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Combined reverse osmosis and constant-current operated capacitive deionization system for seawater desalination

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HIGHLIGHTS

- RO & constant current operated CDI are integrated for seawater desalination.
- High-quality ultrapure water (UPW) & potable water were produced by the same system.
- The UPW produced has total dissolved (TDS) salts less than 0.034 ppm (>18 MΩ cm).
- The produced potable water has TDS < 400 ppm.
- More than 38% of the total water produced is UPW.

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ABSTRACT

There is an increase in the use of water purification technologies to produce the purified water from saline water. The desalination process may either involve the use of a single desalination technology, or may include the utilization of multiple desalination methods. In this study, reverse osmosis (RO) is integrated with the constant-current operated capacitive deionization (CCOCD) to desalinate seawater into high-quality ultrapure water, in addition to producing fresh water from the same system. For systems with the same feed concentration and feed flow rates, the RO–CCOCD hybrid system is superior to the RO–CVOCD (CVOCD is the constant voltage operated capacitive deionization) system. The advantages of RO–CCOCD over RO–CVOCD include a longer adsorption time for CDI cells with the same capacitance and spacer volume/dead volume as that of CVOCD, and increased quality of ultrapure water (>18 MΩ cm) along-with its production. The specific energy consumption for the production of desalted water is generally the same for RO–CCOCD and RO–CVOCD given the same feed concentration and feed flow rate.

1. Introduction

The demand for fresh water is increasing worldwide due to the increase in population and existence of drought in some parts of the world. According to the World Health Organization, fresh water should have a total dissolved salts level of less than 500 ppm to be safe for consumption by humans [1]. There are not enough direct sources of clean water such as rivers, lakes, and underground water to meet the daily consumption needs [2]. Alternative water purification technologies have been developed to desalt saline water from sources like seawater, underground water, and industrial wastewater to a desired water quality level. The purpose of desalination is the separation of salt from saline water. There are many commercial/industrial desalination processes. Desalination technologies may include those which are thermally [3–5], electrochemically [6–8], and membrane based [9–11].

The dominant commercial desalination technologies include reverse osmosis (RO), multi-stage flash distillation (MSF), and multiple-effect distillation (MED). In the year 1999 approximately 78% of the world's water desalination was comprised of MSF and 10% RO. Improvements in RO have led to lower cost water production and altered these statistics considerably. The overall capacity of installed desalination systems has also increased from 61 million m^3/day in 2008, to 66.4 million m^3/day in 2012 and over half of the total desalination in the world comprised of RO since the year 2008, and is rapidly nearing two thirds of the desalination market [12,13]. A comparative analysis of the energy consumption requirements of major desalination technologies is presented in Table 1. As shown, the economic desalination by RO is a significant reason leading to its rapid expansion.

In addition to the conventional desalination technologies, a hybrid desalination system may also be considered. A hybrid desalination system is in fact the combination of two or more desalination processes or its coupling with a power plant. Ample research is available regarding the combination of RO and thermal desalination technologies [14–18].

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Table 1
Energy (electrical/thermal) used by various desalination technologies [13].

Desalination technology	Electrical energy kWh/m^3	Thermal energy kWh/m^3	Total energy kWh/m^3
MSF	2.5–4	7.5–12	10–16
MED	1.5–2	4–7	5.5–9
RO (seawater)	3–4[a]	None	3–4
RO (brackish water)	0.5–2.5	None	0.5–2.5

[a] Including energy recovery system.

In addition to thermal technologies RO can also be combined to various other desalination technologies such as electrodialysis, ultrafiltration, and capacitive deionization (CDI) [19–23]. It is imperative to explore new horizons for hybrid desalination technologies, and to develop a rigorous methodology representing such systems.

The nature of the intended water usage dictates the permitted amount of ions in the desalted water. The microelectronics/semiconductor manufacturing industry requires deionized water containing negligible ionic, organic, and particulate contaminants [24]. Other applications such as laboratory instrumentation, laser cutting, and pharmaceuticals may require deionized water of slightly lower quality [23]. Various methods are used to produce ultrapure water (UPW) such as electrodeionization [24–27], membrane-capacitive deionization [28], and electrodialysis [29]. Recently, the use of hybrid RO and CDI to produce UPW and freshwater from seawater has been reported in Ref. [23], where a constant voltage is applied to operate the CDI cell.

