Effect of Operating Conditions on Lithium Recovery from Synthetic Geothermal Brine Using Electrodialysis Method

Vincent Sutresno Hadi Sujoto1 · Sutijan1 · Widi Astuti3 · Slamet Sumardi3 · Isana Supiah Yosephine Louis4 · Himawan Tri Bayu Murti Petrus1,2

Received: 4 July 2021 / Accepted: 15 December 2021
© The Minerals, Metals & Materials Society 2022

Abstract
The consumption of lithium grows significantly on the global market, especially in Indonesia. To fulfill the demand, valuable lithium extraction from another natural source is considered, such as geothermal brine. During the research, the electrodialysis device was operated using different temperatures (30, 35, and 40 °C) and electric voltage (2 V, 3 V, and 4 V). The direct electric current was supplied by the electricity source, which comes from outside the membrane module. Due to the possible blockage on the membrane, synthetic geothermal brine was used in this study instead of nature-derived. Temperature and potential differences played essential roles in the concentration of lithium from the brine. The highest concentration is gained at temperature and electric voltage of 40 °C and 3 V, respectively.

The contributing editor for this article was Hongmin Zhu.

Himawan Tri Bayu Murti Petrus
bayupetrus@ugm.ac.id

1 Chemical Engineering Department (Sustainable Mineral Processing Research Group), Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika No. 2, Kampus UGM, Yogyakarta 55281, Indonesia

2 Faculty of Engineering, Unconventional Geo-Resources Research Center, UGM, Jl. Grafika No.2, Kampus UGM, Yogyakarta 55281, Indonesia

3 Research Unit for Mineral Technology, National Research and Innovation Agency (BRIN), Jl. Ir. Sutami Km. 15, Tanjung Bintang, Lampung Selatan, Lampung 35361, Indonesia

4 Department of Chemistry Education, Faculty of Mathematics and Natural Sciences, Yogyakarta State University, Jl. Colombo 1, Yogyakarta 55281, Indonesia

Published online: 17 January 2022
Keywords  Lithium · Battery · Green energy · Electrodialysis · Geothermal brine

Introduction

Indonesia has abundant natural resources which can be obtained not only on land but also in air and water. These abundant natural resources can contribute to the essential capital growth for national and regional development if they are being processed accordingly. In contrast, it will either disrupt the environment because of the misconduct process or not exploit optimally. The distribution of minerals in Indonesia is not evenly distributed according to the geological conditions in each region. In mainland Indonesia, which covers 2,027,087 km², various natural resources, especially minerals, are spread unequally [1]. Natural resources utilization must be carried out as effectively as possible to achieve prosperity for all Indonesian people.

Lithium has been widely used to make glass, ceramics, batteries, and in other industries. Although lithium has various applications, the abundance in nature is only 0.0018% [2]. The demand for lithium in the global market is experiencing a rapid increase due to the increasing use of lithium. The lithium demand is forecast to grow dramatically in the coming years as various lithium batteries are the most promising candidates for powering electric vehicles [3]. Lithium consumption, globally, continues to increase, reaching more than 100,000 tons of lithium carbonate per year. It is estimated by 2025, lithium consumption can be more than 160,000 tons per year [4]. Nowadays, two-thirds of the world’s lithium is obtained from brine extraction, half a million liters of brine per ton of lithium carbonate [5]. Since the demand for lithium is relatively huge and lithium resources are still unable to meet the demand, a much larger lithium resource is being considered and exploited. Lithium can be obtained from two categories of sources: artificial sources such as the recycling process of electronic waste and lithium batteries...
Distillation (MD) technology [12]. The problem of MD of membrane technology is the application of Membrane ferent selectivity for different compounds. Another type of membrane acts as a semi-permeable barrier and may have different advantages compared to other membrane separation technology. Fouling is one of the most inhibiting factors limiting the use of more desalination membranes. Fouling occurs due to the presence of particulates, organic matter, biofilm-forming microorganisms, and inorganic scaling. Several studies related to overcoming the fouling phenomenon have been developed [13, 14].

Another type of membrane separation is by using electrodialysis (ED). Electrodialysis (ED) is a process in which ions are transferred through a membrane due to the difference in electrical potential charge [15]. In general, ED experiments are carried out in an electrodialysis stack. Electrodialysis is alternately arranged between a cation exchange membrane (CEM) and anion exchange membrane (AEM), anode electrode (such as an iridium coated titanium electrode), and a cathode electrode (such as a stainless steel electrode) [16]. Most of electrical systems in ED employed direct current (DC) [17–20].

In several studies, lithium ions (Li+) can penetrate the monovalent ion exchange membrane from the brine (feed) into the concentrate (purified solution) under an electric driving force. In contrast, other ions such as Mg^{2+} and Ca^{2+} barely penetrate the monovalent ion exchange membrane and stay in the feed [21]. Permselectivity between ions of the same charge is generally evaluated by equating the specific ion that permeates through the membrane when one equivalent of a standard cation or anion permeates [22]. The ion exchange membrane must be highly permeable to counter ions, but it must be impermeable to co-ions [23]. When ions of the same charge are separated, separation by molecular sieving based on polymer networks is first considered. Smaller ions are thought to permeate selectively through membranes with highly cross-linked structures compared to larger ions [24].

