Desalination 301 (2012) 10–25

Contents lists available at SciVerse ScienceDirect

Desalination

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

Ion-exchange membrane electrodialysis program and its application to multi-stage continuous saline water desalination

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ARTICLE INFO

Article history:
Received 25 March 2012
Received in revised form 31 May 2012
Accepted 6 June 2012
Available online 30 June 2012

Keywords:
Ion-exchange membrane
Multi-stage continuous electrodialysis
Saline water desalination
Computer simulation program
Mass transport
Limiting current density

ABSTRACT

The first part of this article describes the program of a one-stage continuous electrodialysis process operating at a constant current mode. The full continuous electrodialysis program is developed and explained definitely by arranging equations systematically with the following supplementary steps. For preventing scale formation in concentrating cells, salt solutions supplied to the desalting cells are also fed to the concentrating cells. Influence of temperature to the performance of the electrodialyzer is taken into account. Pressure drop in the electrodialyzer is evaluated by incorporating the functions of hydrodynamic diameters of desalting and concentrating cells and slots. An electric current screening effect of a spacer is determined by the volume ratio of spacer rods in a desalting and concentrating cell.

In the second part of this article, saline water is desalinated with the multi-stage electrodialysis program by operating the process at a constant concentration mode. Changing salt concentration of a feeding solution in each stage incrementally, the performances of the electrodialyzer such as; ion and solution flux across a membrane pair; cell voltage; current density; salt concentration in concentrating cells; energy consumption; water recovery; limiting current density; pressure drop in the cells and slots are computed in each stage. Energy consumption, water recovery, pressure drop and membrane area are computed in the total stages to produce drinking water.

1. Introduction

The electrodialysis process is classified to a sheet flow type operated with a one directional direct current (ED; Electrodialysis) and a tortuous flow type operated with a two directional direct current (EDR: Electrodialysis reversal). The ED is the basic process and it has been applied widely for saline water desalination [1–8]. The EDR was developed from ED for preventing organic fouling of the membranes [9] and it is also applied widely [10–14]. This article describes the performance of an electrodialyzer keeping the ED in mind. However, the basis of the discussion is applicable also to the EDR.

ED processes are classified to a continuous, a batch and a feed-and-bleed process. Among these processes, the continuous process is the most fundamental one and it is applied to a large-scale electrodialysis. The performance of the continuous process is discussed from various points so far [15–22].

In the previous investigation, the continuous, the batch and the feed-and bleed ED programs were developed and discussed the performance of saline water desalination processes [23–25]. From constant electric current mode program, the constant voltage mode program is easily developed [26]. The program was revised and applied to evaluate the performance of a seawater concentrating process [27]. The influence of temperature on the performance of an electrodialyzer was discussed [28]. The data obtained by computation were compared to the data observed by operating a practical-scale electrodialyzer for seawater concentration [29].

From the above investigations, the reasonability of the ED program is assumed to be generally demonstrated. The ED program consists of many steps describing many unit processes and it was established based on many fundamental principles and experiments. Precision of the program has been improved every time in the course of the program development. Consequently, the description of the ED program in the previous articles is assumed to become partially insufficient to obtain accurate data at present.

Based on the above improvement, the first part of this article describes the program of a one-stage continuous ED process operating at a constant current mode. The full continuous ED program is explained definitely by arranging equations systematically with supplementary explanations.

The one-stage ED program can be extended to the multi-stage process. In the second part of this article, saline water is desalinated with the multi-stage ED program by operating the process at a constant concentration mode. Changing the salt concentration of a feeding solution in each stage step by step, the performance of the electrodialyzer such as; ion and solution flux across a membrane

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doi:10.1016/j.desal.2012.06.007

pair; cell voltage; current density; salt concentration in concentrating cells; energy consumption; water recovery; limiting current density; pressure drop in desalting and concentrating cells and slots are computed to produce drinking water. Energy consumption, water recovery, pressure drop and membrane area are computed in the total stages.

2. Electrodialysis (ED) program

2.1. Specifications of an electrodialyzer and its operating conditions

(1) Flow-pass thickness in a desalting and a concentrating cell; a (cm)
(2) Flow-pass width in a desalting and a concentrating cell; b (cm)
(3) Flow-pass length in a desalting and a concentrating cell; l (cm)
(4) Membrane area; $S=bl$ (cm^2)
(5) Number of stacks in an electrodialyzer; 1
(6) Number of desalting cells, concentrating cells and membrane pairs integrated in a stack; N, $N+1$, N
(7) Probe electrodes are inserted into concentrating cells integrated at the ends of a stack for measuring cell voltage
(8) Average current density; I/S (A/cm^2)
(9) Salt concentration at the inlets of desalting cells; C'_{in} (eq/cm^3)
(10) Salt concentration at the inlets of concentrating cells; $C''_{in}=C'_{in}$ (eq/cm^3)
(11) Linear velocity at the inlets of desalting and concentrating cells; u'_{in}, u''_{in} (cm/s)
(12) Standard deviation of the normal distribution of solution velocity ratio; σ
(13) Flow system in desalting and concentrating cells; one-pass flow
(14) Diagonal net spacers are integrated in desalting and concentrating cells and in desalting and concentrating slots. Dimensions of a spacer are:

Diameter of a spacer rod d_S = half thickness of the cell $a/2$; Distance between the rods χ; Crossing angle of the rods θ.

