Environmental Impact Assessment of Desalination Plants in the Gulf Region

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Abstract

Currently, desalination plants are essential tools for utilizing water from various natural resources like brackish water and seawater. Worldwide, the number of desalination facilities is rising to fulfill the increased requirement for potable water to be utilized for human consumption, public services, and industrial activities. There exist three principle methods of desalination: thermal, electrical, and pressure. Conversely, the brine released will have several negative effects on the surroundings. The current study aimed to give a general awareness into the present progress in the desalination processes through investigating the various available technologies. Different brine disposal approaches are analyzed as well as compared. We have also compared the different technologies based on energy consumption and water production costs. Moreover, we examine the zero liquid discharge (ZLD) technique, its challenges, advantages, operating as well as environmental characteristics, and the up-to-date research progress in this area. In the end, we have briefly analyzed the upcoming research and development approaches for brine management. It was found that this ZLD process is extremely beneficial to the environment with respect to decreasing the pollution caused by the discharged brine and attaining sustainability. Additional pilot or field studies are necessary for validating their commercial-scale performance as well as feasibility in practicing ZLD.

Keywords

Zero liquid discharge (ZLD) approach • Brine disposal strategies • Thermal technologies • Membrane technologies • Seawater desalination

1 Introduction

With the rising world population and the industrial revolution, the requirement for water has been increasing rapidly where a total of about 17,000 desalination plants worldwide have been contracted with 48% of their capacity in North Africa and the Middle East. There are some important processes (e.g., extraction of source water, pretreatment, post-treatment, etc.) that are executed on a typical desalination process. Consequently, the desalination process has been reliable over the centuries and its productivity has been in continuous upgrading. However, the by-product water stream, known as concentrate/reject stream, or brine, comprising dissolved compounds like minerals, organics, and metals, can negatively impact the surroundings, and hence, the concentrate management should be carried out properly (El-Ghonemy 2018). The by-product brine could be disposed of by various techniques which differ from one another. The brine could be disposed of utilizing different methods like evaporation tanks, surface and sewer discharge, and land usage. On the other hand, the application of these techniques could affect the surroundings by changing the quality of air and aqueous life by carrying the chemical constituents that have been incorporated at the time of the pretreatment process or the concentrated contaminants from feed water. Consequently, the present best practice is to apply the zero liquid discharge (ZLD) method that makes the most of the recovery of pure water and reduces the concentrated water volume rejected. Environmental Impact Assessment (EIA) must be performed for this process for finding the precise effects of the desalination plant

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completely. The source water quality will be affected by the brine or reject which has a high concentration of contaminants, high chlorine concentration, high temperature, high salinity, heavy metals, and low dissolved oxygen concentration. These elements might rise salinity higher than the standard conditions and endanger marine life because of lack of oxygen (Dawoud 2012). In our current study, we analyze the present development of the desalination process by investigating the methods accessible, different brine disposal strategies, developments in ZLD, and up-to-date progress of research in this area.

2 Energy Requirement for Various Desalination Processes

The energy demand could be affected by various factors, like the unit design, the quality of the seawater entering the system, and the capacity of the facility. The energy consumption of MSF, VC, and MED is not impacted by the quantity of salt in the water entering the unit, although membrane processes (RO, ED) are exceptionally altered by the salt content. While comparing the consumed energy for different desalination methods (MED, MSF, and RO), it could be noted that the seawater reverse osmosis (SWRO) process, having an energy recovery system, needs lesser energy (almost 4.0–6.0 kW h/m^3) than MSF and MED techniques. Table 1 presents the energy consumption of the different desalination methods.

3 Strategies for Brine Disposal

Brine water is the water discharged from the plant after the desalination process, and it will contain a higher concentration of salts (55,000 mg/L of TDS) obtained from the feed water. Brine water is generally termed as the reject/concentrate water, and in the section below, we examine the various brine disposal approaches.

Sewer discharge: Utilization of an adjacent wastewater collection system where the concentrate stream is discharged. The cost of disposal is in the range of 0.32–0.66 US\$/m^3 of rejected brine.

Surface water discharge: In this technique, the brine will be discharged directly into oceans, rivers, lakes, or bays. This method is mostly utilized by desalination plants with seawater sources. The disposal cost of surface water discharge is in the range of 0.05–0.30 US\$/m^3 of rejected brine (Panagopoulos et al. 2019).

Deep-well injection: This is a brine injection technique into an underground aquifer that must be deep as well as isolated from any water aquifers on top of it. The expense of disposal is in the range of 0.54–2.65 US\$/m^3 of rejected brine.

