Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.768405

51 (2013) 5132–5137
July

Taylor & Francis
Taylor & Francis Group

Effect of operating conditions on the treatment of brackish groundwater by electrodialysis

Ji-Hee Min[a], Han-Seung Kim[b,*]

[a]*R&D Technology Center, Econity, Korea*
[b]*Department of Environmental Engineering and Energy, Myongji University, Korea*
Tel. +82 31 330 6695; email: kimhs210@mju.ac.kr

Received 8 June 2012; Accepted 28 September 2012

ABSTRACT

Desalination of brackish groundwater by electrodialysis was examined in this study. Groundwater samples were taken from a coastal area in Korea where the intrusion of seawater to groundwater is significant. The ion concentrations of the samples were 1,288 mg/L for Cl^-, 107 mg/L for SO_4^{2-}, 273 mg/L for Na^+, 118 mg/L for Mg^{2+}, 201 mg/L for Ca^{2+}, and 4.7 mg/L for K^+, and electric conductivity was 3.85mS/m. Operating conditions are as follows: applied voltage (from 5 to 30 V), pH (3, 7, 9), concentration of electrolyte solution (from 0 to 10% as Na_2SO_4), flow rate of dilute/concentrate/electrolyte (1.08, 2.16, 3.24 L/min)/(1.08, 2.16, 3.24 L/min)/(1.68, 3.36, 5.04 L/min). Cations and anions of water samples were analyzed using ion chromatography (Alltech). The rapid increase in the removal of salt ions was observed until a certain level of removal reached. The higher removal was achieved as the applied voltage increased and linear increase in the removal was found as the voltage increased up to 20 V, while no significant increase in the removal rate appeared beyond 20 V. Although the removal of anions and cations was higher in neutral pH region, the pH condition on at the range of pH from 3 to 9 gave little effect. Drastic increase in the removal of various ions was observed as the electrolyte concentration increased from 0 to 0.5%, while the removal increased gradually at the electrolyte concentration over 1%. Flow rate of concentrate, dilute, and electrolyte compartments showed positive relationship with the removal of the ions. This study suggested that various operating conditions could have effects on the performance of electrodialysis in desalting the brackish groundwater. Because the desalting efficiency depends largely on the input energy, the optimal operating conditions should be considered based on the quality of raw and treated water, and the economic concerns for a practical use of electrodialysis in securing alternative fresh water resources.

Keywords: Brackish groundwater; Desalination; Electrodialysis; Seawater intrusion

1. Introduction

The shortage of fresh water resources has increased especially in developing countries according to the growing demand of water for portable and industrial uses. Most of industrial complex are located in the coastal areas and require fresh water for sustaining the population and industries. Groundwater will be the best available fresh water resources in the

*Corresponding author.

7th Aseanian Membrane Society Conference (AMS7), 4–7 July 2012, Busan, Korea

aspect of stable water quantity and quality compared with any other water resources. Recently, the intrusion of seawater to groundwater in the coastal area has gradually increased with the rising of seawater level due to climate change and with the lowering of the groundwater level due to exploitation resulting from industrialization. In a surveillance report of Korean government, the evidence of gradual seawater intrusion to groundwater was clearly observed based on annual trace of the major ion concentration in the groundwater of coastal areas in Korea [1]. This report showed that the concentration of ions in the ground water of a west coastal area increased from 123 to 250 mg/L for sodium ion, from 87 to 118 mg/L for magnesium ion, from 4 to 13 mg/L for potassium ion, from 180 to 212 mg/L for calcium ion and from 717 to 1,008 mg/L for chlorine ion during the recent two years. On the other hand, bicarbonate ion decreased from 56 to 40 mg/L. This saline contamination causes the use of groundwater to be constrained, so that such brackish groundwater has to be desalted in order to use as fresh water resource for portable, agricultural and industrial purposes.

