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Review

Membrane-based zero liquid discharge: Myth or reality?

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ABSTRACT

The environmental impacts of brine disposal from seawater desalination plants and wastewater treatment plants represent a subject of growing concern; thus, determining the potential applicability of zero liquid discharge (ZLD) for water treatment is crucial. Membrane-based technologies are a potentially attractive strategy that can be used to reach this goal. Recent studies have highlighted that integrating a series of membrane processes is a viable approach to achieving ZLD for industrial use. However, a relatively limited number of reports have been published on the challenging problems encountered with ZLD approaches. Here, we provide a review of membrane processes that may be used in ZLD approaches and describe their problems as well as potential solutions and innovative technologies for improving their performance. Furthermore, the energy consumption of the different approaches is calculated and analyzed because it represents a major contributor to the total cost, and investments in innovative technologies are discussed. Finally, the prospects for membrane-based ZLD and further research are highlighted.

1. Introduction

With population growth and industrial development, more than 4 billion people face severe water scarcity worldwide; thus, potable water production is becoming an increasingly global issue [1]. The global water scarcity is estimated to increase because of climate change and other factors [2]. Desalination represents a major source of drinking water in arid regions, and reverse osmosis (RO) has been applied extensively. At the end of 2015, global desalination plants were producing 86.55 million m^3/day, and approximately 65% of the product water was from seawater RO (SWRO) [3,4], which presents a water recovery rate below 50%, with the remainder composed of reject brine [5]. Because desalination processes produce a huge amount of reject brine, several methods have been used to manage this brine. These methods mainly depend on the location of the desalination site and include direct discharge to surface water or wastewater treatment facilities, deposition in land disposals, and injection in deep wells [6,7].

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Inland brackish water desalination is more likely to be a critical water source for areas far from the sea, where the disposal of the concentrate to the sea is economically prohibitive [8]. Brine discharged from seawater desalination plants has been reported to have an adverse impact on the environment, including aquatic environments [9], soil and groundwater [7]. Thus, the zero liquid discharge (ZLD) approach was introduced to recover a large amount of water from the reject brine, reduce impacts on the planet and achieve sustainability [10].

In addition to desalination, many industries have begun implementing ZLD approaches, such as oil sands and mining. The wastewater treatment processes in these industries must operate under a policy of ZLD because the water used to extract bitumen from oil sands has a high content of inorganic species, which causes environmental concern [11,12]. The textile industry is another major modern industry, and its disposal streams are tremendous and pose a severe threat to the environment, especially to aquatic life because of the content of the wastewater, which includes azo functional groups [13,14]. The lack of recovery of a huge amount of chemicals in these streams including dyes and salts also leads to the loss of valuable products [15,16]. In addition, the cost of incinerating the final concentrate from membrane systems is a

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major investment depending on the type of incineration process [17]. Based on sustainability, ZLD solutions, including salt reuse, dye recovery [18], and water recycling, have been introduced to address these problems. For example, in oil palm production processes [19], water and energy consumption can be reduced by 95% and 80%, respectively, by scaling up the water recycling processes [20]. These systems could also produce additional economic incentives based on the income from the sale of the salts, and they could also mitigate the environmental issues resulting from the disposal of reject brine.

This study intends to provide an overview of ZLD approaches by integrating different membrane processes that have been introduced thus far. The pros and cons of the membrane units applied in the different approaches are described, including fouling, the feed characteristics, and the scale-up potential. Moreover, the energy consumption of each membrane process used in the ZLD solution are presented and analyzed. In addition, measures for addressing the identified problems and future prospects will be depicted.

2. Development of zero liquid discharge processes

The early ZLD processes were developed in order to treat river water with high salinity for power generation in the 1970s, and during this period thermal-based technologies dominated the ZLD system, such as brine concentrators, crystallizers, spray dryers and solar ponds [21]. In general, conventional evaporative ZLD plants begin with pretreatment steps to remove potential scalants. Thermal brine concentrators are then employed for water recovery. Eventually, the effluent is conveyed to evaporation ponds or crystallizers to produce waste solids or product solids [22].

However, in many cases, mechanical/thermal evaporation is economically prohibitive despite the ability to operate associated devices via green energy, such as solar evaporation [23] and wind-aided intensified evaporation [24]. For example, although evaporation ponds represent a cost-effective option, they still require large land areas and high evaporation rates [25], and they present a severe risk of wastewater leakage into groundwater, which can have a devastating impact on the environment [21]. In addition, during mechanical evaporation processes, scale and corrosion may form on the evaporator surfaces, and their removal requires the application of expensive metals, such as stainless steel or alloys, which results in high costs of construction and installation [26].

