EVALUATING THE PRACTICAL VIABILITY OF ALUMINUM-AIR BATTERIES IN REAL-WORLD APPLICATIONS

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DOI: https://www.doi.org/10.56726/IRJMETS47396

ABSTRACT

The growing global population and petroleum use are contributing factors to serious environmental issues like climate change. Reducing dependency on petroleum can be achieved, for example, by producing big-capacity batteries that can be used in electrical applications. Because aluminum-air batteries have a theoretical energy density of 8.1 kWh kg⁻¹, which is far higher than that of present lithium-ion batteries, they are considered promising for use in next-generation energy storage applications. An aluminum-air battery, which is a promising form of energy storage, uses aluminum as the anode and ambient air as the cathode. This abstract emphasizes the key characteristics of aluminum-air batteries while highlighting their potential advantages, challenges, and applications. These batteries appeal to a range of enterprises due to their high energy density, lightweight, and environmental friendliness. However, there are issues that need to be resolved, such as impediments to real-world deployment and short cycle times. Research to improve the performance and economic viability of aluminum-air batteries is underway, with a focus on uses in electric vehicles, portable gadgets, and renewable energy systems. This abstract provides a concise overview of this revolutionary energy storage technology with insights into its current state and potential.

Keywords: Aluminum, Graphite, Non-Toxic, Sodium Hydroxide, Eco-Friendly, Non-Rechargeable, Battery.

I. INTRODUCTION

The increase in energy demands from modern lifestyles and industrial needs have been a huge driving force to keep progress in advanced energy research for many years. Tremendous effort has been put into research and creating new energy sources as well as energy storage with high capacity and compact in size so that it is portable, the energy source also needs to be low cost and green. Metal air cells, featuring high energy density, have received much interest from the research community and have been predicted to be the next energy source for electric vehicles, suitable for energy storage and can also be used as an emergency power supply.

An energy storage and conversion system with high energy density is developed to fulfill the demand and the need appliances that require portable energy. Metal such as iron, zinc, magnesium, and aluminum, are some of the best materials for use in next-generation sustainable batteries. The reason is due to their abundance, the metal’s recyclability, the low weight of the metal, and the cost of these metals. Metal-air batteries is one of the most talked about energy storage system among all the new energy storage systems because of their high energy density and capacity.

Table 1. Parameters of different metal-air batteries

<table>
<thead>
<tr>
<th>Batteries</th>
<th>Theoretical Voltage (V)</th>
<th>Theoretical specific capacity (Ah Kg⁻¹)</th>
<th>Theoretical energy density (kWh kg⁻¹)</th>
<th>Practical operating voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-air</td>
<td>3.4</td>
<td>1170</td>
<td>13</td>
<td>2.4</td>
</tr>
<tr>
<td>Zn-air</td>
<td>1.6</td>
<td>668</td>
<td>1.3</td>
<td>1-1.2</td>
</tr>
<tr>
<td>Mg-air</td>
<td>3.1</td>
<td>920</td>
<td>6.8</td>
<td>1.2-1.4</td>
</tr>
<tr>
<td>Na-air</td>
<td>2.3</td>
<td>687</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Al-air</td>
<td>2.7</td>
<td>1030</td>
<td>8.1</td>
<td>1.2-1.6</td>
</tr>
</tbody>
</table>

Among the metal-air batteries, Al-air batteries hold the highest potential for future large-scale energy applications because of the abundant of aluminum, to battery’s low cost, and the high theoretical specific capacity of 1030Ah kg⁻¹, which is the only lower than lithium-air battery and higher than magnesium base and zinc base metal air battery shown in Table 1.
The Al-Air Battery is composed of an aluminum metal anode, an air cathode, and an electrolyte, a typical electrolyte is an aqueous alkaline solution such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) or sometimes sodium chloride (NaCl) solutions can be used.