Of the many desalination methods, electrodialysis is a widely applicable technology in the desalination of various kinds of water sources such as seawater, brackish water and industrial wastewater for producing fresh water [2–5]. The removal of undesirable ions from water sources are also the main application field of electrodialysis, such as the treatment of groundwater contaminated with nitrate [6,7]. Despite many advantages of electrodialysis, the relatively high energy is consumed when the feed solution has high salt concentration. It has an economic advantage over other desalination technologies in a certain range of feed water salt concentration or total dissolved solids (TDS). It is considered as a feasible and economic technology for the feed water with TDS less than 5,000 mg/L [8–10]. The combination of renewable energy source like solar power can make the process more efficient because electrodialysis requires DC power as a driving force [11]. While the optimization of system design and operation conditions is necessary for better application of electrodialysis, only a few researches have been performed on those topics [12,13]. In this study, the operating conditions such as applied voltage, pH, electrolyte concentration, and solution flow rate were investigated on the removal of various ions from the real brackish groundwater samples using electrodialysis.

2. Materials and methods

Groundwater samples were taken from a coastal area in Korea where the intrusion of seawater to groundwater is significant. The ion concentrations of the samples were 1,288 mg/L for Cl^-, 107 mg/L for SO_4^{2-}, 273 mg/L for Na^+, 118 mg/L for Mg^{2+}, 201 mg/L for Ca^{2+} and 4.7 mg/L for K^+, and electric conductivity was 3.85 mS/cm. Operating conditions are as follows: applied voltage (from 5 to 30 V), pH (3, 7, 9), concentration of electrolyte solution (from 0 to 10% as Na_2SO_4), flow rate of dilute/concentrate/electrolyte (1.08, 2.16, 3.24 L/min)/(1.08, 2.16, 3.24 L/min)/(1.68, 3.36, 5.04L/min). Cations and anions of water samples were analyzed using ion chromatography (Alltech).

The schematic diagram of the experimental apparatus is shown in Fig. 1. Stack of the electrodialyzer (PS5-ED1-20, Innomeditech Inc.) was composed of 22 sheets of cation-exchange membrane and 20 sheets of anion-exchange membrane (NEOSEPTA CMX and AMX, Tokuyama Co.). The stack has 20 cell pairs and effective area of 0.1 m^2: one cell pair has effective area of 50 cm^2 and size of membrane is 100 mm by 142 mm.

3. Results and discussion

3.1. Effect of applied voltage

When conducting the experiments with different voltages, other operating conditions were fixed with the electrolyte solution of 1% Na_2SO_4, the flow rate of 2.16 L/min for the concentration and dilution solutions and 3.36 L/min for electrolyte solution, and pH without adjustment. The water samples were fed to concentration and dilution flows. Fig. 2 shows the removal of chloride ion according to the applied voltage and the operating time. Rapid increase in the removal was observed until a certain level of removal reached as the operating time increased. Although the differences in the removal for each applied voltage decreased when longer operating time and the removal over 80% appeared even for the applied voltage of 5 V after the operating time of 120 min, the higher removal was clearly observed as the applied voltage increased. Similar phenomena were observed on the removal for other ions including sodium, calcium, magnesium, and sulfate ions. The same inclination was reported that the removal of NaCl increased by elevating the applied voltage from 9 to 18 V [13]. In our results, a linear relationship between the removal and the applied voltage was found as the voltage increased up to 20 V at a given operating time of 10 min, while no significant increase in the removal

