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Brackish Water Desalination by Electrodialysis Cell Technique

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ABSTRACT

In Saudi Arabia, availability of safe drinking water is a burning issue due to high salinity of groundwater used for various purposes. The main objective of this study was to study saline water desalination by a batch containing 3-compartment electrodialysis cell under local conditions. The experimental treatments were the initial concentration of sodium chloride (NaCl) solution in the system and the position of anode electrode and cathode electrode in the compartment with respect to the ion exchange membranes. The relationship between the I and V was very poor with a value of around 3 V and became almost linear when the V increased from 3 and above in the electrodialysis cell used for desalination. It was found that only limited current (amperes) reached to anode and cathode compartments especially when the saline solution was highly concentrated in the middle compartment of the batch containing 3-compartment electrodialysis cell. It was suggested to redesign the electrodialysis cell with 4-compartments instead of 3-compartments with a reduced size of the cell, to avoid its adverse effect on the path of desalination process. The study findings suggested more elaborated investigations using waters of different salt concentrations for system efficiency.

Key words: Brackish water, drinking water, water salinity, electrodialysis cell, anode electrode, cathode electrode

INTRODUCTION

Currently, the shortage of drinking water is a major problem in many arid countries of the world and is necessary to utilize saline groundwater. Recent urban and rural development along with increasing population in the Kingdom of Saudi Arabia has increased manifolds the demand of drinking water. Groundwater resources in Saudi Arabia are not only limited but also non-renewable (Autham, 1983; KFUPM, 1987). Besides, the available groundwater resources are not fit specifically for drinking purposes due to high salinity which might create health problems after consumption and the environmental hazards. To meet the growing demand for fresh water, the government of kingdom of Saudi Arabia has embarked on adopting different water treatment technologies for the production of good quality drinking water (BAAC, 1980; MAW, 1984). These technologies include RO-Process, Nano-Filtration (NF), ultrafiltration (UF), electrodialysis and ceramic membranes.

Presently, out of the different water treatment technologies available, membrane separation processes are gaining increasing importance in desalination, gas separation for petrochemical

industries, pollution control, recovery of metals and salts (Larchet *et al.*, 2002). These processes seem economically feasible, attractive, unique and applicable even at small community places for the provision of safe drinking water. Since, these technologies do not require energy to affect phase changes, hence, the separation units could be operated at reduced energy costs compared to conventional distillation or evaporation.

Recently, Borges *et al.* (2010) integrated the modeling electrodialysis and a photochemical process for the treatment of saline wastewater. Previously, many investigators used electrodialysis system for sea water desalination. Also, the limiting current is a key parameter in electrodialysis. Furthermore, desalination of brackish water is a cost effective means of producing drinking water. (Volckman, 1963; Kuroda *et al.*, 1987; Sadrzadeh and Mohammadi, 2003; Dlugolecki *et al.*, 2009; Tanaka, 2010). In another study, Oren *et al.* (2006) used improved electrodialysis for the removal of boron from sea water and brackish water to improve water quality. Whereas, Kalogirou (2005) applied renewable energy sources for sea water desalination.

Ortiz *et al.* (2005) developed a mathematical model for brackish water desalination applicable for the desalination of a NaCl solution under various experimental conditions. This model can be applied to commercial electrodialyzers working in batches with recirculation. Recently, Al-Nory and Graves (2013) studied extensively water desalination program in Saudi Arabia and reported a set of modular simulation components in order to create complex models to optimize the whole water desalination supply rapidly and easily. Therefore, the main aim of this study was to determine the effect of highly concentrated sodium chloride solution on the limiting current of an electrodialysis cell for saline water desalination.

MATERIALS AND METHODS

To obtain the limiting current in electrodialysis, a three-compartment cell was constructed from glass. The cell comprises two membranes, a middle compartment and two side compartments with square cross section. The volume of each compartment was about 10 L. The middle compartment was separated from one of the side compartments by a cation exchange membrane and from the other by an anion exchange membrane. The membranes used in the experiments were PCSA (anion exchange) and PCSK (cation exchange), products of PCA GmbH company in Germany. The size of membrane was 250×250 mm and the membrane was reinforced by polyester. Each one of the two membranes was sandwiched between two Plexiglas frames and the frames bolted firmly together from outside. Thin strips of rubber tape used by local plumbers were inserted between the membrane surface and the inner surface of the frame to avoid leakage during the experiment. The assembled set was then slipped in grooves built from glass on the walls and bottom of the cell. The cell electrodes were flat plates of graphite and copper having dimensions of about (5×10 cm). Graphite acted as the anode and the copper as the cathode in the cell. The anode was hung in a hole drilled in a plastic tube. The tube itself was supported on two holes drilled opposite to each other on the walls of the cell near the top in one of the outer compartments. Similarly, the cathode was placed in the other outer compartment. The source of electricity was DC power supply with a maximum voltage output of 30 V and maximum current of 2.5 A. The symbol I stands for current in milliamperes (mA) and V stands for electric voltage (V) in the study. Wire sockets were used to connect the cell with the power supply. An isometric view of the cell showing the electrodes and the membrane-frame assembly is presented in Fig. 1.

