

Performance Evaluation of Aluminum Ion Air Battery Using Solid Electrolyte composite

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Abstract - A promising class of battery materials, non-aqueous aluminum batteries (AB) have gained popularity because of their high theoretical capacity and consistent operational safety. However, their practical usage in large-scale applications has been hampered by the absence of appropriate positive electrode materials and the requirement for costly, air-sensitive solid electrolytes. The determination of this study is to examine the positive electrode materials and related electrolytes in ABs in order to inspire the development of the next generation of high-capacity, reasonably priced batteries. Because of their high charge storage capacity, low redox potential, and natural abundance, aluminum batteries are regarded as attractive electrochemical energy storage systems. This work tested five varying compositions of aluminum (Al6061) air cells for performance, with NaCl as the electrolyte assembly. A range of voltages and times were used to compare the experimental results; NaOH was selected because it was less expensive and had a lower concentration, which meant that it would last longer on batteries. The steady-state voltage indicates that electrons transfer between electrodes at their saturation points, and when the voltage reaches a plateau and the rate of electron transfer equalises, the reaction has reached equilibrium. The impact of various electrolyte concentrations on the equilibrium voltage attained might be investigated through more research.

Keywords: Non- aqueous aluminum battery (AAB), High performance, Al6061, Graphite, NaCl.

I. INTRODUCTION

There have been attempts to add aluminum to batteries since at least 1855. Among all batteries, AAB have one of the highest energy densities because they generate electricity through the reaction of aluminum and oxygen in the air. However, because of problems with byproduct removal and expensive anode costs, they are not

commonly used. Despite this, aluminum batteries have the potential to weigh substantially less overall and have a range of up to eight times that of a lithium-ion battery. These primary cells cannot be recharged, and the battery ceases to generate power when air oxygen consumes the anode. On the other hand, fresh aluminum anodes created by recycling the hydrated aluminum oxide can be used to accomplish mechanical recharging.

Aluminum alloy, oxygen reduction catalyst, and electrolyte type are among the elements that affect aluminum-air cells and high energy density primary batteries. Two concerns are examined: the creation of a passive hydroxide layer and the parasitic corrosion of aluminum caused by water reduction on the anode. In order to counter this, Egan et al. (2013) created an ultra-pure aluminum alloy that is used to suppress corrosion or dissolve the hydroxide layer. It contains traces of Magnesium, Tin, In, and Gallium. Since high-purity aluminum alloys are pricey, other approaches involve directly incorporating inhibitors into the electrolyte. A novel approach to preventing self-corrosion is to use gel electrolytes, anionic membranes, or substitute solvents. The development of aluminum-air cells is shown to have potential in the future, and the air cathode is also considered [1]. The AAB is a primary metal air battery, as seen in Figure 1, that employs a three-layer gas diffusion electrode with pure aluminum acting as the anode in this instance due to its passive hydroxide layer. Additionally, an aqueous electrolyte—typically sodium hydroxide, potassium hydroxide, or sodium chloride—is in contact with the air-breathing cathode.

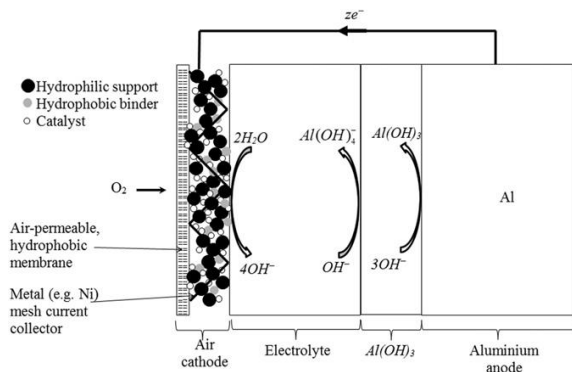


Figure 1. Structure of Aluminum Air Battery

Cheong Tan et al (2021) have presented a novel polypropylene-based AAB that is intended to simplify and economically replace the traditional aqueous electrolyte-based battery. The battery employs polypropylene and Kimwipes as separators, carbon as an air cathode, and aluminum foil as an anode. The polypropylene separator outperforms the Kimwipes separator, according to the study, and there is a negative correlation between electrolyte concentrations and battery capacity. A specific capacity of 375 mAh g⁻¹ is achieved by the battery when 1 M of potassium hydroxide is used as the electrolyte and a discharge current of 30 Ma⁻¹ [2]. The high potential energy density (8100 Whkg) of aluminum air batteries was highlighted in Yisi Liu et al. (2017) overview of the technology's advances. They talked about the difficulties and the latest developments, such as the performance-enhancing alloying of aluminum with transition metal components. They also covered the use of aqueous and nonaqueous electrolytes, the addition of inhibitors to improve electrochemical performance, and experiments on electrocatalytic materials for oxygen reduction. [3].

