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Optimal mass loading rate in low energetic full-scale reverse osmosis desalination

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ABSTRACT

The optimized mass loading rates (MLR) of total dissolved solids (TDS) in low-pressure reverse osmosis (RO) membranes are determined from the efficiency of product water rate (PWR) (L/(min m^2 kN/m^2)). Determination of the loading rates is based on the same demineralization and water recovery rate between runs. Based on the efficiency for five different feed water TDS concentration, different optimal MLRs are obtained. Results show that pressurizing energy; and therefore, environmental impacts such as CO_2 emission, can be reduced upon operation of extreme low-pressure RO elements, which in this study are AP-series of commercial membranes manufactured by GE Power and Water, at obtained optimal mass loading rates. Reverse osmosis using AP-series membranes is low energetic, hence beneficial for the high temperature applications as well.

Keywords: Mass loading rate; Total dissolved solids; Energy consumption; Low pressure; Reverse osmosis

1. Introduction

Energy usage and mass loading rates in unit effective area of retained material are traditionally required in the water and wastewater industries as a basis to guide and operate the water and wastewater treatment plants [1–3]. Reverse osmosis (RO), nanofiltration (NF), and electrodialysis reversal (EDR) technologies are popular for seawater and brackish groundwater desalination. The three technologies are employed, globally, in 80% of the total desalination plants [4]. During years, two major challenges with membrane processes were cross-flow filtration and fouling; which have been studied and improved under numerous operating conditions and physical and mechanical properties of the polymers [5–9]. RO desalination has matured over the past 40 years. Nowadays, it provides 44% of the world desalting production capacity. RO membranes majorly reject monovalent ions (e.g., Na^+, Cl^-, etc.). NF membranes, on the other hand, are favorable to reduce divalent ions (e.g., Ca^{2+}, Mg^{2+}, etc.), which are the main cause of hardness and dissolved organic material in water [10–12]. EDR systems are designed to operate by applying an electric current that attracts total dissolved ions to exchange through parallel ion-exchange membranes, and are normally suitable for feedwater containing a majority of electric current characteristic ions.

Energy usage and pre-design parameters related to EDR desalination are found in system efficiency published research [13–15]. However, there is little published research in energy usage and optimal mass loading rates (MLR) of total dissolved solids (TDS) in RO systems, as well as industrialized RO desalination with natural brackish groundwater. Lab-scale theoretical technology is traditionally innovated in the academic setting, and is expensive per unit product. Funding and regulation agencies are looking for bridging technology innovation and business model demonstration to lower the capital and operational cost in a short period of time. This

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research successfully bridges academic and industrial-scale desalination. The preliminary objective of this article is to determine the optimal mass TDS loading rates. The ultimate objective is to determine required energy per liter of product water and per mass rate of removed TDS to pressurize feedwater for the industrialized RO brackish groundwater desalination system.

2. Materials and methods

The full-scale groundwater desalination is performed with extreme low-pressure brackish water RO elements (AP-4040FM, part number 3063034, active area 7.4 m^2), purchased from General Electric's Water and Process Technologies division. The flow diagram is shown in Fig. 1. Provided from local wells (the US Bureau of Reclamation's Brackish Groundwater National Desalination Research Facility located at Alamogordo, NM), brackish groundwater is pumped through one multimedia and two 5 mm filters as pretreatment stages before being pressurized into six membrane housing pressure vessels. Each pressure vessel contains three spiral wound AP membranes. As displayed in Fig. 1, after passing through the pre-treatment filters, the feed stream is simultaneously pumped into pressure vessels number 1 and 2. The combined brine from the first two membrane housings is, then, fed into vessels number 3 and 4. From there, the new collective brine is sent into the last two; pressure vessels number 5 and 6. Finally, the system outlet brine is collected as combination of the last two membrane housings' concentrate streams. The collective permeate from pressure vessels 1 through 6 is called the product water of the system.

