

Experimental Study of Electrical Energy Generation Using a Simple Aluminum-Carbon Electrochemical Cell in Saline Solution

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ABSTRACT

This study investigates the feasibility of electrical energy generation using a low-cost aluminum–carbon electrochemical cell operating in a saline electrolyte. The experimental setup consisted of aluminum foil as an anode, a carbon rod as a cathode, and a NaCl aqueous solution. Electrical performance was monitored over a three-week period through voltage and current measurements. The system produced an initial open-circuit voltage of up to 20 V and was capable of powering a low-power load. However, the output current remained limited (0.015–0.033 A), significantly restricting practical applications. Strong voltage fluctuations were observed, particularly during morning measurements, with a minimum voltage of 5.8 V, attributed to electrode degradation and electrolyte depletion. Despite these limitations, the system demonstrates potential for educational purposes and low-power backup applications. The integration of a battery storage system improved supply continuity. The study highlights both the feasibility and intrinsic limitations of rudimentary aluminum-based electrochemical energy systems.

Keywords: Electrochemistry; Aluminum-based cells; Saline electrolyte; Low-cost energy systems; Voltage instability

INTRODUCTION

The continuous growth of global electricity demand, coupled with environmental concerns and unequal access to modern energy services, has intensified interest in alternative and decentralized power generation technologies. In many developing regions, a significant portion of the population still experiences limited or unreliable access to electricity, which motivates the exploration of low-cost, small-scale energy generation systems capable of meeting basic power needs [1]. Within this context, electrochemical energy conversion systems offer a direct and efficient means of transforming chemical energy into electrical energy.

Electrochemical cells operate through redox reactions occurring at the electrode–electrolyte interfaces, generating an electromotive force via electron transfer between an anode and a cathode [2]. Advanced electrochemical technologies, such as lithium-ion batteries and fuel cells, exhibit high energy densities and long cycle lives; however, their widespread adoption is often constrained by high costs, complex material requirements, and strict operating conditions [3]. In contrast, simple electrochemical systems employing abundant materials and aqueous electrolytes provide an accessible platform for experimental investigation, educational applications, and proof-of-concept studies [4].

Among metallic anode materials, aluminum has attracted considerable attention due to its high theoretical specific energy, natural abundance, low cost, and recyclability [5]. Aluminum-based electrochemical cells rely on the anodic oxidation of aluminum in an aqueous electrolyte, releasing electrons that can be harnessed for electrical power generation. Despite these advantages, practical aluminum-based systems suffer from intrinsic limitations, including rapid anodic passivation caused by aluminum hydroxide formation, low current density, electrolyte depletion, and significant voltage instability during prolonged operation [6–8]. These phenomena

lead to increased internal resistance and performance degradation, severely restricting long-term and high power applications.

Nevertheless, aluminum-based electrochemical cells remain of interest for low-power and short-duration applications, particularly in educational contexts and emergency or backup energy scenarios. Several studies have demonstrated that even rudimentary aluminum-based systems can generate measurable electrical output when combined with simple electrolytes such as sodium chloride solutions, although with limited efficiency and stability [7,9]. A detailed experimental characterization of voltage evolution, current output, and degradation behavior is therefore essential to better understand the realistic capabilities and constraints of such systems.

In this study, an experimental investigation of a low-cost aluminum–carbon electrochemical cell operating in a saline aqueous electrolyte is presented. The system employs aluminum foil as the anode, a carbon rod as the cathode, and a sodium chloride solution as the electrolyte. Electrical performance, including voltage and current output, was monitored over a three-week period under ambient conditions. The main objectives are to assess the feasibility of sustained electrical energy generation, analyze temporal voltage instability and degradation mechanisms, and evaluate the contribution of energy storage integration to improve supply continuity. By highlighting both the potential and inherent limitations of rudimentary aluminum-based electrochemical systems, this work contributes to a clearer understanding of their applicability in small-scale and low-cost energy generation contexts.

METHODOLOGY

Materials and Equipment

The experimental setup is based on the design of electrochemical cells using a saline solution ($H_2O + NaCl$) as the electrolyte, in which the oxidation of aluminum foil (anode) and the reduction occurring at the carbon rod (cathode) generate an electron flow. Electrical connectivity is ensured by conductive wires, while a multimeter and an indicator lamp are used to monitor electrical performance (voltage and current) in real time.

To optimize the utilization of the generated energy, the cells are arranged in an expandable architecture evolving from two strings of six (6) cells to two strings of twelve (12) cells, thereby increasing the overall output voltage. The circuit is coupled with a charge controller, a storage battery, and a power converter, ensuring stable and usable distribution of the generated electricity. Some of the materials and equipment used are illustrated in the following figures.

