

# Aluminium Electrode Dissolution in Electrocoagulation Process

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## ABSTRACT

The first and the most important step in electrocoagulation process is electrode dissolution which occurs simultaneously with the hydrolysis of water upon application of electric current. As electrocoagulation pollutant removal rate can be dissolution dependent, this paper presents the studies of effects of operating parameters (current, supporting electrolyte concentration and reactor surrounding temperature) on aluminium electrode dissolution. To achieve this, experiments were carried out by varying NaCl concentration (0.5-2.0 g/l) and applied current (0.5-2.0 A) at two different surrounding temperatures of 5 °C (cold water jacket inlet temperature) and 25 °C (room temperature). The electrolysis time for each experiment was in the range of 0 and 45 min. The results showed that dissolution improved with increase in value of applied current in both conditions; when current was varied from 0.5 A to 1 A, dissolution increased from 0.3347 gL<sup>-1</sup> to 0.6025 gL<sup>-1</sup> on cooling and, at room temperature, it increased from 0.4002 gL<sup>-1</sup> to 0.6695 gL<sup>-1</sup>. High temperature seems to favor aluminium dissolution at low concentration of supporting electrolyte. Salinity was found to have negligible effect on dissolution. In addition, the effects of these parameters on energy consumption were investigated.

**Key words:** Electrocoagulation, aluminium electrode, dissolution, temperature.

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## INTRODUCTION

Coagulation is simply agglomeration of small contaminant particles or solid matters into larger particles that can be easily separated by physical methods such as filtration, sedimentation and/or decantation. Chemical coagulation involves addition of chemicals such as alum, ferric chloride to remove organic, inorganic and dissolved/suspended colloids [1] present in aqueous medium. The main problem associated with chemical coagulation is that it produces large amount of sludge. This results from: (1) addition of undesired counter ions present in the coagulant to the solution during formation of coagulating agent. For instance, adding 1 g of alum as KAl(SO<sub>4</sub>)<sub>2</sub>·12(H<sub>2</sub>O) and ferric chloride (FeCl<sub>3</sub>·6(H<sub>2</sub>O)) each introduces 8.57 g and 1.91 g of undesired counter ions to the solution respectively; (2) Coagulant precursors contains very little coagulating agents on a mass basis [2]. This problem is overcome when coagulant is produced from metal itself and not metallic salt.

Electrocoagulation is similar to coagulation in the sense that it also involves formation of a coagulating agent in an aqueous medium. But, in electrocoagulation, coagulating agent is generated from electrolytic oxidation of sacrificial electrodes usually made up of aluminium or iron [3]. Recently, the use of titanium as sacrificial anode has also been reported [4]. On application of electric current, metal electrode dissolves to form metallic ion. Also, water simultaneously dissociates into hydrogen ions and hydroxyl ions. When passive cathode electrodes are used, electro-dissolution occurs at anode only. In addition to metal dissolution, oxygen evolution can also occur. When a non-passive cathode electrode is used, it also

undergoes dissolution. The main reaction at the cathode is reduction which usually leads to evolution of hydrogen. In the solution, metallic ion released into the solution from the anode combines the hydroxyl ions from the hydrolysis of water to form coagulating agent.

At the anode, the following reactions (shown in Equations (1) – (3)) can possibly occur in electrocoagulation process using aluminium electrode. Equation (2) may only occur when the anode potential is sufficiently high [5].



The primary reaction at the cathode can be written as shown in Equation (4).



In the solution, aluminium ion reacts with hydroxyl ion to form aluminium hydroxide. The reaction can be summarized as given below.



