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# Design of electrodialysis desalination plants by considering dimensionless groups and variable equivalent conductivity

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ABSTRACT

Electrodialysis desalination plants, for brackish water, are designed based on different parameters such as feed concentration, current density, and stack construction. Among the various model assumptions, the constancy of the equivalent conductivity of the diluate and concentrate streams is considered a prominent one. In this paper, this assumption is relaxed at different levels and closed-form solutions are obtained to ascertain its effects. It is shown that previously published results can be replicated. Also, a comparison between the lumped and staged model shows that using the inlet flow rate in the lumped model instead of the product flow rate provides more accurate results. Further analysis reveals a non-dimensional number, termed the electrodialytic Biot number, which is the ratio of the total to exit concentration based average cell pair volume resistance. It was found to be physically equivalent to the number of stacks. This provided a clear criterion as to when the lumped model should be used. Specifically, as long as the electrodialytic Biot number is (less than or) equal to 1, the lumped model should be used, otherwise the staged model is a more appropriate choice. It also provides direction for future research. A design chart is also developed to facilitate the calculation procedure.

## 1. Introduction

With a significant percentage of humanity facing potable water shortage or a complete lack thereof [1] as well as a growing population [2], an increased demand for drinking water is anticipated. The need for water, in general, is further exacerbated due to growing agricultural and industrial needs. With 97% of the planet's water unfit for these purposes and natural resources unable to meet the demand, desalination provides a solution. Desalination process technologies can be classified by the presence or absence of phase change. Multiple-effect distillation (MED), vapor compression (VC) distillation and multi-stage flash distillation (MSF) are of the former type while reverse osmosis (RO) and electrodialysis/electrodialysis reversal (ED/EDR) are of the latter type.

Electrodialysis is a process that removes ionized salts from water by ion migration, through anion and cation exchange permselective membranes, under the effect of a DC electric current (See Fig. 1). Therefore, ED/EDR is more robust compared to RO in terms of scaling/fouling [3]. Anion and cation exchange membranes are placed alternately in the salt solution. Therefore, when an electric current is passed through it, the positively charges ions move towards the cation exchange membrane and pass through it but will be stopped by the next membrane. Similarly, the negatively charged ions, move towards the anion exchange membranes and pass through it but are prevented from passing through the next membrane. The net result of this is two types of alternating compartments: diluate compartments that lose ions and concentrate compartments that gain ions. It should be noted that the degree of desalination depends on various factors such as the feed solution concentration and flow rate as well as the electric current passing through the solution.

Concentration polarization is inevitable as electrodialysis is a membrane separation process. It occurs due to differences in the membrane and solution ion transport numbers. It leads to a decrease in ion concentration on the membrane surface facing the diluate cell and vice versa for the concentrate side. This results in concentration gradients on each side between the membrane surface and the respective bulk solutions. On the diluate side, the lack of ions on the membrane surface establishes the limiting current density while, on the concentrate side membrane surface, the build-up of ions may result in salt precipitation [4].

With an installed capacity of 2.59 million gallons per day in 2014 [5], conventional ED has been used for various applications. This includes treating brackish and sea water [6–10], production of salt [11,12], treating industrial effluents [13–15] and demineralization of boiler feed [4] as well as food products [16]. Sea water is found all over the world but brackish water is also found naturally in significant quantities in the form of seas and lakes. It is also found artificially due

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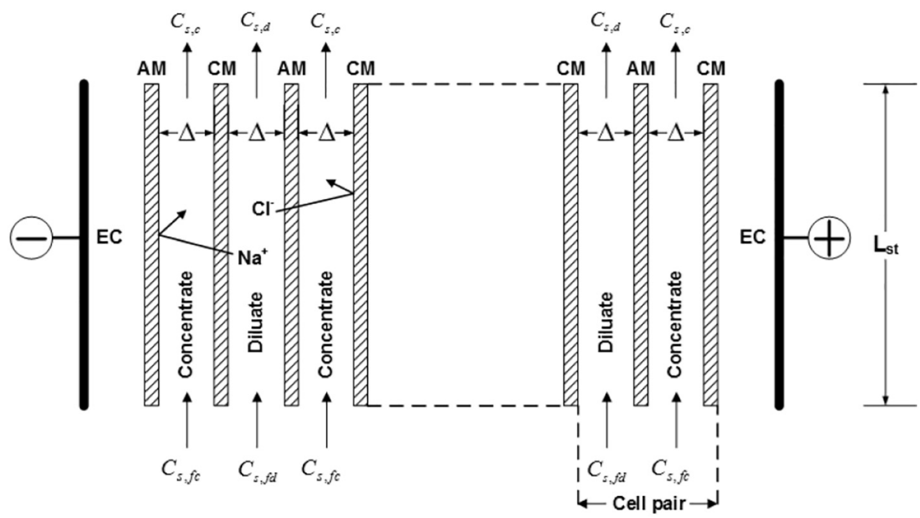


**Fig. 1.** Schematic of electrodialysis stack, where AM = Anion Exchange Membrane, CM = Cathode Exchange Membrane and EC = Electrode compartment.

to human activities such as a waste product of pressure retarded osmosis [17,18]. Brackish water desalination is the largest application of conventional ED followed by demineralization of boiler feed water and waste water treatment. For processes related to ED such as reverse electrodialysis, electrodialysis with bipolar membranes, continuous electrodeionization etc., the reader may consult the work of Strathmann [4].

