Desalination 342 (2014) 126–138

Contents lists available at ScienceDirect

Desalination

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

Development of a computer simulation program of feed-and-bleed ion-exchange membrane electrodialysis for saline water desalination

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HIGHLIGHTS

- Computer simulation program of a feed-and-bleed electrodialysis process is developed.
- Drinking water is produced in a one-stage or a two-stage process.
- Saline water is desalinated in the 1st stage and purified in the 2nd stage.
- Cell pair number in the two-stage process is reduced compared to that in the one-stage process.
- Energy consumption for ion transport and limiting cell voltage are equivalent in both-stage operations.

ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form 6 July 2013
Accepted 3 August 2013
Available online 14 September 2013

Keywords:
Ion-exchange membrane
Feed-and-bleed electrodialysis
Saline water desalination
Drinking water production
Computer simulation
Limiting current density

ABSTRACT

A computer simulation program is developed to predict the desalinating performance of a constant voltage feed-and-bleed electrodialysis process, inputting membrane characteristics, electrodialyzer specifications and electrodialytic conditions. A salt solution is supplied to a one-stage or a two-stage process to produce drinking water. Energy consumption for ion transport and limiting cell voltage in both processes are equivalent. In order to operate the two-stage process effectively, the cell pair number in the first stage should be the same to that in the second stage. Current density in the two-stage process becomes larger than that in the one-stage process because salt concentration in the first stage in the two-stage process is increased. Thus, the cell pair number integrated in the two-stage process is reduced compared to that in the one-stage process for producing the same amount of drinking water. Water recovery of the two-stage process is larger than that in the one-stage process because the cell pair number (thus solution feed to concentrating cells in the two-stage process) is reduced compared to that in the one-stage process.

1. Introduction

Electrodialysis operation is classified into (1) continuous (single-pass), (2) batch and (3) feed-and-bleed. In the continuous operation, a feeding solution flows from a feed source to an electrodialyzer and a desalted solution is produced continuously. In order to increase the desalting ratio, the continuous process is formed in multi-stages. In the batch operation, the desalted solution is recycled through a circulation tank and an electrodialyzer. The solution in the circulation tank is gradually desalted and finally taken out from the tank. The feed-and-bleed process is explained in detail in Section 2. The continuous operation is suitable for large-scale desalination, the batch operation is suitable for small-scale desalination, and the feed-and-bleed operation is suitable for small- and middle-scale desalination.

The reports on the feed-and-bleed operation found in literatures are relatively limited. The followings are the reports published after the 1990s.

Paleologou et al. produced sodium hydroxide and sulfuric acid from sodium sulphate [1], and produced sodium hydroxide and chloric acid from sodium chlorate [2]. The above systems were operated in a feed-and-bleed bipolar electrodialysis mode. Kawahara [3] reported the performance of a saline river water desalination plant (1200 m^3/day) that consisted of a three-stage and six-line feed-and-bleed system. The system is combined with an ion-exchange process to produce pure water. Thompson et al. [4] supplied white liquor to a feed-and-bleed electrodialysis system and concentrated sodium sulphide to maintain sulphur balance in the kraft process. They [5] separated sulphide from hydroxide in kraft white liquor in this system incorporated with monovalent-selective anion-exchange membranes to produce sulphide-rich white liquor. Rapp and Pfromm [6] removed chloride in a kraft pulping process with a feed-and-bleed operation incorporated with monovalent-selective anion-exchange membranes. Ryabtsev et al. [7] developed a two-stage feed-and-bleed set-up for desalination of underground saline

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http://dx.doi.org/10.1016/j.desal.2013.08.016

water. The first stage involves a galvanostatic regime at increased current density, and the second stage profound in a potentiostatic regime resulting in desalted water. Schoeman et al. [8] electrodialyzed an industrial solid waste leachate containing high concentrations of iron, manganese, barium, strontium and phenolics for effluent volume reduction and pollution control. Electrodialysis pilot tests were conducted in a feed-and-bleed mode unit to develop process design criteria for a full-scale application. TDS of the leachate could be reduced from 116,255 mg/l to 2435 mg/l (5 stage ED). Hajdukova et al. [9] electrodialyzed mine water for reducing the influence to surface water quality such as high concentration of dissolved solids, sulphates and chlorides. Electrodialysis tests were conducted in a feed-and-bleed mode.

Zhang et al. [10] electrodialyzed RO concentrate to improve water recovery in waste water reclamation in the feed-and-bleed mode. Ion transport mechanism was studied to monitor the effluent water composition and a factor named critical scaling concentration was established to predict the potential occurrence of scaling. Tran et al. [11] introduced a hybrid system consisting of a pellet reactor and a feed-and-bleed mode electrodialyzer for removing the scaling potential.

Glancing over the above reports, the investigations of the feed-and-bleed process seem to be directed to the process application and the fundamental investigations for discussing the process mechanism are lacking. In order to advance the feed-and-bleed technology, it is necessary to establish a computer simulation model and discuss the fundamental mechanism of the phenomena generating in the process.