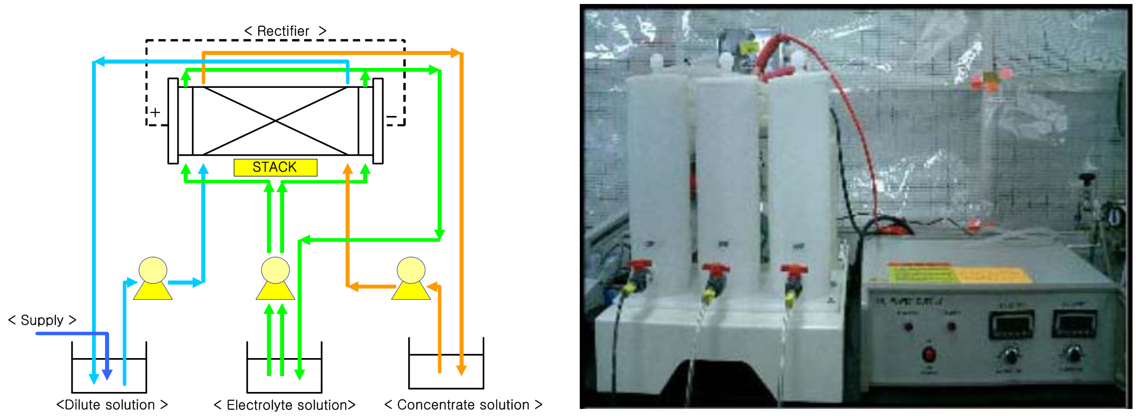

Fig. 1. Schematic diagram and photo of the experimental apparatus.

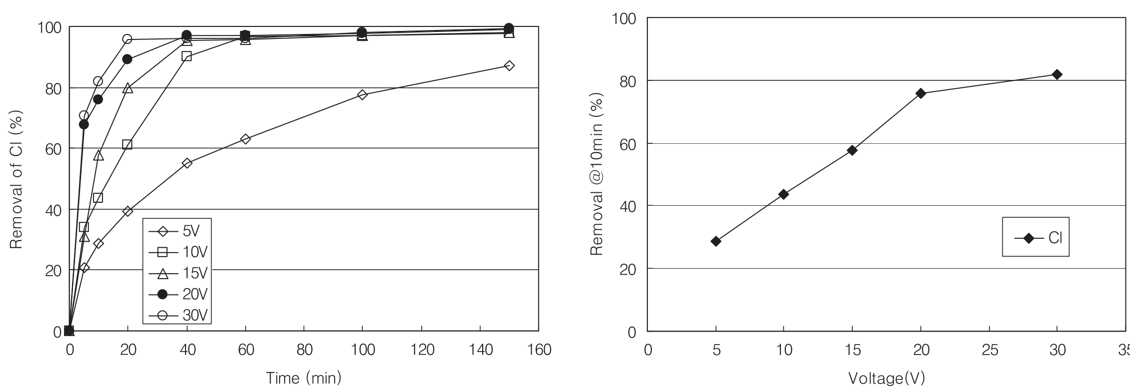

Fig. 2. Effect of applied voltage and time on the removal of chloride ion.

appeared beyond 20 V. This implies that an appropriate applied voltage can be selected for optimizing the system design under a given source water quality and system capacity.

3.2. Effect of pH

In order to examine the effect of pH on the removal of ions, pH of sample water was adjusted to acidic condition of 3 and basic condition of 9 with HCl and NaOH. The operating condition was same as before but fixed applied voltage of 20 V. The removal of all ions increased with operating time for any pH conditions. Fig. 3 showed the removal of various ions at operating time of 10 min. A little difference was found in the removal for each pH condition. Although the removal of each ion was higher in neutral pH region, the pH condition at the range from 3 to 9 gave little effect. These results imply that no adjustment of pH will be necessary for optimizing the removal performance of electrodialysis.

3.3. Effect of electrolyte concentration

Electrolyte solution has an important role in the performance of electrodialysis. The ions will be removed better when the concentration of electrolyte solution is higher because the higher electric current flows as the ion concentration becomes higher with higher concentration of electrolyte solution.

Therefore, it is necessary to design the optimal concentration of electrolyte solution for system efficiency and operating cost. The effect of electrolyte solution was investigated on the removal of ions for the concentration of electrolyte solution (Na_2SO_4) from 0 to 10%. The operating condition except electrolyte solution was same as before. Fig. 4 showed the removal of various ions at operating time of 10 min. Drastic increase in removal of various ions was observed as the electrolyte concentration increased from 0 to 0.5%, while the removal increased gradually from the electrolyte concentration over 1%. In other words, the enhancement of the removal efficiency became smaller as the concentration of electrolyte solution increased especially from 1%. This result