The cell was operated in a batch mode at room temperature (20±2°C). Before starting the experiment, the electrodes surfaces were cleaned thoroughly to remove grease or other dust

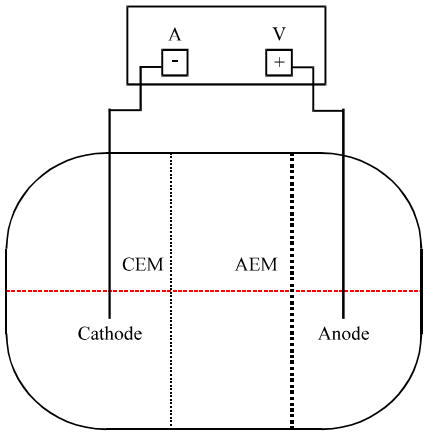

Fig. 1: Electrodialysis cell

particles. The three compartments were filled with sodium chloride solution of the required concentration. The initial conductivity of the solutions was monitored. Output voltage to the cell was adjusted in steps of 0.5 V and the value of cell current was recorded. About 5 min period was allowed to reach a steady of the current before a new change was made to the voltage. The experiment was terminated as soon as the current came to a constant stage. At the end of each experimental run, the solutions were drained and the whole cell was washed thoroughly with distilled water to avoid membrane deterioration by alkalies or acids which might have formed in the electrode compartment during the experiment.

Statistical analysis: Data was analyzed by ANOVA and regression techniques for treatment evaluation at 5% level of significance according to SAS Institute (SAS, 2001).

RESULTS AND DISCUSSION

Electrodialysis is a mass transfer-limited separation process. For removing NaCl from water by electrodialysis, the depletion of chloride (Cl) ion occurs on one face of the anion exchange membrane where the chloride (Cl) ions enter while, the other face accumulates the same ion. The same effects occured for sodium (Na) ions at the cation exchange membrane. For a given bulk concentration of NaCl, a current reached corresponding to zero +ve ion and -ve ion concentrations on the depleting sides of the membrane. A schematic diagram of concentration distribution of sodium (Na) and chloride (Cl) ions, if the middle compartment is desalinated, is shown in Fig. 2.

I-V relationship of electrodialysis cell: The data in Fig. 3, when the three compartments were filled with 25 g L^{-1} NaCl solution and the cathode placed adjacent to the cation exchange membrane, shows that initially the relationship between the I and V was very poor with a value of around 3 V which became almost linear when the V increased from 3 and above in the electrodialysis cell used for desalination. It further indicated that the value of voltage around 2 V must be enhanced in order to initiate the desalination process. Thereafter an increase in the voltage applied to the cell resulted an increase in the current and without reaching to a limiting current. This may be due to the phenomenon that almost all the power given to the cell was consumed for producing hydrogen and chlorine gases in the cathode and anode compartments,

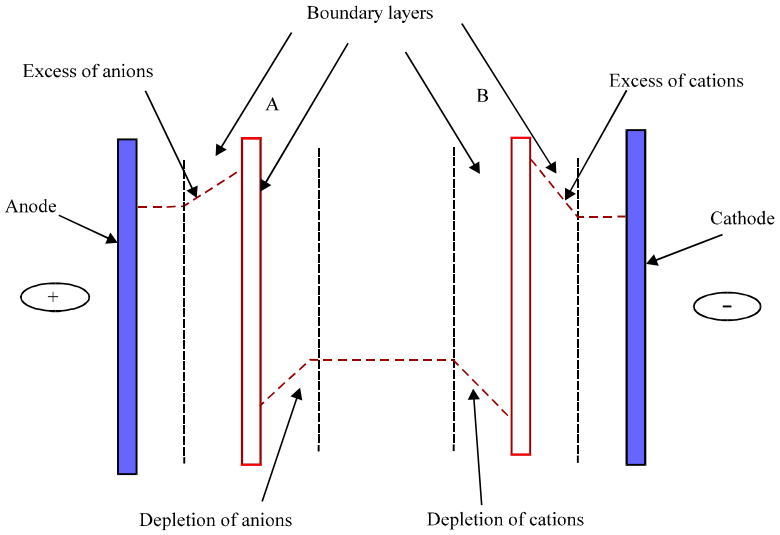

Fig. 2: Schematic representation of concentration polarization with demineralization of the central compartment