Figure 1: Selected Materials: (a) Anode: Aluminum (Aluminum Foil), (b) Cathode: Battery Rod (Carbon), and (c) Electrolytic Solution ($H_2O + NaCl$).



a)

b)

c)

Assembly and Experimental Protocol

The implementation of the system begins with the configuration of the electrochemical cells, whose operating principle relies on the redox reaction between aluminum and carbon. The first phase consists of preparing the electrolyte by dissolving two (02) tablespoons of sodium chloride ($NaCl$) in a container holding 180 mL of water (H_2O) until saturation, thereby ensuring optimal ionic conductivity for charge transport. Once the solution is prepared, the electrodes are assembled by immersing the aluminum foil, acting as the anode, and the carbon rod, serving as the cathode. Care is taken to ensure that these elements are securely fixed and electrically insulated from each other. Sodium chloride ($NaCl$) was dissolved in distilled water at a

concentration corresponding to saturation at room temperature ($\approx 6.1 \text{ mol/L}$). Aluminum foil with an estimated active surface area of 30 cm^2 was used as the anode, while a commercial carbon rod served as the cathode.

To convert the low voltage produced by a single cell into an energy source capable of charging a battery, the cells were organized into “strings” combining series and parallel connections. Initially, Configuration 1 (2×6) consisted of coupling two groups of six cells connected in series, followed by connecting these two branches in parallel. This configuration allowed the stabilization of the voltage of six cells while doubling the available current. Subsequently, Configuration 2 (2×12), composed of two groups of twelve cells connected in series and arranged in parallel, enabled a significant increase in the electromotive force. This voltage enhancement was essential to reach the threshold required by the charge controller, typically set at 12 V or 24 V , thus ensuring efficient energy transfer to the storage system.

The final phase aims to stabilize and convert the chemical energy produced into an electrical power source compatible with household appliances. The installation begins with connecting the output of the battery circuit to the “Source” input of the charge controller. The battery is then connected to the controller to serve as a buffer storage unit, compensating for the natural fluctuations in the output of the saline cell. Finally, a power converter is connected to the battery terminals to transform direct current (DC) into alternating current (AC), enabling the supply of standard electrical equipment according to demand. For an improvement in the design of the proposed device, we are incorporating a closed, anti-evaporation chamber made from corrosion-resistant materials. This modification aims to maintain a stable ion concentration and constant conductivity over long periods of operation.

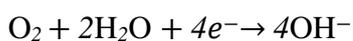
Operating Principle

In this cell, electrical energy is generated through the consumption of the aluminum anode. Unlike conventional batteries, the oxidant (oxygen) is not stored within the cell but is instead supplied directly from the ambient air.

At the anode (negative electrode): Aluminum undergoes oxidation. Aluminum atoms release electrons and are converted into ionic species according to the following reaction:



At the cathode (positive electrode): Oxygen from the air diffuses into the carbon rod, which acts as a porous catalytic electrode, and reacts with water molecules in the electrolyte by accepting electrons:

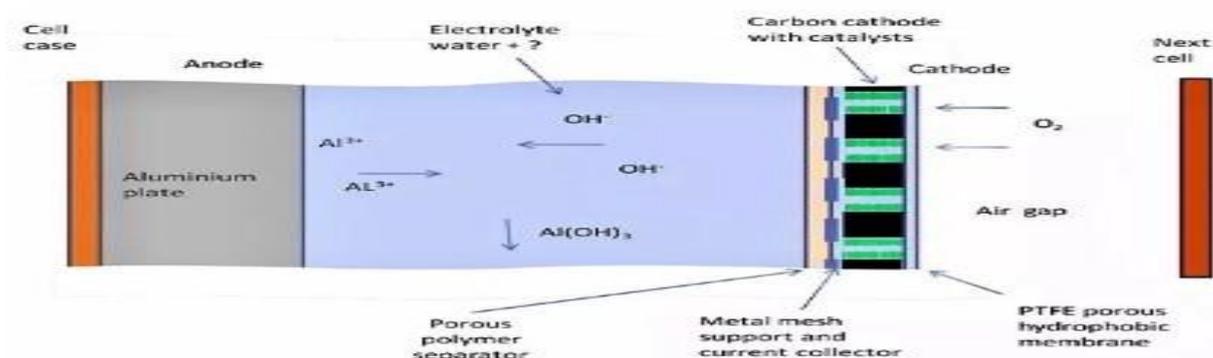


Overall reaction: Aluminum is progressively converted into aluminum hydroxide, which appears as a white precipitate, while electrical current is generated in the external circuit:



A schematic representation of the operating principle of the aluminum–air cell is shown in the figure below.