In the previous investigation [12], the computer simulation program of the feed-and-bleed process was developed based on the fundamental studies. In the feed-and-bleed process, an electrodialyzer and a circulation tank are the main units working in the process. The function of the electrodialyzer is computed based on the continuous program [13] which is developed for analyzing the performance of the continuous operation with no circulation tank. The feed-and-bleed operation is carried out with the electrodialyzer and the circulation tank. The circulation tank is an effective working unit in the feed-and-bleed operation. The computer program of the feed-and-bleed operation consists of (1) the program which describes the function of the electrodialyzer (Section 3) and (2) the program which describes the function of the circulation tank (Section 4).

The continuous program [13] had been developed based on the program for seawater concentration [14]. The reliability of the program for seawater concentration was discussed by comparing the calculated data with experimental data [15] and industrial data [14,16]. The principle of seawater concentration is fundamentally equivalent to saline water desalination. Thus the continuous program developed in the seawater concentration process is applicable to saline water desalination (Section 3) by taking account of the difference between operating conditions in both processes. Functions of the circulation tank which are not included in seawater concentration are cleared based on the mass balance in the feed-and-bleed process in this article (Section 4).

The program must be applicable to discuss the performance of practical electrodialysis systems operating at every possible unit specification and operating condition. For realizing this target, the feed-and-bleed program presented in the previous article [12] is revised in the following parts in this article:

(1) Influence of temperature on physical properties of parameters and the performance of an electrodialyzer is taken into account.
(2) A temperature term is introduced into the limiting current density equation.
(3) Functions of the circulation tank are cleared.
(4) A raw solution is supplied to concentrating cells for preventing scale precipitation (In the previous paper [12], concentrating cells are not supplied with a raw solution. A concentrated solution is immediately extracted to the outside of the process).
(5) The multi-stage operation is discussed and drinking water is produced (In the previous paper [12], the performance of only a single-stage operation is discussed and drinking water production is not discussed).
(6) The electriccal current screening effect is determined by the volume ratio of spacer rods in the cells.

The performance of the feed-and-bleed process can be computed with a single computation with the stand alone software. Calculation is carried out in the spread sheet with a use of common software (Excel) and ordinary operating systems (Windows XP, etc.) during 15–25 min. There are no specific hardware requirements. The program is scheduled to be integrated into web sites [17]. So, readers can operate the program in the web sites (companion sites) by inputting the source code i.e. optional process specifications and operating conditions. The program aims to function as a pilot plant operation. The units in this paper are not unified and are mixed.

2. Feed-and-bleed process

A raw salt solution (salt concentration; C'_0) is assumed to be desalinated by the multi-stage feed-and-bleed electrodialysis process. The one-stage feed-and-bleed electrodialysis process (stage no. = 1) is illustrated in Fig. 1. The electrodialyzer is incorporated with desalting cells and concentrating cells in the stack marked with gray. The number of cells is N for desalting cells, $N + 1$ for concentrating cells and N for cell pairs. The anode and cathode cells are placed at both outsides of the stack and an electric current is supplied between the electrodes. The circulation tank is separated into compartment I and compartment II and the salt solution is supplied to the electrodialyzer through the circulation tank.

The raw salt solution (salt concentration; C^0, volume flow rate; Q^0) is supplied to compartment I in the circulation tank. It is further supplied to desalting cells in the electrodialyzer (C'_{in}, Q'_{in}). Linear velocity in the desalting cells is u'_{in} at the inlets and u'_{out} at the outlets. The solution flowing out from the desalting cells is returned to compartment II (C'_{out}, Q'_{out}). A part of the desalted solution (C'_{out}, Q''') is extracted from compartment II to the outside of the process. Another part of the desalted solution (C'_{out}, $Q_{move} = Q'_{in} - Q^0$) moves from compartment II to compartment I. The process is operated keeping $Q_{move} > 0$.

The raw salt solution is also supplied to concentrating cells in the electrodialyzer ($C^0 = C''_{in}$, Q''_{in}) for preventing scale formation in the cells. Linear velocity in the concentrating cells is u''_{in} at the inlets and u''_{out} at the outlets. A part of the solution extracted from the outlets of concentrating cells is further supplied to the electrode cells and the partition cells (Part), which are equipped for preventing the influence of electrode reactions to the performance of the electrodialyzer. Then, the solution is discharged to the outside of the process with the residual solution flowing out from the outlets of concentrating cells.

In this electrodialysis process, the following parameters are defined:

Flow-pass thickness in a desalting cell and a concentrating cell: a (cm)
Flow-pass width in a desalting cells and a concentrating cell: b (cm)
Flow-pass length of a desalting cell and a concentrating cell: l (cm)
Membrane area: $S = bl$ (cm^2)
Number of desalting cells: N
Number of concentrating cells: $N + 1$
Salt concentration of a raw solution: C^0 (mg dm^{-3})
Volume flow rate of a solution supplied to the circulation tank: Q^0 (cm^{3}s^{-1})
Salt concentration at the inlets and outlets of desalting cells: C'_{in}, C'_{out} (mg dm^{-3})
Salt concentration at the inlets and outlets of concentrating cells: $C''_{in} = C^0$, C''_{out} (mg dm^{-3})
Linear velocity at the inlets and outlets of desalting cells u'_{in}, u'_{out} (cm s^{-1})