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A small-scale membrane electro-dialyser for domestic use

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Abstract. A small-scale electro-dialysis system was constructed for domestic use. It is composed of six compartments in which five special polystyrene ionic membranes are housed. A series of experiments on the transport of sodium and chloride ions through polystyrene membranes was performed and the effects of electric current and voltage on the pH of water were investigated. This electro-dialyser could reduce the NaCl content to an acceptable level (5307 mg/L) when water containing 9945 mg/L of sodium chloride is fed to the electro-dialyser. The reduction was by the action of direct current 60 mA/100 mA when a 15 V/20 V potential is maintained across the membrane. The results showed that the pH of the treated water attained a value in the range of 7-8, with the chloride concentration of 5307 mg/L when the voltage was in the range of 20 volts. This was achieved when two of the small-scale electro-dialysers were placed in series and the solutions from the respective compartments were mixed. This is considered useful because this complies to the requirement of drinking water standard both in terms of chloride and pH. Therefore, this type electro-dialyser has the potential for domestic uses in isolated houses where potable water supply is not available.

Keywords: electro-dialyser; desalination; salt removal; ion-exchange membrane; domestic, drinking / potable water

1. Introduction

Water is the substance that makes life on our earth possible. It is present in most of our everyday food and it is mixed with other things to satisfy our needs. Because water is such a necessity, one can justify without any comment the tremendous and massive investment in water desalination installations achieved by some countries. These installations were built by converting a huge amount of petrodollars into waterdollars (Future Directions 2014). The transaction shows without any doubt that water is more valuable resource than oil or any other resources in this world. The growing demand for water and the new solutions proposed to satisfy this demand are becoming increasingly more effective with the advances of the water separation technology during the last two decades (Ericsson and Hallmmans 1994, Costa *et al.* 2002, Myint and Ghassemi 2012, Min and Kim 2012, Goodman *et al.* 2013, Jiang *et al.* 2014). Reverse osmosis (RO), electro-dialysis (ED), ion exchange, freezing, distillation, membrane distillation and forward osmosis are the most widely applied processes to achieve the goal of water desalination (Wilf and

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Klinko 1994, Industrial Wastewater Treatment System 2014, Ortiz *et al.* 2005, Lawson and Lioyd 1997, Al-Obaidani *et al.* 2008, Yangali-Quintanilla *et al.* 2011, Boo *et al.* 2013). RO is now widely accepted for desalting both brackish and seawater as the most popular separation process; membranes are readily available and lifetime is good. However, the process of RO may require more pre-treatments for desalination of seawater containing higher total dissolved solids (approx. 41000-45000 mg/L) as prevalent in the GCC countries. RO desalination of seawater with higher dissolved solids is likely to produce reject brine with even higher solid concentrations of organic, inorganics and biological components.

ED has the advantage of fewer pre-treatments, less cleaning frequency and may have cost advantages especially in the treatments of brackish water with salinity less than 12000 mg/L (Banasiak *et al.* 2007, Nair and Kumar 2012, Reahl 2002). The application of membrane-based processes such as ED has grown in last two decades with a market share of about 3.6%, it is small in comparison to RO (57.2%). In the Arabian Gulf countries, RO accounts for about 10.7% of total installed capacity whereas ED is only 1.8% (IRENA 2014). Worldwide there are around 1000 ED and EDR plants with 10-20 new large EDR plants being installed annually (Fuji Film 2014). So this technology has the potential to grow in the future as ED/EDR or as hybrid with RO to provide waters in remote places where only brackish water source is available and alternative water supply is not affordable (IRENA 2014).

Over fifty years ago, Ionics invented and introduced ion-exchange membranes and the ED process which incorporates such membranes. ED is a process in which solutions are desalted or concentrated electrically. Today, ED is the most widely used process for treatment of brackish water or highly mineralized waters and particularly for those containing between 1000 and 5000 mg/L of total dissolved solids. Some ED plants have capacities up to a million gallons per day and are in operation at a number of locations throughout the world. Furthermore, this technology is widely applied for industrial and domestic installation in the USA ((Ionics) and in France (Sodemi) and has proven its reliability to produce fresh water for utilities use. This process seems to have potential in countries where the climatic conditions are very severe or in places where modern technology is not available (Sudoh *et al.* 1992, Xue *et al.* 1992, Reahl 2002).