2.1. Membrane-based zero liquid discharge processes

RO systems had been utilized to incorporate with thermal-based technologies in conventional ZLD processing so as to reduce the volume of brine for few decades with benefits of its high efficiency and lower energy consumption compared to thermal brine concentrators. However, RO presents water recovery of only 70%, typically based on high-salt concentrate solution of about 75,000 mg/L because of fouling and insufficient driving force (hydraulic pressure) [27]. Thus, RO process is generally followed by thermal technologies in ZLD systems [22]. Based on the need for ZLD and the disadvantages of recent ZLD processes, including restrictions of high salinity of RO operation and high energy consumption of thermal processing, alternative methods must be developed to enhance concentrate management. Some membrane techniques represent a viable option for use as the major unit in ZLD systems.

Currently, some emerging alternative ZLD technologies that are membrane-based have been proposed and integrated with thermal processes after RO steps or before that for removing selectively specific salts in order to achieve ZLD. These membrane units that

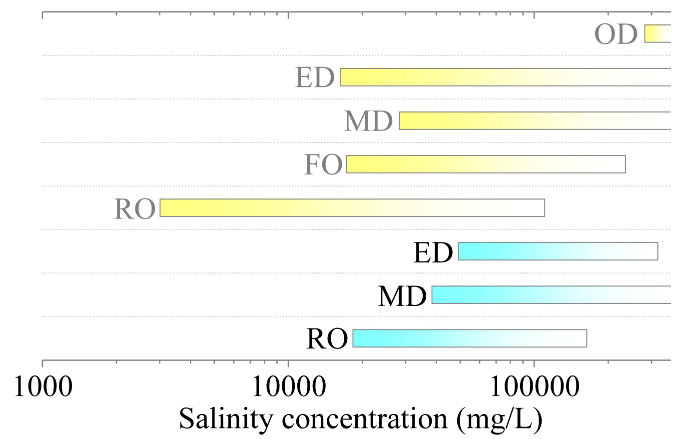

Fig. 1. Different membrane processes for membrane-based zero liquid discharge approaches for desalination plants (yellow bar) and wastewater treatment (blue bar) at their operating salinity concentration (mg/L) [8,17,18,30,33,35–47]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

offer high-salinity solutions, such as electrodialysis (ED), membrane distillation (MD) and forward osmosis (FO), can be used. Thermal methods can be subsequently employed to reduce the brine disposal via the formation of a slurry, and solid-like conventional thermal crystallization units such as salt brine capillary crystallization, which combines the sustainable energy of the sun and wind to evaporate discharged brine [28,29], and eutectic freeze crystallization, which separates ice and salt by density differences [30,31], as well as membrane-based crystallization systems like membrane crystallization (MCr) can also be used.

The current membrane-based technologies applied for ZLD achievement from desalination brine and wastewater at different salt concentrations are shown in Fig. 1. RO is operated for the treatment of feeds with salt concentrations of less than 17,000 mg/L because of issues related to osmotic pressure and fouling, whereas ED is used for salt concentrations of approximately 16,000 to just under 400,000 mg/L. Similarly, FO is a viable method of treating feed water that contains approximately 218,000 mg per liter, whereas MD, including MCr, has a wide operating range and can treat a salinity between below 40,000 mg/L and >350,000 mg/L. Osmosis distillation (OD) is commonly utilized in food industries [32] to treat high-salinity water (more than 28,000 mg/L) [33,34], and also used as a membrane crystallizer for salt recovery [35]. The membrane processes depicted in the figure for the ZLD approaches are listed in Table 1 with citations, and they are described below. A comparison of the different configurations of membrane-based ZLD systems is shown in Fig. 2. In general, at the beginning of the ZLD processes, the feed is processed through a pretreatment system, such as sedimentation, flocculation or microfiltration, to remove micro-sized suspended solids. Then, the water is passed through NF, RO, FO, ED or MD systems. To reach the concentration limit of the treatment process, the concentrate is directly pumped to an evaporator/crystallizer or to an MD, MCr, OD or ED system, and it is then transferred to a crystallizer to achieve ZLD. Different membrane processes and their practical applications for membrane-based ZLD approaches will be introduced in the following sections.

2.2. Pressure-driven membrane processes

2.2.1. Reverse osmosis and nanofiltration

RO is a pressure-driven membrane process that rejects dissolved constituents in feed water using a semi-permeable membrane based on the size, charge and physical-chemical interactions