In this study, extracting lithium from geothermal brine using the electrodialysis (ED) method has been carried out because the ED method can produce fresh water and a salt solution. In addition, the ED method has a high degree of selectivity to monovalent ions and is environmentally friendly. ED has an advantage in terms of fouling because ED only removes ions. Therefore, any bacteria, colloidal material, or silica present in the feed water stream remain in the product stream. To minimize fouling on the system, an additional chemical can be introduced to the system. The system's polarity can also be reversed by electrodialysis reversal (EDR) to reduce fouling. By switching the polarity (and direction of solution flow) several times per hour, the ions move in opposite directions through the membrane, minimizing buildup. This method generally minimizes membrane fouling, reducing pre-treatment requirements compared to other membrane separation methods.
Methods and Materials

Electrodialysis Membrane

This research employed a polyethylene ion exchange membrane from Hangzhou Huamo Technology Co., Ltd., Hubei province, China. The membrane is produced from styrene sulfonic acid-type cation exchange resin, quaternary ammonium styrene anion exchange resin with ethylene binder mixed with pull sheet, and nylon net reinforced by hot pressing. The membrane has a temperature resistance of up to 45 °C, chemical stability with a pH of 1–12, and 40–45% water content.

Feed and Recovery Solution

Feed

This study's synthesis of geothermal water was carried out by dissolving several chloride salts in demineralized water. The composition used follows the composition in Table 1.

The composition of geothermal brine during the research follows the original composition of geothermal brine taken from Dieng, Central Java, Indonesia. Still, the above composition does not include several other components such as silica, boron, and several other components, the feed is assumed to have undergone the removal of impurities using other methods such as precipitation.

Recovery Solution

The recovery solution used in this study was 0.1 M hydrochloric acid solution where the value was taken from research conducted by Hoshino [25]. The synthesis of the recovery solution was carried out by diluting 37% hydrochloric acid solution into water.

Electrodialysis System

The research was conducted on a laboratory scale using a simple electrodialysis device. This cell has an active area of 72.25 cm² (11.2 in²). Variations in operating temperatures were 30, 35, and 40 °C, while the operating voltages were 2, 3, and 4 V. Some research data such as volume, current, and conductivity were recorded every 5 min for 2 h. In addition, the samples before and after the electrodialysis process were analyzed using ICP-OES.

Theoretical Model

In the ED system, the transfer rate equation as a function of time, often called the flux, can be divided into two types: ionic flux and solution flux. Ionic flux is the rate of transfer of specific ions through the membrane per unit of time and area, which can be formulated as the following equation [26]:

\[ J_s = \frac{V \cdot (C_{ct} - C_{cd})}{A \cdot t} \]  

The ionic flux is generally denoted \( J_s \) (g/(m² h)). Index A is effective membrane surface area (m²), \( t \) is time (h), while \( V \) is the permeate volume (L). The initial concentration is denoted \( C_{c0} \) (g/L) and the concentration at \( t \) is indicated \( C_{ct} \) (g/L). The solution flux (\( J_v \)) states the rate of transfer of the solution per unit area and time (L/(m² h)), which can be expressed in the following equation:

\[ J_v = \frac{V}{A \cdot t} \]  

Meanwhile, according to Tanaka [17], ionic flux (\( J_s \)) can be expressed by the following equation [17]:

\[ J_s = \lambda \cdot (I/S) + \mu \cdot \left( C''_p - C'_p \right) = \eta \cdot (I/S)/F \]  

where \( \lambda \) is total ion transfer numbers (eq/C), \( I \) is electric current (A), \( S \) is membrane area (cm²), \( \mu \) is total solute permeability (cm/s), \( C'_p \) is retentate concentration (eq/cm³), \( C''_p \) is permeate concentration (eq/cm³), \( \eta \) is efficiency, and \( F \) is Faraday’s constant = 96,500 A · s/equivalent/cell pair.

The value of \( J_v \) can be expressed by the following equation [17]:

\[ J_v = \phi \cdot (I/S) + \rho \cdot \left( C''_p - C'_p \right) \]  

where \( \phi \) is total electro-osmosis permeability (cm³/C) and \( \rho \) is total hydraulic permeability (cm³/(eq s)). \( \lambda \) represents the number of ions that move through the membrane. The value of \( \lambda \) is directly proportional to \( \rho \). The \( \mu \) value represents the

| Component | Concentration [ppm] | Concentration [M] |
|-----------|---------------------|-------------------|
| Na⁺       | 7120                | 0.310             |
| K⁺        | 2200                | 0.060             |
| Mg²⁺      | 107                 | 0.004             |
| Ca²⁺      | 401                 | 0.010             |
| Li⁺       | 39                  | 0.006             |
membrane’s ability to pass a certain amount of solute. The value of μ is directly proportional to ρ. The value φ means the ability of the membrane to pass a number of particles with the help of electricity. The value of φ can be found using the following equation [17]:

$$\phi = 3.768 \times 10^{-3} \rho^{0.2} + 1.019 \times 10^{-2} \cdot \rho$$

(5)

ρ represents the membrane’s ability to pass fluids. The value of ρ is directly proportional to the feed temperature [17].