The pH of the inlet stream is maintained at 6.71 by injecting HCl to the feedwater before pumping it to the membranes. Additionally, before reaching the membranes, anti-scalant is continuously added to the feed for the purpose of minimizing fouling.

The design of the experiments is presented in Table 1. Twenty tests are performed as one set of experiment with five different feedwaters in a full-scale RO system. Feeds are taken from two wells and modified in temperature and concentration for the purpose of the tests. The first feed is taken from well 1 with normal temperature, and called Well 1 Cold. Feed 2 is provided from well 1 as well, but warmed up to higher temperature, and named Well 1 Warm. Feed 3 is made by adding significant amounts of NaCl to the normal well 1 water to bring up its salt concentration, and is named as Salt-Added Well 1. Feed 4 is taken from well 2, which naturally has higher salt concentration compared to well 1. The last feed (i.e., feed 5) is made by mixing well 1 and well 2 waters in a 50/50 ratio to provide approximately middle point in sodium chloride concentration. The latter feed is called Blend. Table 1 presents the operating condition of each test. The detailed information of the experiments can be found in Vaseghi's thesis [17].

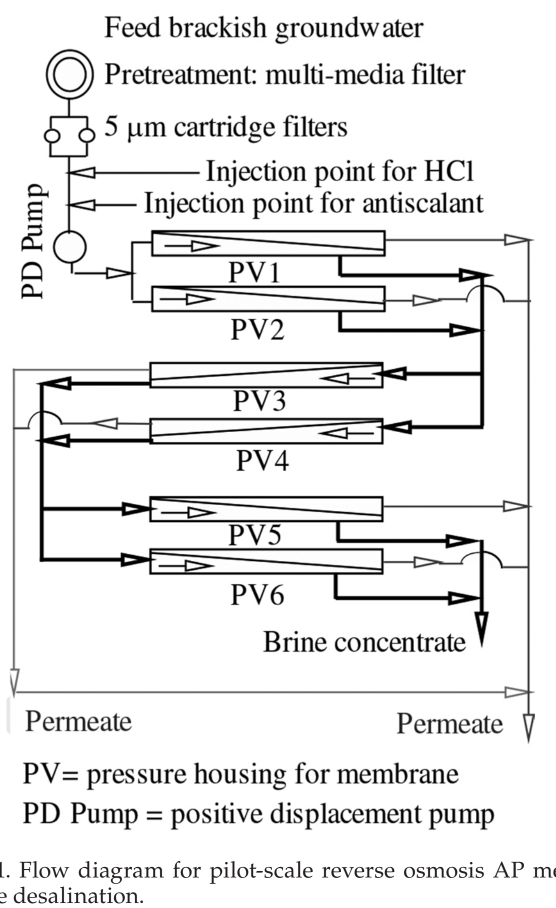

Fig. 1. Flow diagram for pilot-scale reverse osmosis AP membrane desalination.

3. Result and discussions

3.1. Optimal MLR vs. PWR efficiency

Figs. 2 and 3 show the mass rate of removed TDS and demineralization degree of the membrane, respectively, in test numbers 1 to 20.

Performance efficiency, in this study defined as the efficiency of product water rate (PWR), is used to determine MLRs in the feed stream of RO desalination system. PWR is the rate of produced permeate (L) per unit membrane effective area (m^2), unit time (min), and unit pressure consumed to pressurize feedwater passing through the membrane (kN/m^2); therefore, has units of $L/(min\ m^2\ kN/m^2)$. The optimal MLR ($g/min\ m^2$) in the feed stream is graphically determined from the system efficiency vs. energy per mass removed (Figs. 4a and 4b) and system efficiency vs. energy per volume of PWR (Figs. 5a and 5b). The loading rates are obtained based on the same demineralization (95.4%) and water recovery rate (73.9%) between tests.

Table 2 presents the optimal MLRs and pressurizing energies per TDS removed rate and product water for the five different feedwaters aforementioned.

