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An Investigation into Sodium-Metal Battery as an Alternative to Lithium-Ion Batteries

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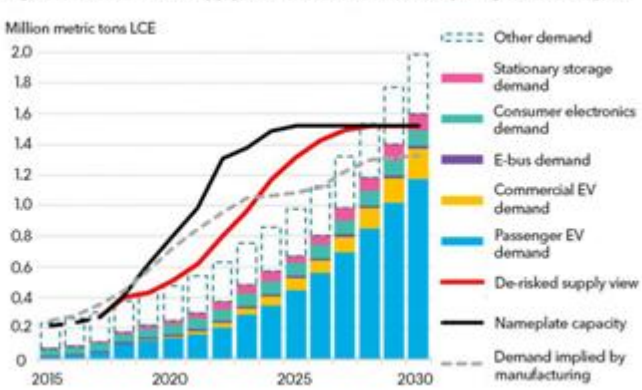
Abstract: ***Sodium-ion batteries have attracted attention by researchers as a more suitable alternative to lithium ion batteries. However, due to its larger ionic radius compared to lithium-ions, a suitable anode that does not hinder the intercalation process is yet to be found. In this work, I demonstrate that issue of large ionic radius of sodium can be avoided with sodium-metal battery. Sodium metal battery involves sodium metal and copper wire, which create electric field. The experimental observations show that the electric field can be easily strengthened by increasing the concentration of sodium chloride solution in which two metals are put (indirectly for sodium metal as it reacts with water). The maximum potential difference obtained by the sodium-metal battery is comparable to that produced by current lithium-ion battery, further supporting the possible suitability of sodium-metal battery as an alternative for lithium-ion battery. This allows us to overcome the current global and local concern of lithium-scarcity, encouraging shift from fossil fuels to renewable energies and help develop technologies.***

Keywords: Lithium-ion batteries, Sodium-ion batteries, Sodium-metal batteries, potential difference, Sodium chloride solution

1. Introduction

Lithium-ion batteries are present in many devices, including phones, cars, computers, tablets, and hearing aids[1]. Furthermore, the recent focus on producing electric vehicles and portable electronics is diversifying the use of rechargeable batteries[2]. Moreover, as the world shifts away from fossil fuels, rechargeable batteries become a key to store the energy produced from renewable sources[3]. However, in contrast to the growing needs of lithium-ion batteries, the demand of lithium is expected to surpass the supply after 2024, unless "more projects are commissioned" to produce more lithium[4]. In India, a very large portion of lithium carbonate and lithium hydroxide used in lithium-ion batteries are imported from overseas. Hence, the electrical industry of India would be particularly and largely affected if the price of lithium rises due to the increasing demand. This problem would torment the entire world, as demand is increasing exponentially.

Figure 1: Global lithium supply and demand forecast, comparing methodologies

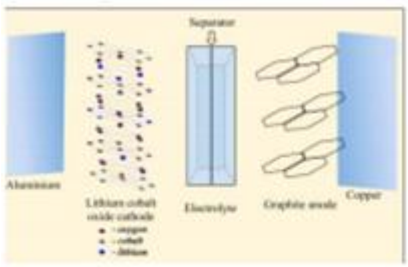


As figure 1 shows, a surge in demand for lithium is anticipated till the year 2030. Without finding an alternative for lithium-ion batteries, no country will be able to remain competitive in the electrical industry. Therefore, amid the concerns regarding the scarcity of lithium, I decided to conduct an investigation on possible alternatives to lithium-ion batteries. (The more defined research question of this paper will be stated after all the background researches are explained.)

2. Background Information

a) Lithium-ion batteries

Since lithium-ion battery has entered commercial market in 1991[5], it has been used as the most popular rechargeable battery due to advantages, such as high energy density, the property of not having memory effect, and its capability of undergoing hundreds of recharging cycles[6] . Although it also has weaknesses such as degradation and its sensitiveness to high temperatures, these are considered insignificant compared to the large advantages that it has[7].