Faraday’s law is the basis for determining the amount of electric current required in an ED process to transfer a certain amount of salt. The following equation is the basic form for calculating the electric current needed to move the ions. When used in ED calculations, Faraday’s law is stated for each cell pair. Efficiency refers to the percentage of the total current that effectively transfers the ions. In ED applications, the efficiency e for salt transfer can be calculated based on the following expression in Faraday’s law [27]:

$$e = \frac{F^* \times F_d \times \Delta N}{I \times N^*} \times 100\%$$

(6)

where I is the direct electric current [A], F* is Faraday’s constant which is 96,500 A s/equivalent/cell pair, F_d is the flow rate of demineralized flow through the membrane [L/s], ∆N is the difference in normality between inlet and outlet, e is efficiency, and N* is number of cell pairs.

The percentage of recovery represents the number of ions recovered from the feed after going through the electrodialysis process, so that the percentage of recovery can be calculated using the following equation [28]:

$$R_{Li}(\%) = \frac{(V_{Ci} \cdot C_{Ci} - V_{Co} \cdot C_{Co})}{V_{Ci} \cdot C_{Ci}} \times 100\%$$

(7)

where V_Ci is the volume at t, V_Co is initial volume, V_Ci is feed volume, and C_Ci is feed concentration.

By knowing the percentage of recovery, the flow rate on the concentrate side can be calculated using the following equation:

$$Q_c = (1 - R_{Li}) \cdot Q_I$$

(8)

The diffusion coefficient in the Stokes–Einstein equation is calculated to determine the effect of the solute and solvent diffusion:

$$D_{AB} = \frac{k \cdot T}{6 \cdot \pi \cdot \mu_B \cdot r_A}$$

(9)

where k is Boltzmann’s constant (0.1380 J/K), T is operating temperature (K), μ_B is solvent viscosity (mPa s), and r_A is the radius of the solute molecule (nm).

The following equation can be used to calculate the total resistance and resistance of the membrane pair [29]:

$$R = \frac{E}{I} = \frac{n}{A} \cdot \left(\frac{2\Delta}{\Lambda_s} \cdot \left(\frac{1}{C_s^{ed}} + \frac{1}{C_s^{sc}}\right) + \rho_{ma} + \rho_{mc}\right)$$

(10)

where E is electrical voltage, I is the total electric current, n is the number of membrane pairs, A is membrane surface area, Δ is membrane thickness, Λs is feed conductivity, C_s^{ed} is retentate concentration, C_s^{sc} is permeate concentration, and ρ_{ma} + ρ_{mc} = r is membrane pair resistance.

Results and Discussion

Operating condition is one of the primary keys in determining the success of a process. By varying various operating conditions, the optimum condition can be obtained. This study used two independent variables: voltage (2, 3, and 4 V) and temperature (30, 35, and 40 °C). The electric current used for the electrodialysis process is DC flow, where this current flows from a point with high potential to a point with low potential (Fig. 1).

The Effect of Operating Condition on the Solution Flux

The flux in the membrane states the amount of permeate that can be passed by the membrane per unit area and per unit time. Therefore, flux is often used as an indicator of the quality of membrane performance. The effect of variations in electric voltage on flux in this study is shown in Fig. 2.

Figure 2 shows that the highest flux in all temperature variations occurred at the beginning of the measurement, where the membrane had not yet experienced fouling. Over time, the flux tends to decrease because the membrane used during the study is getting clogged. The lowest flux in all types of variations in operating conditions in the study was 23 MLH, in which the flux decrease was very slight. Figure 2a shows that the higher the applied voltage, the higher the resulting flux. This phenomenon happens because the higher the voltage, the greater the electricity that flows and the faster the redox reactions that occur at the electrodes. Based on Ohm’s law, the electric voltage is directly proportional to the electric current, so it can be concluded that the greater the voltage, the greater the electric current flowing from the anode to the cathode.

Figure 2b shows a similar movement, where the higher the operating temperature, the faster the resulting solution flux. This event occurs because the ions in solution tend to move faster at higher operating temperatures so that more lithium ions move to the permeate side and vice versa. Thus, based on the solution flux from various operating conditions, it can be concluded that the best condition is at an operating voltage of 4 V and operating temperature of 40 °C because it...
yields the largest solution flux compared to the other operating conditions.

**The Effect of Operating Condition on the Electric Current**

In this study, electric current \( I \) states that a flow occurs due to a voltage or potential difference in an electrically conducting medium in an electrodialysis circuit per unit time. Ohm’s law states that the magnitude of the electric current is greatly influenced by the operating voltage, as shown in Fig. 3.

Figure 3 shows the phenomenon of voltage drop in electrodialysis. The voltage drop is indicated by a decrease in the electric current delivered during the electrodialysis process. Voltage drop is caused by several factors, including the ED system’s amount of electric current and internal resistance. Voltage drop is one of the critical parameters affecting the performance of the ED process. Research conducted by Melnikov et al. stated that the voltage drop is another factor besides the conductivity of the solution that causes an increase in electrical energy consumption [30]. The membrane resistance represents the resistance of the polymer matrix to ionic transport currents. A significant membrane resistance can increase voltage drop [31].