As displayed in Fig. 4a, operating the system at optimal MLR conditions maximizes the PWR efficiency. For instance, for feed 5, with TDS concentration of 6.15 g/L at 24.0°C, the optimum MLR is obtained to be 4.50 $g/(min\ m^2)$, which maximizes the PWR efficiency to 0.00056 $L/(min\ m^2\ kN/m^2)$. For the same feed concentration and temperature, the efficiency of PWR decreases if the MLR is different than the optimum value (Fig. 4a).

Table 1
Design of experiment

Experimental tests	Well #	Feed TDS concentration (g/L)	Temp °C	Permeate flow (Lpm)	Conc. flow (Lpm)	Total flow (Lpm)	Flow recovery %
1	1	1.34	29.9	45.4	20.4	65.9	70.0
2	1	1.34	29.9	68.1	20.8	89.0	75.0
3	1	1.34	29.9	90.8	20.1	110.9	80.0
4	1	1.34	29.9	90.8	34.1	124.9	70.0
5	1	1.36	37.2	45.4	18.2	63.6	70.0
6	1	1.36	37.2	68.1	20.8	89.0	75.0
7	1	1.36	37.2	90.8	19.7	110.5	80.0
8	1	1.36	37.2	90.8	31.0	121.9	70.0
9	1+NaCl	2.07	22.7	45.4	21.6	67.0	70.0
10	1+NaCl	2.07	22.7	68.1	24.6	92.7	75.0
11	1+NaCl	2.07	22.7	94.6	24.6	119.2	80.0
12	1+NaCl	2.07	22.7	90.8	39.4	130.2	70.0
13	Blend	3.55	21.1	45.4	21.6	67.0	70.0
14	Blend	3.55	21.1	68.1	24.6	92.7	75.0
15	Blend	3.55	21.1	94.6	22.3	117.0	80.0
16	Blend	3.55	21.1	90.8	42.0	132.9	70.0
17	2	6.15	24.0	45.4	20.8	66.2	70.0
18	2	6.15	24.0	68.1	23.5	91.6	75.0
19	2	6.15	24.0	90.8	24.2	115.1	80.0
20	2	6.15	24.0	90.8	37.1	127.9	70.0

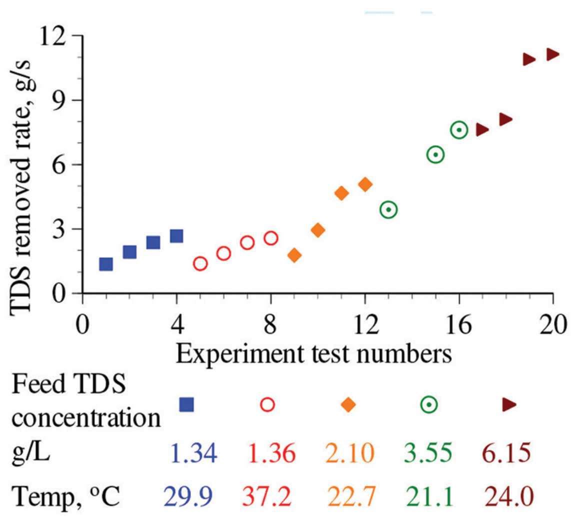

Fig. 2. Mass TDS removed rate in reverse osmosis AP membrane.

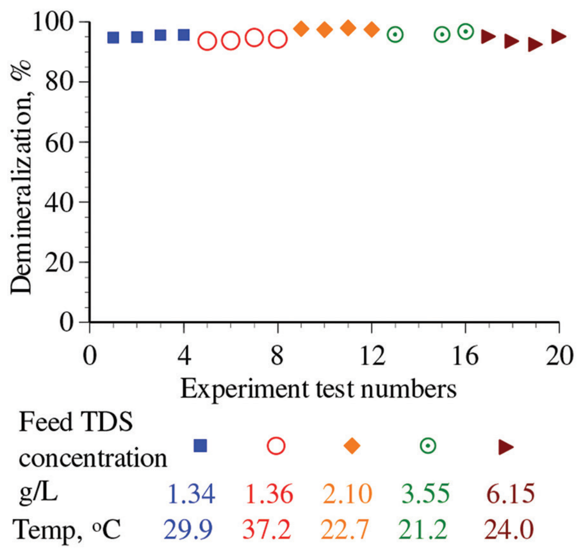

Fig. 3. Demineralization in reverse osmosis AP membrane.