Salts in water dissociate into positively and negatively charged ions. The key to the ED process is a semi-permeable barrier which allows passage of either positively charged ions (cations) or negatively charged ions (anions) while excluding passage of ions of the opposite charge (Delimi *et al.* 1995, Sato *et al.* 1995, Kikushi *et al.* 1995, Fukumoto and Haga 2004, Costa *et al.* 2002, Min and Kim 2012, Myint and Ghassemi 2012, Malek *et al.* 2013, Banasiak *et al.* 2007). These semi-permeable barriers are commonly known as ion-exchange, ion-selective or electrodialysis membranes. When the two types of membrane are coupled, the water between the membranes becomes fully or partly desalted (water with less ions) while the solution on either side becomes more concentrated. Fig. 1 shows the transport of ions within the system.

There are many questions still unsolved regarding the mechanism of ions transport through the selective membranes as well as the mechanical and the chemical resistance of the selective layers on the membranes. One of these questions is why the membranes and other active surfaces tend to become “fouled” or “scaled” over time by organic and inorganic substances present in the water? The electrodialysis reversal (EDR) process was developed and introduced by Ionic in the early 1970’s to deal with this problem and also discussed in details in the literature (Strathmann 2004, 2010). By reversing the electrical current and exchanging the fresh product water and the concentrate wastewater streams within the membrane stack several times per hour, fouling and scaling constituents that build up on the membrane surface in one cycle are removed in the next

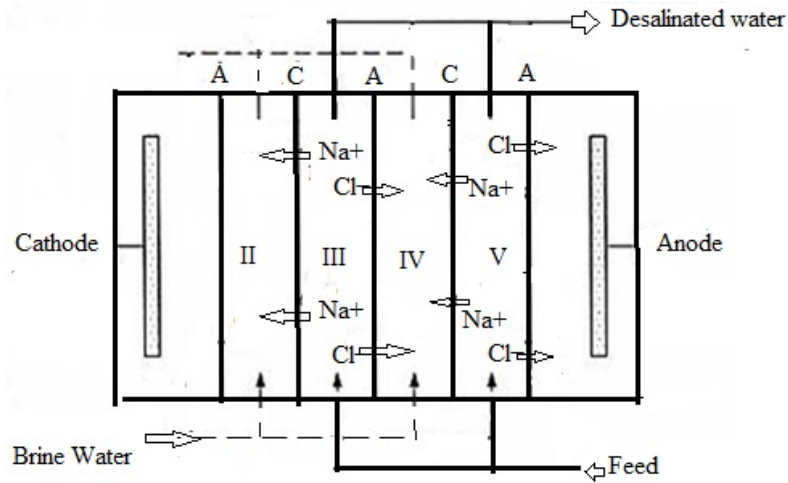


Fig. 1 Basic ions transport through the ion-exchange membranes

Table 1 Description of the components of the electro-dialyser (UNIT 1)

Components	Description
Cation exchange membrane	Amberlite 200C Na
Anion exchange membrane	Amberlite 4200 Cl
Number of membranes	5
Active membrane cell area	6.2 cm ²
Total cell active area	31 cm ²
Anode	Graphite
Cathode	Graphite
Anode active area	6.15 cm ²
Cathode active area	6.15 cm ²

reversing cycle (Valero *et al.* 2011). These factors limit the prospects for domestic applications of these membranes. Therefore the development of an appropriate apparatus model is important in understanding the separation properties of the membrane and to provide some guidelines in manufacturing of small electro-dialysers that can be used in small-scale applications. The investigation presented in this study is entirely devoted to this purpose and aimed at designing a small-scale ionic membrane electro-dialyser that may be used for domestic purposes.

