s) or Watts. The parameter n refers to the number of electrons transferred per reaction, which in this study is taken as 2. F is Faraday's constant (96,485 C/mol), used to relate the amount of electric charge to the number of moles of electrons. N_{H2} represents the molar flow rate of consumed hydrogen (mol/s), and ΔH is the higher heating value (HHV) of hydrogen, defined as 286 kJ/mol. Equation (5) indicates that the theoretical efficiency of a fuel cell is directly proportional to its output voltage. The voltage used in Equation (5) refers to the actual voltage obtained from the output of the fuel cell system. In this calculation, it is assumed that the fuel (hydrogen) is completely converted within the fuel cell without any loss or waste of reactants. This assumption represents an ideal condition in which the entire chemical energy contained in the hydrogen is fully converted into electrical energy.

3. Results and Discussions

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 320-330

3.1 Voltage

Based on the graph in Fig. 4, it is clear that increasing the concentration of nickel (Ni) in the Ni/C catalyst notably enhances the voltage output of the alkaline fuel cell. As shown in Fig. 4(a), the catalyst with no nickel content (0%) exhibits the lowest peak voltage, registering at just 8.40 mV. When the Ni concentration is increased to 10%, the voltage rises sharply to 33.41 mV, and further increases to 111.17 mV at 20% Ni concentration. This represents an approximate voltage increase of 297.7% from 0% to 10% Ni, and 232.7% from 10% to 20% Ni. These results indicate a clear enhancement in cell performance with higher nickel loading. Fig. 4(b) shows the voltage response over 10 minutes for each catalyst variation. The trend shows that voltage consistently increases with time across all variations, with the steepest rise occurring in the 20% Ni sample. At minute 2, the 20% Ni catalyst already reaches 18.43 mV, far surpassing the other samples. By minute 10, it peaks at 111.17 mV, compared to 35.38 mV for the 10% Ni and only 8.40 mV for the 0% Ni catalyst. This time-based voltage development indicates that catalysts with higher nickel content not only produce greater voltage output but also reach peak performance more rapidly.

The upward trends observed in both graphs are primarily driven by the catalytic role of nickel in the hydrogen oxidation reaction (HOR). Nickel offers an increased number of active sites for hydrogen adsorption (H_{ads}), which then interacts with hydroxide ions (OH^-) within the electrolyte to produce water and assist electron release. This mechanism contributes directly to higher voltage generation. In addition, nickel reduces the activation energy of electrochemical reactions [11]; [22], thereby accelerating reaction rates and enhancing electron production. In conclusion, both Fig. 4(a) and Fig. 4(b) confirm that increasing the nickel content in the Ni/C catalyst improves the electrochemical performance of the alkaline fuel cell in terms of both voltage magnitude and response time. This supports the use of nickel as an effective and economically favorable catalyst for improving fuel cell efficiency.

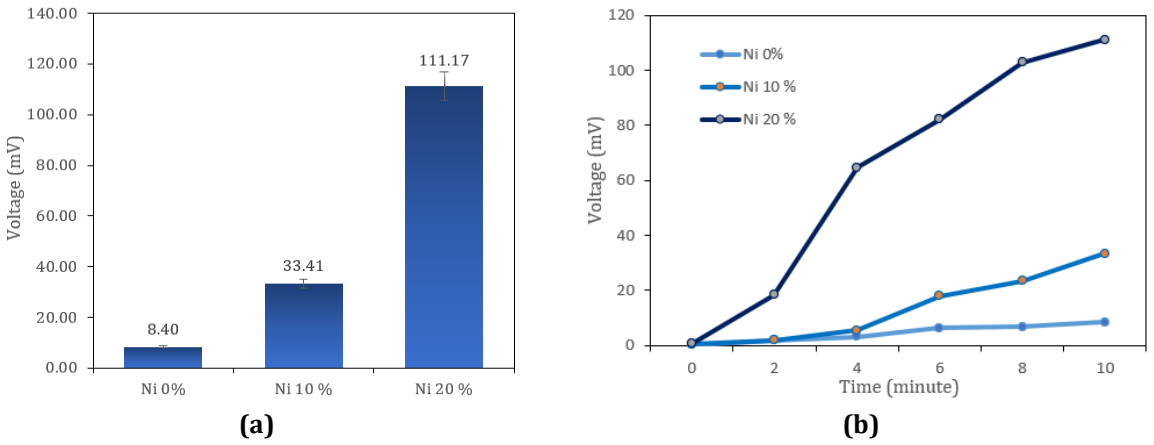

Fig. 4 *Comparison of voltage at different Ni/C variations (a) Maximum voltage; (b) Voltage vs. experimental time*

3.2 Current Density

In this study, current density served as a primary indicator to assess how the composition of Ni/C catalysts influences the overall performance of an alkaline fuel cell. It was determined by dividing the electric current generated by the electrode surface area, which allowed for consistent comparisons across varying experimental conditions. As shown in Fig. 5(a), an increase in nickel concentration in the catalyst corresponds with a rise in electric current density. The catalyst with 0% nickel produced a maximum current density of 0.0037 mA/cm^2. Increasing the nickel concentration to 10% resulted in a current density of 0.0057 mA/cm^2. The highest performance was observed at 20% nickel, with a peak current density of 0.0073 mA/cm^2. This represents a 100% increase compared to the variation without nickel, which highlights the crucial role of nickel in enhancing electrochemical reactions. Meanwhile, Fig. 5(b) shows the current density trend over time during the 10-minute experimental period. All samples exhibited an increase in current density over time, with the most significant growth observed in the 20% nickel sample. At the two-minute mark, all samples experienced a rapid initial increase; however, the 20% nickel sample consistently maintained the highest current density throughout the experiment. This trend suggests that nickel improves not only the current output but also the stability of fuel cell performance.