3.2. Optimal MLR vs. pressurizing energy

Figs. 4a and 4b show that by operating at optimal MLRs the respective PWR efficiencies are maximized with the minimum energy required per mass rate of removed TDS. Optimal MLR of 4.50 g/(min m^2) for feed 5 maximizes the efficiency of PWR with minimum consumption of energy

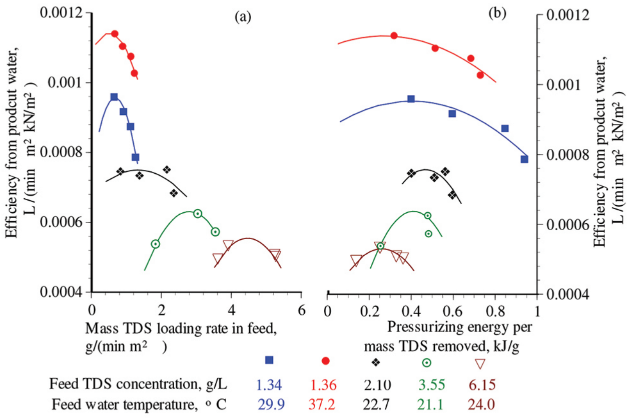

Fig. 4. (a) Efficiency of product water rate vs. TDS MLR in the feed per unit effective area of the membrane, (b) Efficiency of product water rate vs. pressurizing energy required per mass rate of removed TDS.

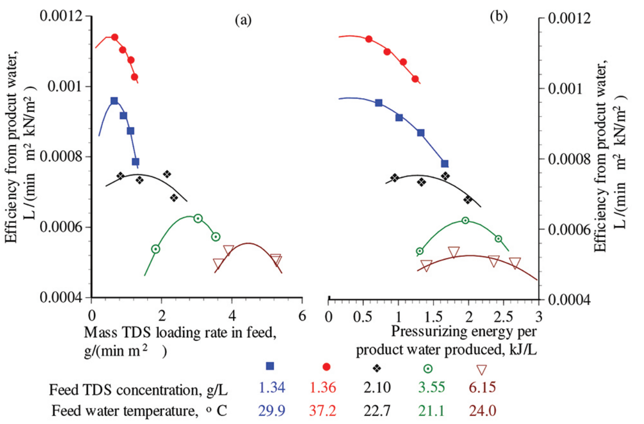

Fig. 5. (a) Efficiency of product water rate vs. TDS MLR in the feed per unit effective area of the membrane, (b) Efficiency of product water rate vs. pressurizing energy required per product water rate.

per mass TDS removed rate, which is 0.252 kJ/g in this case. For the same feed concentration and temperature, if the MLR is greater than 4.50 g/(min m^2), energy per mass rate of removed TDS increases (Figs. 4a and 4b). Figs. 5a and 5b show similar correlation between the optimized PWR efficiencies and the required energies per product water rate when operating at optimal MLRs. For the same example of feed and optimal loading rate (feed 5, 4.5 g/(min m^2)), only 2.0 kJ/L energy is required per product water rate, which is the minimum amount for the related TDS concentration and temperature. With no change in feed concentration, demineralization, and temperature, the MLR greater than 4.50 g/(min m^2) increases the energy consumption per product water rate (Figs. 5a and 5b).

3.3. Effects of feedwater temperature

The PWR efficiency is significantly different between warm feed 1 and 2 with similar TDS concentrations (~1.35 g/L), respectively at 37.2°C and 29.9°C, as shown in Fig. 4a. Higher temperature of feed water resulted in higher efficiency. Moreover, it is observed in Figs. 4b and 5b that different temperatures of similar concentration feedwaters 1 and 2 cause the difference in energy consumption rate. Feed 2 with higher temperature requires less pressurizing energy per mass TDS removed or per product water compared to feed 1 with lower temperature. Therefore, desalination of brackish water using low-pressure RO elements can be beneficial for high temperature applications when performing at optimal MLRs.

