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Optimal design and operation of electrodialysis for brackish-water desalination and for high-salinity brine concentration

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ABSTRACT

Electrodialysis (ED) is a desalination technology that has been deployed commercially for decades. However, few studies in the literature have looked at the optimal design and operation of these systems, especially for the concentration of high-salinity brines. In this paper, a set of constraints is defined to allow a fair comparison between different system sizes, designs, and operating conditions. The design and operation of ED are studied for the applications of brackish-water desalination and of high-salinity brine concentration for a fixed system size. The set of variables that determine the power consumption of a fixed-size system is reduced to include only the channel height and the velocity, with all the other design and operation variables depending on these two variables. After studying the minimization of power consumption for a fixed system size, the minimum costs associated with the different system sizes are studied, and the differing trends in brackish-water and high-salinity applications are compared. Finally this paper presents the effect of the cost modeling parameters on the trends of the optimal system size, current density, length, channel height, and velocity for the two applications studied.

1. Introduction

Electrodialysis (ED) is a desalination technology that uses an electric work input and ion-exchange membranes to move salt from a diluted solution to a concentrated solution. ED has successfully been used for the desalination of brackish water [1–9], and for the concentration of seawater [10,11] or reverse-osmosis brine for salt production [1,12,13]. Despite the large number of studies published on ED, only a small number of these has analyzed the optimal design and operation of ED systems, with the bulk of the work being focused on brackish-water desalination. Select studies on the optimal design and operation of ED systems are described below.

Sonin and Isaacson [14] presented a dimensional analysis of a general electrochemical system where fluid flow enhanced the limiting current density. They presented two conditions for optimal hydrodynamic design, which they defined as the choice of the channel geometry and the flow speed in the channels. The first condition required operating at a low-enough current density such that the negative effects of concentration polarization are negligible. The second condition required a velocity low enough for the pumping cost to be much smaller than the capital costs of the system. They also stated that the channel height should always be minimized. They applied this dimensional analysis to the example of brackish-water ED to determine the optimal spacer design and to identify areas for improvement.

Hattenbach and Kneifel [15] studied the effects of the flow velocity and the channel height on the cost of electrodialysis. They reported that velocity affected the pumping power and the limiting current density while the channel height affected both the pumping power and the ED stack power. The current was always set to 70% of the limiting current density, so that the velocity set the operating current and the required membrane area. They concluded that the channel height should be minimized, and they specified a range of velocities that minimized the total cost.

Nikonenko et al. [16] minimized the system cost by varying the channel height and the stack voltage, but they fixed the length of the system and did not vary the velocity as an independent variable. They concluded that the channel height should be small and that the velocity should be large so that the required area and the ED power consumption are decreased.

Lee et al. [2] set the applied current density to a fixed fraction of the limiting current density. They concluded that the cost of desalination of brackish water using ED is minimized at the highest possible limiting current density. However, as will be shown later in this paper, this conclusion was reached only because Lee et al. did not include the

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Nomenclature

Acronyms

AEM	Anion-exchange membrane
CEM	Cation-exchange membrane
MS	Maxwell-Stefan

Symbols

A	effective cell-pair area [m^2]
a	activity [–]
C	cost [\$/m^3 product]
c^*	normalized cost [(\$/m^3 product)/(\$/kWh)]
c	concentration [mol/m^3]
D	diffusion coefficient of salt [m^2/s]
$Đ_{ij}$	Maxwell-Stefan diffusion coefficient for species i and j [m^2/s]
F	Faraday constant, 96,487 [C/mol]
f	friction factor [–]
h	channel height [m]
i	current density [A/m^2]
i	annual interest rate [–]
J	flux [mol/m^2-s]
K_e	cost of electricity [\$/W-s]
K_m	fixed cost per unit cell-pair area per unit time [\$/m^2-s]
$K_{m,0}$	fixed cost per unit cell-pair area per unit time at time 0 [\$/m^2-s]
k_m	mass transfer coefficient [m/s]
L	effective stack length [m]
L_s	salt permeability [m/s]
L_w	water permeability [mol/m^2-s-bar]
m	molality [mol/kg]
N	molar flow rate [mol/s]
N_{cp}	number of cell pairs [–]
P	power consumption [W]
Q	volumetric flow rate [m^3/s]
R	universal gas constant, 8.3145 [J/mol-K]
Re	Reynolds number, Eq. (F.5) [–]
r	electric resistance [Ω-m^2]
r	cost ratio, Eq. (9) [W/m^2]
S	salinity [g/kg]
Sc	Schmidt number, Eq. (F.6) [–]
Sh	Sherwood number, Eq. (F.1) [–]
T	absolute temperature [K]
T_s	salt transport number [–]
T_w	water transport number [–]
V	voltage [V]
v	velocity (at the product outlet) [m/s]
W	stack width [m]
z	charge number

Greek

Δ	difference or change
∇	gradient
ε	spacer volume fraction [–]
Φ	electric potential [V]
$\gamma_\pm$	mean molal (or molar) activity coefficient [–]
μ	dynamic viscosity [Pa-s]
μ_i	electrochemical potential of ion i [J/mol]
μ_s	chemical potential of the salt [J/mol]
μ_w	chemical potential of water [J/mol]
π	osmotic pressure [bar]
τ	plant life [years]
ρ	density [kg/m^3]

Subscripts

avg	average
C	concentrate
cp	cell-pair
D	diluate
i	ion i
m	at membrane interface
s	salt
w	water

Superscripts

m	in membrane
s	in solution

pumping power in their cost calculation.

Tsiakis and Papageorgiou [7] accounted or pumping power in their optimization, but they also set the operating current at a fixed fraction of the limiting current density.

Turek [17] studied the effect of channel height on the performance of a fixed-size electrodialysis stack. The current density was set to a fixed fraction of the limiting current density, and an intermediate channel height was found to be optimal.

Choi et al. [18] determined the optimal current density based on capital costs, maintenance costs, ED stack power, and pumping power. However, they studied a batch system that operated at a fixed circulating velocity.

While the studies described above have studied the effect of select parameters on the design of ED systems, none of them comprehensively included the effects of all the important variables on the optimal design of ED systems. Thus, important trade-offs between variables were missed. For example, in several studies, the ratio of the applied current density to the limiting current density was kept constant, leading to the trade-off between ED power consumption and pumping power being poorly captured. Additionally, in some studies, the length of the system or the flow velocity was held constant, limiting the optimization possible. This has led to an incomplete understanding of how ED systems should be designed and operated. In this paper, a set of constraints is defined to allow a fair comparison of the different designs and operating points. To fully optimize ED systems, and to reach general conclusions, it is essential that no design variables be held constant. The approach presented is applied to brackish-water desalination and to high-salinity brine concentration. The constraints needed for a fair comparison between different designs and operating points are discussed in detail in Section 2 while the analytical ED models used in our analysis are discussed in Section 3.

2. Constraints for a fair comparison between different designs and operating points

In order to determine the optimal design and operation of an ED system, it is essential to decide on a set of system constraints that results in a fair comparison between the different designs and operating points. In deciding on these constraints, we can think about a general desalination or water treatment system which takes in a fixed amount of feed at a fixed salinity and is required to treat this feed to result in a fixed flow rate of product at a set salinity. Allowing different systems to treat different amounts of feeds with different recoveries or different product quality would result in an unfair comparison between these systems. In