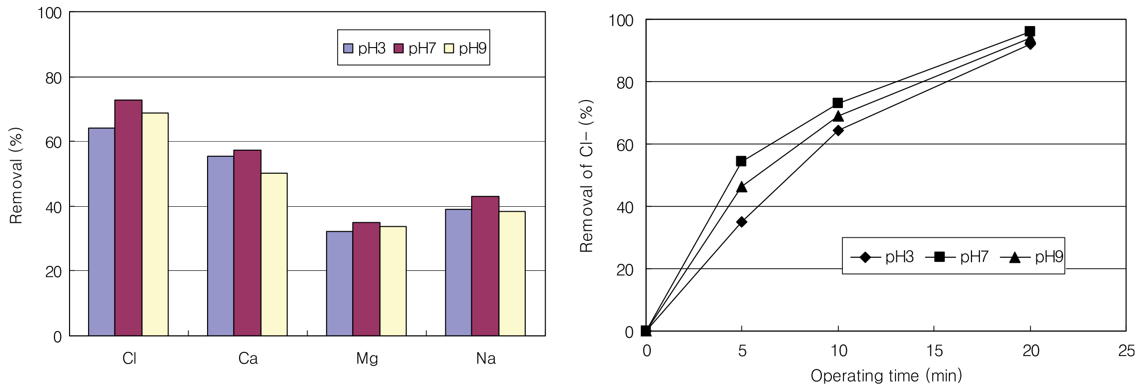

Fig. 3. Effect of pH on the removal of various ions.

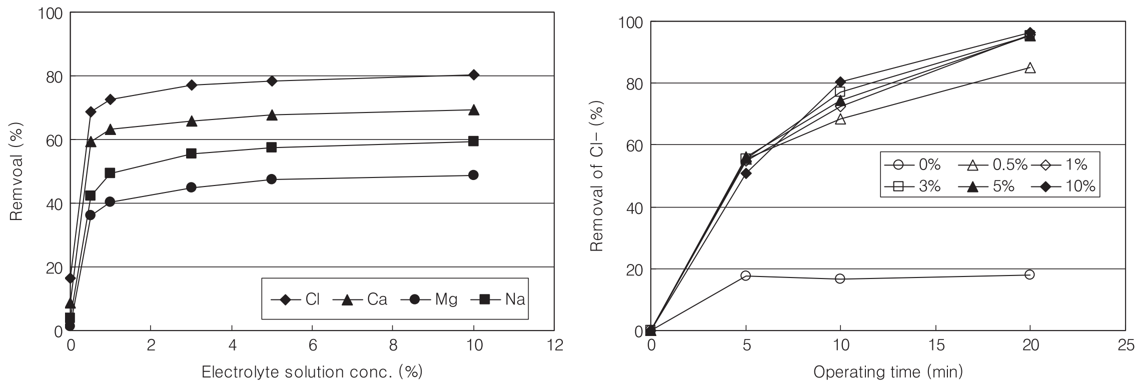

Fig. 4. Effect of the concentration of electrolyte solution on the removal of various ions.

suggests that an appropriate value of electrolyte concentration be selected for optimal performance of the system from the aspects of the efficiency and the economy.

3.4. Effect of electric conductivity of dilute solution

The experiment with different concentration of concentrate compartment solution was executed in order to evaluate the effect of concentration of concentrate on the removal efficiency. Deionized water, groundwater (3.85 mS/cm, same electric conductivity as the sample water) and groundwater (7.38 mS/cm, twice electric conductivity of the sample water) were introduced to the concentrate compartment for the sample water used as dilute compartment solution. Each ratio of electric conductivity of dilute solution to concentrate solution was zero, same and twice, respectively. The experiment was conducted under the operating condition of unadjusted pH and 20 V. Fig. 5 showed the removal of various ions at operating time of 10 min. Higher removal was observed as the electric conductivity increased in the concentrate compartment solution. Ions move faster from the dilute compartment to the concentrate compartment due to lower electric resistance as the electric conductivity become higher when the ion concentration in the concentrate compartment solution increases. On the other hand, the efficiency of electric power decreases due to the increase in electric current. When considering the system efficiency, it would be reasonable to select same solution for concentrate and dilute compartment solutions from the result that not much increase in removal was achieved for doubling the concentration of concentrate compartment solution compared to that of dilute compartment solution.