The aim of this work is the exploration and assessment of a flexible hybrid desalination technology that is able to operate with different feed salinities, produce water of desired purity, and consume less energy; all while increasing UPW recovery. The use of constant current operated CDI (CCOCD) in combination with RO is investigated for the production of high-quality UPW and freshwater from seawater. The performance of the RO–CCOCD system is compared with the hybrid RO–constant voltage operated CDI (CVOCD) system. The performance of the system is judged in respect to the amount of UPW produced, the quality of the produced water, the energy consumption, and the cycle time. Cycle time in this study refers to the total time that a CDI cell has to undergo charging and discharging during operation [30–32].

2. Methodology

2.1. Reverse osmosis

The RO simulation of seawater desalination is explained in a previous work [23]. The calculation for the specific energy consumption (SEC) and energy recovery using an energy recovery device (ERD) is summarized below for RO:The energy consumption (SEC_{RO}) in RO can be calculated as follows:

$$\mathrm{SEC}_{RO} = \frac{\dot{W}}{Q_p}, \tag{1}$$

where Q_p is the permeate flow rate. The pump power consumption $\dot{W}$ can be calculated using

$$\dot{W} = \frac{Q_f \Delta P}{\eta_p} \tag{2}$$

where Q_f is the feed flow rate, ΔP is the pressure difference between the pump suction and discharge, and η_p is the pump efficiency. The power recovered by the energy recovery device (PR_{ERD}) is

$$PR_{ERD} = (\Delta P^*) Q_{f_{ERD}} \eta_{ERD}, \tag{3}$$

where the pressure difference between the streams entering and leaving the ERD is ΔP^*, the water flow rate through the ERD is $Q_{f_{ERD}} = Q_f - Q_p$, and η_{ERD} is the ERD efficiency. The pressure of the stream leaving the ERD was assumed to be equal to the atmospheric pressure.

The net power (NPC_{RO}), and net SEC (SEC_{RO-net}) consumed in RO can be calculated as

$$\begin{aligned} NPC_{RO} &= \dot{W} - ERD_p \\ SEC_{RO-net} &= \left(\frac{NPC_{RO}}{Q_p}\right). \end{aligned} \tag{4}$$

2.2. Capacitive deionization

The model used in this study for the constant current operated CDI cell is reported by Jande and Kim [33]. In this model, the steady state condition during charging is defined as

$$C_{alowest} = c_f - \frac{\lambda I}{zF\phi}, \tag{5}$$

where c_f is the feed concentration, I is the applied constant current, F is Faraday's constant (96,540 C/mol), ϕ is the flow rate, and z is the average valence. The differential charge efficiency, λ, is assumed to be one, which is justified by considering either using proper electrostatically redesigned electrodes [34] or using good charge barrier membranes [35–37]. The use of ion exchange membranes (charge barrier membranes) enables selectivity of ions, for example only negative ions pass through the membrane to the positively charged electrode from the saline water stream. The same results can be achieved if the electrodes are properly electrostatically redesigned; implying that functional groups such as anionic or cationic are contained within the pore volume (mesopores and micropores) of the electrode material causing the polarized electrode to be selective to the salt ions; please refer to the patent of Andelman [34] for more details. The ion selectivity increases the ratio of adsorbed ions to the electronic charge–charge efficiency. The constant current is chosen in such a way that the steady-state concentration approaches a zero value.

The CDI cell charging time is

$$t_a = \frac{CV_t}{I}, \tag{6}$$

where C is the capacitance and V_t is the target voltage. New electrode materials are developed so as to have better desalination performance of the CDI cell [38–44]. The electrodes made of carbon nanotube and reduced graphene oxide composite are found to have the specific capacitance of 311 F/g [43] and the one produced from $\mathrm{MnO_2}$/nanoporous carbon composite has the specific capacitance of 204.7 F/g [44]; these values are higher than those of the conventional activated carbon materials. The energy stored by the cell during charging is determined using the formula

$$E = \frac{1}{2} nCV_t^2, \tag{7}$$

where n is the number of electrode pairs used by the CDI cell. Dividing the stored energy by the charging time, the amount of power can be computed. The average concentration of the pooled purified water is computed by finding the average area under the CDI cell dynamic response curve at a given time interval [23,33].

2.3. Integrated RO–CDI system

The use of an integrated RO–CVOCD system for the production of ultrapure water and fresh water from seawater is reported in a recent work [23]. In the present work the RO–CCOCD system is studied further to understand the different aspects of the integrated RO–CDI system. A schematic of the integrated RO–CDI system is presented in Fig. 1.