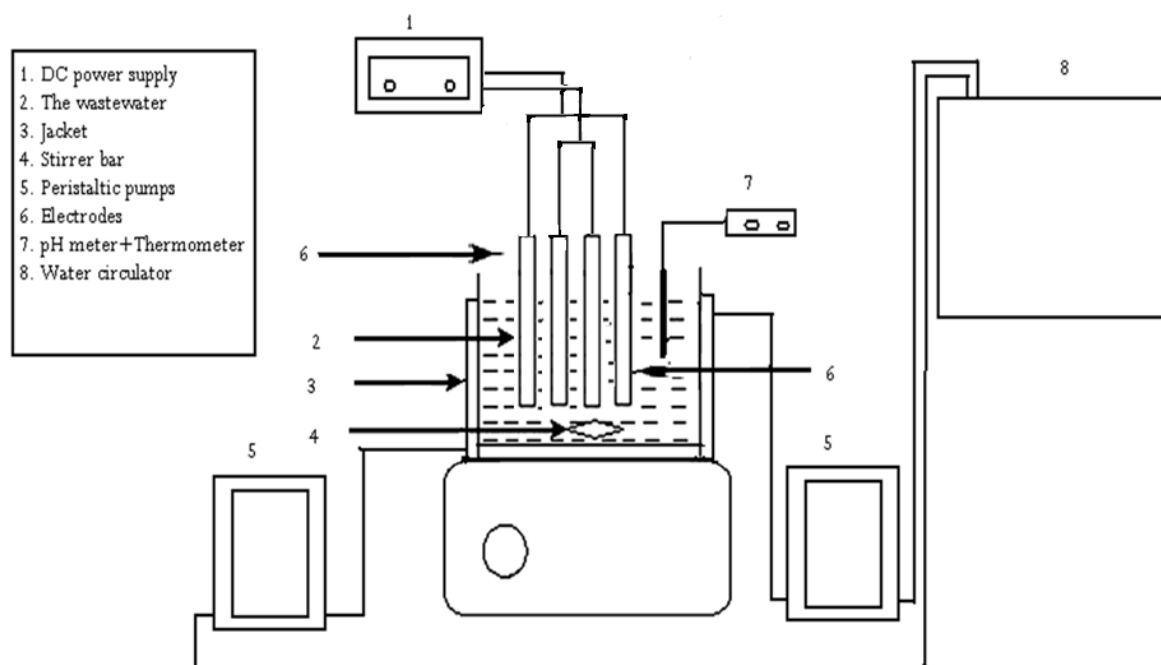
Evolution of hydrogen gas can make the solution more basic at the cathode (Equation (4)). As moles of hydrogen ion in the solution reduce, its pH increases. On the other hand, Generation of hydrogen ions at anode makes the solution in its vicinity acidic (Equation 3). Also, formation of aluminium hydroxide (Equation (5)) is expected to lower the solution pH because it reduces the moles of hydroxyl ion in the solution. However, after electrolysis, the final pH of the resulting solution may be higher [6] or lower than (or approximately the same as) [7] its initial pH. This may be due to amphoteric nature [8] of coagulant  $Al(OH)_3$  produced. The overall efficiency of the process can be affected by water characteristics such as initial pH, initial conductivity and operational variables like current density and electrolysis time [9]. Applied current or current density has been noted to possibly have a warming effect on system solution [10] as electrodes dissolves, and this effect can be positive or negative on the efficiency of the process which is related to the dissolution of electrodes. Dissolution of aluminium electrode can occur chemically and electrochemically. Chemical dissolution is simply metal corrosion caused by a chemical reaction where the electrons released by the dissolving metal species are not part of the cell current [2]. Chemical dissolution of cathode electrodes is said to be induced by evolution of hydrogen, it makes cathode vicinity alkaline and hydroxyl ions chemically attack the electrode [11]. Anodic chemical dissolution, on the other hand, is induced by hydrogen ions produced from water hydrolysis. It is believed that the chemical reactions always contribute to the dissolution when actual electrode dose is much greater than faradic dose [2]. This is mostly observed when aluminium is used as both cathode and anode. The effects of current density, pH and salinity on electrode dissolution at ambient temperature [2], [12] and 30 °C [11] have been

reported. But, in these studies heating joule was not considered and nothing was said concerning the solution temperature.

As the efficiency of electrocoagulation can be affected by temperature, this work has investigated the effect of temperature on aluminium electrode dissolution by varying values of applied current and NaCl concentration at two different temperatures. During the experiments, the responses of the used water characteristics such as temperature and pH to change of operating parameters were also investigated.

## MATERIALS AND METHODS

The experiments of this work were carried in a Plexiglas made batch reactor with active capacity of 1 L, using four aluminium electrodes placed 1.5 cm apart in the cell and connected in mono-polar mode to a D.C power source. Prior to each experiment, the electrodes were thoroughly washed and rinsed with distilled water in order to remove any impurities that may negatively affect dissolution. Electrode dosing was determined by gravimetric method in which the electrodes were weighed before and after 45 min of the experiment using an analytical balance (Scaltec SBC 31) with readability of 0.0001g. Tap water was used for the experiments. During each experiment, the solution was gently stirred using a magnetic stirrer (Chiltern HS31) to ensure uniform temperature of the solution. The pH and temperature were measured using a pH meter and thermometer respectively. The cooling system used to achieve a cold reactor surrounding consisted of cold water circulator connected to the jacket via two peristaltic pumps. The schematic of the setup of the batch electrocoagulation is given in Figure 1. Energy consumption per volume of water used was calculated using Equation (6). The integral was evaluated numerically according to trapezoidal rule using MATLAB R2012a.