2. Materials and methods

2.1 Description of the electro-dialyser unit (UNIT 1)

The electro-dialyser cell, constructed from Perspex and glass consisted of six circular compartments and numbered as (I, II,....., VI). Each compartment had two glass ports (inlet and outlet) fitted with a Quickfits screw closure. Five membranes are placed in the cell between the

compartments and this set-up is designated as UNIT 1. The compartments are sealed with neoprene rubber gasket and are held in place with 5 brass bolts. Compartments (II, III, IV and V) have a volume of 6 cm³ whereas compartments (I and VI) have a volume of 3 cm³ because they contain the electrodes. The electrodes consist of disks made of carbon and having a diameter of 2.8 cm and a thickness of 0.5 cm. The distance between the electrodes is 6 cm and the distance between two membranes is 1 cm. The components of this electrodialyser unit are described in Table 1.

2.2 Preparation of solutions and test procedure

The cell was filled with an NaCl solution containing 9997.7 mg/L of sodium chloride in distilled water. The voltage across the cell was kept at 15 volts and the intensity of the direct current maintained at 60 mA for 10, 20 and 30 minutes. Concentrations of Cl⁻ and Na⁺ ions were measured in each compartment of the cell along with pH measurements. All these experiments were conducted in one cell when the current was fixed at 60 mA and the voltage at 15 volts.

2.3 Membrane preparation

A number of techniques of preparing electrodialysis membranes can be found described in the literature. It is a heterogeneous membrane that was prepared to fulfil these criteria: (i) high mechanical and chemical resistance; (ii) a selectivity in the range 0.75-0.95, (iii) low resistivity (below 1 ohm/cm²).

The membrane consists of two layers formed from anionic and cationic ion exchange resins (each layer has been prepared from selective material (maximum grain diameter 50 microns)). Amberlite 200 C (ionic form Na) and Amberlite 4200 (ionic form Cl) from Rohm & Hass, USA, were used as cation and anion resins, respectively. These were mixed with a polymeric solution of polystyrene and benzene (5% polystyrene by weight). The polystyrene with a purity of 99.995% and benzene with a purity of 99% were from BDH, England. The resulting mixture of resins and polymer solution was then spread on the support of the membrane to get two selective surfaces, one on each side of the membrane. The support of the membrane was made of a simple filter paper. The active surfaces are represented by A (anionic membrane) and C (cationic membrane), respectively (Fig. 1).

The filter paper was soaked in the solution for 15 minutes then the powder was deposited over the sides by means of standard sieves. The membrane was dried at room temperature when the active layer on each side of the membrane was about approximately 0.2 mm. The membranes were cut in circles to fit between the compartments of the cell.

2.4 Membrane characteristics

A number of anionic and cationic membranes were prepared from different polystyrene benzene solution and ionic resins. They were fitted in the cell and tested for mechanical and chemical resistance. The test was as follows:

A synthetic brackish water solution was prepared and kept in the cell for few days to condition the membranes and test their mechanical and chemical resistance. It was found that the membranes prepared from a high concentrated (more than 25% w/w) polystyrene benzene solution were too stiff and crack when placed in the cell. It was also noticed that the membranes prepared from a

very dilute polystyrene solution (less than 2% w/w) were very weak and they could not resist in the water for a long time and were easily damaged. The best mechanical resistance of the layers was obtained when the polystyrene-benzene solution contained 5% polystyrene by weight.

These membranes were adopted in the cell and tested for performance.

2.6 Construction and operation of the electro-dialyser unit (UNIT 2)

The larger electro-dialyser unit (shown in Fig. 2) and is designated as UNIT 2. The electro-dialyser unit consists of three DC small pumps; two cells (two UNIT 1), six collectors and an electrical source that supplies the desired electrical intensity and voltage. The pumps have been employed to transport water periodically in the electro-dialyser. Pump P1 was applied to supply water via the collector CE in order to wash the electrodes located in compartments I and VI of both cells. Pump P2 allows the transport of brackish water to the collector C1 and to compartments III and V of the first cell (the one at the left-hand side). At this point the salinity of the water is