A metal-air secondary battery based on an aluminum-oxygen pair is presented by Revel et al. (2014). It has an average voltage of 0.6–0.8 V, a low self-discharge rate, and the ability to support large current densities (up to 0.6 mA cm²). This novel kind of electrolyte is a promising alternative for energy storage since it may be applied as an internal, independent, and self-sustaining energy source [4]. The microstructure, corrosion characteristics, and discharge performance of as-cast and as-rolled aluminum alloy anodes were examined by Xiang Yin et al. (2017). In comparison to the as-cast alloy anode, the as-rolled alloy anode demonstrated a greater battery voltage, anode efficiency [5]. More than fifteen aluminum air cells with different electrolyte assembly, absorber thickness, MnO₂

catalyst ratio, and cell area were examined by Shahab et al (2022) and Hamza. The results indicated that MnO₂ did not perform as well as other cell assemblies, but it did so with 20% less NaOH, which is less costly and prolongs battery life by accomplishing the same activity at a lower concentration. The figure 2 illustrate the pure molar concentration produces the best voltage and amperes [6]. A solid polymer electrolyte membrane has been used by Sahaydul et al (2024) to create a prototype Li-ion battery (LIB) in place of a liquid electrolyte and separator. The SPE was created utilizing an N-methyl-2-pyrrolidone solvent with a composition ratio of 1:5 lithium chloride to polystyrene. The SPE demonstrated a microporous structure and a homogeneous, consistent texture that suggested Li-ion flow through the membrane. In TGA study, the battery demonstrated exceptional thermal stability up to 400 °C. The output voltage of the pouch cell increased from 0.4 V to 1 V after charging with a constant 4 V supply, according to electrochemical analysis, which demonstrated superior charging and discharging characteristics. The battery presents a viable substitute for conventional LIB in contemporary industrial applications [7].

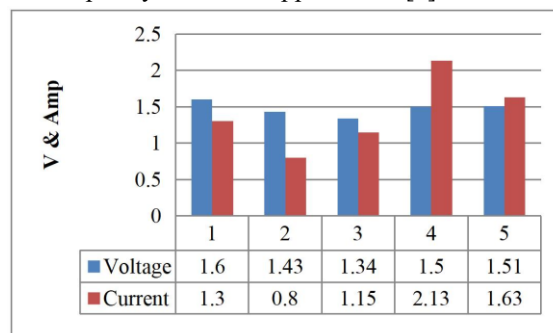


Figure 2. Different Composition of Electrolyte Mixtures

A novel ion conductor, Na_{3-x}Y_{1-x}Zr_xCl₆ (NYZC), has been found by Erik A et al (2021) It is compatible chemically with oxide cathodes and electrochemically stable. Compared to oxide coatings, NYZC has a greater ionic conductivity of 6.6 × 10⁻⁵ S cm⁻¹ at room temperature. The composite cathode, NaCrO₂ + NYZC, can cycle over 1000 cycles with 89.3% capacity retention at 40 °C and shows an amazing first-cycle Coulombic efficiency of 97.1% at ambient temperature. These findings highlight the potential of halides in SSSB applications [8]. The cycle performance and safety of conventional lithium-air batteries (LABs) are compromised by volatility, leakage, byproduct formation, and short circuits. Solid-state electrolytes (SSEs) have become the solution of choice because

they stop impurities from getting to the anode and stop lithium dendrites from forming. The research progress on SSEs for LABs is reviewed by Qiancheng Zhu et al. (2023), who also talk about the opportunities and challenges for synthesis and characterization as well as future strategies for creating safe and high-energy density LABs [9].

A clay-based quasi-solid-state electrolyte has been created by Chaonan Lv et al. (2023) for use in AAB, which have the advantages of inexpensiveness, safety, and a high theoretical capacity. Aluminum ions can be efficiently removed from clay and the activity of free H₂O molecules is decreased due to its remarkable compatibility and liquid-like ionic conductivity. This prevents the aluminum anode from corroding itself. The manufactured battery outperformed earlier records with a maximum energy density of 4.56 KWh kg⁻¹, using inexpensive clay in the electrolyte formulation could help aluminum-air batteries become more commercially viable. [10].