**Figure 1.** Experimental setup for the batch electrocoagulation

$$E(\text{kWh}/\text{m}^3 \text{ water}) = \frac{I}{v} \int_{t_0}^{t_n} V(t) dt \quad (6)$$

Where E, I, v, V(t), t<sub>0</sub> and t<sub>n</sub> are energy consumption (kWh/m<sup>3</sup>), current (A), volume of water used (m<sup>3</sup>), voltage as a function of time (V), initial and final time of electrolysis (h) respectively.

## RESULTS AND DISCUSSIONS

The results obtained from this work showed that dissolution improved with increase in value of applied current both at ambient temperature and when the system was cooled at 5°C jacket inlet temperature at all NaCl concentrations except at 2 g/l where increasing current from 1.5 A to 2.0 A yielded no significant change on electrode dose on cooling the system, but reverse was the case at room temperature. As shown in Table 1, At 0.5 g/l and 45 min electrolysis time, when the system was not cooled, increasing the current from 0.5 A to 1.0 A, 1.5 A and 2.0 A increased the electrode dose from 0.4002 g to 0.6695 g, 0.9327 g and 1.6944 g respectively. Under the same conditions but with cooling when the current was 0.5 A, 1.0 A, 1.5 A and 2.0 A, the electrode dose was 0.3347 g, 0.6025 g, 0.8601 g and 1.4499 g respectively (see Table 2).

**Table 1.** The effect of current on electrode dose at ambient temperature and different concentration of NaCl

Current, A	D (g) at T <sub>s</sub> =25 °C			
	0.5 g/l NaCl	1.0 g/l NaCl	1.5 g/l NaCl	2.0 g/l NaCl
0.5	0.4002	0.3087	0.2870	0.3704
1.0	0.6695	0.4737	0.8772	0.7443
1.5	0.9327	0.9650	1.1675	0.7832
2.0	1.6944	1.2214	1.2508	1.3138

**Table 2.** The effect of current on electrode dose on cooling at different concentration of NaCl

Current, A	D (g) at T <sub>s</sub> = 5°C			
	0.5 g/l NaCl	1.0 g/l NaCl	1.5 g/l NaCl	2.0 g/l NaCl
0.5	0.3347	0.3608	0.2923	0.3157
1.0	0.6025	0.6695	0.7595	1.6405
1.5	0.8601	0.7832	0.9316	1.7578
2.0	1.4499	1.4238	1.0445	1.7705

By thought, increasing current applied to electrodes should lead to increase in the value of final pH of the solution. Since evolution of hydrogen gas can lead to increase in solution pH and the evolution can be current dependent [3]. Though, under all operating conditions investigated, the final pH was found to be greater than initial pH. But, increase in current values did not affect the final pH of the solution in any significant manner irrespective of reactor surrounding temperature and supporting electrolyte concentration. For instance, at ambient temperature and 0.5 g/l NaCl, the final pH decreased with increase in current values for up to 1.5 A. But, increasing current from 1.5 A to 2.0 A led to an increase in final pH, as seen in Table 3. On cooling the system, at the same NaCl concentration, increasing current value beyond 1 A had insignificant effect on the final pH. These results have demonstrated the complexity of electrocoagulation process. Thus, it has been discovered that it cannot be predicted from theoretical point of view alone. However, by comparing Table 3 and Table 4 it can be noted that the final pHs obtained at 5 °C were greater than those obtained at 25 °C.