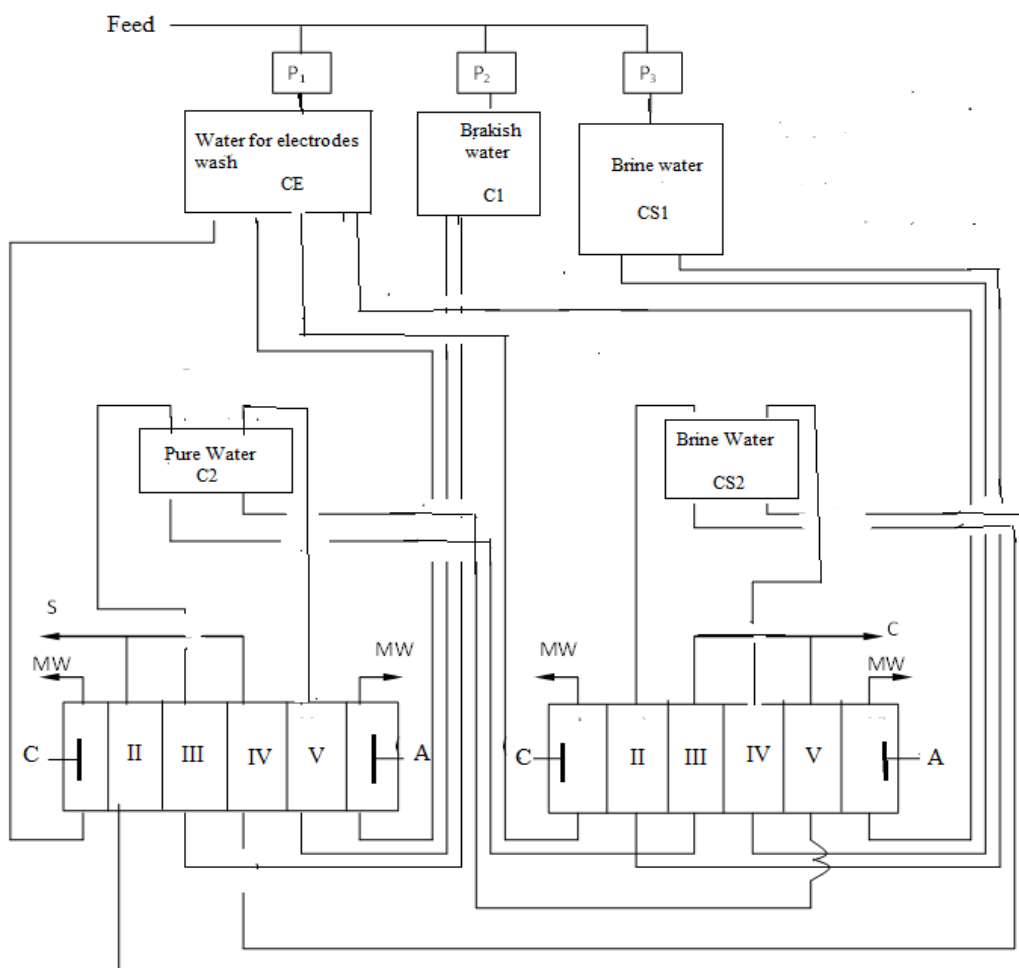


Fig. 2 A schematic diagram of the two-stage electro-dialyser unit (UNIT 2)

expected to be largely reduced. Furthermore, the water transported to the compartments II and IV) through collector CS1 and CS2 to the drain located at point S. A set of inte III and IV of the second cell through the collector C2 and exits this cell at point C. The water collected at point C is desalinated water (can be considered as potable water). Finally, pump P3 is applied to transport the brackish water from the first cell (at compartments II and IV) and from the second cell (at compartments rmediate tanks (a kind of mixing device) were applied to allow flow of water through the electrodialyser and isolate every compartment of the cell. After the completion of the whole process, the two cells were tested and were found electrically neutral.

2.6 Analytical methods

The concentration of chlorine was measured by titration using Mohr procedure (Rodier 1978) and the concentration of sodium was measured by means of a digital flame analyser, Model 265500 (Cole Palmer Instrument Company, Chicago, USA). The pH of both the treated water and the brine water was regulated by a pH meter (Model 620, Fisher Accumet, USA).

3. Results and discussion

The contact time was considered as the operating variable as the voltage across the cell was fixed.