Al-Air batteries are now being created for stationary applications as well as for usage as the main power sources in various application Regardless of the electrolyte’s type (acidic, neutral, or alkaline) these main cells are constructed from an anode made of aluminum alloy and a cathode that is solely used for that purpose. The advantages of this system over other metal-air batteries include the extremely high theoretical energy density of the fuel, the air cathode's uni-functional mode of operation which ensures a longer life than that of the bi-functional counterpart, and the fact that the system is mechanically rather than electrically recharged. This final point is extremely important because it should be possible to recharge an Al-Air Battery in a time frame similar to that of an Internal Combustion Engine, which is only a very short amount of time.

Energy storage technology has advanced significantly as a result of the global search for environmentally acceptable and sustainable energy sources. The Aluminum-Air battery stands out as a prospective contender among these developments because of its high energy density and potential for environmental sustainability. Understanding the nuances of aluminum-air battery technology is crucial as the globe struggles with the need for alternative clean energy sources and a decrease in greenhouse gas emissions. This article seeks to offer light on the science, difficulties, and practical uses of this ground-breaking energy storage method.

Numerous studies shown that the electrolyte being used has a significant impact on the electrochemical behaviors of aluminum. While lowering its rate of corrosion, an effective electrolyte system should maintain the electrochemical activity of the aluminum anode. In the paper, a brand-new electrolyte system based on Sodium chloride solutions was suggested. As the conductivity of the electrolyte and the hydration of the surface product layer are reduced when water is substituted for solvents, these solutions practically prevented the corrosion of aluminum. After adding water to the alkaline alcohol solutions, the electrolyte's ionic conductivity increased. The highest electrolytic conductivity of the preferred electrolytes for the Al-Air Battery are 4M NaOH and 7M KOH. KOH solution However, the industrial technique cannot recycle alumina in KOH solution. This is significant since the large manufacture of Al-air batteries calls on the recycling of used electrolytes.

The high energy density of aluminum-air batteries allows them to store a lot of energy in a relatively small and light body. They are therefore promise for a variety of uses, especially in electric vehicles, where energy density is essential for greater driving distances. The use of aluminum, a commonly available and recyclable metal, makes these batteries environmentally benign. They are a sustainable way to cut carbon emissions because the reaction between aluminum and oxygen creates power without the release of any damaging pollutants or greenhouse gases. Also, in Long Driving Range for EV Compared to current lithium-ion batteries, aluminum-air batteries have the potential to greatly increase the driving range of electric vehicles. This might alleviate "range anxiety" and improve the use of EV for a wider variety of consumers. Recharging an aluminum-air battery quickly only requires the quick replacement of the aluminum anode. As opposed to lithium-ion batteries, which require a lengthy recharge procedure, aluminum-air batteries can be used in applications where quick recharging is necessary.

Recharging an aluminum-air battery quickly only requires the quick replacement of the aluminum anode. As opposed to lithium-ion batteries, which require a lengthy recharging process, aluminum-air batteries can be used in EV and other portable electronic devices where quick recharging is necessary. Various Applications aside from electric vehicles (EV), aluminum-air batteries have a wide range of other uses including backup power supplies, off-grid or remote energy storage, and military equipment. They are particularly helpful when constant, long-lasting power is needed.

Ongoing research and development in the area of aluminum-air batteries aims to improve their efficiency, security and longevity while also boosting their significance for the future of energy storage. It’s important to note that aluminum-air batteries also have drawbacks, such as a low cycle life and the necessity for effective ways to replenish the aluminum anode.

II. METHODOLOGY

The creation of an aluminum-air battery is a multi-phase process that involves careful material selection, electrode preparation, cell design, testing, and subsequent data analysis. This systematic approach is essential
for developing efficient and reliable aluminum-air batteries, which are a type of metal-air Battery using aluminum as the anode and ambient air as the cathode. Here is an expanded explanation of each phase in building an aluminum-air battery:

2.1 Material Selection:

Electrode Materials:
The choice of electrode materials is critical. Graphite is commonly used as the air cathode because of its excellent electrical conductivity and corrosion resistance. Aluminum is chosen as the anode material due to its high energy density and reactivity.

Electrolyte:
The electrolyte plays a pivotal role in facilitating ion transport between the anode and cathode. Alkaline solutions like potassium hydroxide (KOH) or sodium hydroxide (NaOH) are preferred electrolytes for aluminum-air batteries due to their compatibility with aluminum and the promotion of electrochemical reactions.

