Desalination 437 (2018) 133–143

Contents lists available at ScienceDirect

Desalination

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

Parameter-based performance evaluation and optimization of a capacitive deionization desalination process

Muhammad Wajid Saleem[a,b], Woo-Seung Kim[c,*]

[a] Department of Mechanical Design Engineering, Hanyang University, 55 Hanyangdaehak-ro-Sangnok-gu Ansan Kyeonggi-do, Republic of Korea
[b] Department of Mechanical Engineering, Institute of Space Technology, Islamabad, Pakistan
[c] Department of Mechanical Engineering, Hanyang University, 55 Hanyangdaehak-ro-Sangnok-gu Ansan Kyeonggi-do, 15588, Republic of Korea

ARTICLE INFO

Keywords:
Capacitive deionization
Water desalination
Performance evaluation
Performance optimization
Genetic algorithm

ABSTRACT

Capacitive deionization (CDI) is an emerging alternative desalination technology that electrochemically purifies brackish water using electrically polarized capacitive electrodes. This research focuses on the performance of the CDI system. A number of performance criteria were used to assess the desalination system based on the requirements. The performance of the CDI system was assessed in terms of lowest effluent water concentration during the deionization process (mM), specific energy consumption either per gram of salt adsorbed (kJ/g) or per liter of fresh water recovered (J/L), accumulated desalinated water concentration (ppm), salt ions adsorbed in electrodes (g), and the volume of freshwater recovered (L) for different operating parameters. Furthermore, the performance of the desalination system was optimized based on operating parameters of flow rate, applied voltage, cell volume, and capacitance of the CDI cell. Three optimization techniques were suggested according to desalination requirements. Single-objective and multi-objective genetic algorithms (GA) were used to optimize the performance of the CDI system subject to constrained decision variables. The feasible solution obtained through GA optimization showed significant improvement in CDI system performance. Furthermore, the optimized results suggest different optimal solutions based on specific needs, such as maximum salt ion adsorption, lowest desalination energy consumption, high volume of desalinated water, or purest water extracted.

1. Introduction

The world's population has increased to 7.5 billion and is estimated to be over 8 billion by the end of 2025 [1]. Consequently, there is an ongoing need of fresh water for domestic, industrial, and agricultural use. In an article in Fortune magazine, Shawn Tully wrote that “water will be the oil of this century” [2]. Continents like Asia and Africa have large populations but relatively little water [3,4]. Furthermore, a major portion of available water in developing countries is used for agricultural purposes instead of human consumption [3,4]. Thus, it is the requirement of current time and one of the future priorities to produce fresh water for the world's population [3,5]. Around 98% of available resources of water are either sea water or brackish water [3]. Therefore, one option to fulfill the world's water requirement is to desalinate sea and brackish water. Various desalination technologies have been developed for this purpose.

Existing desalination process are generally grouped based on their principle of operation such as thermal, membrane, and electrical desalination process [3,6]. Thermal desalination is considered the oldest and first commercially viable process due to its ability to integrate with dual-purpose cogeneration facilities [7]. Three major thermal desalination processes are multistage flash distillation (MSF), multiple effect distillation (MED), and vapor compression (VC) [8]. However, a drawback of the distillation methods is the requirement of high evaporation energy. Membrane-based desalination processes are currently the most commonly used processes [3,9]. The two major desalination processes are reverse osmosis (RO) and membrane distillation (MD) [3]. Due to high energy consumption, these membrane-based processes are good for high salinity feed water [10]. For low salinity feed water, electrical desalination is an alternative process [11]. As the name depict, an electrical desalination method is based on the application of electrical potential. An electric field is developed to extract salt ions from the inlet feed solution and produce deionized water as a desalination product [12]. Two fundamentally different methods used for electrical desalination are capacitive deionization (CDI) and electrodialysis (ED) [13].

CDI is a promising and economical desalination method. Since no chemical is utilized for the process, and electrodes are less fouled compared to membranes. Little maintenance is required compared to other desalination technologies, electrodes are stable for number of CDI

---

[*] Corresponding author.
E-mail addresses: engr.wajidsaleem@gmail.com (M.W. Saleem), wskim@hanyang.ac.kr (W.-S. Kim).

https://doi.org/10.1016/j.desal.2018.02.023
Received 24 July 2017; Received in revised form 21 February 2018; Accepted 22 February 2018