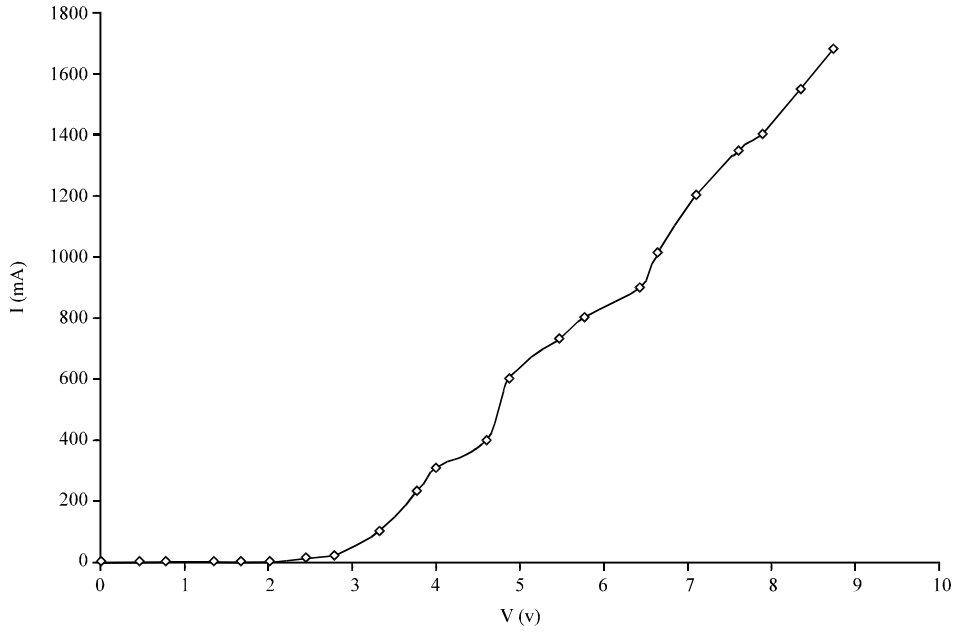

Fig. 3: Polarization curve concentration of compartments (25 g L^{-1}) and anode facing anion exchange membrane

respectively. Data in Fig. 4 show a repetition of the previous experiment with an initial concentration of 10 g L^{-1} of NaCl in the three compartments. Similar behavior was observed in the I-V relationship but the initial low salt concentration increased the observed current by a factor of 1.6 which may be due to low degree of secondary reactions.

However, when the positions of the electrodes were reversed (cathode adjacent to anion exchange membrane) by placing the higher concentration solution in the middle compartment, it

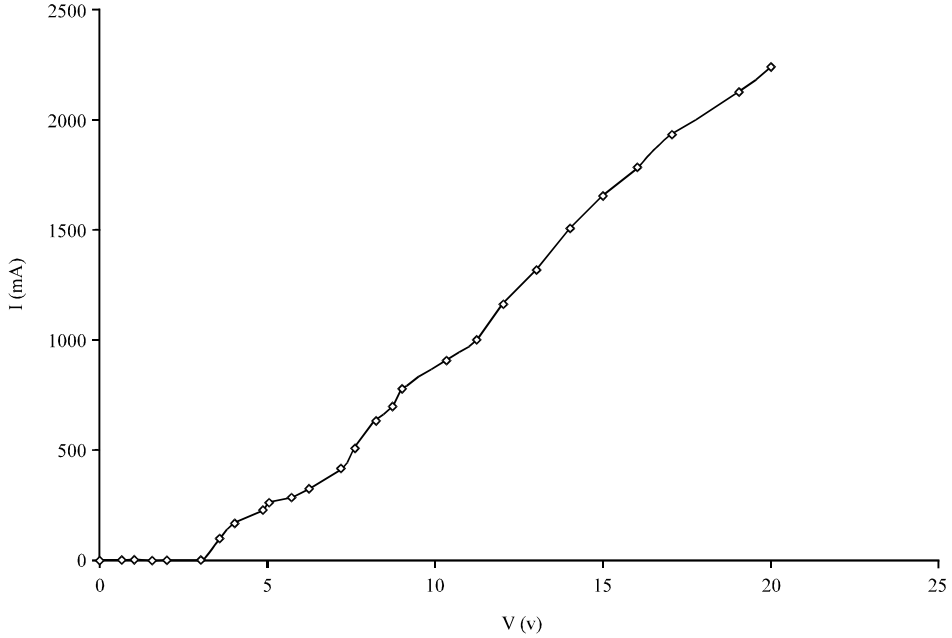

Fig. 4: Polarization curve concentration of compartments (10 g L^{-1}) and anode facing anion exchange membrane