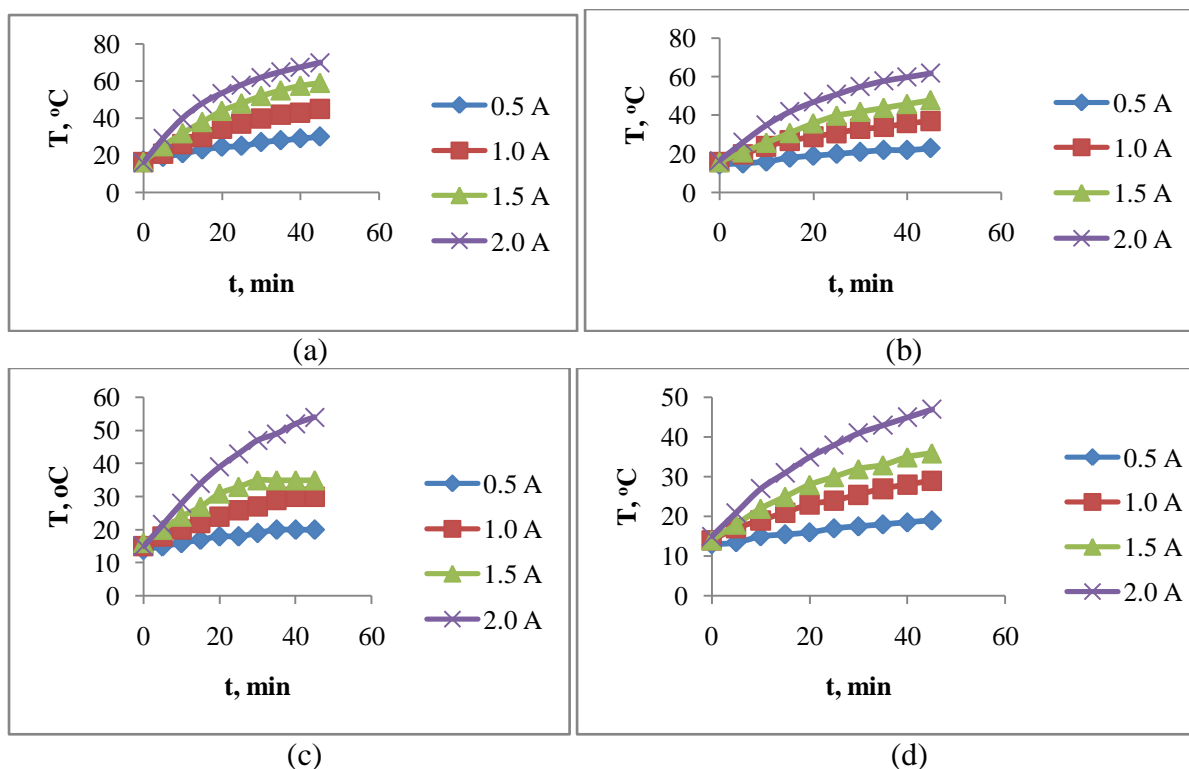
**Table 3.** The effect of current on solution final pH at ambient temperature and different supporting electrolyte concentrations

Current, A	Final pH, at $T_s=25\text{ }^\circ\text{C}$			
	0.5 g/l NaCl	1.0 g/l NaCl	1.5 g/l NaCl	2.0 g/l NaCl
0.5	7.97	8.43	8.51	8.78
1.0	7.90	8.12	8.67	8.47
1.5	7.16	8.27	8	8.43
2.0	8.19	7.88	8.43	8.70

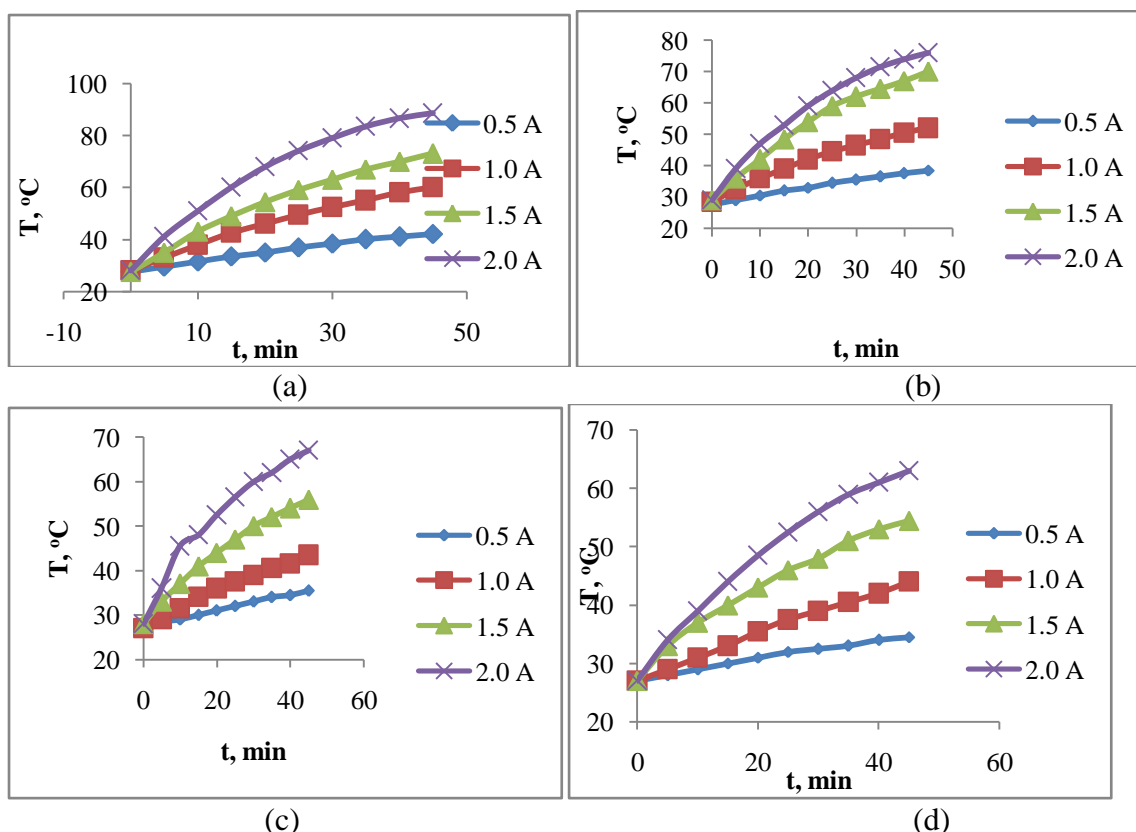
**Table 4.** The effect of current on solution final pH at  $5\text{ }^\circ\text{C}$  surrounding temperature and different supporting electrolyte concentrations

