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Improvement in design of electrodialysis desalination plants by considering the Donnan potential

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ABSTRACT

Electrodialysis desalination (ED) is an efficient process to desalinate brackish water and to minimize brine salinities to the level of seawater salinity. From the many models reported in the literature, some are simple but have a limited accuracy while others are complicated with a good accuracy. In this context, we explore the improvement of a fundamentally 'lumped' model by considering the voltage drop at the interfaces between membranes and solutions (which is the so-called Donnan potential) while conserving the model simplicity. The present model is developed by accounting for an electrical resistance of the Donnan potential in the total cell pair resistance. The results are presented in terms of total membrane area, flow path length, number of stacks and specific energy consumption. The results show that the improvement resulting from involving the Donnan potential was substantial for a high difference between the feed and product salinities as well as for low salinities (< 500 ppm) of the product water and low flow velocities (< 0.05 m/s). In general, the inclusion of Donnan potential improved the results from 4.4% up to 39.2% based on the studied cases.

1. Introduction

There is an increase in fresh water demand for drinking, cooking and industrial purposes; plus the limitations on fresh water resources. This is mainly due to population growth, which has been pushing many countries toward desalination and water treatment processes to alleviate water shortage problems. The selection of a certain desalination process depends upon the energy efficiency, degree of salinity, productivity and cost effectiveness. In this scenario, reverse osmosis (RO) is considered to be the most cost-effective technology for seawater desalination; however, there appears to be so far no robust desalination technology that may replace existing technology. On the other hand, the electrodialysis desalination (ED) process has been recommended for treating brackish water [1–3] and reducing the salinity of brine to the salinity level of seawater to be further treated by RO [2,4].

Electrodialysis is a process of removing salt ions from saline water by applying a direct current (DC) potential. ED is more productive and robust against scaling/fouling than RO [5]. Therefore, many researchers investigated ED by experimental [6–10] and mathematical [1,11–16] methods to represent and improve this technology.

ED plants have been installed all over the world with a capacity of 2.59 million gallons per day in 2014 [17]. For example, conventional ED systems have been used for various applications including desalinating brackish and sea water [1,18–21], producing salt [2,22], lowering the salinity of industrial effluents [23–25], demineralizing the feed water for boilers [26] and securing fresh water for food products [27]. In particular, ED systems are most often used for brackish water desalination as well as for demineralizing the boiler feed water and treating wastewater.

The required improvement factors for ED systems are diverse. From materials aspect, producing highly stable and robust membranes, besides having a low electrical resistance and a low cost, is critically needed. From new applications perspective, the utilization of ED in different industrial sectors, needs to be investigated [26]. Concerning mathematical models, simple and accurate models under a wide range of salinity are needed to enable designers to easily design, improve and optimize the performance of ED systems. In this regard, many models have been proposed to study ED and electrodialysis reversal (EDR) systems [1,3,11–13,15,28–32]. The simplest model was proposed by Lee et al. [1] for a single-voltage ED plant. The model was claimed to have a reasonable accuracy under brackish water salinities. An update to the lumped model of Lee et al. [1] has been made by Tsiakis and Papageorgiou [3] by considering a multi-voltage plant, in which the model was applied to each stack of the plant. The multi-voltage plant method resulted in a more accurate evaluation of energy consumption than that of the lumped model.

The Nernst–Planck model with empirically determined membrane properties has been investigated by Fidaleo and Moresi [11] for

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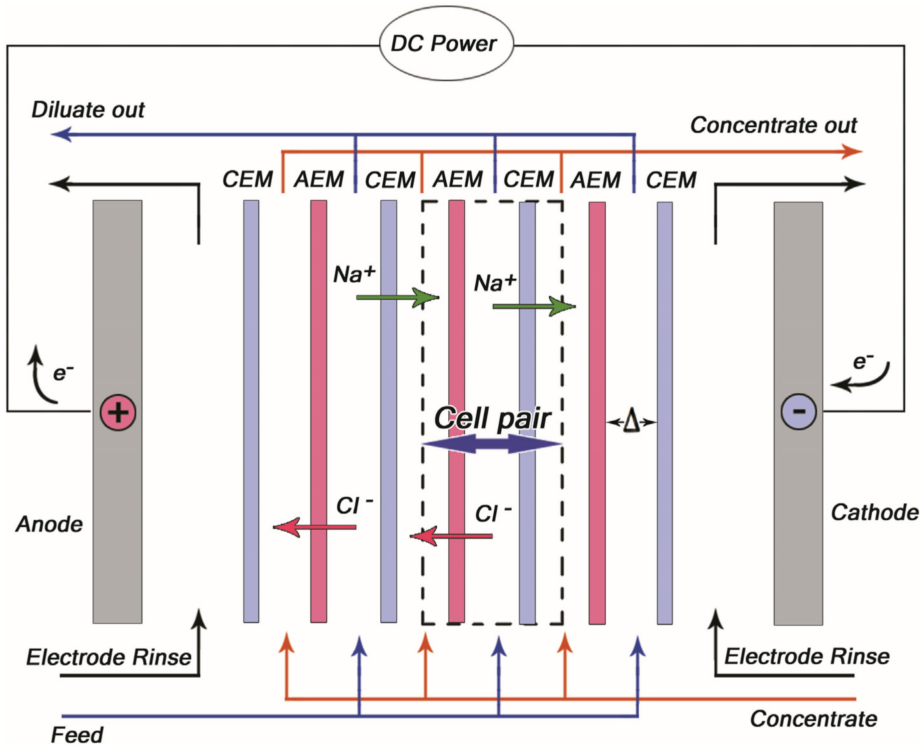

