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Exergy and sensitivity analysis of electrodialysis reversal desalination plants

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HIGHLIGHTS

- Exergy analysis shows the stack with highest exergy destruction in an actual plant.
- Sensitivity studies are then carried out on a modelled electrodialysis stack.
- Concentration and current efficiency are the most significant variables.
- Plant size is affected less at higher feed salinities compared to lower feed salinities.
- A large variation in plant cost may occur while operating at higher concentrations.

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ABSTRACT

In this paper, a normalized sensitivity analysis is done on an electrodialysis plant for various design and performance parameters. From the angle of design and performance, the most significant variables were the feed concentration and current efficiency, respectively. For the design aspect, plant size determination is affected less at higher feed salinities due to variations in the feed concentration, which seems to be favorable for high salinity applications. For the performance aspect, it is found that larger fluctuations in plant cost may occur while operating at higher feed concentrations. The desired diluate concentration and, thus, limiting current density as well as expected energy consumption may be more difficult to maintain at higher current efficiencies. Yet, the limiting current density is less sensitive at higher flow velocities. Therefore, the above problem could possibly be countered by using a combination of higher current efficiencies with higher flow velocities.

1. Introduction

The world's population is facing an increasing problem of water shortage [1]. Different technologies are being employed to produce potable water such as reverse osmosis, multi-stage flash distillation, multi-effect distillation, vapour compression desalination etc. Another technology being used for this purpose is electrodialysis (ED), which consumes less energy compared to reverse osmosis. This is a membrane-based process that has been in use for decades, which applies an electric field to transport anions and cations. The first commercial electrodialysis based equipment was developed in the 1950s. Desalination of brackish water has been the well-known application of this technology as it exists under two-thirds of the United States. Another early application was production of salt from seawater while a more recent one includes the treatment of industrial wastewaters. A typical ED plant contains anodes and cathodes arranged alternately with space in between for the solutions to be treated to pass through. The applied electric field causes the negative ions to the anode and the positive ions to the cathode. The ion concentration increases in alternate compartments. On the other hand, the remaining compartments lack ions. The former is often called the concentrated solution while the latter is termed the diluate. Typically other parts of the plant consist of pre-treatment, pumps and post-treatment. For further information, the work of Strathmann [2] may be consulted.

Lee et al. [3], Parulekar [4], Fidaleo and Moresi [5] and Ortiz et al. [6] modelled batch processes. The first group did work on a two-stage ED process. The other two provided descriptions based on constant current and constant voltage, respectively. Moon et al. [7] proposed three models where two were for a one- and two-dimensional continuous ED process and the third for a batch process. The effect of superficial velocity in the boundary layer, the electromigration and diffusion of ions in the polarization region as well as convection and electromigration in the bulk region was examined. A steady state model was presented

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Nomenclature

a	constant used in Eq. (5)
A	membrane area (m^2)
b	constant used in Eq. (5)
C_s	salt concentration (ppm)
D_B	diffusion coefficient (m^2/s)
E_{sp}	specific energy consumption (kW h/m^3)
F	Faraday constant (A.s/kmol)
i	limiting current density (A/m^2)
I_{st}	total stack current (A)
k_s	mass transfer coefficient (m/s)
L	path length per stack (m)
L_{ch}	characteristic length (m)
N_{cp}	number of cell pairs
N_{st}	number of stages
P	power (kW)
$\dot{Q}$	volumetric flow rate (m^3/s)
$\bar{r}_m$	total area resistance of membranes (Ω m^2)
R	recovery ratio
R_g	gas constant (kJ/kg·K)
s	safety factor
Sh	Sherwood number ($k_s L_{ch}/D_B$)
t_m	ion transport number in the membrane
t_s	ion transport number in the solution
T	temperature (°C or K)
u	linear flow velocity (m/s)
$\dot{W}$	power requirement (kW)
x	specific exergy (kJ/kg)
$\dot{X}$	rate of exergy (kW)
y	mole fraction
z	valence

Greek symbols

α	volume factor
β	shadow factor
Δ	cell chamber thickness (m) or change of a variable
Λ	equivalent conductivity (kmol/m^3)
ζ	current efficiency

Subscripts

0	dead state
b	brine
c	concentrate
ch	chemical
d	diluate
D	destruction
dl	discharge line
err	error
ED	electrodialysis stacks
eq	equivalent
emp	empirical
f	feed
fc	incoming on concentrate cell
fd	incoming on diluate cell
ftr	filter
p	permeate
pp	pump
prac	practical
tot	total
TV	throttle valve

by Sadrzadeh et al. [8], which was based on regression analysis. Gong et al. [9] developed differential equations using Kedem-Katchalsky equations and irreversible thermodynamics. However, Lee et al. [10] developed a practical set of equations to design a series of ED stacks based on quantities such as the shadow factor and volume factor. A safety factor was used to determine a practical value for the limiting current density. A complete example was also provided. Therefore, this model was mainly used in the current work.

Very recently [11], it was found that ED plants have very low exergetic efficiency for brackish water feed. For a feed salinity of 900 ppm, Kahraman et al. [12] had shown that the pumping and piping systems had been responsible for the most exergetic destruction in an ED plant. This conclusion needs to be re-checked as it was based on seawater properties that were not accurate [13]. Based upon this new analysis, the component responsible for the most exergy destruction can be identified and a sensitivity analysis can then be applied to ascertain important variables that govern it. Furthermore, as sensitivity analysis identifies those independent variables in any system that influence important design and performance factors, it is beneficial to perform such an analysis, in general, of the ED stack based upon the model of Lee et al. [10]. In this regard, it was found that Walker et al. [14–16] experimentally performed a sensitivity analysis for brackish water reverse osmosis concentrate. These works ascertained the effect of superficial velocity, voltage application, membranes, concentration and hydraulic recovery on electrodialysis performance. Although, it should be noted that the feed salinity range for these experiments was 7890–18,600 ppm while the current work will focus on salinities below this range.

The objective of this work is, therefore, to initially perform a detailed exergy analysis of an ED desalination plant using accurate seawater properties to determine the component responsible for the most exergy destruction. After which, a normalized sensitivity analysis will be performed of this component in order to understand the component not only from an exergetic point of view but also, generally, from a design and performance angle. For this purpose, the ED stack modeling is presented in Section 2 while the exergy analysis is given in Section 3. A detailed normalized sensitivity analysis for the design and performance case is presented in Section 4. Finally, the conclusions are given in Section 5.

2. Electrodialysis modeling

An electrodialysis plant is studied using the model provided by Lee et al. [10] with two modifications. A schematic of an electrodialysis cell pair is shown in Fig. 1 to illustrate some geometric quantities, indicate the locations of the concentrations used and the co-current flow path. The following assumptions were made:

- Concentrate and diluate cells have an identical geometry.
- The flow rates in the concentrate and diluate compartments are the same.
- Only parallel flow configuration is taken.
- The current density will not be allowed to go beyond the limiting current density.
- Activity coefficients are taken as unity.
- Osmotic water transport is neglected along with diffusion due to concentration gradients.
- The membrane thickness is neglected.
- The valence z is taken as 1.

The first modification performed was to use the updated equivalent conductivity (Λ) equation provided by Fidaleo and Moresi [5] (instead of the one provided by Lee et al. [10]) where the equivalent conductivity is a function of concentration as shown below:

$$\Lambda = 11.33 - 7.4\sqrt{C_{s,eq}} + 6C - 2.3\sqrt[3]{C_{s,eq}} \tag{1}$$