The figure above shows the composition of one of the most common lithium-ion batteries, cobalt oxide battery, which has lithium cobalt oxide as the cathode and graphite as the anode[8] .

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1 "The Batteries Report 2018"
2 ibid
3 Qi Li 2017
4 "End in Sight to Near-Term Lithium Supply Shortages", 2017
5 "Lithium-Based Batteries Information",2018
6 Marshall, Brain, 2016
7 "Lithium-Based Batteries Information", 2018
8 Kazda, Tomáš, and Petr Vanýsek, 2016

The conductive metal layers, aluminum and copper function as collectors to aid the electrodes in collecting and distributing electrons[9]. An electrolyte is a transport medium which is permeable for lithium ions but not for electrons[10]. Through this electrolyte, lithium ions move between cathode and anode so that it can neutralize the charge built up by electrons (which travel through the external circuit) to prevent electrons from repelling each other[11]. Furthermore, the separator, which is also permeable for ions, is placed between cathode and anode, to prevent short circuit when electrolyte evaporates due to high temperatures in abnormal conditions[12].

b) Sodium-ion battery, and its limitations

Since 2012, sodium-ion battery has been attracting attention from scientists globally as a possible alternative for lithium-ion battery, as seen from the increasing number of publications on it[13]. This is because sodium has similar chemical properties as lithium as it is an element one period below on the periodic table. Moreover, the abundance of sodium is as high as 2.36×104 mg/L, whereas that of lithium is merely 20 mg/L[14]. This also means that the cost of the raw material, sodium, for this type of battery is cheap, too. In fact, the cost of mining sodium is approximately $150 US dollars per ton, while mining lithium costs $150,000 per ton[15].

However, one of the biggest problems with sodium-ion batteries is the difficulty with finding a suitable anode. Although graphite is commonly used as an anode in lithium-ion battery as shown in figure 2, a graphite anode is not functional in sodium-ion battery due to the larger ionic radius of sodium (116pm) compared to lithium (90pm)[16], which hinders the intercalation process[17]. Therefore, lots of research is focused on anode material, such as research conducted by Komaba et al. on hard-graphite[18], Jache and Adelhem on expanded graphite[19], and others[20][21]. However, a suitable anode is still at the stage of development and the commercial application of sodium-ion battery is yet to be implemented.

Hence, the focus of investigation must be broadened out of sodium-ion battery with conventional graphite anode.

c) Sodium-metal battery

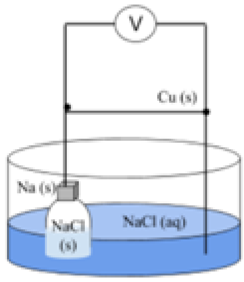
Sodium-metal battery is a battery type that has similar structure with sodium-ion batteries, except it does not involve a graphite-anode. 'Sodium metal battery' means that sodium metal itself is an electrode, instead of it being a compound. This avoids the difficulty of finding a suitable material for battery anode in sodium-ion battery. Furthermore, this sodium metal battery also holds the advantage of using sodium which is significantly more abundant than lithium.

However, despite this advantage of sodium-metal batteries and successful results obtained from researches done by Cohn, Adam P., et al.[22], researches into sodium metal batteries are very little compared to sodium-ion batteries.

Therefore, I decided to focus my research on sodium-metal battery, particularly, on one possible factor that might affect the potential difference that can be produced from a battery with the research question**: "What is the effect of concentration of sodium chloride solution on the potential difference (p.d.) produced across the sodium metal battery model?"**

3. Experimental Set-Up

Figure 3 shows a diagram of the battery model. This was adopted from a video posted on YouTube by Ian Berry[23].The video used a very basic concept of sodium battery model. Thereafter, I modified the model by conducting multiple preliminary experiments to create the best method for obtaining relevant and reliable data for this research inquiry.



3.1 Justification of model and experimental design

Rechargeable batteries are similar to capacitors, and the idea of capacitors can help understand the mechanism of my battery model, which has two conducting metals, copper and sodium, and two dielectrics, NaCl crystal and NaCl solution.