Evaporation ponds: Using direct solar power in shallow lined earthen basins, the brine evaporates slowly. The disposal expense of this approach will be the most expensive in the range of 3.28–10.04 US\$/m^3 of rejected brine.

Land application: It is a technique of brine disposal, where brine is sprayed on plants and grasses which are salt-tolerant in parks, golf courses, and lawns.

The above-stated methods could be assessed mostly based on the environmental and economic features and the easiness of execution. The surface water discharge technique has lower capital and operating expenses; therefore, it is regarded to be an inexpensive technique compared to the others. Apart from its beneficial impacts, the aqueous environment could be disturbed as the salinity of the semiclosed seas could be increased, and consequently, the environmental regulations should be followed by diluting the brine competently. Evaporation ponds, as well as deep-well injection, are appropriate choices for inland facilities. Even though deep-well injection is regarded as an economical technique, it is not appropriate for high seismic areas, due to the groundwater pollution hazard. The expensive technique

Table 1 The energy consumption of the desalination process

Properties	Thermal vapor compression	Multiple effect distillation	Brackish water reverse osmosis	Seawater reverse osmosis	Multi-stage flash distillation	Mechanical vapor compression
Size of the unit (m^3/day)	10,000–30,000	5000–15,000	Up to 98,000	Up to 128,000	50,000–70,000	100–3000
The consumed thermal energy	227	145–230	–	–	190–282	–
The consumed electrical energy (kW h/m^3)	1.8–1.6	2.0–2.5	1.5–2.5	4–6 with ER	2.5–5	7–12
The equivalent amount of electrical to thermal energy	14.5	12.2–19.1	–	–	15.83–23.5	–
The total electricity consumed	16.26	14.45–21.35	1.5–2.5	4–6	19.58–27.25	7–12

for brine disposal is considered to be the evaporation pond due to the proportionality between the treatment capacity and its footprint area. Moreover, this technique's efficiency could only be identified in areas with high rates of evaporation as well as the dry climate seen in GCC nations (Ladewig and Asquith 2011). Lastly, the land application technique is also a better disposal technique, however, limited to lower brine volumes.

4 ZLD Approach and Its Challenges

ZLD is an engineering method for the treatment of water, where the plant does not release any liquid discharge into surface water. This would lead to a total elimination of the pollution related to the treatment. Moreover, the ZLD eradicates the liquid waste and gets most out of the water usage. The most important driving factor for the zero liquid discharge process is the severe environmental regulations for wastewater disposal. There exist several challenges facing the zero liquid discharge implementation and part of these challenges are (1) proper designing of a recovery system that is capable of capturing more than 95% of wastewater, (2) operating cost and capital cost, (3) effluent composition as well as its characteristics, and (4) material compatibility. One of the major challenges is to select the appropriate method based on wastewater characteristics, composition, associated temperature and corrosion issues, and target capacity (Ahirrao 2014). Further, the capital expense and operating expense of zero liquid discharge inclusive of chemical costs as well as energy costs related to the evaporation and treatment processes are noted to be higher than in any other disposal method. There are three categories of prevailing technologies, generally the thermal ZLD systems, reverse osmosis-based thermal ZLD systems, and other emerging technologies like forward osmosis (FO), membrane distillation (MD), and electro dialysis (ED). Table 2 shows the advantages and limitations of MD, FO, RO, and ED technologies. For all environmental evaluation techniques used in a study by Raluy et al. (2006), the reverse osmosis has an environmental load associated considerably less than thermal desalting processes (MED and MSF), as RO is very effective and its energy utilization, with respect to primary energy, is almost 5–6 times less than thermal technologies. Further, if the current trend of the energy utilization reduction of RO is retained, a significant decrease in its environmental load (almost 50%) can be anticipated in the next few years. The zero liquid discharge process is extremely important to the environment with respect to dropping the water pollution and attaining sustainability. Conversely, there are environmental problems that are associated with zero liquid discharge systems and applications. One of the foremost operational issues is caused by the organics existing in the wastewater. Decomposing these organics is not very easy by utilizing the conventional biological processes because of their chemical stability or toxic nature. Henceforth, there will be a hazard of fouling development in the membrane system which can threaten the system's stability (Cherif and Belhadj 2018). Some processes might help the conventional biological treatment systems, like designing the process and applying an advanced oxidation process that helps promote the separation of harmful organics. There are some problems as well as challenges related to the emerging techniques. Mainly, the mixed salts of solid waste are not appropriate for reuse. They might produce odors and influence different organisms negatively, and there is a danger of leakage if they are kept in evaporation ponds. Furthermore, they might result in chemical leaching if they are dumped in landfills. Accordingly, substantial concerns about storage as well as disposal will happen due to these waste solids, and thus hazardous waste disposal facilities would be required.

