Journal of Membrane Science 453 (2014) 136–154

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Analysis of reverse osmosis membrane performance during desalination of simulated brackish surface waters

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ARTICLE INFO

Article history:
Received 31 July 2013
Received in revised form
15 October 2013
Accepted 17 October 2013
Available online 4 November 2013

Keywords:
Reverse osmosis
Permeate
Brackish water
Salt ion rejection
Pretreatment

ABSTRACT

In this study, three different brackish surface water qualities, which represented the water quality in the Iraqi marshes, were simulated and used as feed waters to run a flat sheet reverse osmosis (RO) membrane system. The performance of three different types of the RO membrane (Thin-Film Composite (SE), Cellulose Acetate (CE), and Polyamide (AD)), under these water qualities, was investigated. The effect of the high and low feed water temperature (37 °C and 11 °C) on the operation efficiency of the three RO membranes was also investigated. In addition, using the Microfiltration (MF) membrane to pretreat the feed water and its effect on the performance of the RO membrane was examined. The results revealed that the SE membrane produced the highest permeate flux, while the AD membrane produced the lowest permeate flux in all three feed waters. Also, the elemental analyses showed that the CE membrane had the least rejection percentage (from 91.1% to 99.2%), but the AD membrane had the highest rejection percentage (from 97.6% to 99.5%) for all the existing feed water ions. Moreover, using the MF membrane increased the permeate flux, particularly of the runs conducted with a high temperature, and slightly improved salt ions rejection ratios by the RO membranes. Additionally, all membranes at the temperature of 37 °C exhibited higher permeate fluxes than those of corresponding membranes at a lower temperature (11 °C).

1. Introduction

Water is essential for life. Owing to the increase in population and the commercial and industrial applications worldwide, fresh water resources for drinking water and domestic uses continue to decline [1]. Most of the world's water is seawater, brackish water or groundwater. Approximately, 97.4% of the entire water mass available on earth is salty and 1.984% is located in the ice caps and glaciers, while 0.592% is located as groundwater and only 0.014% of the earth's water is readily available as fresh water [2]. In addition, many dry or arid areas around the world do not have fresh water resources in the form of surface water such as rivers, lakes, etc. As a consequence, seawater and brackish water have become alternative resources for drinking water. Fresh water can be defined as the water that contains less than 1000 mg/L of the total dissolved solids (TDS) and waters containing 1000–10,000 mg/L of TDS are considered as brackish water while seawater contains 10,000–60,000 mg/L of TDS [3–5]. High concentration of TDS and other minerals that exist in brackish water and seawater need to be removed using advanced treatment. Desalination of seawater and brackish water is one of the technologies that have been introduced to remove salt and other minerals from saline and salty water to make it suitable for human consumption or industrial use. In 1983, the first major seawater desalination plant was built in Saudi Arabia [6]. According to the NRC [7] and GWI [8], in 2006, the global desalination water production was approximately, 42 million m^3/day including seawater and brackish water for multiple purposes such as municipal, industrial, agricultural, power, military, and many other applications. By the end of 2007, there were over 14,000 desalination plants worldwide with total treatment capacity of about 53 million m^3 of water per day [1].

Iraq has plenty of water which is considered as brackish water that can be exploited for drinking water purposes [9]. Marshes (Mesopotamian Marshlands) which are located in southern of Iraq and were created by the Tigris and Euphrates rivers have a TDS ranging from 725 to 3308 mg/L and can be considered as a major source of surface brackish water [10]. Although the quantity of water in the marshes fluctuates, because it depends mainly on the water quantity in the Tigris and Euphrates rivers, it can also be used as a water source of drinking water facilities for many cities in this region. The area of these marshes ranges from 15,000 to

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http://dx.doi.org/10.1016/j.memsci.2013.10.051

20,000 km^2 (5791-7722 $mile^2$) [10]. The quality of the water of the marshes compared to the available ground water in this region, which has high concentrations of elements (4000 mg/L magnesium (Mg^{+2}), 2000 mg/L calcium (Ca^{+2}), 10,000 mg/L sulfate (SO_4^{-2}), 1750 mg/L chloride (Cl^-), 10,000 mg/L sodium (Na^+), and 64,613 mg/L TDS) as reported by Al-Dabbas and Manii [11] makes it a potential good source for water treatment facilities. Recently, taking advantage of the reverse osmosis process to help in drinking water production, several pilot desalination plants were implemented in the region of the Iraqi marshlands [9], and more water desalination facilities are expected to be implemented and operated within the next decades. The expansion of the new technology of reverse osmosis membrane process in this area requires studies that can assess and minimize the problems this technology encounters. Some of these problems include membrane fouling, which limits both operation productivity and life-time of the membrane, and the environmental impacts of the concentrate.

In this study, the potential impacts of the variation of the feed water, which is similar or close to the water quality of the brackish surface water in the Iraqi marshes, on the fouling and the productivity of three different RO membrane types were investigated. Also, the effect of the high and low feed water temperature (37 °C and 11 °C) on the operation efficiency of the three RO membrane types and the total time to achieve the required water recovery was studied. Moreover, using the Microfiltration (MF) membrane as a pretreatment unit for the simulated feed water and its effect on permeate flux productivity and salt rejection percentage of the used RO membranes was examined.