3.4. Energy saving

Figs. 4 and 5 display energies, respectively, per mass removed rate and product water rate for five relevant MLRs of five different feed waters. It is observed from both figures that operating at optimal MLRs result in reduced pumping energy required per mass of removed TDS or permeate rate. In addition, decreasing the mass loading rate per unit effective area of the membrane linearly decreases the amount of pressurizing energy for the system. For example, when 1.26 g(min m^2) mass TDS is loaded in the system, 0.94 kJ/g energy is required to pressurize the feed. However, this amount is reduced to 0.85 kJ/g for 1.12 g/(min m^2) MLR, and optimized to be 0.27 kJ/g for mass loading rate of 0.66 g/(min m^2). Figs. 4a and 4b show this trend of data for all five feed water concentrations. Pressurizing energies per product water rate, also, decrease with decreasing the mass loading rate of the system. For instance, this energy changes from 1.70 kJ/L for 1.26 g/(min m^2) loading rate to

Table 2
Optimal mass TDS loading rates and pressurizing energies

Data set	Feed water TDS concentration g/L	Measured feed temp °C	Optimal mass TDS loading rate in feed g/(min m^2)	Full scale pressurizing energy per TDS removed kJ/g	Full scale pressurizing energy per product water kJ/L
1	1.34	29.9	0.659	0.267	0.314
2	1.36	37.2	0.493	0.398	0.300
3	2.10	22.7	1.308	0.460	1.250
4	3.55	21.1	2.784	0.300	1.926
5	6.15	24.0	4.500	0.252	2.000

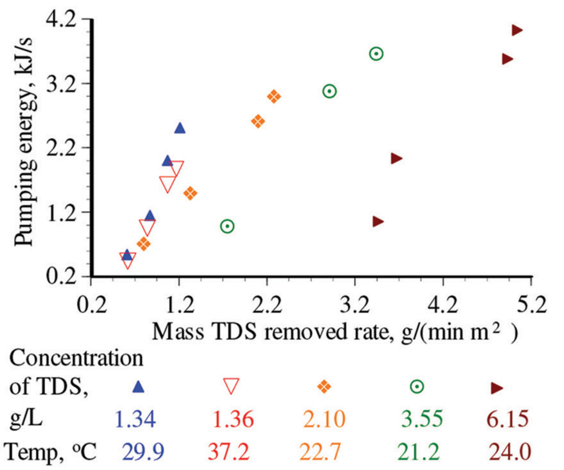

Fig. 6. Mass TDS removed rate g/(min m^2) vs. pressurizing energy kJ/s.

1.30 kJ/L for 1.12 g/(min m^2), and is optimized at 0.31 kJ/L for 0.66 g/(min m^2) mass loading rate per unit effective area of the membrane. Although the reduction rate is different for the two energies, the trend is linear for both. Figs. 5a and 5b demonstrate this result for five feed waters.

The required energy to remove TDS by RO membranes varies with two factors; the concentration of TDS in the feed stream and the rate of the removed TDS. Both factors directly affect the energy as shown in Fig. 6. However, the concentration has bigger weight than temperature, as the feed with 6.15 g/L of TDS at 24°C temperature requires almost twice pumping energy of the one with 1.36 g/L TDS at 37.2°C.