II. MATERIAL DESCRIPTION

2.1 Aluminum

Due to the instability of pure aluminum as an anode, Al alloys are frequently used in Al-air batteries to increase battery life and reduce corrosion rate. The overall performance of batteries and anode stability are improved by these alloys. In the present work, aluminum plates are used as well as anodes. Additionally, the lightweight nature of aluminum makes it easier to work with and transport, making it a practical choice for many engineering projects. Here, aluminum sheet was chosen for the experiment due its affordability. Its ability to resist

corrosion also makes it a reliable option for long-term use. The 7mm thickness of the plate provides the necessary strength for the experiment while still being manageable and easy to handle.

Table 1. Properties of Al 6061

Property of Al 6061	Value	Units
Electric Conduction	0.0251	10 ⁶ / Ω mm
Mass Density	0.0027	g/mm ³
Young’s Modulus	68.9	GPa
Poisson’s Ratio	0.33	-
Specific Heat Capacity	0.896	J/g °C
Thermal Conductivity	167	W/m K

2.2 Graphite

A kind of carbon is called graphite. every carbon in graphite A single covalent connection connects the atom to three more carbon atoms to form a hexagonal ring that is layered. Graphite is typically utilized as an electrode in pencil-shaped batteries. It is composed of two-dimensional structural layers. It is an inert material which absorbs energy transferred through NaCl. This experiment used a 7-mm-thick graphite electrode as a cathode, a high-temperature resistance conductive material made from petroleum coke, needle coke, and coal tar pitch through various processes like mixing, shaping, roasting, impregnation, graphitization, and mechanical processing to act as a cathode. The graphite electrode was chosen for its high thermal and electrical conductivity, making it suitable for use in high-temperature applications such as this experiment. Additionally, the electrode's stability and durability under extreme conditions allowed for accurate and reliable results to be obtained.

Table 2. Properties of Graphite

PROPERTIES OF GRAPHITE	VALUE
Density	2.21-2.25 g/cm ³
Porosity	20-32%
Temperature of Melting	4073-4173 K
Thermal Conductivity	30-32 Kcal/m hour K
Factor of linear expansion in an interval 273-1273 K	3.5 – 8 X 10 ⁻⁶ 1/K

2.3 Electrolyte (NaCl)

Na and Cl ions are present in a 1:1 ratio in sodium chloride, popularly referred to as salt. It is the main salt found in seawater and living things with many cells, used as a food preservative, seasoning, and in manufacturing for plastics and products. Its basic structure, known as the NaCl structure or rock salt crystal structure, is found in many compounds and

is used as an electrolyte in chemical processes like electrolysis and batteries. The positive sodium ions and negative chloride ions allow for electricity flow, and this structure gives sodium chloride its characteristic properties, such as high melting and boiling points. The NaCl structure is fundamental in various industries and plays a crucial role in everyday life, influencing everything from food

preservation to the functioning of electronic devices. Its ability to conduct electricity makes it essential in the production of batteries and other electronic components. In addition, the high melting and boiling points of sodium chloride make it ideal for use in industrial processes that require extreme temperatures. This work uses liquid state NaCl to sprinkle on a sheet, ensuring an even distribution of salt. This method utilizes the unique properties of sodium chloride, which is versatile in both solid and liquid forms, making it a valuable tool in various applications.

Table 3. Properties of NaCl

PROPERTY	DESCRIPTION
Chemical Formula	NaCl
Atomic Weight of Na	22.9898
Atomic Weight of Cl	35.4527
Appearance	Clear or White Solid
Density	$2.2 \times 10^3 \text{ kg/m}^3$
Melting Point	801 °C
Boiling Point	1465 °C

III. BATTERY PREPARATION

Select an appropriate aluminum square plate (50×50 mm) and graphite flat (50×50 mm) plate of the same size as shown in fig 3 which illustrate aluminum is anode and the Graphite is act as a cathode. Then take 5% vol. of NaCl which is used as an electrolyte and sprinkle over the surface of aluminum plate and paper as shown in Fig 4. For avoiding the contact between the aluminum and the graphite plate, place a normal paper/foil over the electrolyte. Then Place the graphite plate on the top of the electrolyte which is placed over the paper as shown in Fig 5. This forms a complete single cell and need to measure the voltage using a multimeter the below fig 6 shows the multimeter voltage for the current experiment battery.