Firstly, electric potential difference (p.d.) is the difference in the electric potential energy between two points[24]. This p.d. then causes current through a circuit as the electrons are repelled from the negative side and attracted to the positive side and flows through the complete circuit.

Furthermore, p.d., is work done when a charge moves through an electric field[25], which are related by equation:
Equation 1[26]: $V = Ed$, where E is the electric field strength, V is the p.d., and d is the separation between the conductors.

This equation indicates that p.d. is proportional to electric field strength and as the electric field strength increases, the p.d. increases.

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[9] Tablante, Teddy, 4 Mar. 2019
[10] ibid
[11] ibid
[12] ibid
[13] Sawicki, Monica, and Leon L. Shaw, 2015
[14] Todd Helmenstine, 2018
[15] Brooks Hays, 2017
[16] "Periodic Table"
[17] Yasuyuki Kondo, et al., 2019
[18] Shinichi Komaba, et al., 2011
[19] Birte Jache and Philipp Adelhelm, 2014
[20] Xinwei Dou, et al., 2019
[21] Hongshuai Hou, et al., 2017
[22] Cohn, Adam P., et al., 2017
[23] Ian Berry, 2016
[24] "Electric Potential Difference"
[25] "Electric Potential Difference"
[26] "Permittivity and Relative Permittivity or Dielectric Constant." 2019

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Finally, electric field strength is dependent on the relative electric permittivity of the dielectric between the conductors.

The relative electric permittivity of a material is its ability to polarize to the external electric field[27], related by an equation:

Equation 2[28]: $E = D/\varepsilon_0\varepsilon_r$ *, where D is the flux density, ε_0 is the absolute permittivity of vacuum which is constant, and ε_r is the relative permittivity of the medium.*

This suggests that the electric field strength (and hence p.d.) across the metals is inversely proportional to the relative permittivity of the dielectrics between them. Given this idea, I will now move onto explaining how each of the components of the battery model contributes to the p.d. across the metals.

3.2 P.d. and Electrodes

Batteries undergo electrochemical processes which involves the oxidation of the battery anode due to the removal of electrons and reduction of the battery cathode due to the gain in electrons. The build-up of charge on electrodes then creates p.d. and causes the electrons to move from the negatively charged end to the positively charged end, creating current.

In my battery model, the anode is the sodium metal and the cathode is the copper wire. This can be understood from the electrode potentials of sodium and copper: sodium has a value of -2.71V and copper has a value of +0.15V[29]. This suggests that sodium is more likely to be oxidized than copper, thus becoming an anode, making copper wire a cathode.

For this component, the areas of metal which are in contact with the dielectric ultimately contribute to the p.d. obtained. This relationship can be understood with the equation:

Equation 3[30]: $D = Q/$, where Q is the charge built-up and A is the area of the conductors in contact with the dielectric.

Equations 1 and 2 have shown the proportionality between the flux density and electric field strength, and the proportionality between electric field strength and p.d. respectively. Therefore, these equations show how the areas of conductors in contact with dielectrics and the p.d. are related. Hence, the areas of sodium metal and copper were controlled, which is further explained in the experimental design section.

3.3 Use of NaCl crystal as the prevention of Coulomb explosion

Next, the battery model includes two dielectrics, one of which is NaCl crystal. The main function of NaCl crystal in the model is to elevate the sodium metal to prevent "coulomb explosion" from happening without disturbing the p.d. Firstly, when an alkali metal and water are in direct contact, coulomb explosion takes place, which is an "explosive alkali metal-water reaction that leads to rapid migration of electrons from the metal into water"[31]. When I tried to measure p.d. while sodium metal and NaCl solution are in direct contact, coulomb explosion occurred extremely rapidly that p.d. was unable to be detected. In addition, since the reaction is explosive, a battery model in which alkali metal and water are in direct contact would be practically useless.