Effect of the operating time

Fig. 3 depicts the variation of chloride concentration in different compartments of UNIT1 at three different times (10 minutes, 20 minutes and 30 minutes) under applied voltage of 15 V. It is seen in this Figure that for each time interval the concentration of chloride exhibit similar behaviour. When the contact time is short (i.e., 10 minutes) the concentration of chloride varies

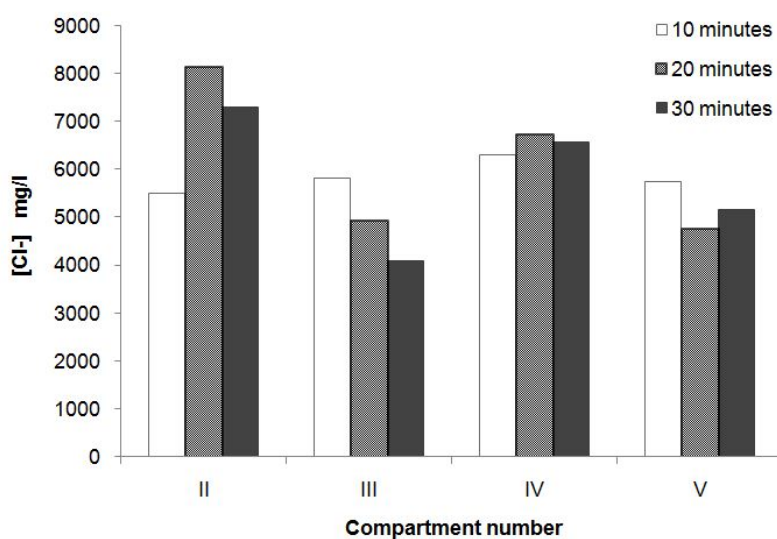


Fig. 3 Variation of chloride concentration (Cl^- , mg/L) in five compartments of UNIT 1

slightly from one compartment to the other. When the contact time is increased to 20 minutes and 30 minutes, the concentration of chloride changes drastically from one compartment to the other. The concentration of chloride is low at compartments III and V and high in compartments II and IV.

Fig. 4 shows the concentrations of sodium at compartments II, III, IV and V. Compartments III and V, where the potable water (with reduced concentration of NaCl) is expected to be produced, contains low concentrations of sodium. In contrast the compartments II and IV, where the brine water is produced, show higher concentrations of sodium as expected.

Fig. 5 shows the values of the pH obtained in the compartments of UNIT 1. When the

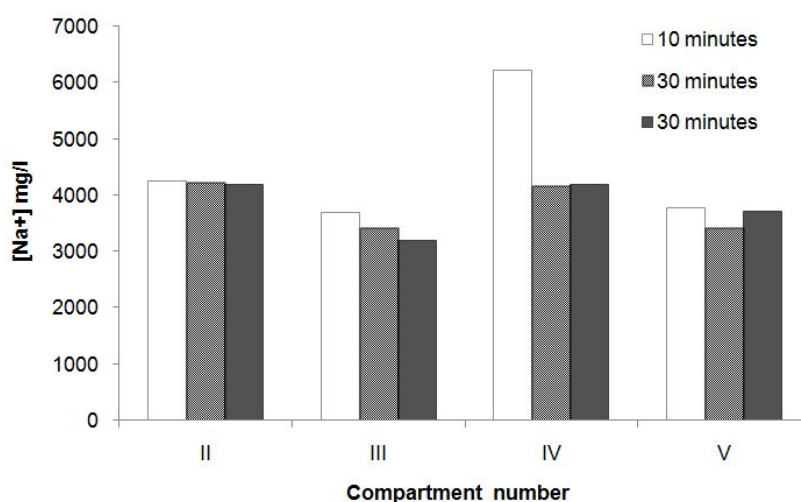


Fig. 4 Variation of sodium concentration (Na^+ , mg/L) in five compartments of UNIT 1