(a)



(b)

Figure 3. Aluminum(a) and Graphite(b)



Figure 4. (5 % of NaCl Sprinkled on Paper & Al)



Figure 5. Gr placed over the NaCl

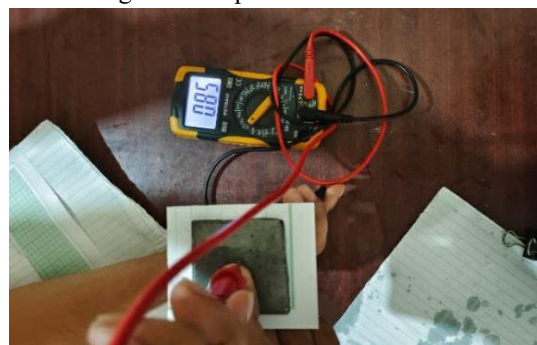


Figure 6. Measuring voltage

The experiment is repeated with increasing amounts of NaCl in the electrolyte solution, up to 50% in volume as a fraction of each 10%. The voltage readings are taken at regular intervals of 5 minutes for a total of 30 minutes each time.. This setup, with aluminum as the anode, graphite as the cathode, and NaCl as the electrolyte, provides a simple yet effective way to study the effects of different

electrolyte concentrations on the voltage output of a single cell. The results of the experiment showed a clear trend - as the concentration of NaCl increased in the electrolyte solution, the voltage output of the cell also increased. This indicates that the conductivity of the electrolyte solution plays a significant role in determining the voltage output of the cell. By using this setup, researchers can further investigate the relationship between electrolyte concentration and voltage output, potentially leading to advancements in battery technology and energy storage systems. Overall, this experiment provides valuable insights into the behavior of single cells under varying conditions of electrolyte concentration.

IV. RESULT AND DISCUSSION

The experimental measurements (time v/s voltage) for the aluminum ion battery's performance assessment on varied percentage volumes of added NaCl are listed in Table 4 below. Here we have chosen the relationship between time and voltage because we cannot get accurate results over a period of time, that's why tests are taken at 5-minute intervals for a total of 30 minutes. By increasing the amount of electrolyte solution (NaCl) from 10% to 50% we get different results. The voltage that is measured and the time are exactly related. As shown in the following Figures

Table 4. Experimental Results

TIME (mins)	10% vol. of NaCl	20% vol. of NaCl	30% vol. of NaCl	40% vol. of NaCl	50% vol. of NaCl
5	0.73	0.74	0.76	0.78	0.81
10	0.74	0.76	0.77	0.79	0.82
15	0.75	0.76	0.78	0.80	0.83
20	0.76	0.77	0.78	0.81	0.84
25	0.77	0.78	0.79	0.82	0.85
30	0.77	0.78	0.79	0.82	0.85

