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Application of Capacitive Deionisation in water desalination: A review

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HIGHLIGHTS

- We review 180 years of breakthroughs and research in Capacitive Deionisation (CDI).
- The critical deficiency in CDI is the need of low cost/high efficiency electrodes.
- The CDI complex electrosorption process requires a comprehensive and robust model.
- No comprehensive environmental assessment is done yet for CDI.
- The CDI field lacks long term reliability and operation, pilot scale demonstration.

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ABSTRACT

This manuscript spans over 180 years of ideas, discoveries, inventions, breakthroughs and research in Capacitive Deionisation (CDI) and Membrane CDI (MCDI) desalination. Starting with the first discovery of the dissociation of ions in solution under an electric field by M. Faraday (1833), through the pioneering work of carbon aerogel flow through capacitors by J. Farmer's group (1996) at Lawrence Livermore National Laboratory (LLNL), to the utilization of novel graphene and carbon nanotube (CNT) materials as electrodes, the CDI and MCDI technologies are progressively making its path to the desalination industry. Through this review various deficiencies of this technology have been identified, first and far most was the need for low cost and efficient electrode materials. The review identified that a low cost and high efficiency electrode capable of processing high salinity (seawater) stream still does not exists and is considered important if the technology is to make it to the industry. Furthermore, the lack of long term reliability, operation demonstrations and experience meant that information about scaling and fouling are rather scarce. Taking a step further, no comprehensive environmental assessment such as Life Cycle Assessment (LCA) or Environmental Impact Assessment (EIA) has been performed yet.

Contents

Abbreviations: ACF, Activate Carbon Fiber; AC, Activated Carbon; AMC, Activated Mesoporous Carbon; AEM, Anion-Exchange Membrane; BET, Brunauer–Emmett–Teller; CDI, Capacitive Deionisation; CDT, Capacitive Deionisation Technology; CDC, Carbide Derived Carbon; CA, Carbon Aerogel; CC, Carbon Cloth; CNF, Carbon Nanofiber; CNT, Carbon Nanotube; CEM, Cation-Exchange Membrane; DWNT, Double Walled Nanotubes; ED, Electrodialysis; EDR, Electrodialysis Reversal; EIA, Environmental Impact Assessment; FO, Forward Osmosis; GO, Graphite Oxide; LLNL, Lawrence Livermore National Laboratory; LCA, Life Cycle Assessment; MCDI, Membrane Capacitive Deionisation; MC, Mesoporous Carbon; MED, Multi-Effect Distillation; MSF, Multi-Stage Flash; OMC, Ordered Mesoporous Carbon; ppm, Parts Per Million; RF, Resorcinol Formaldehyde; RED, Reverse Electrodialysis; RO, Reverse Osmosis; SWNT, Single Walled Nanotubes; VC, Vapor Compression; WHO, World Health Organisation.

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1. Introduction

There is no doubt that the global water shortage has led mankind to energy intensive water extraction and treatment methods such as desalination. Brackish water and seawater desalination is one of the key strategic solutions to the ever increasing global water demand and ever decreasing natural fresh water resources due to climate change and unsustainable industrial depletion of natural fresh water resources. Safe, simple, low cost and high capacity and recovery desalination technologies have always been the goal for scientists and engineers. Today Reverse Osmosis (RO) membrane desalination, Electrodialysis (ED), Multi-Effect Distillation (MED) desalination and Multi-Stage Flash (MSF) desalination are by far the dominating technologies that are delivering fresh water to millions of people around the World. Alternative less energy intensive technologies have always existed but never made it to industrial deployment due to deficiencies in cost and salinity limits, one of these technologies is Capacitive Deionisation (CDI) and Membrane CDI (MCDI).