Voltage drop is an unavoidable phenomenon in the electrodialysis process. Therefore, to maintain the performance of the electrodialysis process, a backwash process is needed, which is carried out periodically to reduce the fouling phenomenon. In this study, we do not discuss the effect of the backwashing method to show the phenomena in the electrodialysis system. The voltage drop has occurred because when a short circuit occurs at an early stage, the electrolyte solution still behaves as a suitable capacitor and in the voltage area where dissociation reactions can occur. However, after the dissociation reaction occurs, the energy stored in the solution turns into chemical energy [32]. Another factor that causes a voltage drop is membrane blockage (fouling). During the electrodialysis process, the membrane tends to get clogged continuously. Membrane blockage that occurs can increase electrical resistance. An increase in electrical resistance can cause a decrease in the electric current carried by electricity. This phenomenon is also shown in Eq. (10), where the electrical resistance of the membrane is inversely proportional to the electric current flowing in the electrodialysis system. Based on the electric current flowing from various operating conditions, it can be concluded that the best conditions in the study were still at a voltage of 4 V and a temperature of 40 °C because, in these conditions, the electric current was the largest compared to other operating conditions.
The Effect of Condition Operations on Conductivity

Conductivity expresses a measure of the total concentration of electrolytes in water. The content of electrolytes, which in principle are salts dissolved in water, is related to the ability of water to conduct electricity. Therefore, conductivity is used to measure electrolyte solutions or fluids. The greater the number of ions from a solution, the higher the conductivity value, as shown in Fig. 4.

The conductivity in this study indicates the number of metal ions that pass through the membrane. When observed from the ionic radius, lithium is the component that can pass to the permeate side because, among other metals, the lithium radius is the smallest. Figure 4 shows the increase in conductivity on the permeate side over time. Initially, a significant increase in conductivity occurs. However, the increase in conductivity that occurred continued to decrease, and at the end of the study, the increase in conductivity from the permeate side became very small. The lessened conductivity increase was due to the continuous membrane clogging as the study progressed. Thus, the optimum condition statement is clarified by the conductivity values of the permeate solution from various operating conditions where the greatest conductivity of the permeate solution lies in the operating conditions of 4 V and 40 °C.

The Effect of Condition Operations on the Ionic Flux

The ionic flux in the electrodialysis system states the number of ions passed by the membrane per unit area and per unit time. Therefore, ionic flux is often used to indicate the quality of membrane performance in the electrodialysis process. Based on the concentration data from the ICP-AES analysis and using Eq. (1), a graph can be drawn showing the effect of variations in operating conditions on ionic flux, as shown in Fig. 5.

Figure 5a and b show a similar tendency regarding decreasing operating conditions on the ionic flux of lithium, where the lower the operating conditions, the greater the ionic flux of lithium is. The trend on the voltage variation in Fig. 5a occurred because the increase in the electric voltage will affect the growth in electron density. The excitation process will increase, which means that more lithium ions will be delivered through the cation membrane. The higher the cations that pass through the membrane cations, the lower the electrical energy delivered [33, 34]. An increase in the production rate accompanies this decrease in
current. Therefore, the consumption of electrical energy will decrease so that an increase in H₂ gas will occur drastically. This phenomenon causes a decrease in the ionic flux over time. So the role of electric voltage in this study is crucial in increasing the effectiveness of the transfer of lithium ions because the faster the redox reaction, the faster the process of ion movement is.

Meanwhile, Fig. 5b shows a movement similar to the voltage variation where the higher the operating conditions, the higher the ionic flux produced and vice versa. Several factors lead to this event. The first factor is that when the operating temperature (T) increases, the viscosity of the solvent (B) will decrease and will affect the amount of the diffusion coefficient (D_{AB}), whose value tends to increase, causing increased molecular diffusion. This statement is strengthened by Eq. (9), where the diffusivity coefficient is inversely proportional to the viscosity of the solution. So it can be concluded that the lithium recovery ratio in all brine systems increases with the rising temperature.

The second factor is decreasing hydrated ions with increasing temperature, which has been proven through many X-rays and neutron diffraction studies [35, 36]. Water molecules in hydrated shells from Li⁺ ions can be partially removed. In higher temperature feed solution, the hydrated Li⁺ ionic radius decreases with increasing temperature which significantly affects the migration process (Fig. 6).

Another factor is the swelling of the cation exchange membrane with the increasing temperature [28]. The swelling event occurs mainly due to the nature of the polymer chains in the membrane, which is sensitive to temperature.
changes. Furthermore, the swelling affects the migration of hydrated ions, resulting in the migration rate of monovalent cations (sodium, potassium, and lithium) that change synchronously from relatively low to high. Thus, the separation coefficient of sodium/potassium and lithium has a slight change at the same lithium recovery ratio as the temperature increases. In summary, the temperature does not significantly affect the separation of coexisting cations and lithium, but rather on the recovery ratio of lithium.

The above explanation is reinforced by the data from Fig. 7, which can be calculated using Eq. (8) and Fig. 8. Figures 7 and 8 show the same trend related to the effect of operating condition on the decrease in the trendline of the concentrate flow rate and the normalized concentration of lithium ion, where the lower the operating condition, the significant the reduction in lithium normalized concentration and the lower the concentrate flow rate and vice versa.

The flux of lithium ions formed strongly influences the percentage of recovery lithium. The higher the lithium ionic flux, the higher the percentage of lithium recovery is. This phenomenon shows that the percentage of lithium's rate of return is also greatly influenced by the changes of operating condition variations during the study. Based on Fig. 9, it can be concluded that the higher the operating condition, the greater the rate of lithium return is.