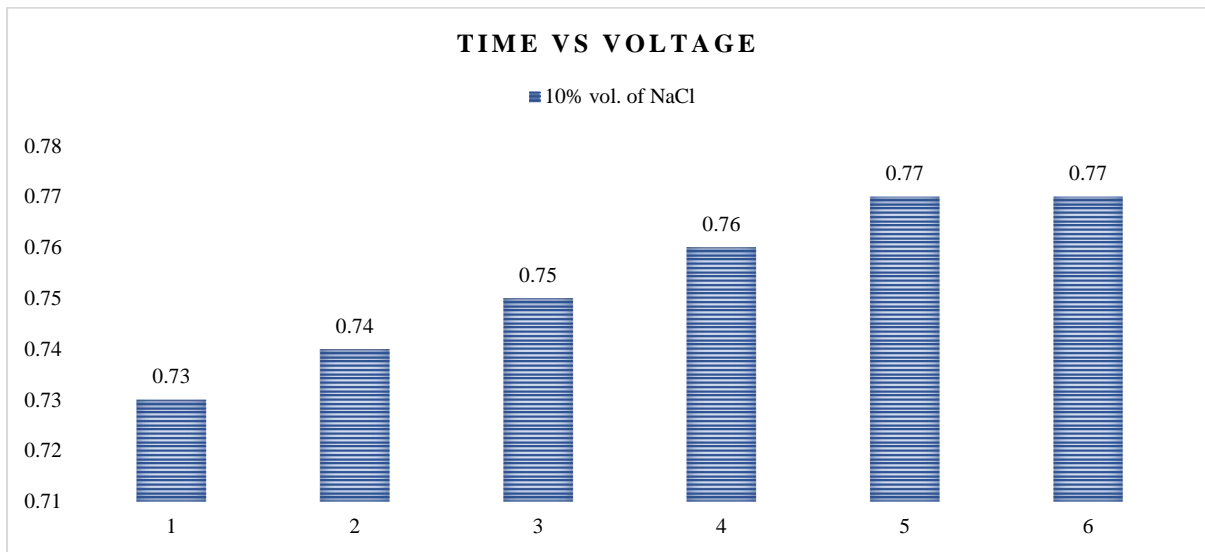


Figure 7. Time-Voltage graph for 10% vol. of NaCl electrolyte

The above fig 7 represent the Time Voltage for 10% of NaCl electrolyte, The voltage at 5 minutes is 0.73 V and the voltage is gradually increasing up to 25 minutes. After that the voltage remains constant.

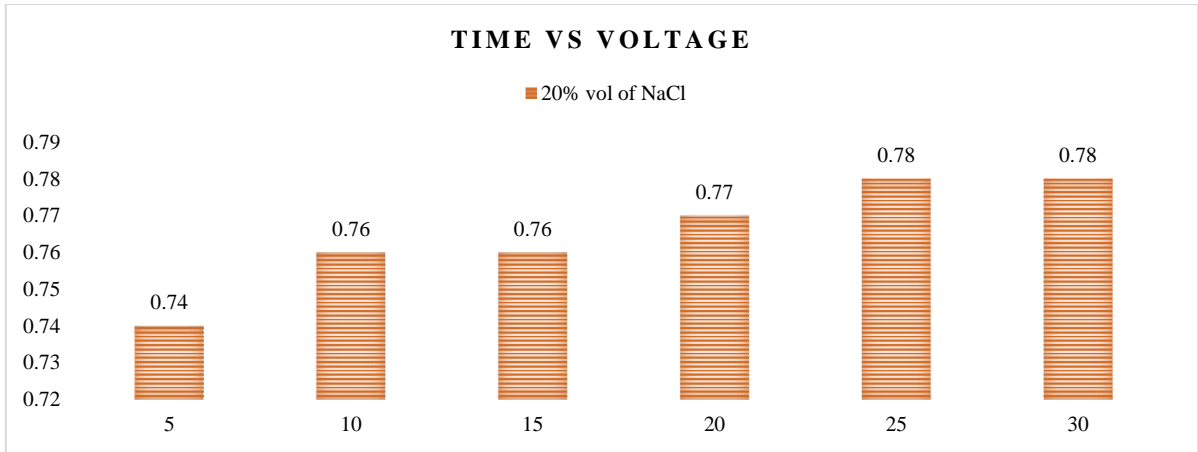


Figure 8. Time-Voltage graph for 20% vol. of NaCl electrolyte

The above fig 8 represent the Time Voltage for 20% of NaCl electrolyte The voltage at 5 minutes is 0.74 V and the voltage is gradually increasing up to 25 minutes. After that the voltage remains constant.