2.2 Electrode Preparation:
The anode is fabricated by cutting an aluminum sheet into the required size and shape for the electrode. It's important to ensure the anode's structural integrity.

The cathode is typically created by applying a catalyst to a conductive substrate, which is usually made of a carbon-based material. This catalyst enhances the oxygen reduction reaction that occurs at the cathode. Some designs also use a solid thin sheet of carbon-based material as the cathode.

2.3 Cell Design:
The electrodes are assembled within a designated battery container, ensuring proper separation between the anode and cathode to avoid direct contact. An electrolyte solution is added to the cell, immersing the electrodes and allowing for ion transport between them. The cell is then sealed with insulating materials to prevent leakage and maintain a secure enclosure.

2.4 Testing:
Initial tests are conducted to assess the battery's performance. These tests include measuring the initial voltage and current output to evaluate its basic functionality. Voltage stability is determined by measuring the open-circuit voltage over time to assess how the battery maintains its voltage under different conditions.

Discharge experiments are performed to evaluate the battery's capacity, energy density, and overall effectiveness in delivering electrical power. These experiments help assess the practicality and performance of the battery under load.

2.5 Data Analysis:
Data collected during testing is meticulously analyzed to make informed decisions regarding improvements and modifications to the battery design. Different electrolyte solutions tested and compared to determine which one offers the best performance and efficiency, with a focus on optimizing the battery's output and reliability.

III. SYSTEM DEVELOPMENT

3.1 System development

Creating an aluminum-air battery involves assembling the necessary components and setting up the electrochemical reaction between aluminum, graphite and oxygen. Here's a basic procedure for making an aluminum-air battery:

3.1.1 Materials and Equipment:
- Aluminum anode (Al-plate)
- Graphite cathode (typically a porous material that allows oxygen from the air to reach the electrolyte)
- Electrolyte (usually an alkaline or acidic solution, such as salt water or sodium hydroxide)
- Non-conductive container (here we are using acrylic plate and PVC foam board)
- Electrical wires and connectors (multi strand wire and lugs)
- Multimeter (for measuring voltage and current)
3.1.2 Flow of Hardware

A. Prepare the Aluminum Anode:
Cutting aluminum sheet to the desired size and shape, ensuring it fits inside the battery container shown in Figure 1.

![Aluminum Anode](image1)

**Figure 1: Aluminum Anode**

B. Prepare the Air Cathode:
The air cathode should be made of a porous material, such as graphite shown in Figure 2., to allow oxygen from the air to reach the electrolyte. Shaping the air cathode to fit inside the battery container and ensure good contact with the aluminum anode.

![Graphite cathode](image2)

**Figure 2: Graphite cathode**

C. Assemble the Battery:
Placing the aluminum anode and air cathode inside the non-conductive container, keeping them separate but in close proximity. Making sure the aluminum anode and cathode do not physically touch each other to prevent short-circuiting.

D. Prepare the Electrolyte:
Preparing the electrolyte solution according to the specifications of research papers. Commonly used electrolytes are potassium hydroxide (KOH), sodium hydroxide (NaOH) and Sodium Chloride (NaCl) solutions with varying concentrations. Different types of solutions are used as electrolyte.

E. Filling the Container with Electrolyte:
Pouring the prepared electrolyte solution into the container, ensuring that it covers both the aluminum anode and cathode. The level of the electrolyte should be sufficient to allow the electro-chemical reactions to occur.

F. Connect the Components:
Connecting the aluminum anode to the positive terminal of your multimeter or external load. Connecting the air cathode to the negative terminal of your multimeter or external load.

G. Data Collection:
Recording voltage, current and power.

H. Safety Precautions:
Utilizing extreme caution when handling chemicals, particularly the electrolyte. keeping the battery ventilated properly while handling it.

I. Shutdown and Analysis:
When finished experiment, disconnecting the components and analyze data. Considering factors such as the efficiency, current and voltage profiles of the aluminum-air battery based on measurements and observations.
3.2 Hardware Implementation

Figure 3: Hardware Implementation of Al-Air Battery

Figure 3 illustrates the Hardware Implementation of Al-Air Battery, which involves a 12-cell battery arrangement designed for specific improvements in weight and anode-cathode distance, along with connections to a load consisting of a 4V motor.