Current, A	Final pH, at $T_s=5\text{ }^\circ\text{C}$			
	0.5 g/l NaCl	1.0 g/l NaCl	1.5 g/l NaCl	2.0 g/l NaCl
0.5	8.15	10.34	8.65	8.81
1.0	8.92	8.89	8.99	8.93
1.5	8.91	8.5	8.94	9
2.0	8.54	8.77	9.09	9.32

During the experiments, at all the values of NaCl concentration and electrolysis time, even when the system was cooled, increasing current value led to increase in solution temperature. For instance, at 0.5 g/l NaCl concentration and 10 min electrolysis time, when the current values were 0.5 A, 1.0 A, 1.5 A and 2.5 A, with cooling, the temperature were  $21^\circ\text{C}$ ,  $26\text{ }^\circ\text{C}$ ,  $32\text{ }^\circ\text{C}$ , and  $40\text{ }^\circ\text{C}$ , without cooling the temperatures measured were  $31.5\text{ }^\circ\text{C}$ ,  $38\text{ }^\circ\text{C}$ ,  $43\text{ }^\circ\text{C}$  and  $51\text{ }^\circ\text{C}$  respectively (see Figures 2 and 3). Also, from these figures it was noted that, at a specific value of current and electrolysis time, as the NaCl concentration increased, the solution temperature decreased. For example, at 2 A and 45 min electrolysis time, when the concentration of NaCl was 0.5 g/l, 1.0 g/l, 1.5 g/l and 2.0 g/l, on cooling and at ambient temperature respectively, the solution temperatures were  $70\text{ }^\circ\text{C}$ ,  $62\text{ }^\circ\text{C}$ ,  $54\text{ }^\circ\text{C}$  and  $47^\circ\text{C}$ , and  $88.5\text{ }^\circ\text{C}$ ,  $76\text{ }^\circ\text{C}$ ,  $67\text{ }^\circ\text{C}$ , and  $63\text{ }^\circ\text{C}$  respectively. From these results, it has been seen that the extent to which the current has affected the solution temperature depended on the concentration of the supporting electrolyte.