Figure 2: Schematic diagram illustrating the operating principle of an aluminum–air battery.



RESULTATS AND DISCUSSION

Initial Electrical Performance

The measurements and analysis of the electrochemical cell performance recorded over a three-week period are presented in the following tables.

Table 1. Voltage values recorded during the first week.

	Saturday 26/04/25	Sunday 27/04/25	Monday 28/04/25	Tuesday 29/04/25	Wednesday 30/04/25	Thursday 01/05/25	Friday 02/05/25
Morning	20,0V	13,7V	11,7V	13,6V	11,4V	11,1V	11,3V
Evening	18,4V	12,1V	16,7V	12,7V	13,1V	13,5V	11,6V

Table 2. Voltage values recorded during the second week.

	Saturday 03/05/2025	Sunday 04/05/2025	Monday 05/05/2025	Tuesday 06/05/2025	Wednesday 07/05/2025	Thursday 08/05/2025	Friday 09/05/2025
Morning	12,2V	08,6V	12,8V	11,2V	11,3V	14,6V	16,2V
Evening	14 ,8V	15,6V	14,4V	13,6V	16 ,6V	17,4V	15,8V

Table 3. Voltage values recorded during the third week.

	Saturday 10/05/2025	Sunday 11/05/2025	Monday 12/05/2025	Tuesday 13/05/2025	Wednesday 14/05/2025	Thursday 15/05/2025	Friday 16/05/2025
Morning	09,3V	16,6V	16,9V	14,6V	10,1V	05,8V	13,6V
Evening	17,5V	17,1V	16,5V	9,7V	14,9V	15,9V	16,4V

The voltage variation over the three-week monitoring period, with both morning and evening measurements, is illustrated in Figure 3.

Figure 3. Voltage variation over three weeks.

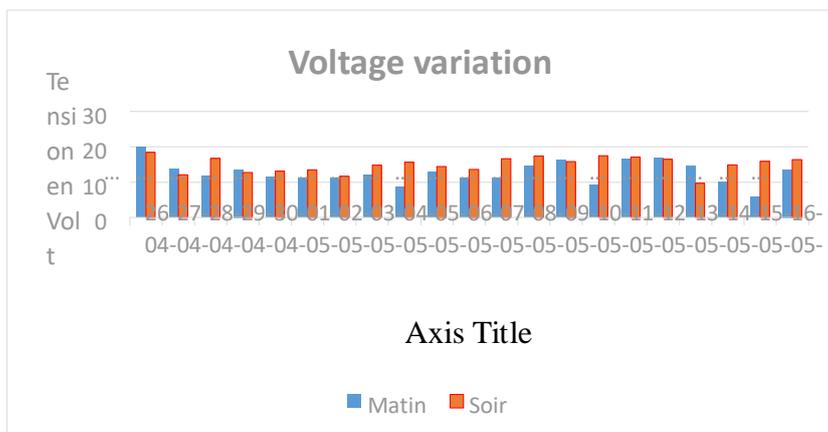


Fig. 3 shows the temporal evolution of the output voltage over three weeks under open-circuit conditions.

The graph reveals a progressive overall voltage decay, punctuated by occasional recoveries and marked instability. These behaviors are mainly associated with electrode degradation and variations in environmental conditions. The maximum voltage observed was 20 V on 26/04/25, while the minimum voltage reached 5.8 V

on the morning of 15/05/25. In general, higher voltage values were recorded in the evening (13–17 V), whereas stronger fluctuations were observed during morning measurements in weeks 2 and 3.

The higher evening voltages may be attributed to improved thermal stabilization and enhanced ionic diffusion within the electrolyte. Conversely, the abrupt voltage drop to 5.8 V is likely due to local anode depletion or partial drying of the electrolyte. The low measured current values further confirm that this system is only capable of supplying very light electrical loads.

Regarding system limitations, a rapid degradation of materials, intermittent energy production, strong performance variability, and uncontrolled experimental conditions, such as temperature fluctuations and electrolyte evaporation were observed.

Rapid switching phenomena and instability associated with the use of aluminum with NaCl electrolyte are examined, along with a comparative analysis including other electrochemical couples, notably Zn–Cu, as well as KCl electrolyte. This analysis relies on standard electrochemical potentials, chemical stability, and performance reported in the literature. Li (2020) experimentally compared the influence of different electrolytes on a Zn–Cu cell, showing that the electrolyte composition alters the output voltage and, in terms of performance, demonstrated that potassium hydroxide is a superior electrolyte for the Cu–Zn battery compared to NaCl. The effect of anions (notably chloride) on current rates and resistance in Cu–Zn electrochemical deposits, shedding light on the role of chloride-based electrolytes, is analyzed in [13]. See Table 4.