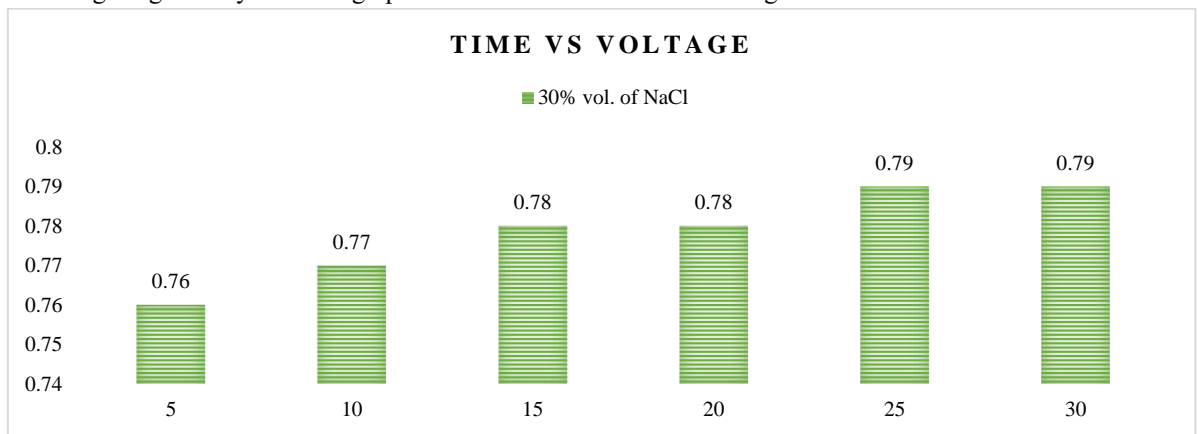


Figure 9. Time-Voltage graph for 30% vol. of NaCl electrolyte

The above fig 9 represent the Time Voltage for 30% of NaCl electrolyte The voltage at 5 minutes is 0.76 V and the voltage is gradually increasing up to 25 minutes. After that the voltage remains constant.

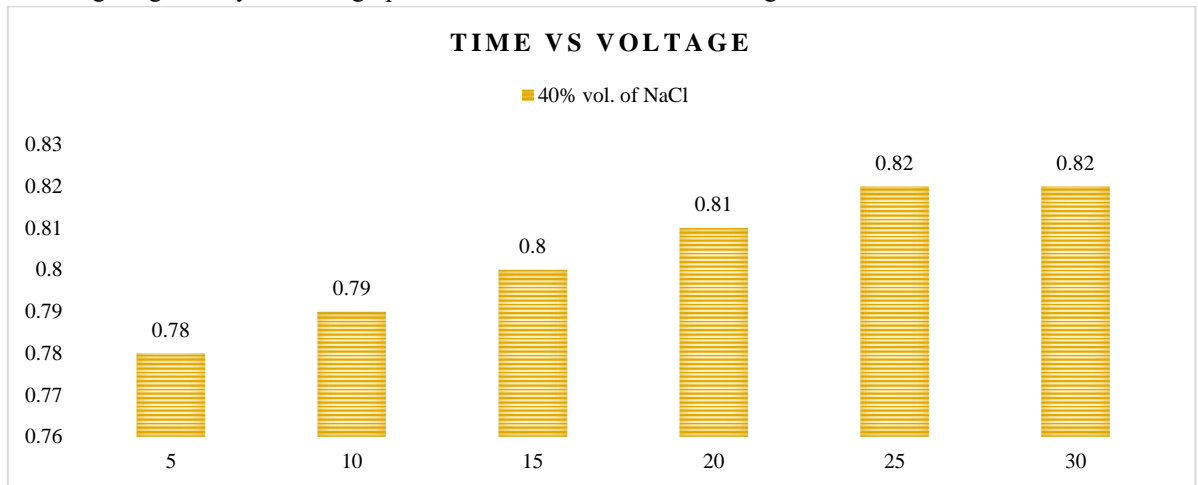


Figure 10. Time-Voltage graph for 40% vol. of NaCl electrolyte

The above fig 10 represent the Time Voltage for 40% of NaCl electrolyte The voltage at 5 minutes is 0.8 V and the voltage is gradually increasing up to 25 minutes. After that the voltage remains constant.