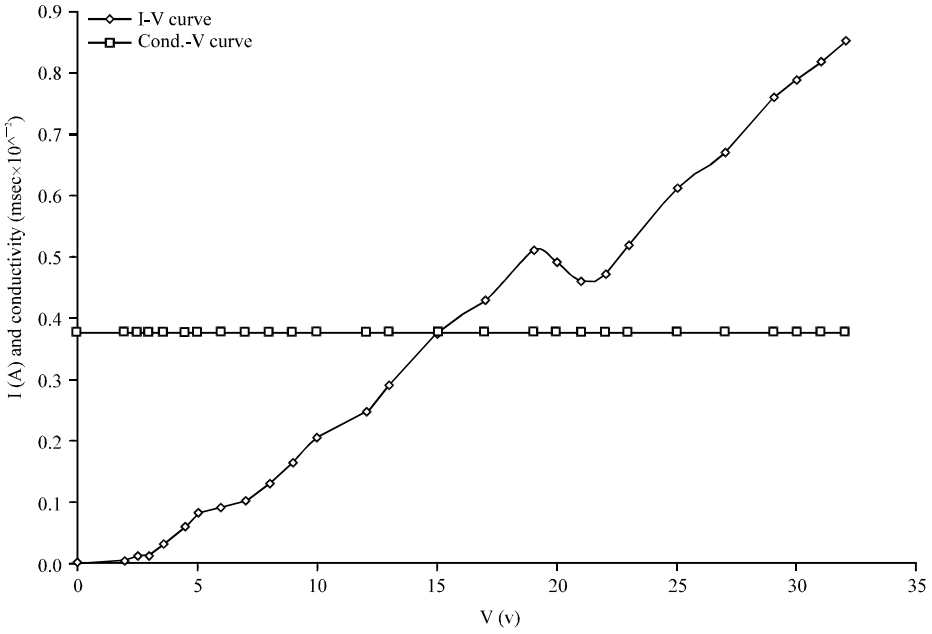

Fig. 5: Polarization curve concentration of middle compartment (25 g L^{-1}) and concentration of outer compartments (1 g L^{-1}) and anode facing cation exchange membrane

did not improve the efficiency of desalination process (Fig. 5). For example, if the initial concentration of the test solution in the middle compartment (10 g L^{-1}) is higher than the outer compartments (1 g L^{-1}), a limiting current of around 0.4 A was observed (Fig. 6). This result supported the above stated reasons for the failure of the last two experiments.