Figure 10 compares the recovery of lithium on the retentate and permeate sides. Figure 10 indicates a movement of lithium toward the permeate side of the membrane. As shown in Fig. 10, the recovery of lithium on the permeate side tends to increase. On the retentate side, it continues to experience a decrease as the operating voltage increases. In addition, Fig. 10 shows that the voltage variation has a more significant impact than the temperature variation.

Based on the lithium ionic flux from various operating conditions, it can be concluded that the best condition in this study remains at a voltage of 4 V and a temperature of 40°C because it produces the largest lithium ionic flux compared to other operating conditions. This statement is supported by the concentrate rate, concentration rate, and percentage of lithium recovery.

Indeed, the ion that passes the membrane surface is the ion with the smallest radius, namely, lithium. However, the research results shown in Fig. 11 described a different result, where potassium has the lowest rejection rate. This phenomenon occurs due to hydration events that happen in the system, where according to Table 2 potassium has the smallest
ionic hydration radius, so lithium is not the owner of the lowest rejection rate. Hydration occurs due to the interaction between the positive charge of the cation and the lone pair of electrons of the oxygen atom. Cations that usually experience the phenomenon of hydration are weak cations, such as sodium ions (Na⁺), which are large cations with low electrical charges [37].

In addition, in Fig. 11, it can be seen that along with the operating voltage, the rejection rate of the magnesium ion continues to decrease drastically. Even though the hydration radius of magnesium should be higher than that of other ions, the resulting rejection voltage is not following the ion hydration theory discussed previously. This phenomenon occurs due to concentration polarization. Research conducted by Nie et al. shows a possibility of concentration polarization due to the higher power usage during the process [16]. It is desirable to operate with the highest possible current density in the electrodialysis process to achieve maximum ion flow per unit membrane area. However, the operation is limited by concentration polarization [38].

The concentration polarization during the study can also occur because the feed flow rate is not too high. As a result, a layer near the membrane with a lower concentration is formed. This concentration polarization phenomenon can cause a decrease in ion movement. The sudden increase in electric field strength in the diffusion layer causes deformation of the ion primary hydration sheath. As a result, the ions are transferred across the interface with a smaller number of water molecules. At the same time, magnesium has the highest level of conductivity, so that the number of Mg ions that pass through the membrane will be pretty large [39]. In short, concentration polarization can cause the phenomenon of salt leakage [40]. Thus, it can be concluded that the operating voltage is very influential not only on lithium recovery but also on its separation from other ions (Table 3).

Based on the percentage of solution rejection of each voltage variation, the best condition in the first study is at a voltage of 3 V. At a voltage of 4 V, there is a concentration polarization phenomenon. This phenomenon causes salt leakage so that the separation between lithium and other cations cannot be conducted properly. Therefore, the consideration of the percentage of rejection discussed above breaks the previous conclusions regarding the best condition in this first study which is 4 V. In conclusion, the best condition is operated at 3 V voltage.

At temperature variations (Fig. 12), potassium is still the ion with the lowest rejection rate due to the hydration event, as previously explained on voltage variations. However, if the percentage of rejections in Figs. 11 and 12 is compared,
it can be seen that the temperature variation gives a lower impact compared to the voltage variation. This statement supports the previous information regarding the effect of a less significant operating temperature on the separation of lithium and other coexisting cations.

Based on the percentage of solution rejection from various voltage variations, the best condition is at a temperature

---

**Table 2** Ionic hydration radius of various ions contained in the salt solution

| Ion    | Li⁺ | Na⁺ | K⁺ | Mg²⁺ | Ca²⁺ |
|--------|-----|-----|----|------|------|
| Rₖ (nm)| 0.382| 0.358| 0.331| 0.428| 0.412|

*Source* Zhao et al. [28]

---

**Table 3** Constant value to determine the total hydraulic permeability equation, total ion displacement rate, and total solute permeability

| A       | B                 | C          | D                         | E                 |
|---------|-------------------|------------|---------------------------|-------------------|
| 6.4676×10⁻⁵ | 2.4941×10⁻⁵ | 6.52×10⁻² | 4.2931×10⁻¹⁴ | 2.220×10⁻¹⁴ |

---

**Fig. 11** The percentage of rejection of several ions from research results with variations in the operating voltage

---

**Fig. 12** The percentage of rejection of several ions from the research results with temperature variations
of 40 °C. Theoretically, the higher the operating temperature, the lower the rejection of each ion. This phenomenon causes a decrease in the rejection rate of all ions. Therefore, the temperature variations in this study have more role in the return ratio of lithium compared to the separation of lithium from other cations. Overall, the best conditions are at an operating voltage of 3 V and a temperature of 40 °C.

**Evaluation of Parameters and Model**

The analysis of several parameters shows that variations in temperature and electric voltage in the electrodialysis system play an essential role in the lithium recovery process. Therefore, the appropriate model is expected to predict the air flux during the lithium recovery process using the electrodialysis method accurately.

Several parameters were analyzed qualitatively to determine the effect of voltage variations on these parameters in the previous discussion. Based on the results of the qualitative analysis previously discussed, it can be concluded that an increase in electric voltage and operating temperature can result in an increase in the feed flux, ionic flux, and concentration rate and reduce the rejection rate.

