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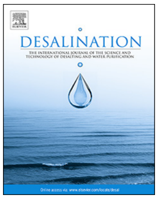

On the merits of using multi-stage and counterflow electrodialysis for reduced energy consumption

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ABSTRACT

The cost of electrodialysis (ED) systems can be decreased by decreasing their power consumption. Such reductions may be achieved by using degrees of freedom in the system's configuration to obtain a more uniform spatial distribution of the rate of entropy generation, as explained by the theorem of equipartition of entropy generation. In this paper, we study possible improvements to the energy efficiency of electrodialysis through the use of two electric stages with different voltages, and through operation in a counterflow configuration. We first consider how a two-stage ED system should be operated. In particular, we look at how the voltages and current densities should be chosen. In addition, we quantify the effect of operating under two voltages in brackish-water desalination and in high-salinity brine concentration. Finally, we quantify the effect of operating ED in counterflow for the same applications. We show that high ED fixed costs prevent the achievement of significant improvements in energy efficiency. If fixed costs are reduced, and larger systems become cost-effective, we show that a power reduction of up to 29% is possible by going from a single-stage to a two-stage configuration.

1. Introduction

Electrodialysis (ED) is a desalination technology that can treat brackish water [1-8], seawater [9-13], and high-salinity brines [3, 14, 15], and has many applications in the food and beverage industry [3, 16].

The cost of ED can be decreased through the reduction of its power consumption. One way power consumption can be decreased is by increasing the system size[1]. The trade-off that exists between the costs related to the system size and the energy costs is well understood, and the choice of system size is determined through cost minimization, as was done in a previous study [17] for the use of ED for brackish-water desalination and high-salinity brine concentration.

1.1. Reducing energy consumption using the theorem of equipartition of entropy generation

A less commonly employed concept is that, for heat and mass transfer systems of fixed size, additional operation flexibility can also reduce power consumption. This can be explained by the theorem of equipartition of entropy generation, which was first introduced by Tondeur and Kvaalen [18]. This theorem states that, given a fixed duty (total quantity to be transported) and a fixed system size, the optimal configuration is that which minimizes the spatial or temporal variance in the rate of entropy generation. A more physical way of thinking about this concept is by considering the distribution of the available area. By better distributing the rate of entropy generation, the driving force is also better distributed (when flux is a linear function of the driving force), and more area is allocated to the part of the system where the driving force is higher. Thus, in a poorly equipartitioned system, part of the available area is wasted on sections where the driving force is very small, resulting in low fluxes.

1.2. Equipartition through the use of multiple stages and of counterflow operation

One way to achieve better equipartition of entropy generation is by operating the system under multiple stages. Staging results in additional degrees of freedom, which, even at a fixed system size, can lead to improvements in the system's energy efficiency. The idea of multi-staging has been previously applied to multiple desalination technologies such as humidification-dehumidification [19-22], membrane distillation [23], and reverse osmosis [24]. In the case of ED, each stage can be operated at a different voltage to better control the distribution of the flux. This is referred to in the literature as 'electric staging' of ED systems. In this paper, we use the term 'multi-staging' to exclusively

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[1] At least until a certain limit, as explained in Appendix A.

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Nomenclature

Acronyms

AEM	anion-exchange membrane
CEM	cation-exchange membrane

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	driving force [J/mol-m-K]
h	channel height [m]
i	current density [A/m^2]
i	annual interest rate [-]
J	molar duty [mol/s]
j	molar 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 at time 0 [\$/m^2]
k_m	mass transfer coefficient [m/s]
L	phenomenological coefficient [K-mol^2/J-m-s]
L_s	salt permeability [m/s]
L_w	water permeability [mol/m^2-s-bar]
M	molar mass [g/mol]
m	molality [mol/kg]
P	power consumption [W]
R	universal gas constant, 8.3145 [J/mol-K]
Re	Reynolds number, Eq. (D.4) [-]
r	electric resistance [$\Omega -$ m^2]
r	cost ratio, Eq. (G.2) [W/m^2]
S	salinity [g/kg]
S	entropy [J/K]
$\dot{S}_{gen}$	entropy generation rate [W/K]
$\dot{S}_{gen,\ equip}$	entropy generation rate of the equivalent equipartitioned system [W/K]
$\dot{s}'''_{gen}$	volumetric rate of entropy generation [W/m^3-K]
$\dot{s}''_{gen}$	entropy generation rate per unit area [W/m^2-K]
Sc	Schmidt number, Eq. (D.5) [-]
Sh	Sherwood number, Eq. (D.1) [-]
T	absolute temperature [K]
T_s	salt transport number [-]
T_w	water transport number [-]
V	Volume [m^3]
V	voltage [V]
V_1^*	voltage of the first stage divided by that of the single-stage system [-]
$V_{1,P}^*$	normalized first-stage voltage that minimizes power consumption [-]
$V_{1,Var(i)}^*$	normalized first-stage voltage that minimizes the variance of the current density [-]
$V^*_{1,Var(\dot{s}''_{gen})}$	normalized first-stage voltage that minimizes the variance of rate of entropy generation [-]
W	stack width [m]
z	charge number

Greek

Δ	difference or change
δ	diffusion layer thickness [m]
∇	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]
τ	plant life [years]
Ξ	equipartition factor [-]
ρ	density [kg/m^3]

Subscripts

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

imply ‘electric staging’, and use ‘two stages' and ‘two voltages' interchangeably.

Another way to better distribute the driving force over the available area is by operating a heat or mass exchanger in a counterflow configuration. In the case of ED, this can serve to better distribute the concentration profiles over the length of the system, which might lead to improvements to the system's energy consumption.

Few studies have looked at the operation of ED under multiple voltages or in counterflow configurations. Tsiakis and Papageorgiou [25] modeled ED systems with multiple hydraulic and electric stages. The conditions at each stage were optimized numerically to minimize total system costs. Turek [9] studied a counterflow two-stage ED seawater desalination system and reported energy and cost numbers. Ryabtsev et al. [26] implemented a two-stage desalination system. The first stage was operated under a constant current density, and the second stage was operated under a constant voltage. Tanaka [27] presented a multi-stage ED computer model that combines multiple stacks in series. McGovern et al. [7, 28] used a counterflow ED system coupled with reverse osmosis to decrease the costs of water production.

Even though these ideas have been previously presented in the literature, there has not been a detailed study on how to make the best use

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