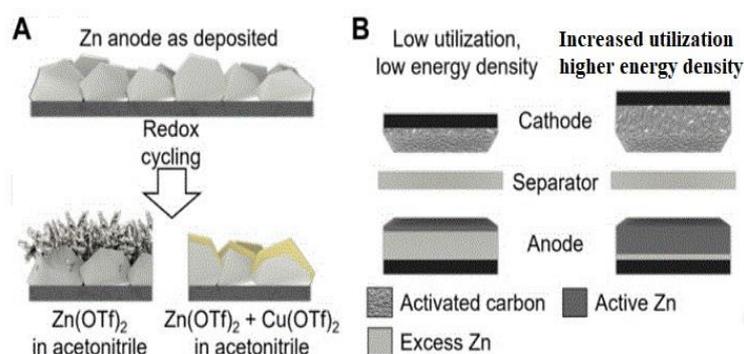
Table 4 Summary of the issues to handle (depending on the compound and/or additive) with the selected electrolyte for secondary zinc-based battery applications.

Electrolyte Issues	AQUEOUS			NON-AQUEOUS			
	Alkaline	Neutral	Acid	SPE	GPE	RTILs	DES
Formation of carbonates	X						
Hydrogen evolution reaction	X	X	X				
Dendrite formation	X		X				
Low solubility of zinc salt				X	X		
Ionic conductivity ($S\text{cm}^{-1}$) ^a	0.5–0.6	0.2–0.3	0.5–0.7	10^{-8} – 10^{-6}	10^{-4} – 10^{-3}	10^{-5} – 10^{-2}	10^{-5} – 10^{-3}
Sensitive to impurities – high purity and expensive products are required –						X	
Lower temperature range	X	X	X				
High viscosity				X	X	X	X
Limited electrochemical window	X	X	X				
Water evaporation or ambient moisture uptake	X	X	X			X	

Mainar et al. (2017) provide a review of electrolytes for zinc-air systems, highlighting the importance of electrolyte choice for durability and electrochemical efficiency. Multi-ion electrolytes improve the stability of Zn–Cu cells by reducing side reactions such as dendrite formation, as demonstrated in the literature [14].

Figure 4. Dendrite problems and low anode utilization in zinc-ion devices.

- (A) Concept of using a dual-ion electrolyte to suppress dendrite formation.
- (B) Minimizing excess zinc capacity by plating and stripping the top portion of the anode to increase areal energy density.



Controlled environmental tests will be introduced to isolate the effect of temperature and humidity on the observed voltage fluctuations. An analysis of the influence of temperature on electrochemical kinetics and ionic conductivity, as well as of humidity on electrolyte evaporation and corrosion processes, will be added and discussed in light of the experimental results and compared with data from the literature.

The formation of a white precipitate of aluminum hydroxide ($\text{Al}(\text{OH})_3$) on the anode surface is a common chemical phenomenon associated with aluminum corrosion in aqueous media. Recent studies show that this precipitate develops through pH- and potential-dependent mechanisms, altering the surface layer structure and influencing corrosion kinetics [16]. XPS analyses have also revealed that these passivating layers contain aluminum hydroxide compounds that affect corrosion by blocking or altering active sites.

The self-corrosion behavior, electrochemical properties, composition and microstructure of the alloys, and their relationships, were systematically investigated using a hydrogen collection method, electrochemical measurements, and multiple characterization studies. The results show that the aluminum alloy exhibits a low hydrogen evolution rate and superior electrochemical performance. The hydrogen evolution reaction is inhibited by increasing the current density. The appropriate anode exhibits high anodic efficiency [17].

CONCLUSION

This study demonstrates that a simple aluminum–carbon electrochemical cell is capable of producing a usable voltage; however, its performance remains constrained by low current output and significant instability. The device represents an accessible alternative for educational purposes, awareness-raising on renewable energy concepts, or as a very low-power auxiliary energy source. System stability can be enhanced through the integration of an energy storage device and the use of more efficient materials.

From a future perspective, the use of more effective electrode pairs such as Zn–Cu, graphite, or porous carbon is proposed, along with improvements in the electrolyte composition, including potassium chloride (KCl) or highly diluted sulfuric acid. The systematic incorporation of a battery to compensate for voltage fluctuations, as well as the design of an anti-evaporation and anti-corrosion enclosure, are also recommended to improve overall system reliability and performance.

The possibility of using a more robust catalytic cathode, such as a porous carbon with enhanced oxygen diffusion, can be considered. This approach could help to increase the limiting current density and improve the overall performance of the system, as widely reported in studies on metal-air batteries [16]. This improvement represents an important direction for future developments.

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