This section will discuss the quantitative analysis of the research that has been carried out. Quantitative analysis is carried out to determine the effect of the model used in calculating the parameters in the electrodialysis (ED) process that are not measured during the study and cannot be calculated by qualitative analysis. Based on the research data, the results of previous qualitative calculations, and the equations that have been derived previously, some constants, and parameters can be obtained as follows:

So the following equations can be obtained:

\[ \mu = 2.220 \times 10^{-14} \cdot \rho \]  

By combining all the equations, an equation can be written that relates the temperature and flux of the solution as follows:

\[
\begin{align*}
J_s & = \phi \cdot (1/S) + \mu \left( C_{p}^{o} - C_{f}^{o} \right) \\
J_s & = (3.768 \times 10^{-5} \cdot (6.4676 \times 10^{-5} \cdot T + 2.9491 \times 10^{-5})^2 + 1.019 \times 10^{-2} \cdot (6.4676 \times 10^{-5} \cdot T + 2.9491 \times 10^{-5}) \left( \frac{4}{5} \right) + (6.4676 \times 10^{-5} \cdot T + 2.9491 \times 10^{-5}) \left( C_{p}^{o} - C_{f}^{o} \right) \\
J_s & = (4.912 \times 10^{-17} \cdot T + 1.894 \times 10^{-17})^2 + 6.59 \times 10^{-7} \cdot T + 2.541 \times 10^{-7}) \left( \frac{4}{5} \right) + (6.4676 \times 10^{-5} \cdot T + 2.9491 \times 10^{-5}) \left( C_{p}^{o} - C_{f}^{o} \right)
\end{align*}
\]

Meanwhile, the effect of temperature on the flux of lithium ions can be written as follows:

\[
\begin{align*}
J_s & = k \cdot (1/F) + \mu \left( C_{p}^{o} - C_{f}^{o} \right) \\
J_s & = (0.0652 \cdot (6.4676 \times 10^{-5} \cdot T + 2.9491 \times 10^{-5})^2 + 4.2931 \times 10^{-14} \cdot \left( \frac{4}{5} \right) + 2.220 \times 10^{-14} \cdot (6.4676 \times 10^{-5} \cdot T + 2.9491 \times 10^{-5}) \left( C_{p}^{o} - C_{f}^{o} \right) \\
J_s & = (4.217 \times 10^{-6} \cdot T + 1.626 \times 10^{-14}) \left( \frac{4}{5} \right) + (1.436 \times 10^{-18} \cdot T + 5.537 \times 10^{-19}) \left( C_{p}^{o} - C_{f}^{o} \right)
\end{align*}
\]

Equation (10) and research data can be used to calculate the wet membrane thickness value of 4.301 mm with a membrane pair resistance of $1.5875 \times 10^{-5} \Omega \cdot \text{cm}^2$ so that the equation that connects the ionic flux to the electric voltage can be obtained as follows:

\[
J_s = \frac{F^s \cdot F_d \cdot \Delta NV}{I \cdot N^s \cdot S \cdot \frac{n}{A} \cdot F \cdot \left( \frac{0.2602}{\Lambda_s} \cdot \left( \frac{4}{5} + \frac{1}{C_{p}^{o}} \right) + 1.5875 \times 10^{-5} \right)}
\]

Meanwhile, the equation that connects the solution flux with the voltage can be written as follows:

\[
J_s = \frac{F^s \cdot F_d \cdot \Delta NV}{I \cdot N^s \cdot S \cdot \frac{n}{A} \cdot F \cdot \left( \frac{0.2602}{\Lambda_s} \cdot \left( \frac{4}{5} + \frac{1}{C_{p}^{o}} \right) + 1.5875 \times 10^{-5} \right) \left( C_{p}^{o} - C_{f}^{o} \right)}
\]

**Conclusion**

The conclusions obtained from the research that has been done include the following:

1. The research that has been done shows that temperature and potential difference are essential parameters in separating lithium from brine, such as synthetic geothermal brine used during this research. The increase in feed temperature and the potential difference in the ED system increased the concentration of lithium obtained and the resulting permeate flux. However, based on the results obtained, voltage variations play a more critical role than temperature variations.
2. Temperature variation has more effect on the ratio of lithium obtained than the separation of lithium from other cations.

3. Based on the experimental data analysis that has been carried out using the existing equations, an equation that relates the operating temperature and flux can be modeled as follows:

\[ J_v = \left( 4.912 \times 10^{-7} \cdot T + 1.894 \times 10^{-17} \right)^{0.2} + 6.59 \times 10^{-7} \cdot T + 2.541 \times 10^{-7} \right) \cdot \left( \frac{1}{S} \right) + (6.4676 \times 10^{-5} \cdot T + 2.4941 \times 10^{-5} \right) \cdot \left( C''_p - C_p \right) \]

\[ J_s = \left( 4.217 \times 10^{-6} \cdot T + 1.626 \times 10^{-14} \right) \cdot \left( \frac{1}{S} \right) + (1.436 \times 10^{-18} \cdot T + 5.537 \times 10^{-19} \right) \cdot \left( C''_p - C_p \right) \]

