CHEMICAL ENGINEERING RESEARCH AND DESIGN XXX (2014) XXX–XXX

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

A simulation tool for analysis and design of reverse electrodialysis using concentrated brines

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A B S T R A C T

Reverse electrodialysis (SGP-RE or RED) represents a viable technology for the conversion of the salinity gradient power into electric power.

A comprehensive model is proposed for the RED process using sea or brackish water and concentrated brine as feed solutions. The goals were (i) reliably describing the physical phenomena involved in the process and (ii) providing information for optimal equipment design. For such purposes, the model has been developed at two different scales of description: a lower scale for the repeating unit of the system (*cell pair*), and a higher scale for the entire equipment (*stack*).

The model was implemented in a process simulator, validated against original experimental information and then used to investigate the influence of the main operating factors and on power output. Feed solutions of different salinities were also tested. A good matching was found between predictions and experiments for a wide range of inlet concentrations, flow rates and feed temperatures. Optimal feed conditions, for the adopted system geometry and membranes, have been found employing brackish water (0.08–0.1 M NaCl) as dilute and brine (4.5–5 M NaCl) as concentrate to generate the highest power density at 40 °C temperature.

The model can be used to explore the full potential of the RED technology, especially for any investigation regarding the future scale-up of the process.

Keywords: Salinity gradient power; Reverse electrodialysis; Sea water; Brine; Process simulator; Multi-scale model

1. Introduction

The importance of exploring renewable sources of energy, both for environmental issues and for reducing our dependence from fossil fuels, has already been broadly discussed and accepted. In this context, a promising energy source almost equally distributed worldwide is salinity gradient power (SGP), i.e. the energy available from mixing two aqueous solutions at different salinity. The success in collecting this chemical energy and convert it into a more exploitable form is related to managing the mixing in suitably controlled conditions. Up to now, three different technologies have been proposed in the literature: reverse electrodialysis (RE or RED) (Lacey, 1980; Pattle, 1954), pressure retarded osmosis (PRO) (Post et al., 2007) and capacitive double layer expansion (CDLE) (Brogioli, 2009). The first two are membrane-based technologies, in which the controlled mixing is achieved by the use of suitable membranes acting as semi-permeable barriers, thus allowing the transport of either ions (RED) or water (PRO). Although both of them are promising processes and many efforts are being made in research and development, RED has, in fact, a remarkable advantage with respect to PRO: in this latter, SGP is

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http://dx.doi.org/10.1016/j.cherd.2014.05.009

