Desalination 342 (2014) 61–69

Contents lists available at ScienceDirect

Desalination

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

Seawater predesalination with electrodialysis

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HIGHLIGHTS

- ED seems a suitable technique to predesalinate seawater.
- Electro-osmotic water transport is proportional to the applied current density.
- Stack resistance causes the main energy loss in an electrodialysis system.
- Applied current density >50 A/m^2 leads to minor back diffusion and water losses.
- Application of ED potentially leads to desalination energy reduction compared to SWRO.

ARTICLE INFO

Article history:
Received 28 March 2013
Received in revised form 17 June 2013
Accepted 16 July 2013
Available online 7 August 2013

Keywords:
Electrodialysis
Seawater desalination
Electro-osmosis
Osmosis
Coulombic efficiency

ABSTRACT

The suitability of ED for seawater desalination was investigated and we quantified the energy losses that play a role in electrodialysis. The combination of electrodialysis (ED) and brackish water reverse osmosis (BWRO) is presented as an alternative desalination strategy for seawater reverse osmosis (SWRO). Experiments have been performed with a recycling batch electrodialyzer. From this we conclude that in most cases the membrane stack is responsible for the main energy loss in the system. Energy losses due to water transport are generally low. At low applied current density, osmotic water transport is relatively large and as such the energy loss, while electroosmosis was found to be directly proportional to the applied current density. The relative energy loss caused by back diffusion was found to be only of minor importance for higher current densities and was only more pronounced at the lowest applied current density of 10 A/m^2. Combining ED with BWRO in a hybrid system does not lead to a reduction in energy consumption compared to ED as standalone technique, when the applied current density becomes lower than 50 A/m^2. At low applied current density (10 A/m^2) ED can perform desalination energetically cheaper at lower operational costs than SWRO.

1. Introduction

1.1. Hybrid seawater desalination with ED as first step

Of all water on earth 2.5–3.5% is fresh water, and only 0.3–0.8% of this fraction is available to us as liquid fresh surface water [1–3]. Due to uneven distribution of the freshwater sources and a growing world population freshwater sources have become scarce; 1.2 billion people live in areas of physical water scarcity and another 500 million people are approaching this situation [4]. Desalination techniques can supply fresh water, wherever salt or brackish water sources are available. By converting only a small fraction of the salty water sources into fresh water, already a significant contribution to solving the problem of water scarcity could be achieved [2].

Seawater desalination is often considered as too energy-consumptive and too expensive [5,6]. In 2011, Post et al. [5] wrote a paper about desalination costs of seawater reverse osmosis (SWRO) and several alternative hybrid desalination strategies. The combination of electrodialysis (ED) and brackish water reverse osmosis (BWRO) is presented as an alternative desalination strategy that could lead to a desalination cost reduction of about 0.15 €/m^3 dilute produced, compared to seawater reverse osmosis (SWRO). A benefit of ED is the possibility of adjusting the salt concentration of the water produced. Therefore ED can be used as a pre-desalination technique, reducing the salt concentration to a desired level. The limitations for ED and BWRO are respectively low conductivity at lower salt concentration for ED and high osmotic pressure at higher salt concentrations for BWRO. When ED–BWRO is used and after a certain degree of salt removal the internal resistance of the ED stack becomes high, brackish water reverse osmosis

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http://dx.doi.org/10.1016/j.desal.2013.07.012

Nomenclature

A	Membrane area (m^2)
a	Activity of an ion (−)
c	Concentration (mol/m^3)
D_w	Osmotic water transfer coefficient (m^2/s)
E_0	Reversible voltage (V)
E_{OCV}	Open circuit voltage (V)
E_{stack}	Membrane stack voltage (V)
F	Faraday constant (C/eq.)
I	Current (A)
j	Current density (A/m^2)
m	Osmotic water transport (mol)
N	Number of cell pairs (−)
n	Amount of ions (mol)
Q	Electric charge (C)
R	Gas constant (J/mol·K)
R	Resistance (Ω)
r	Water recovery factor (−)
T	Temperature (K)
t	Time (s)
t_w	Water transfer number (mol H_2O/F)
V	Volume (m^3)
W	Specific energy required (kWh/m^3 dilute)
z	Valence (eq/mol)

Greek letters

α	Membrane permselectivity (−)
α	Concentration ratio of feed and outlet dilute (−)
β	Concentration ratio of feed and outlet concentrate (−)
δ	Membrane thickness (m)
η	Coulombic efficiency (−)

Subscripts

c	Concentrate
d	Dilute
f	Feed
i	Ion
r	Reversible

(BWRO) can continue the desalination process at relatively low pressure [5].