2. Material and methods

2.1. Feed water

Several studies [9,10,12,13] conducted water quality investigations in different locations of the Iraqi marshes and some of the selected sites are shown in Fig. 1. In addition, Table A1 (Appendix A) displays some of the water quality parameters of 19 sites (denoted in Fig. 1) located in these marshes, which were reported by Al-Saad et al. [10], Hamdan et al. [12], United Nation Environment Program, UNEP [9], and Richardson and Hussain [13]. The minimum and maximum values of major parameters included in this table are 7.36–9.52 pH, 3.6–52 NTU turbidity, 84–366 mg $CaCO_3$/L alkalinity, 420–1480 mg $CaCO_3$/L total hardness, 98–1278 mg/L sulfate (SO_4^{-2}), 30–1595 mg/L chloride (Cl^-), 148–920.2 mg/L sodium (Na^+), and 1.2–13.9 mg/L total organic carbon (TOC).

From Table A1, it can be seen that some of the important constituents of the water quality are missing. TOC, for example, is available only at the first six locations (1, 2, 3, 4, 5, and 6) which were reported by UNEP [9], and the last three locations (17, 18, and 19), which were reported by Richardson and Hussain [13]. Moreover, sodium is available at two locations (13 and 14) which were reported by Al-Saad et al. [10], and two other locations (15 and 16) which were reported by Hamdan et al. [12]. After studying the available data in Table A1 and their distribution over the Iraqi marshes, three water analyses were selected as feed water to run a lab-scale RO membrane system in this study. The locations of these water analyses, which are 1 (Al-Jeweber), 5 (Al-Hadam), and 6 (Al-Masahab), are circled in Fig. 1. One of the reasons behind selecting these water analyses is that their locations represent nearly all the area of the marshes because they were located in three different provinces in the south of Iraq (Thi-Qar, Maysan, and Al Basrah). Moreover, the concentration of the constituents of water quality of these sites varied from high levels to low levels. For instance, the concentrations of TDS, SO_4^{-2}, Cl^-, Ca^{+2}, and Mg^{+2} at location 6 were 2,750, 692, 1,100, 118, and 85 mg/L, respectively, which are considered as high levels of concentration. However, the concentrations of TDS, SO_4^{-2}, Cl^-, Ca^{+2}, and Mg^{+2} at location 5 were 1,270, 310, 440, 49.9, and 17.2 mg/L, respectively, which are considered as low levels of concentration. At location 1, the concentrations of TDS, SO_4^{+2}, Cl^-, Ca^{+2}, and Mg^{+2} were 2,380, 670, 710, 79.4, and 51.7 mg/L, respectively, which can be considered as moderate levels of concentration compared to the other two locations (5 and 6) [9].

Salinity and TOC were also considered in selecting the locations of the water quality samples. Location 5 had low salinity (700 mg/L) and low TOC (1.2 mg/L), while location 6 had high salinity (2000 mg/L) and high TOC (4.71 mg/L). In addition, these three sites were chosen in different places that have different sources of water. Location 1 is located where the source of the water for the marshes is the Euphrates River, while location 5 is located where the Tigris River is the source water. However, location 6 is located further to the south near Shatt al-Arab where the Tigris and Euphrates Rivers are joined.

The most common vegetation in the Iraqi marshes are common reed (*Phragmites australis*), reed mace (*Typha angustifolia*), giant reed (*Arundo donax*), and papyrus (*Cyperus papyrus*) [12,14]. In order to create TOC and add it to the simulated water at the same TOC concentration, as seen in the Iraqi marshes, reed mace (*Typha angustifolia*) and giant reed (*Arundo donax*), which were available in Oklahoma, were used. The genius and species of the plants were identified by Fishbein [15]. Two mixed bunches of these plants were submerged into distilled water. One bunch was already wet (submerged in the water) denoted as S1, and the other one was dried denoted as S2. The plants were left in the distilled water for more than 9 months, and the pH of the two solutions was frequently measured. After significant breakdown of the plants, the solutions of S1 and S2 were decanted and their COD was measured by using the Hach Chemical Oxygen Demand (COD) high range method (method 8000) (Hach Company, Loveland, CO). The main purpose of measuring COD was to know the approximate level of TOC concentration in each solution. In addition, the Hach Total Organic Carbon (TOC) low range direct method (method 10129) (Hach Company, Ames, IA) was used to test the TOC level of the two solutions. A DR5000 spectrophotometer (Hach Company, Loveland, CO) was used in both COD and TOC test methods. The results of TOC concentration of solution S1 were confirmed by Accurate Environmental laboratory (Accurate Environmental, Stillwater, OK). To keep the TOC concentration constant for both samples, the solution was screened through a sieve number 40 (0.422 mm) to remove all the remaining plant material and the remaining solution was stored in dark containers at room temperature.

The two samples (S1 and S2) were further analyzed to determine the concentration of ions which need to be considered during the making of the feed water batches. Ion chromatography analysis (DX-120, Ion Chromatograph, Dionex, Hayward, CA) was used to determine the concentrations of the anions (SO_4^{-2}, Cl^-, and PO_4^{-3}) of each sample. In addition, an Inductively Coupled Plasma (ICP) spectrometer (Spectro Ciros at the Soil, Water and Forage Analytical Laboratory, Oklahoma State University) was used to find the concentrations of the cations (Ca^{+2}, Mg^{+2}, Na^+, Fe^{+2}, K^+, and Zn^{+2}) of S1 and S2. Based on the available ions in Table A1, an electrical balance was used to determine the missing concentrations of sodium for the three selected sites.

The following inorganic salts were used to prepare the salt stock solutions. Zinc sulfate ($ZnSO_4 \cdot 7H_2O$, certified A.C.S.), calcium nitrate ($Ca(NO_3)_2 \cdot 4H_2O$, certified A.C.S.), magnesium chloride ($MgCl_2 \cdot 6H_2O$, certified A.C.S.), sodium bicarbonate ($NaHCO_3$, certified A.C.S.), sodium sulfate anhydrous (Na_2SO_4, certified A.C.S.), and sodium chloride (NaCl, certified A.C.S.) were purchased from