Fig. 1. Electrodialysis stack scheme, where AEM is anion exchange membrane and CEM is cation exchange membrane.

simulating a multi-stage ED system having a salinity < 90 g/kg. The exchange of salt and water through the membranes was driven by electro-migration, diffusion, electro-osmosis, and osmosis. An ideal solution was assumed and kinetic coupling between the water and salt was neglected. Ortiz et al. [12] used a batch model to analyse a single-stage ED. The model considered the electro-migration and diffusion of salt through the membranes. Kraaijeveld et al. [14] proposed a detailed model for ED using Maxwell-Stefan equations. The model focused on some details including non-ideal solutions, boundary layers, Donnan potential (the voltage drop at membrane interfaces), non-ideal salt ions and water passing through the membranes. Chehayeb et al. [2,33] have also used the Maxwell Stefan model for the same reported membranes by Kraaijeveld et al. [14] to optimize the performance and show the irreversibility of ED systems.

The Nernst–Planck model with empirically fitting membrane parameters was conducted by McGovern et al. [34]. The model could represent a high salinity up to 192 g/kg. The Nernst–Planck model deals with ideal solutions, unlike Maxwell Stefan model. The most recent update to Nernst–Planck model was proposed by Tedesco [16,35]. The Nernst-Planck equations were extended to include co-ion and water transport through membranes. Also, a multi-physics CFD model based on Navier–Stokes, continuity and Nernst–Plank equations was recently implemented to study ED and EDR systems [36–40].

Amongst all the above-mentioned models, the simplest one to facilitate the ED design and investigation is that reported by Lee et al. [1]. Aside from the model's simplicity, it considers various operating, performance and geometrical parameters such as ED stack construction, feed and product concentration, membrane properties, required membrane area and length, flow velocities, current density, recovery rate, energy consumption, etc. However, the accuracy of this model is not high, especially for high salinity water. For this reason, Tsiakis and Papageorgiou [3] and Qureshi and Zubair [32] tried to improve the model accuracy while keeping it as simple as possible. In this regard, a substantial improvement in the Lee et al. model is still recommended [32].

The effect of Donnan potential was neglected in the ED design models [1,3,32], whereas the Donnan equilibrium is important to provide reliable predictions of electrical potential and ionic concentration drops at the membrane interfaces [41]. This potential was handled by Donnan dialysis to remove undesirable ions (co-ions) from membrane surfaces and for recovery of valuable metal ions [42]. More details about the Donnan dialysis is explained by Tanaka [43]. The Donnan potential was highlighted as an important component to evaluate the unit cell voltage [2,14,33,36,39].

In this paper, the effect of voltage drop at the interfaces between solutions and membranes (Donnan potential) are considered to update the ED model presented by Lee et al. [1]. Because the Donnan potential is an important contributor in the estimation of the total stack electrical potential [2,33], its inclusion to the design model presented by Lee et al. [1] is expected to improve the model accuracy while maintaining its simplicity.

2. Electrodialysis desalination system description

In general, electrodialysis desalination (ED) is a salt removal process resulting from applying an electrical potential. Because a salt exists in a solution as separated ions, (positive ions (cations) and negative ions (anions)), the applied DC current attracts ions to the counter charged poles. In addition, membranes are designed to have positive or negative charges to mostly permit the passage of counter ions. The negatively charged membrane is called cation exchange membrane (CEM) and the positively charged membrane is called anion exchange membrane (AEM). The anion and cation exchange membranes are placed alternately in a salt solution to divide the ED stack into concentrate and diluate compartments.

The cations move toward the CEM and migrate through it but will be stopped by the next AEM. Similarly, the anions move toward AEM and migrate through it but are prevented from passing through the next CEM. Thus, the salt is removed from the diluate compartments and accumulates in the concentrate compartments, as depicted in Fig. 1. A ‘cell pair’ consists of an AEM, a CEM, one concentrate compartment and one diluate compartment. An electrodialysis stack is usually of > 100