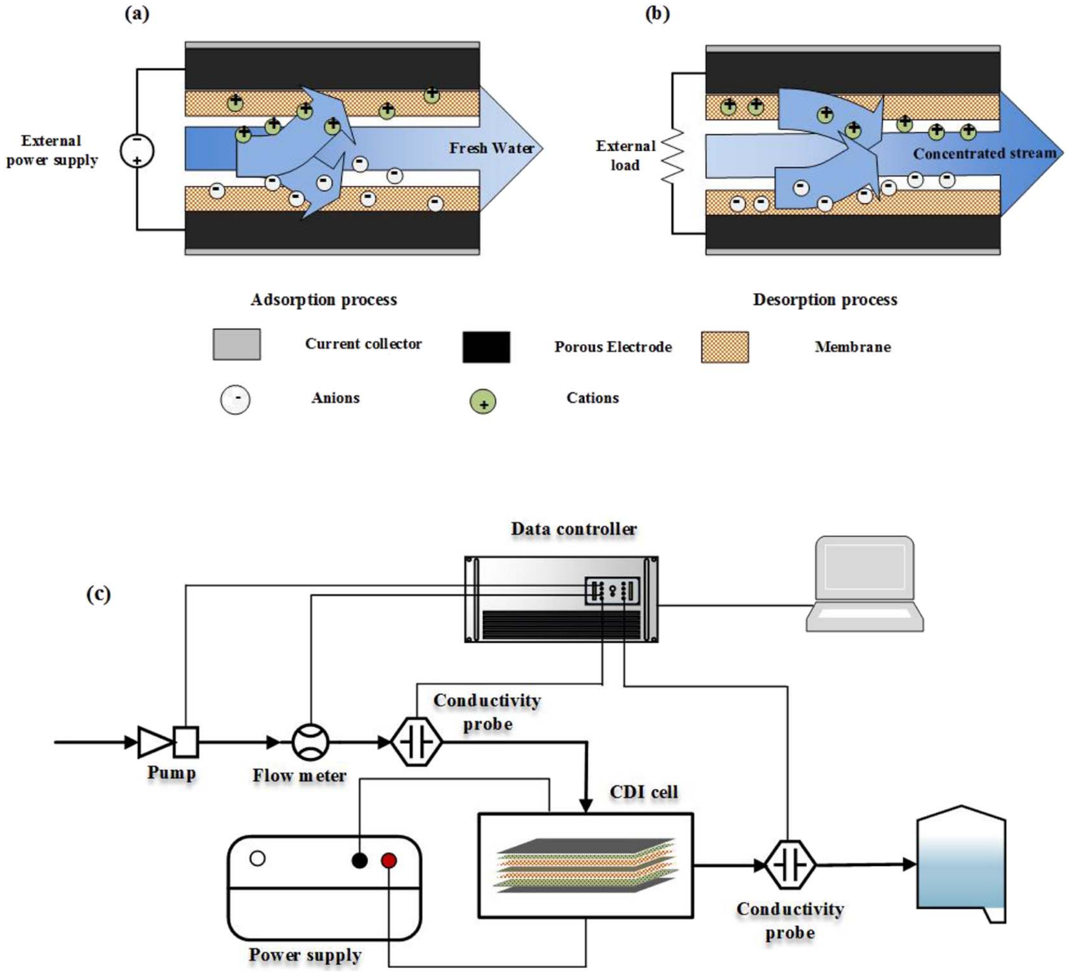

Fig. 1. Schematic of a CDI cell. (a) Adsorption process, (b) desorption process, and (c) process flow diagram.

cycles, and almost 20% to 80% of supplied energy can be recovered, depending on the operating conditions [6,11,14–16]. In the CDI desalination process, brackish water is deionized through electrically polarized capacitive electrodes. The capacitive electrodes adsorb charged ions from the inlet feed stream during the adsorption process of CDI and produce fresh water at the outlet of the cell (Fig. 1a). The adsorbed ions in charged electrodes then desorbed in the next process and produced a concentrated effluent stream during the desorption process of CDI (Fig. 1b). Two operating processes are used based on the power supplied to the CDI system: constant voltage (CV) and constant current (CC). As the name suggests, constant voltage is used as an external power source in a CV process to charge the capacitive electrodes for ion adsorption. Similarly, constant current is used for a CC process to deionize the inlet feed water [17]. The two processes have different desalination responses and are used according to the system requirements [18,19]. Fig. 1c illustrates a schematic diagram of a CDI desalination process.

Since, CDI desalination process has been already developed. Thus, current focus is to decrease its energy consumption and enhance system performance in order to make the CDI system more efficient and commercially feasible for water desalination. In general, performance of the CDI desalination system is improved in two ways: either improve the properties of the capacitive electrodes or modify the operating process of the deionization system. However, performance improvement of the CDI system occurs mainly by improving the electrode's properties like capacitance, BET surface area, electro-sorption, conductance of electrodes, and pore size for high salt removal during the desalination process in CDI [12,13]. Therefore, different strategies were employed in literature to improve the electro-sorption capacity and kinetics of CDI electrodes, such as: preparation of composite materials to improve the capacitance of electrodes [20,21]; addition of carbon black (CB) to improve the conductivity; addition of NaCl during the electrodes preparation to improve the electrolyte permeability into the electrodes with increasing macro-porosity in the electrodes; optimization of electrodes thickness to improve the deionization process [22]; reduction of binder ratio in electrodes preparation to minimize blockage of pores for ions flow in electrodes [23–25]; and the usage of different materials for electrodes preparation in order to improve the energy efficiency and cost efficiency of the system to make it competitive with other commercially available desalination technologies.

Moreover, for process modifications, different techniques were employed in literature, to improve the performance of CDI [13,26]. Various mathematical models are developed to predict the CDI cell performance, such as P.M. Biesheuvel et al., [27] formulated a CDI mathematical model based on Gouy-Chapman-Stern (GCS) model for electronic double layer (EDL) materials and compared the results with electric current and effluent ion concentration experimental data. R. Zhao et al. [17] explained the concept of constant current in CDI process and its energy consumption. Furthermore, for performance improvement based on process design modification, O.N. Demirer et al., [6] presented the operational conditions to switch adsorption and desorption process in CDI cycle to improve the CDI system's thermodynamic efficiency and average adsorption rate. Ion exchange membrane in front of porous electrode was added to improve the performance of CDI cell in terms of salt removal and charge efficiency [13,28–31]. P. Dlugolecki et al. [15] and J. Kang et al. [16] explained