Nomenclature

Latin letters

$a_{open,x}$	spacer open area in the direction along IEM
$a_{open,y}$	spacer open area in the direction perpendicular IEM
a	parameter of Islam et al.' equation
A	membrane area or cell pair area (m^2)
A_1	Debye–Hückel constant (0.3915 at 25 °C)
b	channel (or membrane) width (m)
b'	constant of Pitzer equation
B'	parameter of Islam et al.' equation, ($m^{1/2}\,mol^{-1/2}$)
B'_1	parameter of Islam et al.' equation, ($S\,m^3\,mol^{-3/2}$)
B'_2	parameter of Islam et al.' equation ($m^{3/2}\,mol^{-1/2}$)
B^γ	second virial coefficient of Pitzer equation ($kg\,mol^{-1}$)
B^φ	second virial coefficient of Pitzer equation ($kg\,mol^{-1}$)
c	molar concentration (mol/l)
C	salt concentration ($mol\,m^{-3}$)
$\bar{C}'_{HIGH,k}$, $\bar{C}'_{LOW,k}$	salt concentration averaged between inlet-centre of kth channel
$\bar{C}''_{HIGH,k}$, $\bar{C}''_{LOW,k}$	salt concentration averaged between centre-outlet of kth channel
C^γ	third virial coefficient of Pitzer equation ($Kg^2\,mol^{-2}$)
C^φ	third virial coefficient of Pitzer equation ($Kg^2\,mol^{-2}$)
D_{NaCl}	NaCl permeability coefficient (m^2/s)
E_{cell}	cell pair voltage (V)
E_{stack}	stack voltage (V)
F	Faraday constant (96,490 $C\,mol^{-1}$)
f_y,f_x	spacer shadow factor in the direction perpendicular/along IEM
f_m	membranes resistance correction factor
F'	parameters of Islam et al.' equation
I	electric current (A)
I'	ion strength (mol/l)
j	current density ($A\,m^{-2}$)
J'_w	volumetric water flux ($m^3\,m^{-2}\,s^{-1}$)
J_{tot}	salt molar flux ($mol\,m^{-2}\,s^{-1}$)
J_{eosm}	electro-osmotic flux ($mol\,m^{-2}\,s^{-1}$)
J_{osm}	osmotic flux ($mol\,m^{-2}\,s^{-1}$)
J_w	net water flux ($mol\,m^{-2}\,s^{-1}$)
L	channel length (m)
L_p	water permeability coefficient ($m^3\,bar^{-1}\,m^{-2}\,h^{-1}$)
m	electrolyte molal concentration ($mol\,kg^{-1}$)
N	number or cell pairs
P_d	gross power density (W/m^2 cell pair)
$P_{d,net}$	net power density (W/m^2 cell pair)
P_{pump}	pumping power (W)
Q_{HIGH}, Q_{LOW}	concentrate/dilute solution flow rate in single channel ($m^3\,s^{-1}$)
Q_{tot}	total feed flow rate ($m^3\,s^{-1}$)
R	universal gas constant ($8.314\,J\,mol^{-1}\,K^{-1}$)
R_{AEM}, R_{CEM}	AEM/CEM areal resistance ($\Omega\,m^2$)
R_{HIGH}, R_{LOW}	concentrate/dilute compartment areal resistance ($\Omega\,m^2$)
R_{blank}	electrode compartments (blank) resistance ($\Omega\,m^2$)
R_{cell}	resistance of a single cell pair ($\Omega\,m^2$)
R_{stack}	total stack resistance ($\Omega\,m^2$)
R_u	external load ($\Omega\,m^2$)
T	temperature (K)
v	fluid velocity ($m\,s^{-1}$)
x	flow direction (m)
z	ion valence

Greek letters

α_{AEM}, α_{CEM}	AEM/CEM permselectivity
β	permselectivity correction factor
$\gamma_\pm$	mean activity coefficient
δ_{HIGH}, δ_{LOW}	HIGH/LOW compartment thickness (m)
δ_m	membrane thickness (m)
δ_{tot}	total cell pair thickness (m)
ε	dielectric constant
ε_{sp}	spacer porosity
φ	osmotic coefficient
ϑ_{HIGH}, ϑ_{LOW}	polarisation coefficients
ΔC^*_{HIGH}	concentration drops in the diffusion boundary layer for the concentrated solution
ΔC^*_{LOW}	concentration drops in the diffusion boundary layer for dilute solution
ΔP	pressure drop (Pa)
$\Delta\Pi^*$	real osmotic pressure difference (Pa)
η	viscosity of solution (Pa s)
η_p	pump efficiency
υ	van't Hoff factor
Λ	equivalent conductivity ($S\,m^2\,mol^{-1}$)
Λ^0	equivalent conductivity at infinite dilution ($126.5 \times 10^{-4}\,S\,m^2\,mol^{-1}$)
$\bar{\Lambda}'_{HIGH,k}$ $\bar{\Lambda}'_{LOW,k}$	equivalent conductivity averaged between inlet-centre of kth channel
$\bar{\Lambda}''_{HIGH,k}$ $\bar{\Lambda}''_{LOW,k}$	equivalent conductivity averaged between centre-outlet of kth channel

Subscripts and superscripts

c	collector
cell	cell pair
d	distributor
ext	external circuit
LOW	dilute solution
HIGH	concentrated solution
bulk	bulk conditions
int	membrane–solution interface

Acronyms

AEM	anionic exchange membrane
CEM	cationic exchange membrane
IEM	ion exchange membrane
RE or RED	reverse electrodialysis
SGP	salinity gradient power
DBL	diffusion boundary layer
CFD	computational fluid dynamics

Please cite this article in press as: Tedesco, M., et al., A simulation tool for analysis and design of reverse electrodialysis using concentrated brines. Chem. Eng. Res. Des. (2014), http://dx.doi.org/10.1016/j.cherd.2014.05.009