4. In addition, based on the calculated data and experimental data, the following equation can be obtained connecting the electric voltage and flux:

\[ J_v = \frac{F^+ \cdot F_d \cdot \Delta N \cdot V}{F^+ \cdot F_d \cdot N^+ \cdot S \cdot \frac{\partial \mu}{\partial \gamma} \cdot \left( \frac{0.2602}{\lambda} \right) \cdot \left[ \frac{1}{C_v} + \frac{1}{C_f} \right] + 1.5875 \times 10^{-5} \right] \cdot \left( C''_p - C_p \right) \]

\[ J_s = \frac{F^+ \cdot F_d \cdot \Delta N \cdot V}{F^+ \cdot F_d \cdot N^+ \cdot S \cdot \frac{\partial \mu}{\partial \gamma} \cdot \left( \frac{0.2602}{\lambda} \right) \cdot \left[ \frac{1}{C_v} + \frac{1}{C_f} \right] + 1.5875 \times 10^{-5} \right] \]

5. The selection of the best conditions is based on research results according to the theoretical statement that the higher the operating conditions, the more lithium can be obtained and is limited by the concentration polarization phenomenon. Therefore, it can be concluded that the best operating conditions are at a temperature of 40 °C and using a voltage of 3 V.

Acknowledgements  The authors are grateful for the support of Gadjah Mada University and the collaboration of the Research and Development Division for Mineral Technology, Indonesian Institute of Sciences (LIPI) Lampung for the laboratory facilities used in the research

Funding  This study was financially supported by Ministry of Research, Technology and Higher Education of the Republic of Indonesia (RISTEKDIKTI) through Penelitian Dasar and support from the Research Unit for Mineral Technology, National Research and Innovation Agency (BRIN) Lampung.

Declarations

Conflict of interest  The authors declare that they have no conflict of interest.

References

1. Sumaatmadja N (1988) Studi Geografi Suatu Pendekatan dan Analisa Keruangan. Alumni, Bandung
2. Glasstone S, Sesonske A (1994) Nuclear reactor engineering. Engineering C. https://doi.org/10.1007/978-1-4615-2083-2
3. Optiz A, Badami P, Shen L et al (2017) Can Li-Ion batteries be the panacea for automotive applications? Renew Sustain Energy Rev 68:685–692. https://doi.org/10.1016/j.rser.2016.10.019
4. Murodjon S, Yu X, Li M et al (2020) Lithium recovery from brines including seawater, salt lake brine, underground water and geothermal water. Thermodyn Energy Eng. https://doi.org/10.5772/intechopen.90371
5. Flexer V, Baspineiro CF, Galli CI (2018) Lithium recovery from brines: a vital raw material for green energies with a potential environmental impact in its mining and processing. Sci Total Environ 639:1188–1204. https://doi.org/10.1016/j.scitotenv.2018.05.223
6. Hartono M, Astrayudha MA, Petrus HTBM et al (2017) Lithium recovery of spent lithium-ion battery using bioleaching from local sources microorganism. Rasayan J Chem 10:897–903. https://doi.org/10.7324/RJC.2017.1031767
7. Siekierka A, Tomaszewska B, Bryjak M (2018) Lithium capturing from geothermal water by hybrid capacitive deionization. Desalination 436:8–14. https://doi.org/10.1016/j.desal.2018.02.003
8. Grosjean C, Herrera Miranda P, Perrin M, Poggi P (2012) Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renew Sustain Energy Rev 16:1735–1744. https://doi.org/10.1016/j.rser.2011.11.023
9. Qurrahman AH, Wilopo W, Susanto SP, Petrus M (2021) Energy and exergy analysis of dieng geothermal power plant. Int J Technol 12:175–185. https://doi.org/10.14716/ijtech.v12i1.4218
10. Setiawan FA, Rahayuningsih E, Petrus HTBM et al (2019) Kinetics of silica precipitation in geothermal brine with seeds addition: minimizing silica scaling in a cold re-injection system. Geotherm Energy. https://doi.org/10.1186/s40517-019-0138-3
11. Tomaszewska B, Szczepański A (2014) Possibilities for the efficient utilisation of spent geothermal waters. Environ Sci Pollut Res 21:11409–11417. https://doi.org/10.1007/s11356-014-3076-4
12. Sutiljan, Sujoto VSH, Mustika PBCW et al (2022) Lithium recovery with the membrane distillation method: a review. INSIST (in press)
13. Chen V, Li H, Li D et al (2006) Cleaning strategies for membrane fouled with protein mixtures. Desalination 200:198–200. https://doi.org/10.1016/j.desal.2006.03.294
14. Petrus HB, Li H, Chen V, Norazman N (2008) Enzymatic cleaning of ultrafiltration membranes fouled by protein mixture solutions. J Membr Sci 325:783–792. https://doi.org/10.1016/j.memsci.2008.09.004
15. Mülter M (1996) Basic principles of membrane technology. Kluwer Academic Publishers, Dordrecht. https://doi.org/10.1007/978-94-009-1766-7
16. Nie X-Y, Sun S-Y, Sun Z et al (2017) Ion-fractionation of lithium ions from magnesium ions by electrodialysis using monovalent selective ion-exchange membranes. Desalination 403:128–135. https://doi.org/10.1016/j.desal.2016.05.010
17. Tanaka Y (2015) Electrodialysis. Prog Filtr Sep. https://doi.org/10.1016/B978-0-12-384746-1.00006-9
18. Chen Q-B, Ji Z-Y, Liu J et al (2018) Development of recovering lithium from brines by selective-electrodialysis: effect of coexisting cations on the migration of lithium. J Membr Sci 548:408–420. https://doi.org/10.1016/j.memsci.2017.11.040