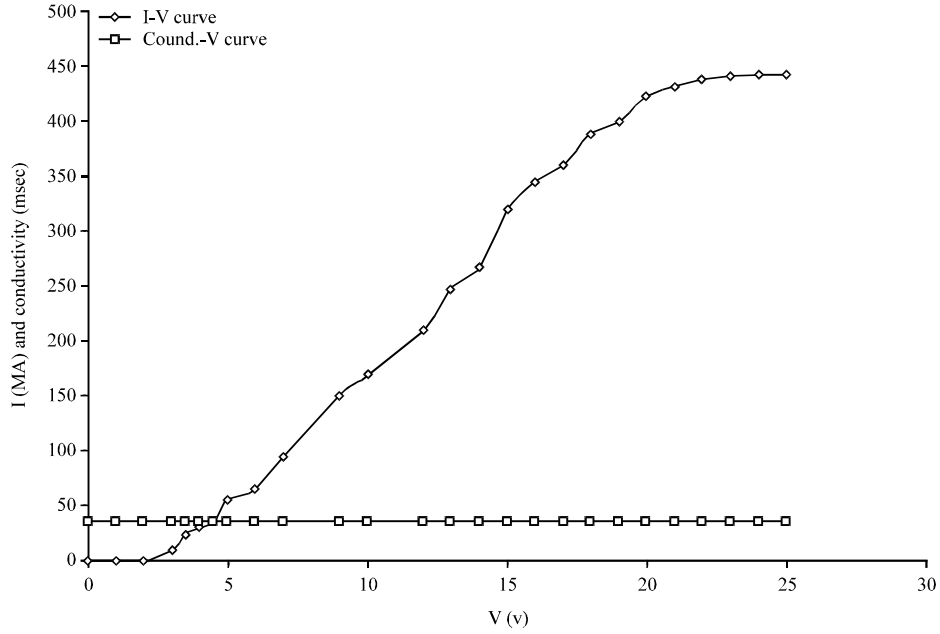

Fig. 6: Polarization curve concentration of middle compartment (10 g L^{-1}) and concentration of outer compartments (1 g L^{-1}) and anode facing anion exchange membrane

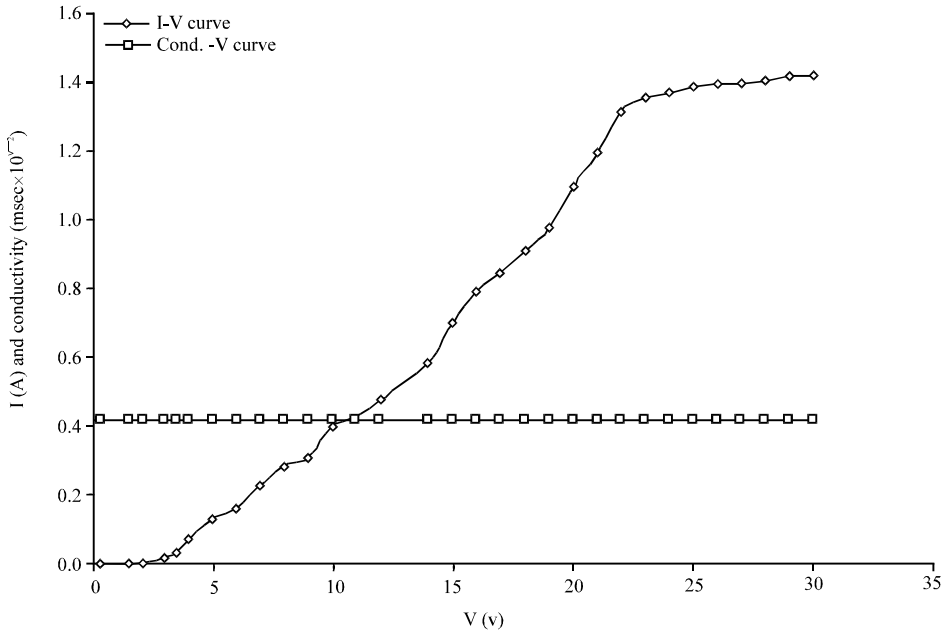

Fig. 7: Polarization curve concentration of middle compartment (1 g L^{-1}) and concentration of outer compartments (10 g L^{-1}) and anode facing anion exchange membrane

In another trial, when a low concentration solution was placed in the middle compartment (1 g L^{-1}) and a higher concentration (10 g L^{-1}) in the outer compartments, a limiting current of about 1.4 A was obtained. This may be due to the fact that the amount of transferred current increased as compared to the conditions of the previous experiment as shown in Fig. 7.

DISCUSSION

In this study, initially the relationship between the I and V was very poor with a value of around 3 V which almost achieved linearity with increasing value of V from 3 and above in the electrodialysis cell used for desalination. Also, a limiting current of about 1.4 A was obtained by keeping low concentration solution in the middle compartment (1 g L^{-1}) and a higher concentration (10 g L^{-1}) in the outer compartments. The results agree with those of Banasiak *et al.* (2007) who recommended an optimum voltage of 12 V to determine the influence of initial salt concentration on the desalination of aqueous solutions containing 1, 5, 10, 20, 25 and 35 g L^{-1} NaCl. Similar to this investigation, Ali *et al.* (2009) investigated a brackish water desalination technique by electrodialysis using a membrane separation process based on the selective migration of aqueous ions through ion exchange membranes. They recommended an initial concentration of 3 g L^{-1} of salts as the maximum recommended feed concentration for system efficiency.

CONCLUSION

The correct operation of a batch consisting of 3-compartment electrodialysis cell depends on the relative concentration between the feed solution compartment and the cathode and anode solution compartments. The position of the electrodes with respect to the membranes must be chosen to fulfill the process requirement. Based on the study findings, it is suggested to redesign the electrodialysis cell with 4-compartments instead of 3-compartments and the size of the cell should be reduced to avoid its adverse effect on the path of the desalination process.

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