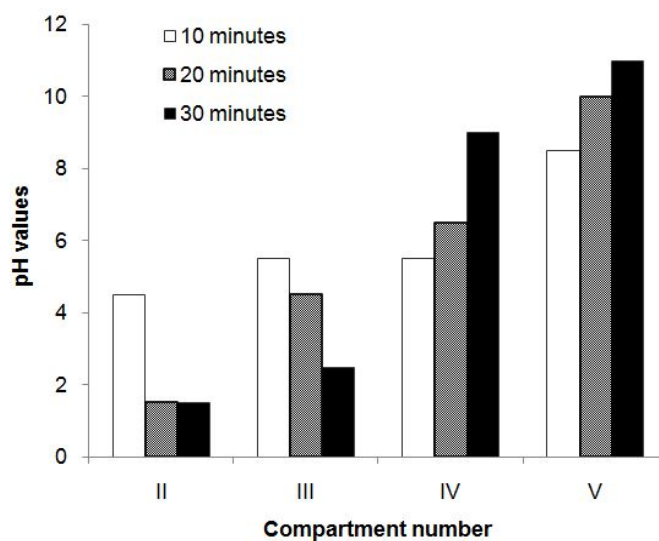


Fig. 5 Variation of pH in five compartments of UNIT 1

Table 2 Comparison of the results of 15V (UNIT 1) and 20V(UNIT 2) tests

Time (Sec)	Potential V	Current mA	potable water [Cl] mg/L	Brine water [Cl] mg/L
1800	15	60	4920.3 (pH = 2.5) At compartment III	8115.3 (pH = 1.5) At compartment II
1800	15	60	4757.0 (pH = 11) At compartment V	6723.7 (pH = 9) At compartment IV
1800	20	100	5598.4 (pH = 7.0) At point C	6869.3 (pH = 6.5) At point S
1800	20	100	5314.4 (pH = 7.0) At point C	6854,5 (pH = 6.0) At point S

experiment was run for 10 minutes the change in the pH in the compartments III and V (potable water chambers with reduced NaCl concentrations) was in the range of 5-8. With the increase in contact times (20 minutes and 30 minutes) pH variation was higher. After 20 minutes the pH was in the range of 5-10.5 and after 30 minutes the range was approx. 2.5-11.5. This findings suggest that if these exit solutions from these two compartments are mixed it would give a pH value within an acceptable range for drinking water. This idea was followed and discussed in the next paragraphs.

To overcome the unbalanced pH, to control the sodium and chloride concentrations and to produce more water it was decided to use two identical units of UNIT 1. This larger electro dialyser has been designated as UNIT 2 where the two UNIT 1 are placed in series. The results of the proposed electro dialyser model are described below.

The treated water from both UNIT1 was mixed as it was easy to withdraw from compartments III and V at point C as shown in Fig. 2. For all the experiments carried out with this larger electro dialyser the voltage was fixed at 20 volts and the intensity was kept at 100 mA and the model was run for 30 minutes. Concentrations of Cl⁻ and the pH, of the brine solution at point S and the potable water at point C, were measured the results presented in Table 2. For comparison the results obtained for one UNIT 1 are also presented in Table 2. It is shown that the pH of the potable water attained a near neutral value (approx. 7) when 20V is applied for 30 minutes and the solutions are mixed at point C. This was duplicated to confirm the accuracy. The brine solution attained a higher Cl⁻ concentration and lower pH. These values for both potable water and brine can be considered within acceptable limits.

In the literature the effect of contact time and the applied voltage was reported in the electro dialysis of reverse osmosis concentrate (Banasiak *et al.* 2007). Direct comparison cannot be made as the two systems are different in terms of feedwater, the purpose of treatment and the range of applied voltage. The effect of contact time and the applied voltage was observed and optimum values were reported. But the attainment of pH was not mentioned whereas the findings reported here clearly shows that the pH attained by electro dialysis of feedwater (similar to brackish water) was within limit of drinking water standard.

More work need to be carried out to determine the effect of a wider feed concentration range, the effects of other ions ("real" brackish water sample) and the effect of flow rate.

4. Conclusions

A small-scale electrodialyser system was constructed and the desalination performance was evaluated. The electrodialysis treatment of saline water was effective in removing NaCl from 9945 mg/L to 5307 mg/L by the action of direct current 100 mA when a 20 V potential is maintained across the membrane. The results showed that the pH of the treated water was in the range of 7-8 with low Cl⁻ concentration, both being in the acceptable range. A contact time of 30 minutes in a two-unit electrodialyser (operated in series) is required and the solutions from the respective compartments have to be mixed to achieve this desalination performance.

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