(15) Number and dimension of the cells and slots in a cell pair are:

	Number	Thickness	Width	Length
Desalting cell	1	a	b	l
Concentrating cell	1	a	b	l
Desalting slot	n_{de}	a	w_{de}	h_{de}
Concentrating slot	n_{con}	a	w_{con}	h_{con}

Fig. 1 illustrates the desalting cell and concentrating cell.

2.2. Continuous ED process

Mass transport in an electrodialyzer is illustrated in Fig. 2. A salt solution (raw salt solution, concentration: C'_{in}) is supplied to the inlets of desalting cells (De) at average linear velocity of u'_{in}. For preventing scale formation in concentrating cells, a part of a raw salt solution is supplied also to the inlets of concentrating cells (Con) at the average linear velocity of u''_{in}. By supplying an electric current I, ions and solutions are transferred from desalting cells to concentrating cells across an ion-exchange membrane pair and their flux is defined by J_S and J_V respectively. In desalting (concentrating) cells, salt concentration is decreased (increased) from C'_{in} ($C''_{in}=C'_{in}$) under applied average current density I/S and

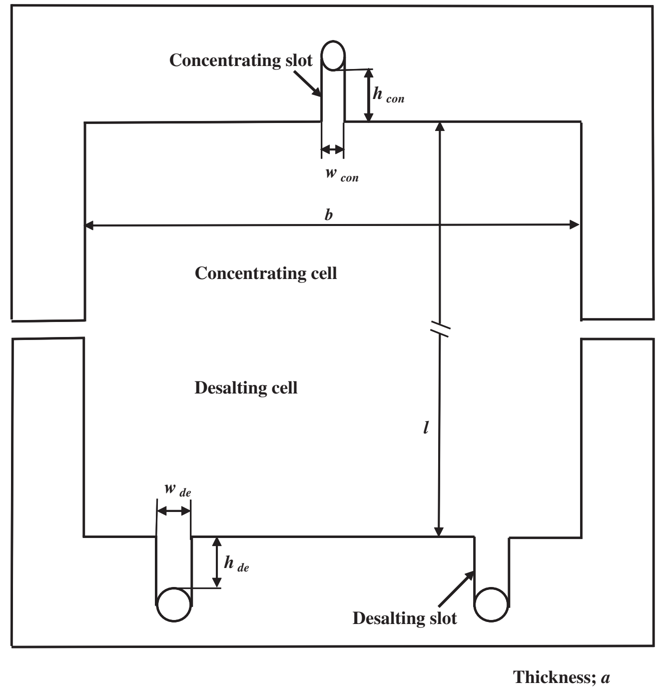

Fig. 1. Structure of a desalting cell and a concentrating cell.

reaches average salt concentration C'_{out} (C''_{out}) at the outlets of desalting (concentrating) cells. Salt concentration change in desalting cells causes current density change along the flow-pass from i_{in} at the inlets to i_{out} at the outlets. The current density becomes i at x distant from the inlets of desalting cells. I/S, J_S, J_V, C'_p, C''_p, u'_p and u''_p are altogether the values at $x=pl$ distant from the inlets of desalting and concentrating cells. V_{in}, V_{out} and V_p are voltage difference between electrodes respectively at the inlets ($x=0$), the outlets ($x=l$) and $x=pl$ of desalting cells ($V_{in}=V_p=V_{out}$).

2.3. Overall mass transport equation and membrane characteristics

Fluxes of ions J_S and a solution J_V across an ion exchange membrane pair at $x=pl$ distant from the inlets of desalting and concentrating cells are expressed by the following overall mass transport equation [30].

$$J_S = \lambda(I/S) - \mu\left(C''_p - C'_p\right) = (t_K + t_A - 1)(I/S)/F - \mu\left(C''_p - C'_p\right) = \eta(I/S)/F \quad (1)$$

$$J_V = \Phi(I/S) + \rho\left(C''_p - C'_p\right) \quad (2)$$

in which λ (eqC^{-1}) is the overall transport number, μ (cm s^{-1}) is the overall solute permeability, Φ (cm^{3}C^{-1}) is the overall electro-osmotic permeability and ρ (cm^{4}eq^{-1} s^{-1}) is the overall hydraulic permeability. t is the transport number of counter-ions in the membrane. η is current efficiency and F is the Faraday constant. ρ versus λ, μ and Φ plots are given by the following empirical equations.

$$\lambda = 9.208\times10^{-6} + 1.914\times10^{-5}\rho \quad (3)$$

$$\mu = 2.005\times10^{-4}\rho \quad (4)$$

$$\Phi = 3.768\times10^{-3}\rho^{0.2} - 1.019\times10^{-2}\rho \quad (5)$$