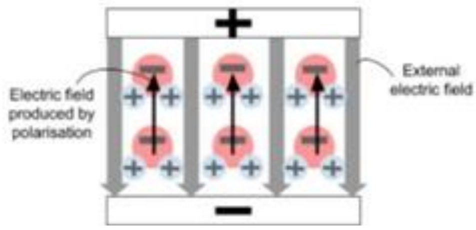
Therefore, I tried to prevent direct contact of the water and the metal by elevating the metal above NaCl solution with NaCl crystal.

Again, NaCl crystal is a dielectric with a dielectric constant of 6.1[32], and an electric field can travel through it[33]. Therefore, this allows p.d. to be measured without coulomb explosion occurring.

NaCl crystal is used because even if it dissolves in the solution during the experiment, it will not affect the composition of the solution, which helps reduce random errors.

3.4 NaCl solution and p.d. obtained

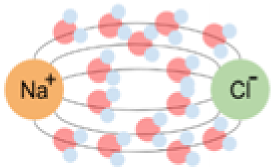
The final component is the second dielectric, NaCl solution. This largely accounts for the p.d. obtained and it acts like an electrolyte in the model.



Firstly, water is a dielectric with a relative permittivity of 80.2 at 58° F[34](20 °C). It has been introduced earlier that permittivity is a measure of the material's ability to polarize to an external electric field. This polarization actually creates a new electric field opposing the original external field, and results in the reduction of the field strength between the conductors[35]. An example of the effect of polarization is shown with water molecules in above figure.

Additionally, parts of the research by D H Dagani et al. show that the permittivity of the water decreases as NaCl concentration increases[36]. Further research by Nir Gavish and Keith Promislow shows that NaCl ions in the solution creates local electric field and causes polar water molecules to align with this field creating a "hydrogen shell"[37] as shown in figure below

27 Nave, Carl Rod
28 "Permittivity and Relative Permittivity or Dielectric Constant." 2019
29 Haynes, Willian M., et al., editors., 2014
30 "Permittivity and Relative Permittivity or Dielectric Constant." 2019
31 Phillip Mason et al., 2015
32 "Dielectric Constant Values"
33 Richard Williams, 1963
34 "Dielectric Constant Values"
35 Nave, Carl Rod
36 Gadani, D H, et al. 2012
37 Gavish, Nir, and Keith Promislow, 2016



Moreover, they found that the permittivity of NaCl solution decreases with concentration by the process called "dielectric decrement", which is expected to be linear for dilute solutions (≤ 1.5M) and saturate at higher concentrations[38]. This is because in concentrated solutions, larger number of NaCl ions polarize the water molecules to their field, reducing water molecules' ability to polarize (permittivity) to the external electric field. This ultimately means that increasing the NaCl concentration results in the reduction of the field strength opposing the external field, and hence increasing the external electric field strength (hence p.d.).

4. Hypothesis

Overall, the research shows how the dielectric decrement is linear at lower concentrations and saturates at higher concentrations, the electric field strength is inversely proportional to the permittivity, and electric field is directly proportional to the p.d.

Therefore, I hypothesize that p.d. produced across the battery increases rapidly at lower concentrations and stabilize at higher concentrations. However, the extent to which this occurs will be under investigation throughout the experiment.

5. Experiment

Materials:
- Sodium metal
- NaCl crystal
- NaCl solutions (0M, 1M, 2M, 3M, 4M)

Apparatus:
- Data logger with p.d. sensor
- Copper wire
- Crocodile clip

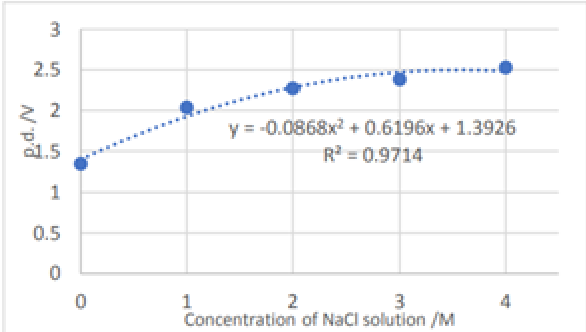
6. Results

I. Raw data table

Conc. of NaCl solution /M	Avg. p.d. measured within an interval of 5sec./V					
	1	**2**	**3**	**4**	**5**	Avg
0.00	1.441	1.078	1.483	1.570	1.095	1.333
1.00	2.016	2.084	2.004	1.959	2.109	2.034
2.00	2.261	2.263	2.266	2.290	2.269	2.270
3.00	2.437	2.403	2.359	2.353	2.355	2.381
4.00	2.543	2.470	2.509	2.556	2.571	2.530