The challenges facing ED/EDR are multi-faceted. From a materials perspective, development of better membranes is needed that possess characteristics such as increased stability, higher permselectivity and lower electrical resistance at lesser costs. From the point of view of applications, newer uses for the process in different industries and sectors need to be investigated [4]. From the angle of modeling, simpler models with wide applicability in terms of salinity need to be developed as well.

In the context of brackish water desalination, many researchers have modelled the process such as [6,19–27]. A summary of some existing ED models that are not necessarily restricted to brackish water feed is given in Table 1 with a discussion in the following paragraph.

Fidaleo and Moresi [22] modelled a multi-stage ED system using the Nernst-Planck equations. Even though an ideal solution is taken and kinetic coupling between the water and salt is ignored, ED operation was modelled up to 90 g/kg. It is noted that this required fitting many membrane parameters and that this is best suited to determine performance of a specific system. McGovern et al. [28] applied a similar approach and managed to model ED operation up to 192 g/kg while Ortiz et al. [23] applied it for desalinating brackish water. The Nernst-Planck equation was extended by Tedesco et al. [29,30] to the membrane while the water transport through the membrane was modelled with the Maxwell-Stefan equation. Kraaijeveld et al. [31] showed that Maxwell-Stefan mass transfer description can be used to model an ED process. This model assumes a non-ideal solution and is the closest to the fundamental equations. It is noted that the use of such a detailed model seems to be more suited to high salinity applications. The multi-stage single-voltage model of Lee et al. [6], applied by Tsiakis and Papageorgiou [21] to a multi-stage multi-voltage system, manages to model a complete ED plant. The authors applied various factors such as the shadow factor to determine the correct required membrane area, void factor to calculate the true flow rate and a safety factor for determining the limiting current density in order to make a practical plant model. The assumptions involved limit its application to brackish water but it is also noted that, in comparison to the other models, this approach is much simpler. Therefore, this model was selected for the purpose of improvement and further analysis.

Among the common assumptions that are made is that the equivalent conductivity is constant and sometimes even same for both the concentrate and diluate streams. Therefore, the effect of this remains unclear on the results of such models as mentioned by Brauns et al. [32]. Alternatively, it is assumed to be a linear or non-linear function of concentration. But, in none of these cases, has closed-form analytical solutions been obtained from the governing differential equations.

In this paper, the effect of removing the assumption of constant and same equivalent conductivity of the concentrate and diluate streams is investigated for the ED model presented by Lee et al. [6]. This is done in order to clarify doubts about making such assumptions on results. The assumption will be relaxed in the following three ways in Section 2: i) equivalent conductivity is constant but different for each stream, ii)

**Table 1**
A summary of literature on existing ED models.

| Author(s) | Type of study | Phenomena modelled | Major outcomes | Comment(s) |
|---|---|---|---|---|
| Lee et al. [6] | Steady-state | Electro-migration | Single-voltage plant model | Limited to brackish water |
| Tsiakis and Papageorgiou [21] | Steady-state | Electro-migration | Multi-voltage plant model | Limited to brackish water |
| Fidaleo and Moresi [22] | Batch mode | Electro-migration, Diffusion, Electro-osmosis, Osmosis | Modeling multi-stage ED system by empirically fitting membrane parameters | Models up to 90 g/kg |
| McGovern et al. [28] | Batch mode | Electro-migration, Diffusion, Electro-osmosis, Osmosis | Modeling multi-stage ED system by empirically fitting membrane parameters | Models up to 192 g/kg |
| Ortiz et al. [23] | Batch mode | Electro-migration, Diffusion | Single-stage ED model through controlled potential | Can be applied to commercial plants |
| Tedesco [29,30] | Steady-state | Electro-migration, diffusion, electro-osmosis, osmosis, convection | Two-dimensional model including water transport | Nernst-Planck equations extended to membrane |
| Kraaijeveld et al. [31] | Batch mode | Electro-migration, diffusion, electro-osmosis, osmosis, convection | Showed that Maxwell-Stefan mass transfer description can be used to model ED | Two systems studied: NaCl-HCl, two amino acids |