Seawater and brackish water desalination have emerged to become the strategic supply of water for many countries around the globe and for the Arabian Gulf countries in particular. Through the past decades technological advancement in MSF, MED and RO in particular commenced with great improvement in desalination cost reduction and increased flux and selectivity with reduced fouling. Consequently the MSF, MED and RO technologies became the most widely used large scale desalination techniques worldwide, while other technologies ceased to compete due to deficiencies in cost, efficiency, scalability and salinity. Currently the dominating desalination technology by capacity is RO (Fig. 1) with a share of 64% followed by MSF and MED with a share of 23% and 8% respectively. The technology with the lowest global desalination capacity is ED (4%) and CDI doesn't even come into the picture here because it hasn't made it to full industrial scale yet. This shows that CDI requires significant development to be a competing and viable desalination technology with respect to the well-established technologies RO, MED and MSF. This is a review on the potentials of the CDI process and the developments this technology has undergone since its early development stages to the most recent advancements.

The main factors hindering the CDI process from competing with RO, MED and MSF are scalability, salinity, electrode efficiencies and cost effectiveness [1,2]. One of the largest and most comprehensive tests using the CDI technology (termed capacitive deionization technology, CDT) was performed by T. J. Welgemoed and C.F. Schutte [3] where they demonstrated a 3785 m^3/day CDI desalination unit. Typical RO desalination plants have desalination capacities on the order of 100,000 m^3/day. Considering cost and salinity limits, their study also showed that CDI can be cost effective against RO at low salinities. Furthermore, CDI can only compete at higher salinities only if there is significant enough reduction in capital cost. Their results showed that for the case of 2000 parts per million (ppm) feed solution, the desalination cost for RO was 0.35 \$/m^3 while that for CDI was 0.11 \$/m^3. In water softening application, CDI has proven the ability to remove 85% of divalent ions [4]. In the pharmaceutical industry, CDI has proven to be a good separation technique for the purification of insulin [5]. Microbial fuel cells have also been integrated with CDI units as power sources for very low salinity feed [6,7]. Lab scale demonstrations have shown that in general the CDI technology can assist in several separation processes [8–10]. Although successful implementation of the CDI technology in the seawater desalination has not been achieved yet, CDI has already found its place in the brackish water desalination industry. One of the very few manufacturers of CDI systems is Voltea, which had announced the commercialization of a CDI technology back in 2012 [11] and released this as the CapDI technology.

CDI desalination technology [13] is a member of the family of electricity based desalination techniques also consisting from MCDI [14–16], ED [17,18], EDI [19,20] and electrodialysis reversal (EDR) [21]. The concept of CDI stems from the two words capacitive and

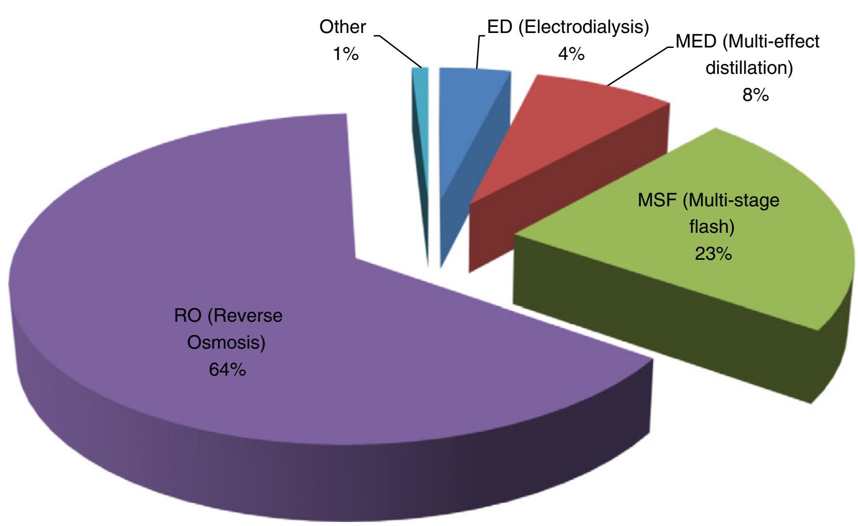

Fig. 1. Global desalination technologies share by capacity, adapted from Ref. [12].