Table 1: raw data table presenting the p.d. measured on LoggerPro within the duration of 5 seconds

II. Processed data



Graph 1: Different concentrations of NaCl solution plotted against the average p.d. measured

Graph 1 shows an overall increase in p.d. as the concentration of NaCl increases as hypothesized. Since p.d. increased greatly at lower concentrations but it seemed to maximize at about 4M, a quadratic trend line, y = $0.0868x^2 + 0.619x + 1.3926$, is plotted, which has a high R^2 value of 0.9714. This equation also suggests that the rate of change in p.d. decreases linearly with concentration. This can be understood from the research that trend of the dielectric decrement is rapid at lower concentrations and saturates at higher concentrations. The processes of dielectric decrement and hydrogen shell resulted in decrease of permittivity with increase in NaCl concentration which led to increasing external electric field strength and hence increasing the p.d. across the model.

In this battery model, average maximum p.d. obtained was 2.530V with 4M NaCl solution. Graph 2 compares this maximum p.d. obtained from approximately 0.125g of sodium metal and 18650 lithium-ion battery cell which has approximately 0.6g of lithium content per cell[39] and produces a maximum p.d. of 4.2V per cell[40]. The bar represents the ratio of the maximum voltage produced to the mass of metals (sodium and lithium) for sodium-metal battery model and lithium-ion battery.

[38] Gavish, Nir, and Keith Promislow, 2016

[39] "Is Lithium-Ion the Ideal Battery?"

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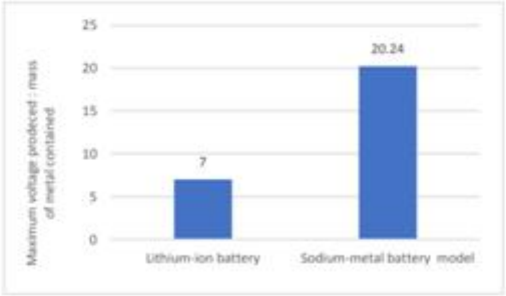

Graph 2: The comparison between the ratios of maximum voltage produced to metal contained, between 18650 lithium-ion battery and sodium-metal battery model

From graph 2, it is evident how the maximum p.d. produced per mass of sodium-metal battery model is nearly three times that of lithium-ion battery cell. This clearly visualises advantage that sodium-metal battery has over lithium-ion battery in terms of the maximum p.d. produced. This initial result strongly supports the potential of sodium metal battery as an alternative to lithium-ion battery.

7. Conclusion

Many of the electric devices are relying on lithium-ion batteries in the current world, and the recent focus on producing electric vehicles and finding a way to store renewable energies has further enhanced the demand of rechargeable batteries. However, the foreseen scarcity of lithium and price that rises corresponding to its demand are causing concerns in the world, especially in Japan where lithium is imported and hence largely affected by the price increase. The sodium-ion battery, which has been suggested as a possible alternative for lithium-ion batteries has a major problem that its larger ionic radius hinders the intercalation process to the graphite anode (which is a common anode used in lithium-ion batteries).

This paper aimed to offer insights into the effectiveness of sodium-metal battery as an alternative to lithium-ion battery through experiment with a sodium-metal model. The result indicates that there is potentially greater p.d. produced using sodium metal in a battery than lithium per unit mass of each metal.

However, much more experimentation is needed to validate this finding as discussed following an analysis of the data. Furthermore, more research into the alternative rechargeable batteries to lithium-ion batteries must be conducted to meet the current global power demands and to aid the use of renewable energy sources and reduce our reliance on fossil fuels.

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