Even though the zero liquid discharge has been established in places like the Middle East, Canada, Australia, European Union, and Mexico, examples from China, the United States, and India are emphasized, as these countries signify the major zero liquid discharge markets with majority population and more economic power. The United States EPA lately completed its guidelines reviewing the prevailing regulations on wastewater emission from thermal power plants. Compliance with these stricter wastewater discharge standards offers new regulatory incentives for zero liquid discharge installation in the United States power plants. In the recent past, China announced a new Action Plan for tackling the water pollution issue, and the plan emphasized rigorous control of pollutant discharge and supports water recycling/reuse, thus, offering regulatory support for zero liquid discharge setup. Further, the present three-year target set by the government of India, termed as the "Clean Ganga" project, enforces firmer regulations on wastewater emission and transfers the high-polluting industries toward zero liquid discharge.

5 Future Research Development and Approaches in Desalination

More research should be carried out to develop proper techniques for water characterization that are technically suitable as well as economical. This is because of the rise in the membrane desalination market and the membrane unit's incapability for withstanding the thermal units for feed water quality. Process optimization is extremely important for examining the treatment of the feed stream for removing the dissolved inorganic materials. From a technical viewpoint, the optimization process should be associated with its

Table 2 Benefits and drawbacks of FO, ED, RO, and MD techniques (Yaqub and Lee 2019)

Technology	Advantages	Limitations	Energy consumption kW h/m^3
RO	Energy efficient	Scaling possibilities, limited salinity range, and high fouling propensity	2–6 or 1.5–2.5 (b)
ED/EDR	Lesser fouling tendency and higher salinity limit	Incapability of removing noncharged contaminants, higher energy consumption, and high-quality water product	7–15 (a)
FO	Lesser fouling tendency and higher salinity limit	Lower flux at high salinity limited use	21 (a)
MD	Lesser fouling tendency and higher salinity limit	Limited area of application, low flux, low recovery, and requires post-treatment	40–45, 22–67 (b)
MVC	Higher salinity limit and technical maturity	High energy consumption and higher operating, maintenance, and capital expenses	20–25, 28–39 (a)

Where (a) signifies the energy used in kW h/m^3 of the water fed to the process, whereas (b) signifies the energy used in kW h/m^3 of the water produced

implications for the financial side of the process. The optimization of the process might result in increased capital costs; on the other hand, it may reduce the maintenance and operational costs and enhance the plant service life successfully. Accordingly, the process optimization should be able to analyze the service life of the plant and the efficiency of the process. Brine management is a key research area that was mostly unnoticed by numerous scientists for many years, however, current environmental pressures have resulted in certain attention to it. Based on the reject characterization with respect to dissolved inorganic species, the possibility and assessment of salt recovery are limited (Xu et al. 2013). Therefore, any progression in the feed water characterization will be beneficial. The thermal and membrane-based separation techniques need to be combined with more effort for recovering and restoring salt. Additional enhancement for the viability of salt recovery could be accomplished by constructing a common location for water and power plants, hybridization of membrane and thermal systems, and waste heat availability. Therefore, software has to be designed such that it has the capability for serving these requirements and works according to the basics of thermodynamics, and relates to process optimization to avoid equipment scaling.

6 Conclusions

The different desalination technologies discussed in our study have their own distinctive benefits and drawbacks. It was noted that thermal processes will experience scale formation and corrosion problems more than membrane-based processes. However, the thermal-based desalination process does not need pretreatment processes as required by the membrane-based processes, which is vital for membrane efficiency and increased service life. Hence, the proper technology selection depends on the feed water source as well as the geographical location, instead of the quality of product water. By proven economic and technical feasibility, both membrane and thermal desalination technologies have practically reached their maturity levels. Furthermore, emergent desalination technologies are being developed with increased productivity as well as comparatively higher energy efficiency. On the basis of the process type, it was noted that the energy use changes from process to process. In addition to this, the major by-product of desalination plants, concentrate, can lead to several ecological impacts; and hence it must be treated, reused, or discharged appropriately. Furthermore, zero liquid discharge systems have been recognized to perform an important role in industrial wastewater management like avoiding the wastewater discharge, protecting the environment, promoting sustainability, reducing the cost of wastewater disposal operation, complying with regulations, and thereby enhancing the water supplies worldwide. It is suggested to concentrate more research toward forming proper methods as well as technologies for the characterization of feed water and developing appropriate indicators for organic fouling and colloidal fouling. Indeed, the developments in computational approaches and a combination of theoretical principles and progressive empirical analysis would prolong the opportunity of desalination process development.

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