

An analysis on ion transport process in electro dialysis desalination



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HIGHLIGHTS

- A parabolic set of Nernst–Planck equations is proposed for electro dialysis.
- All governing equations are combined into ordinary differential equations.
- One can easily estimate salt concentration of the concentrate and its flow rate in an electro dialysis stack.
- The present analysis agrees well with available experimental data.
- The model can be used to estimate limiting current density in an electro dialysis stack.

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ABSTRACT

An analysis based on the Nernst–Planck equation has been carried out on the transport process of salt ions in the ion-exchange membrane electro dialysis technology. The individual transport equations for both diluate phase and concentrate phase are considered to investigate the conservation of mass and salt ions driven by convection, molecular diffusion and electrophoresis. For the first time, the ion transport flow across the membranes driven by the osmotic pressure has been accounted for the overflow type of electro dialysis with the concentrate compartments sealed at the bottom end. The equations are integrated across the desalination channel and the concentrate reservoir to form one dimensional set of the transport equations with respect to the bulk velocities and concentrations of the diluate and concentrate phases. Subsequently, the equations are solved by the Runge–Kutta–Gill method, and the results are found to agree well with available experimental data. An analytic expression has been obtained for estimating a limiting current density.

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1. Introduction

Desalination is defined as the removal of dissolved minerals such as salts from seawater, wastewater or brackish water e.g. [1–5]. Water desalination processes producing drinking water from brackish water have become quite important due to current water scarcity.

Electro dialysis using ion-exchange membranes e.g. [1] is a means of producing diluate and concentrate under the influence of an applied electric potential difference. The ion-exchange membrane electro dialysis stack consists of two electrodes (anode and cathode) between which a number of diluate (feed) channels and concentrate (brine) compartments are placed alternately, as shown in Fig. 1. Each cell in the stack consists of a diluate channel and a concentrate compartment formed by an anion exchange membrane (Anion E. M.) and a cation exchange

membrane (Cation E. M.) placed alternately under the applied electric field.

In this overflow type of the electro dialysis stack, the salt water is supplied below from the diluate channels. The dissolved ions in the diluate channels are removed through ion exchange membranes to the concentrate compartments which are sealed at the bottom end. The desalinated water goes out from the upper exit of the diluate channels, while the concentrate water overflows from the top of concentrate compartments.

Electro dialysis processes are preferred as compared to distillation techniques and other membrane based processes such as those using reverse osmosis, in the sense that dissolved species are moved away from the feed water rather than removing the water from the feed water. Thus, the electro dialysis gives us a practical advantage of much higher feed recovery in most applications, since the quantity of dissolved salts in the feed water is substantially less than that of the solvent.

In this study, we shall investigate the transport process of ions in the electro dialysis stack under the influence of an applied electric field,

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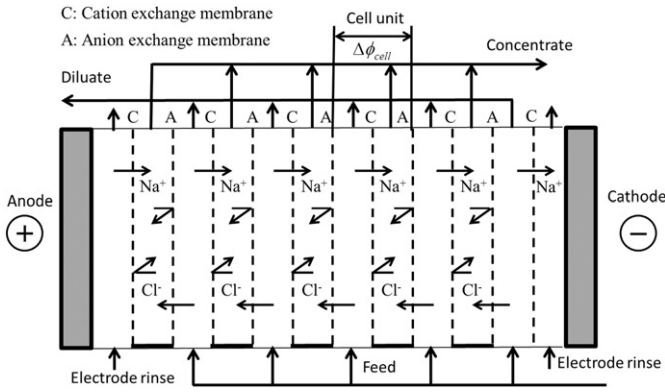


Fig. 1. Electrodesialysis stack.

using the Nernst–Planck equation. We shall focus on one electrodesialysis cell consisting of a diluate channel and a concentrate compartment formed by an anion exchange membrane and a cation exchange membrane. The performance of the stack can easily be estimated from the results obtained from this representative cell. The ions within the diluate channel are influenced by convection, molecular diffusion and electrophoresis, as they pass through the membrane to the concentrate compartment. The osmotic pressure resulting from the concentration difference across the membrane drives the solvent permeating through the membrane, diluting the concentrate especially in the upper part of the concentrate compartment.

A number of researchers e.g. [6–8] carried out theoretical analyses using the Nernst–Planck equation, to investigate ion transport through membranes. Most of these investigations focus on one-directional ion transport along the axis perpendicular to the membrane surface. In the electrodesialysis stack, however, the salt concentrations in both diluate channel and concentrate compartment decrease downstream. Moreover, due to the osmotic pressure driven cross flow, the flow rate in the diluate channel decreases downstream, whereas that in the concentrate compartment increases downstream. Thus, a parabolic flow treatment is needed to capture the longitudinal variations of both flow rate and ion concentrations, in order to investigate ion transport characteristics in such electrodesialysis stacks.