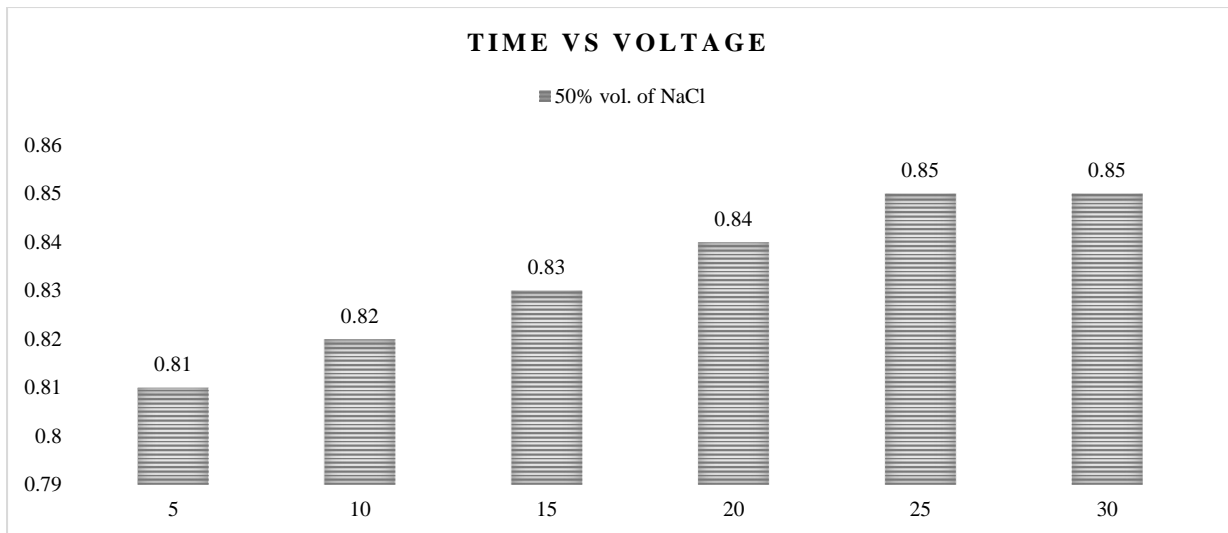


Figure 11. Time-Voltage graph for 50% vol. of NaCl electrolyte

The above fig 11 represent the Time Voltage for 50% of NaCl electrolyte. The voltage at 5 minutes is 0.82V and the voltage is gradually increasing up to 25 minutes. After that the voltage remains constant. To replicate the electrolyte (sodium chloride) battery performance of an AAB (aluminum air batteries) cell. By contrasting the anticipated discharge curves for voltage and time consumption measurements, the model was verified. The conclusion that can be drawn from analyzing the discharge curve changes is that adding more NaCl will raise the voltage and enhance the air battery's performance.

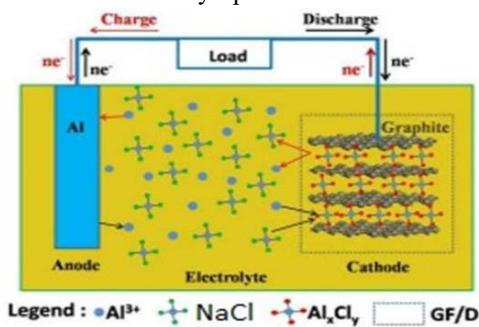
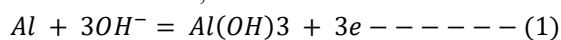


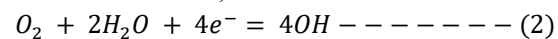
Figure 12. working principle of Al-air battery

The above figure 12 represent the Schematic working Principle of Al air battery. Al-air batteries are a type of metal-air battery. These batteries have a high energy density and are commonly used in military applications due to their long shelf life and ability to be easily transported.

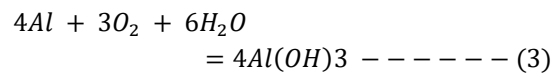
Reaction at anode,



Reaction at cathode,



Overall reaction,



4.1 Advantages

1. High storage capacity
2. Long range
3. Cost effective
4. Recyclable

4.2 Disadvantages

1. Non – rechargeable
2. Should be stored in a closed environment

V. CONCLUSION & FUTURE PERSPECTIVES

Al batteries have emerged as a viable secondary battery mechanism that could rival lithium-ion batteries, which are already widely used in commerce. Al batteries are thought to be significantly safer than Li-ion batteries, and their enormous abundance and volumetric capacity are among its most alluring qualities. Bipolar ion storage techniques and low-cost organic cathode materials are promising fields as well.

Different discharge currents and NaCl electrolyte concentrations were used to assess the performance of the paper-based separator in the AAB. Using aluminium sheet as the anode, graphite sheet serving as the cathode, paper serving as a separator, and sodium chloride (NaCl) as the electrolyte, an aluminum-air battery was conceived and built. The aluminum-air battery with a paper separator may produce an open circuit voltage of 0.85 V at a 50% concentration of NaCl in 30 minutes, according to the findings of a detached circuit test. The electrolyte concentration utilized in the separator has a significant impact on how well the battery operates.

When voltage rises, so does the concentration of NaCl. Elevated concentrations may lead to an increased rate of corrosion on the aluminum anode, hence degrading the battery's performance. To enhance battery performance, the NaCl concentration needs to be closely observed.

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