3.5. Effect of solution flow rate

Flow rate of concentrate, dilute and electrolyte compartment solution is one of the parameters affecting the removal efficiency of electrodialysis. The removal efficiency can be enhanced by better migration of ions through ion-exchange membrane due to the mitigation of boundary layer or concentration polarization formed on the membrane surface when the surface

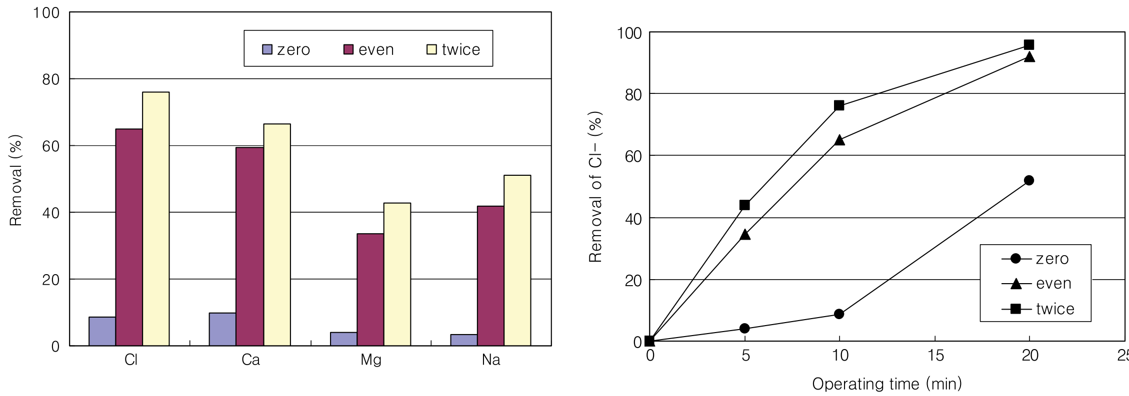

Fig. 5. Effect of the electric conductivity ratio of dilute to concentrate solution on the removal of various ions.

velocity or the flow rate increases. For investigating the effect of the flow rate on the removal efficiency, the experiment was performed with various flow rate conditions that the flow rates of concentrate and dilute compartment solution were simultaneously set at 1.08, 2.16, and 3.24 L/min corresponding to the valve opening ratio of 1/3, 2/3, and full, respectively. The flow rate of electrolyte compartment solution was set at 1.68, 3.36, and 5.04 L/min corresponding to 1.56 times the flow rate of concentrate and dilute compartment solutions. Fig. 6 showed the effect of the flow rate on the removal of various ions. The removal of each ions increased with the increase in the flow rate of concentrate/dilute compartment solution from 1.06 to 2.16 L/min, while the decrease in the removal was observed with further increase in the flow rate. This implies that the movement of ions towards the membrane may be disturbed beyond a certain value of flow rate due to higher tangential flow to the membrane against the electric migration flow of normal direction to the membrane, although the resistance of electric migration by boundary layer would be mitigated until the flow rate of solution reaches a certain value. This result suggested that the flow rate of solution in the system be also considered for evaluating the system optimization.

4. Conclusions

In this study, various operating conditions were investigated to evaluate the performance of electrodialysis for treating the brackish groundwater. The results show that electrodialysis can be effectively used to remove various ions contained in groundwater that has a certain degree of salinity in the influence of seawater intrusion. It was clear that applied voltage and operating time should be regarded as main parameters affecting the removal performance for system design. Concentration of electrolyte and concentrate solution as well as flow rate of solutions were also recommended to be considered as important operating conditions for optimizing the