19. Song Y, Zhao Z (2018) Recovery of lithium from spent lithium-ion batteries using precipitation and electrodialysis techniques. Sep Purif Technol 206:335–342. https://doi.org/10.1016/j.seppur.2018.06.022

20. Ji PY, Ji ZY, Chen QB et al (2018) Effect of coexisting ions on recovering lithium from high Mg2+/Li+ ratio brines by selective-electrodialysis. Sep Purif Technol 207:1–11. https://doi.org/10.1016/j.seppur.2018.06.012

21. Zhang Y, Wang L, Sun W et al (2020) Membrane technologies for Li+/Mg2+ separation from salt-lake brines and seawater: a comprehensive review. J Ind Eng Chem 81:7–23. https://doi.org/10.1016/j.jiec.2019.09.002

22. Hosseini SM, Gholami A, Madaeni SS et al (2012) Fabrication of (polyvinyl chloride/cellulose acetate) electrodialysis heterogeneous cation exchange membrane: characterization and performance in desalination process. Desalination 306:51–59. https://doi.org/10.1016/j.desal.2012.07.028

23. Kariduraganavar MY, Nagarale RK, Kittur AA, Kulkarni SS (2006) Ion-exchange membranes: preparative methods for electrodialysis and fuel cell applications. Desalination 197:225–246. https://doi.org/10.1016/j.desal.2006.01.019

24. Sata T (1994) Studies on ion exchange membranes with permselectivity for specific ions in electrodialysis. J Membr Sci 93:117–135. https://doi.org/10.1016/0376-7388(94)80001-4

25. Hoshino T (2015) Innovative lithium recovery technique from seawater by using world-first dialysis with a lithium ionic super-conductor. Desalination 359:59–63. https://doi.org/10.1016/j.desal.2014.12.018

26. António M, Rodrigues S (2014) Electrodialysis and water reuse. Springer, Berlin. https://doi.org/10.1007/978-3-642-40249-4

27. Murray P (1995) Electrodialysis and electrodialysis reversal—manual of water supply practices, m38 (1st edition). Am Water Work Assoc, Denver, pp 30–31

28. Zhao LM, Chen QB, Ji ZY et al (2018) Separating and recovering lithium from brines using selective-electrodialysis: sensitivity to temperature. Chem Eng Res Des 140:116–127. https://doi.org/10.1016/j.chemer.2018.10.009

29. Strathmann H (1995) Chapter 6: Electrodialysis and related processes. Membr Sci Technol 2:213–281. https://doi.org/10.1016/S0927-5193(06)80008-2

30. Melnikov S, Sheldeshov N, Zabolotsky V et al (2017) Pilot scale complex electrodialysis technology for processing a solution of lithium chloride containing organic solvents. Sep Purif Technol 189:74–81. https://doi.org/10.1016/j.seppur.2017.07.085

31. Mei Y, Tang CY (2018) Recent developments and future perspectives of reverse electrodialysis technology: A review. Desalination 425:156–174. https://doi.org/10.1016/j.desal.2017.10.021

32. Kleperis J, Linkov V (2012) Electrodialysis. InTech, London. https://doi.org/10.5772/2820

33. Yan Z, Chen L, Wang H (2008) Hydrogen generation by glow discharge plasma electrodialysis of ethanol solutions. J Phys D Appl Phys. https://doi.org/10.1088/0022-3727/41/15/155205

34. Mizuno T, Akimoto T, Ohmori T (2002) Confirmation of anomalous hydrogen generation by plasma electrodialysis. In: Proc 4th Meet JCF, pp 1–34

35. Brodholt JP (1998) Molecular dynamics simulations of aqueous NaCl solutions at high pressures and temperatures. Chem Geol 151:11–19. https://doi.org/10.1016/S0009-2541(98)00066-7

36. Yamaguchi T, Ohzono H, Yamagami M et al (2010) Ion hydration in aqueous solutions of lithium chloride, nickel chloride, and caesium chloride in ambient to supercritical water. J Mol Liq 153:2–8. https://doi.org/10.1016/j.molliq.2009.10.012

37. Roy Y, Warsinger DM, Lienhard JH (2017) Effect of temperature on ion transport in nanofiltration membranes: diffusion, convection and electromigration. Desalination 420:241–257. https://doi.org/10.1016/j.desal.2017.07.020

38. Krol JJ, Wessling M, Strathmann H (1999) Chronopotentiometry and overlimiting ion transport through monopolar ion exchange membranes. J Membr Sci 162:155–164. https://doi.org/10.1016/S0376-7388(99)00134-9

39. Zabolotskii VI, Pis’Menskii VF, Demina OA, Novak L, (2013) Effect of concentration polarization on electrodialytic concentrating of dilute NaCl and NH4NO3 solutions. Russ J Electrochem 49:563–570. https://doi.org/10.1134/S1023193513060153

40. Baker RW (2011) Membrane technologies and applications. Membr Technol Appl. https://doi.org/10.1002/0470020393

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.