The observed rise in electric current correlates well with the voltage variations across different catalyst formulations, in line with Ohm's law, which establishes that current is directly proportional to voltage when resistance remains unchanged. It is important to recognize, however, that the magnitude of the current is also affected by the resistance present in the electrical circuit, such as contact resistance and internal cell resistance,

which can be limiting factors for the maximum current achievable. Overall, Fig. 5 clearly supports the conclusion that increasing the nickel concentration in the Ni/C catalyst markedly improves the performance of the alkaline fuel cell, both in terms of voltage output and current density.

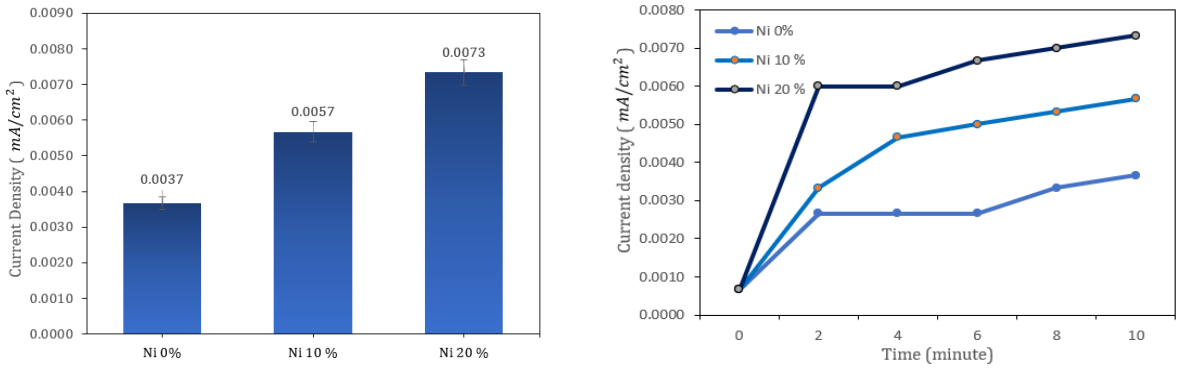

Fig. 5 *Comparison of current density at different Ni/C variations (a) Current density; (b) Current density vs. experimental time*

3.3 Electrical Power

The amount of electrical power generated can be shown through the graph in Fig. 6. Catalyst variation with a nickel concentration of 0% (without nickel) produces the highest electrical power of 9.24×10^{-4} mW. Catalyst variation with a nickel concentration of 10% generates the highest electrical power of 56.80×10^{-4} mW. Catalyst variation with a nickel concentration of 20% produces the highest electrical power of 244.57×10^{-4} mW.

The electric power generated by the alkaline fuel cell increases with the addition of nickel concentration provided at the anode. A significant increase in electric power occurred with the highest nickel concentration given in this study, which is 20%, reaching the highest electric power of 244.57×10^{-4} mW. The power increase from the variation of 0% to 10% Ni is 533%, while from the variation of 10% to 20% Ni it is 330%. The data illustrated by the graph indicates that increased nickel concentration correlates with higher electrical power output. Specifically, as the concentration of nickel rises, both the voltage and current produced by the fuel cell also increase proportionally. This relationship can be proven through Equation (1), which demonstrates that the electrical power generated is the product of voltage and current from the fuel cell [10]. These findings align with the results of this study, where the alkaline fuel cell achieved its highest current and voltage outputs at a nickel catalytic concentration of 20%.

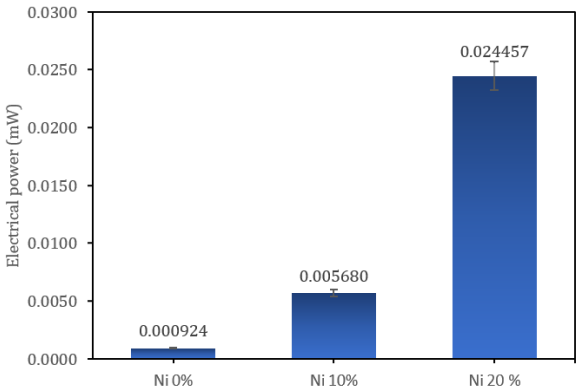

Fig. 6 *Comparison of the electrical power of AFC at different Ni/C variations*

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 320-330

3.4 Alkaline Fuel Cell Efficiency

The efficiency of a fuel cell is essentially the ratio of electrical energy produced to the amount of hydrogen fuel consumed. It reflects how effectively the fuel cell converts the chemical energy stored in the hydrogen into usable electrical power. The resulting efficiency can be illustrated in a graph in Fig. 7. The highest electrical power in the catalyst variations with nickel concentrations of 0%, 10%, and 20% occurs at the 10th minute. The catalyst variation with a nickel concentration of 0% (without nickel) generates the highest efficiency of 0.57%. The catalyst variation with a nickel concentration of 10% achieves an efficiency of 2.39%. The catalyst variation with a nickel concentration of 20% produces the highest efficiency of 7.50%.