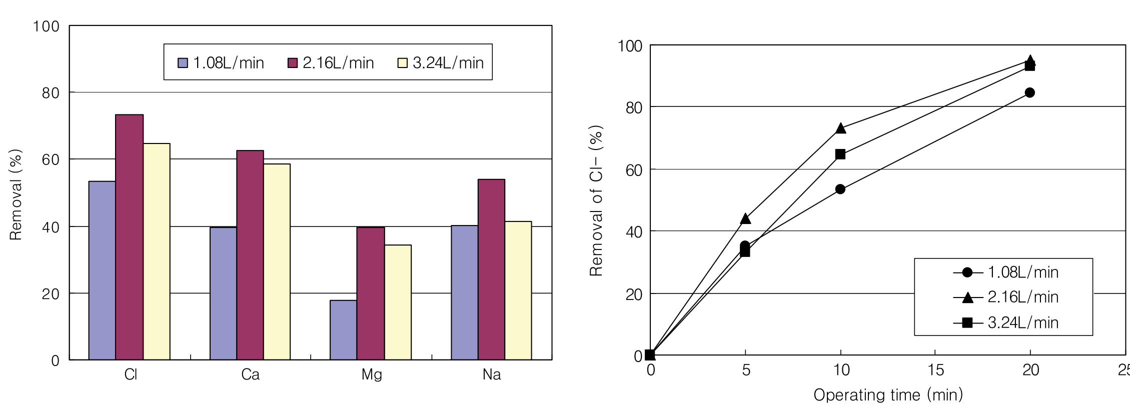

Fig. 6. Effect of the flow rates on the removal of various ions.

system performance. Although the optimal conditions would be varied with different water sources to be treated, the electrodialysis systems can be operated efficiently and economically when considering operating conditions appropriately. Electrodialysis would be a promising technology for securing alternative fresh water resources in the region where brackish water has to be used as water resource.

Acknowledgement

This research was supported by GGEC(Gyeonggi Green Environment Center) Grant funded by Korean Government (MOE).

References

[1] MIFAFF (Ministry for Food, Agriculture, Forest and Fisheries) of Korea, Annual Reports on the Seawater Intrusion Survey, 2007, p. 122.

[2] B. Pilat, Practice of water desalination by electrodialysis, Desalination 173 (2005) 173–186, (widely used).

[3] R.K. Nagarale, G.S. Gohil, V.K. Shahi, Recent developments on ion-exchange membranes and electro-membrane processes, Adv. Colloid Interf. Sci. 119 (2006) 97–143, seawater.

[4] J.M. Ortiz, J.A. Sotoca, E. Exposito, F. Gallud, V. Garcia-Garcia, V. Montiel, Brackish water desalination by electrodialysis: batch recirculation operation modeling, J. Membr. Sci. 252 (2005) 65–75, brackish.

[5] T. Sirivedhin, J. McCue, L. Dallbauman, Reclaiming produced water for beneficial use: salt removal by electrodialysis, J. Membr. Sci. 243 (2004) 335–343, industrial.

[6] A. Elmidaoui, F. Elhannouni, M.A. Menkouchi Sahli, L. Chay, H. Elabbassi, M. Hafsi, Pollution of nitrate in Moroccan ground water: removal by electrodialysis, Desalination 136 (2001).

[7] J.H. Min, H.S. Kim, The removal of Nitrate–nitrogen from groundwater by electrodialysis, J. Korean Soc. Water Wastewater 22 (2008) 307–313, (ground).

[8] S.A. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci. 31 (2005) 242–281.

[9] H. Strathmann, Membrane separation processes, J. Membr. Sci. 9 (1981) 121–189.

[10] H. Strathmann, Electrodialysis, a mature technology with a multitude of new applications, Desalination 264 (2010) 268–288.

[11] A. Hanafi, Desalination using renewable energy sources, Desalination 97 (1994) 339–352.

[12] P. Tsiakis, L.G. Papageorgiou, Optimal design of an electrodialysis brackish water desalination plant, Desalination 173 (2005) 173–186.

[13] L.J. Banasiak, T.W. Kruttschnitt, A.I. Schafer, Desalination using electrodialysis as a function of voltage and salt concentration, Desalination 205 (2007) 38–46.