ED has some other benefits over SWRO in seawater treatment. Compared to SWRO, ED requires only little pretreatment efforts [7] and relatively high water recoveries can be reached. Water recovery of an ED (reversal) system is not limited by pressure but depends mainly on the scaling potential of the concentrate [8,9]. Electrodialysis was successfully used at supersaturated solutions with divalent ions [10] which suggests that high water recoveries should be possible at desalination with seawater. For seawater desalination with ED water recoveries were reported from 50 to 60% [11,12], and it is expected that with ED reversal higher water recoveries can be obtained [9]. Another benefit is that ED does not need an energy conversion step (e.g. electrical to mechanical energy in the high pressure pumps), but electrical energy can be directly utilized, which makes ED also suitable to combine with renewable energy sources [13], even when the available energy input changes [14].

The proposed use of ED in a seawater desalination scheme is remarkable as it is generally accepted that ED is primarily suitable to desalinate brackish water, whereas SWRO is favourable over ED for seawater desalination [5,7,15–17].

1.2. Why ED is considered to be a brackish water treatment technique and unsuitable for seawater desalination

In ED, an electrical field is applied to migrate ions through feed water and ion-exchange membranes. Increasing the conductance of the feed water reduces the internal resistance against ion migration and therefore the energy consumption. This would make ED particularly energetically suitable for application on feed water with high salinity, like seawater [11,12,18] and RO concentrates [19]. In the literature it is mentioned that ED is less suitable to treat feed water with less than 400 mg/l dissolved solids, because of high energy requirements [14], suggesting high salinity application to be more favourable.

Below we present possible major reasons causing ED to be less suitable for seawater desalination. When applying ED to feed waters with increasing water salinity:

1. *The amount of ions to be transported increases.* In ED the amount of desalination energy is proportional to the ions removed [14,16,17], which indicates that ED is less suitable for desalination of high saline feed water. This contrasts with RO, in which the amount of water molecules to be transported for desalination is independent of the salinity of the feed water.
2. *The amount of water molecules that are co transported increases.* With the transport of ions also water will be transported and this influences the efficiency of the separation process. The efficiency losses due to water transport will increase to considerable levels at higher salinity of the feed water.
3. *The coulombic efficiency decreases.* According to [6] the reached separation at high salinity is rather low, which is due to low membrane selectivity at high external salt concentration and limited ion exchange capacity of the membranes which enhances concentration polarization phenomena. As a result, the ratio between electrical current and ionic current (the so-called coulombic efficiency) is low at high salinity.

The relative contribution of these three factors in reducing ED efficiency has not been quantified yet and was therefore the focus of the research reported here.

1.3. Objectives

With these three considerations in mind, we investigated the ED process with an experimental set-up as a seawater pre-desalination step. The ED process was analysed in terms of (i) ion transport, (ii) water transport, and (iii) back diffusion (and associated coulombic efficiency loss). This investigation was used to elucidate the contribution of the different processes in ED with respect to energy losses and how these are related to the applied current density. Another goal is to clarify the concentration range of the desalinated water where ED should be succeeded by BWRO when a hybrid ED–BWRO system [5] is used.

2. Materials and methods

2.1. Materials

The ED stack comprised ten repeating cells, each consisting of a cation exchange membrane (Neosepta CMS; Tokuyama Co., Japan) and an anion exchange membrane (Neosepta ACS; Tokuyama Co., Japan). These membranes are separated by silicone gaskets that form flow channels for alternating the concentrate and dilute. At the beginning of the stack one extra CEM membrane was placed in order to close the first cell (see Fig. 1). The area of each membrane was 104 cm^2. A squared electrode was placed on both sides of the membrane stack. As anode a titanium electrode (mesh 1.7, area 96.04 cm^2) with a mixed metal oxides coating (Magneto Special Anodes BV, The Netherlands) was used, and as cathode a titanium electrode (mesh 1.7, area 96.04 cm^2) with a 50 g/m^2 platinum coating was used (Magneto Special Anodes BV, The