IV. RESULTS

The testing of different series-parallel configurations of the 12 cells shown in below Figure 4 was a critical step in optimizing the performance of the aluminum-air battery system. This approach allowed for the exploration of various electrical arrangements to determine the configuration that would yield the maximum output in terms of voltage and current.

Figure 4: Final structure of Al-Air Battery

This approach allowed for the exploration of various electrical arrangements to determine the configuration that would yield the maximum output in terms of voltage and current. After extensive experimentation and analysis, it was determined that the most efficient combination, which produced the highest overall performance, was connecting six cells in series and then connecting this combination of series cells in parallel.
This specific arrangement of series-connected cells followed by parallel connections is commonly referred to as a "6S-1P" configuration. In this configuration:

1. **6S (Six Cells in Series):** When six cells are connected in series, their voltages are added together. This results in an increased total voltage, while the current remains the same. This series connection is ideal for increasing voltage, which can be beneficial for many applications requiring higher voltage levels.

2. **1P (One Group in Parallel):** The group of six series-connected cells is then connected in parallel with another identical group. When cells are connected in parallel, the voltage remains the same, but the current is combined. This parallel connection ensures that the current capacity of the battery system is effectively multiplied.

The 6S-1P configuration strikes a balance between increasing voltage and current, ultimately achieving the maximum power output. This choice maximizes the overall efficiency of the battery system while providing a high voltage for applications that require it and ensuring sufficient current capacity.

The meticulous testing and analysis conducted to determine this configuration underscore the importance of system optimization in battery technology. Such configurations are crucial for applications ranging from portable electronics to electric vehicles, where achieving the right balance of voltage and current is vital for optimal performance.

### Table 2. Connections & results of Al-Air Battery

<table>
<thead>
<tr>
<th>Configuration No.</th>
<th>Combination of battery cells</th>
<th>Results</th>
<th>Voltage (V)</th>
<th>Current (mA)</th>
<th>Power (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td><img src="image1" alt="Series Connection Diagram" /></td>
<td></td>
<td>2.2</td>
<td>64</td>
<td>0.20</td>
</tr>
<tr>
<td>2)</td>
<td><img src="image2" alt="Parallel Connection Diagram" /></td>
<td></td>
<td>2.7</td>
<td>53</td>
<td>0.14</td>
</tr>
<tr>
<td>3)</td>
<td><img src="image3" alt="Parallel Connection Diagram" /></td>
<td></td>
<td>3.98</td>
<td>43</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Different voltage and current were obtained for various parallel and series connections as shown in Table 2.

1. The connectivity of three series and four parallel sets is shown.
2. Three parallel sets, each set consisting of four series cells.
3. Displays how two parallel cells and six series are connected.
In Figure 5, a comprehensive graphical representation of the project's results is depicted, showcasing a systematic exploration of various combinations of battery cells. This visual depiction serves as a vital tool for evaluating the project's outcomes. Each line or data series within the graph likely represents a distinct combination of battery cells, allowing for a clear comparison of their performance metrics. By analyzing the trends, fluctuations, and variations in the data, researchers and stakeholders can discern which specific combinations yield the most favorable results, such as improved energy capacity, efficiency, or longevity. This visual data aids in making informed decisions regarding the selection of battery configurations, advancing the project's overall goals and objectives.

V. CONCLUSION

This paper presents a comprehensive exploration of the Al-Air Battery implementation, focusing on the construction and analysis of a multi-cell battery system. Our research and development efforts have illuminated the remarkable potential of this technology. Notably, the Al-Air Battery has exhibited an impressive capacity for high energy density, enabling the efficient storage of substantial energy within a compact structure. Furthermore, its minimal environmental impact, marked by low greenhouse gas emissions during operation, underscores its eco-friendliness. Equally compelling is the battery's long-lasting performance, ensuring reliability and endurance in low power applications. This research offers valuable insights into a promising, sustainable energy storage solution.

VI. REFERENCES


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