Naturally, the cation concentration stays nearly constant away from the membranes and decreases sharply toward the diluate side of the cation exchange membrane, which is referred to as “concentration polarization”. Likewise, the anion concentration drops toward the diluate side of the anion exchange membrane. Such concentration drops are more significant for higher current density. The ion concentrations on both membrane surfaces further decrease downstream as the bulk ion concentration in the diluate channel decreases downstream. Thus, under a certain current density, the ion concentration totally vanishes at the exit of the diluate channel so that the electric resistance goes infinity there. Such current density is termed “limiting current density” e.g. [9]. Any electrodesialysis stack should be operated at a current density below the limiting current density. This limiting current density, which is one of the most important design parameters in the electrodesialysis stacks, can only be determined by treating ion transport in the electrodesialysis stacks as one of parabolic convective flows. Such a parabolic convective flow treatment to find out the limiting current density has been proposed here for the first time.

In this study, the conservation equations for the mass and ion concentrations in both diluate channel and concentrate compartment are considered in full details. These governing equations for the diluate channel and concentrate chamber are integrated across the channel width and the compartment width, respectively. The membrane characteristics are described in terms of its hydraulic permeability and conductivity. The set of the governing equations based on the Nernst–Planck equation are finally transformed into a set of the ordinal

differential equations for the bulk velocities and ion concentrations of the diluate and concentrate phases. These equations can easily be solved by a standard numerical integration scheme. An analytic expression will be derived for estimating the limiting current density for given geometrical configurations of electrodesialysis stacks.

There are some mathematical models available for ion-exchange membrane electrodesialysis for desalination of saline water, including those of Tanaka [9–13]. However, in the present analysis, we shall focus on the overflow type of electrodesialysis with the concentrate compartments sealed at the bottom end. Electrodesialysis systems of this type have an advantage of producing high concentration concentrate and thus are commonly used salt production in Japan. An analysis on this type becomes quite formidable, since osmotic pressure driven flows across the membranes are no longer negligible. To the best of authors’ knowledge, there are no other analytical treatments available on such electrodesialysis systems.

2. Mathematical model

A unit cell in the electrodesialysis, as shown in Fig. 2, is considered for the analysis. This representative cell ($0 \leq y \leq (1 + \varsigma)W + l_m$) can represent any one of cells in the electrodesialysis stack, where l_m is the membrane thickness. Thus, analyzing convective ion transport within the unit cell, we can understand how overall stack system will perform under specified feed conditions. The sodium chloride ions are dissolved in the diluate (feed) stream, such that



Since the ionization degree of the salt ($NaCl$) is close to 1, its concentration in terms of mol/m^3 is nearly the same as that of cation Na^+ and that of anion Cl^- .

Without loss of generality, we shall focus on the transport of the cation Na^+ , knowing that the counterpart anion Cl^- should follow likewise, but in the opposite direction. In both diluate channels and concentrate compartments, forced convective motions and osmotic pressure driven motions are equally important in diluate channels and concentrate compartments. Thus, the governing equations are given as follows:

For the diluate channel and concentrate compartment:

$$\nabla \cdot \vec{u} = 0 \quad (2)$$

$$-\nabla p - \frac{\mu}{K} \vec{u} = 0 \quad (3)$$

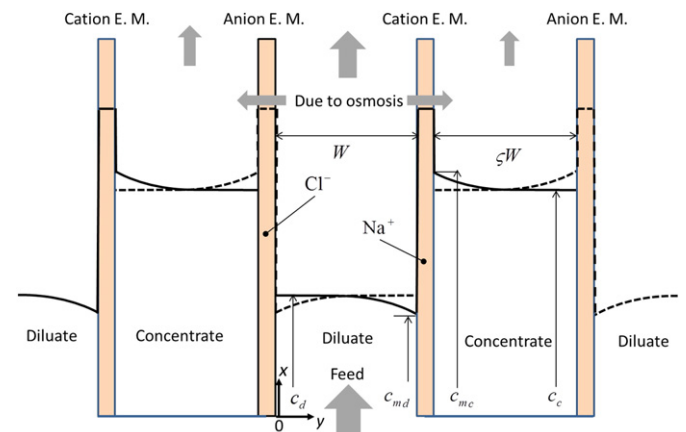


Fig. 2. Electrodesialysis cell unit.

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