Based on the graph presented in Fig. 7, the efficiency of the alkaline fuel cell shows an increase as the concentration of nickel (Ni) catalyst at the anode increases. This efficiency is calculated using an equation that utilizes the output of the alkaline fuel cell in the form of electric voltage as the main variable. The highest efficiency increase of 7.50% is achieved at a nickel concentration variation of 20%, which also produces the largest electric voltage in this study. Overall, from the variation of 0% to 20% Ni, there is a 1216% increase in efficiency. This efficiency increase can be explained by nickel's ability to enhance the rate of electrochemical reactions in the alkaline fuel cell, as reported by [20]. This study clearly demonstrates that employing a nickel catalyst at an optimal concentration can notably enhance the performance and overall efficiency of the alkaline fuel cell, as reflected by the observed increase in efficiency.

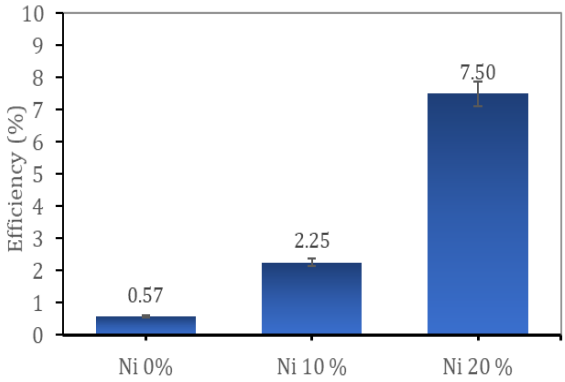

Fig. 7 *Efficiency of an alkaline fuel cell at different Ni/C variations*

It is important to emphasize that the alkaline fuel cell evaluated in this study was constructed with a single-cell stack and did not incorporate bipolar plates. Consequently, the active surface area available for the electrode was limited, as was the gas coverage, which contributed to a relatively high internal resistance within the cell. These limitations were among the reasons the power and efficiency were low, with a maximum efficiency of only 7.5 %. Despite these constraints, this work presents an effective endeavor to illustrate the impact of Ni/C catalyst variation on the electrochemical properties of a simple and low-cost AFC prototype, which can be a platform for further study in the future. Furthermore, the observed performance trends are consistent with earlier studies [16], confirming that the addition of carbon black enhances catalytic activity by improving conductivity and hydrogen adsorption.

4. Conclusion

Based on the results of this study, it can be concluded that increasing the concentration of nickel catalyst on the anode of an alkaline fuel cell significantly enhances its performance. Higher nickel concentrations lead to increased electrical voltage due to the expansion of the reactive surface area, which facilitates hydrogen absorption and electrochemical reactions, thereby generating more electrons. Additionally, the electrical current also increases proportionally with voltage, in accordance with Ohm's law, supported by the improved electrical conductivity at the anode. The highest electrical voltage achieved was 111.17 mV, while the maximum current reached 73×10^{-4} mA/cm^2. Moreover, fuel cell efficiency improved with increasing nickel concentration, with the highest efficiency of 7.50% recorded at 20% nickel. These findings confirm the effectiveness of nickel as a non-noble metal catalyst in enhancing voltage, current, and overall efficiency of the alkaline fuel cell.

Even though this study shows that Ni/C catalysts have potential for AFCs, more advancements are needed to reach higher performance. Future studies should look for ways to optimize the catalyst microstructure, like lowering the size of the nickel particles, alloying them with other transition metals (like Co or Fe), or changing the

carbon support to improve conductivity. To assess catalyst stability and electrolyte management, long-term durability tests conducted under continuous operation are also required. These findings highlight the feasibility of low-cost Ni/C catalysts for AFC applications, although optimization is required for large-scale implementation.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***supervision and project administration:*** *Nasrul Ilminnafik,* ***study conception and design:*** *Nasrul Ilminnafik, Raafi Aditya Nugraha, M. Rifqy Alfariz, Digdo Listyadi Setyawan, M. Khadafi Ibnu;* ***data collection:*** *Raafi Aditya Nugraha, M. Rifqy Alfariz, M. Khadafi Ibnu;* ***analysis and interpretation of results:*** *Nasrul Ilminnafik, Raafi Aditya Nugraha, M. Rifqy Alfariz, M. Khadafi Ibnu;* ***draft manuscript preparation:*** *Nasrul Ilminnafik, M. Rifqy Alfariz, Raafi Aditya Nugraha, Digdo Listyadi Setyawan, M. Khadafi Ibnu. All authors reviewed the results and approved the final version of the manuscript.*

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