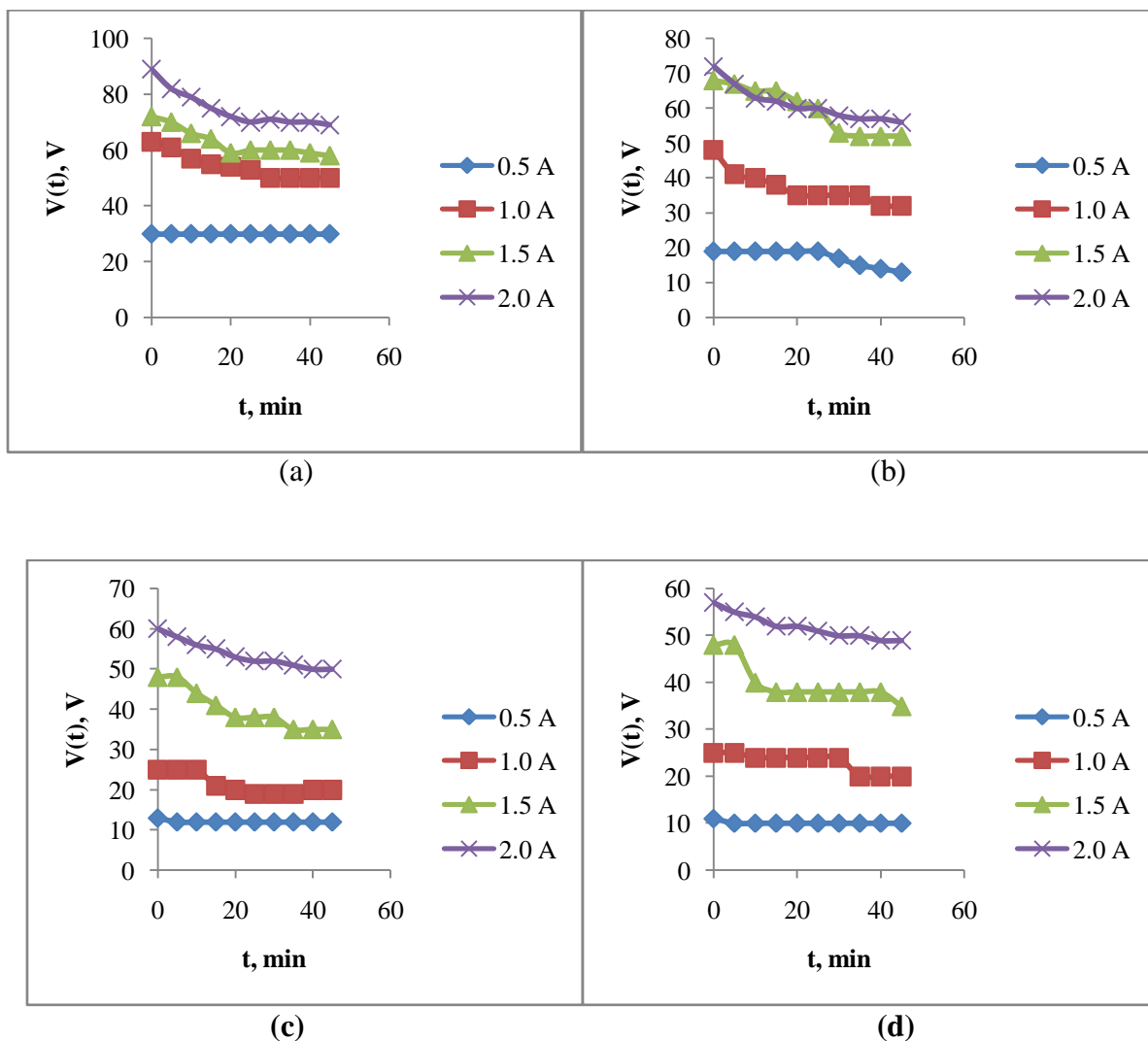


**Figure 2.** The effects of current and electrolysis time on solution temperature. Operating conditions: initial pH= 7.01, reactor surrounding temperature ( $T_s$ )=5 °C, (a) 0.5 g/l NaCl (b) 1.0 g/l NaCl (c) 1.5 NaCl (d) 2.0 g/l NaCl



**Figure 3.** The effects of current and electrolysis time on solution temperature. Operating conditions: initial pH= 7.01, reactor surrounding temperature ( $T_s$ )=25 °C, (a) 0.5 g/l NaCl (b) 1.0 g/l NaCl (c) 1.5 NaCl (d) 2.0 g/l NaCl

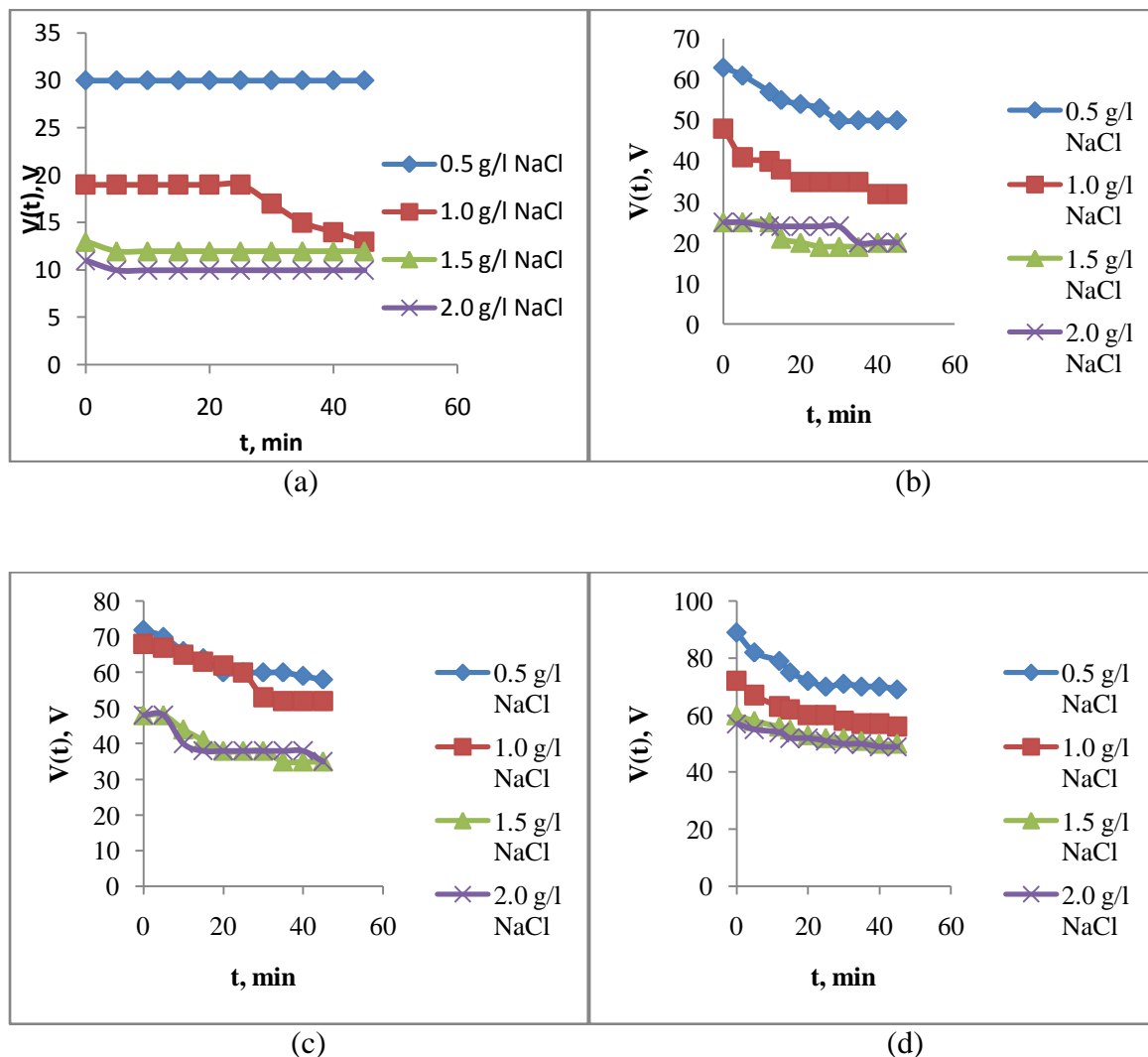
Experimental results revealed that at both temperatures of reactor surrounding, the voltage was observed to vary with the applied current values and the electrolysis time. At specific value of NaCl concentration, increasing the current led to increase in voltage which later decreased as electrolysis time was increased. This was due to the fact that as electrolysis proceeded, the number of ions in the solution decreased as a result of the chemical reactions that occurred in the process. Thus, as electrolysis time increased, the ions or particles in the solution also decreased due to electrolytically induced chemical reactions and, thus, less voltage was required to pass the same amount of current to the electrocoagulation system. However, in some cases, the variation of voltage with electrolysis time was found not be very important. This was noted when the applied current was 1.0 A and NaCl concentration was 1.5 g/l and 2 g/l (as shown in Figure 4). At the current value of 0.5 A and all the values of NaCl concentration, irrespective of the reactor surrounding temperature, the voltage was noticed to vary insignificantly with electrolysis time.



**Figure 4.** The effects of current and electrolysis time on voltage. Operating conditions: initial pH= 7.01, reactor surrounding temperature ( $T_s$ )=25 °C, (a) 0.5 g/l NaCl (b) 1.0 g/l NaCl (c) 1.5 NaCl (d) 2.0 g/l NaCl

Also, investigated in this work was the effect of NaCl concentration on voltage as a function of time. As shown in Figure 5, at each concentration of NaCl and constant current

value greater than 0.5 A, the voltage was observed to vary with electrolysis time. Increasing NaCl concentration up to 1.5 g/l significantly decreased the voltage, except at 1.5 A where varying NaCl concentration from 0.5 g/l to 1.0 g/l had negligible effect on voltage between 10 and 25 min. However, beyond this time range, the voltage was found to decrease due to increase in NaCl concentration.



**Figure 5.** The effects of NaCl concentration and electrolysis time on voltage. Operating conditions: initial pH= 7.01, reactor surrounding temperature ( $T_s$ )=25 °C, (a) 0.5 A (b) 1.0 A (c) 1.5 A (d) 2.0 A

Furthermore, energy consumption was observed to vary with current and NaCl concentration at both surrounding temperatures investigated. Looking at Tables 5 and 6, it can be seen that energy consumption decreased across the rows from left to right for up to 1.5 g/l NaCl, but it increased down the columns of each of the table. This shows that during the experiments, at specific electrolysis time and NaCl concentration, increasing values of current led to increase in energy consumption. On the other hand, at 45 min electrolysis time and current values except 0.5 A, increasing the NaCl concentration up to 1.5 g/l decreased the energy consumption. This was due to the fact that the addition of NaCl reduces ohmic resistance which is proportional to voltage and current. Provided current is constant, decreasing ohmic resistance will decrease voltage. However, beyond 1.5 g/l NaCl, increase in



NaCl either increased or insignificantly decreased energy consumption. The increase in the energy consumption at very high NaCl concentration was due to the occurrence of side reactions such as high hydrogen gas evolution. This was only a side reaction that took place since the final pH values of the solution at all operating conditions were basic.

**Table 5.** The effect of current and NaCl concentration on energy consumption at ambient temperature

Current, A	Energy consumption (kWh/m <sup>3</sup> ) at T <sub>s</sub> =25 °C			
	0.5 g/l NaCl	1.0 g/l NaCl	1.5 g/l NaCl	2.0 g/l NaCl
0.5	11.25	6.5417	4.5	3.75
1.0	40.5417	27.5833	15.875	17.2917
1.5	70.5	67	44.8125	44.6875
2.0	111.3333	91.3333	80.3333	77.6667

**Table 6.** The effect of current and NaCl concentration on energy consumption at cold reactor surrounding temperature

Current, A	Energy consumption (kWh/m <sup>3</sup> ) at T <sub>s</sub> =5 °C			
	0.5 g/l NaCl	1.0 g/l NaCl	1.5 g/l NaCl	2.0 g/l NaCl
0.5	11.25	6.5625	4.5	3.75
1.0	42.83	37.5	15.75	22.5
1.5	77.25	66.875	45	52.8125
2.0	107.8333	96.9167	71.75	87.0833

However, alteration of reactor surrounding temperature seems not to have any significant effect on energy consumption. By comparing Tables 5 and 6, at 0.5 g/l of NaCl, when the currents were 0.5 A, 1.0 A, 1.5 A and 2.0 A, at room temperature, the energy consumptions obtained were 11.25 kWh/m<sup>3</sup>, 40.54 kWh/m<sup>3</sup>, 70.5 kWh/m<sup>3</sup> and 111.33 kWh/m<sup>3</sup> respectively, when the surrounding temperature was 5 °C, the energy consumed in the system were 11.25 kWh/m<sup>3</sup>, 42.83 kWh/m<sup>3</sup>, 77.25 kWh/m<sup>3</sup> and 107.83 kWh/m<sup>3</sup> respectively.

## CONCLUSIONS

In this paper, by varying current and NaCl concentration, the effects of reactor surrounding temperature on aluminium dissolution, solution temperature, voltage and energy consumption have been studied. At the end of 45 min electrolysis time, electrode dose and energy consumption were found to be largely affected by the current irrespective of the surrounding temperatures (5 °C and 25 °C). Both electrode dose and energy consumption were found to increase with increase in the current. However, increasing NaCl concentration (up to 1.5 g/l) decreased the cell voltage and the energy consumption. Increase in solution temperature with time was observed at both surrounding temperatures. At specific electrolysis time, increasing the current led to increase in the solution temperature. But it decreased with increase in NaCl concentration at both surrounding temperatures. Based on the results of the experiment, it was discovered that temperature did not possess any significant effect on the electrode dissolution energy consumption; but it affected the final pH values of the solution. The values of the final pH values obtained at 5 °C were greater than those obtained at 25 °C. This revealed that the variation of surrounding temperature affected the chemistry of electrocoagulation. Thus, it is suggested that low temperature should be preferred while carrying out electrocoagulation experiments. Also, during electrocoagulation,

if high current is to be applied, then the conductivity of the solution should be high enough to prevent both heating of the solution, which can negatively affect the pollutant removal efficiency of the process [13-14], and high energy consumption.

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