The energy consumption per volume of permeate rate and mass rate of removed TDS are both provided in Table 3 as a function of temperature, feedwater TDS concentration, and mass TDS loading rate. Results show the energy per removed mass decreased with the increase of the feedwater TDS concentration. The variation of energy requirement per mass rate of removed TDS based on feedwater TDS concentration and temperature is significant. Table 3 also

Table 3
Pressuring energy per volume of permeate and per mass rate of removed TDS

Tests	Feed TDS g/L	Feed water temp °C	Permeate TDS g/L	Feed mass TDS loading rate g/(min m^2)	Indivi. PEPP kJ/L	Indivi. PETDS kJ/g	Indivi. TDSRPLP g/L	Literature values PEPP kJ/L
1	1.31	30.4	0.10	0.65	0.72	0.40	1.8	
2	1.37	30.0	0.09	0.91	1.01	0.60	1.7	1.04 [16]
3	1.34	29.7	0.07	1.12	1.32	0.85	1.6	
4	1.34	29.6	0.08	1.26	1.66	0.94	1.8	
5	1.40	35.7	0.13	0.67	0.58	0.32	1.8	
6	1.33	37.0	0.11	0.89	0.84	0.51	1.6	
7	1.36	38.0	0.09	1.13	1.07	0.68	1.6	1.44 [18]
8	1.34	38.0	0.10	1.23	1.24	0.73	1.7	
9	1.63	23.0	0.06	0.82	0.94	0.40	2.4	
10	1.96	23.0	0.07	1.37	1.32	0.51	2.6	
11	2.40	23.1	0.06	2.15	1.66	0.56	3.0	
12	2.40	21.8	0.09	2.34	1.98	0.59	3.3	
13	3.64	21.2	0.23	1.83	1.30	0.25	5.1	
14								
15	3.46	21.6	0.18	3.04	1.95	0.48	4.1	3.6* [19–21]
16	3.55	21.0	0.17	3.54	2.42	0.48	5.0	
17	7.27	25.7	0.52	3.62	1.40	0.14	10.1	25.2 [18]
18	5.68	24.9	0.49	3.91	1.79	0.25	7.1	
19	6.15	22.7	0.58	5.31	2.36	0.33	7.1	
20	5.49	22.7	0.37	5.27	2.66	0.36	7.4	

Indivi. = Individual.

PEPP = pressuring energy required to pressurize water passing through membrane per volume of product water.

PETDS = pressuring energy required to pressurize water passing through membrane per mass of TDS removed.

TDSRPLP = mass TDS removed per liter product water.

* The theoretical minimum energy for desalination of the typical seawater (35 g/L of total dissolved solids) is ~ 1 kWh/m^3 (3.6 kJ/L), assuming a thermodynamically reversible process at 50% water recovery.

finds energy usage per product water of this study being comparable to those values from literature [16,18].

The discussion above means RO process using AP-series membranes consumes lower pressurizing energy per volume of permeate and per mass rate of removed TDS for the higher temperature of feedwater when compared with the low temperature in the same feed TDS concentration. The low pressurizing energy per volume of permeate is ranged from 0.58 to 1.24 kJ/L at 37.2°C, while for the feed 29.9°C the energy is ranged from 0.72 to 1.66 kJ/L. For the energy per mass rate of removed TDS, at 37.2°C it covers from 0.32 to 0.73 kJ/g, while going from 0.40 to 0.94 kJ/g at 29.9°C in the same range of mass loading rate as presented in Table 3.

4. Conclusion

The optimal MLR, as a pre-design parameter, is determined from system performance efficiency of the extreme low pressure brackish water RO membranes in the same demineralization and water recovery rate between feed streams with various TDS concentrations and temperatures. Pressurizing energies per product water required for five different feed waters at the optimal mass TDS removed rate are acquired. Effects of TDS concentration and temperature of the feed stream on the efficiency and energy consumption of desalination using these membranes are studied. Results show reverse osmosis AP-series of GE membranes are found to be beneficial for high feed water temperature. Therefore, they are suitable to be used in desalination facilities located at hot and arid areas such as southern states, as well as the applications in which the temperature of feed stream could be or have to be brought up in a high level. Additionally, energy consumption is minimized upon desalination using AP membranes at obtained optimal MLR values. Considering the growing concern about limited resources and costs of waste management, results of this work are economically favorable. Moreover, environmental studies show that saving energy usage directly affects major environmental impacts, such as CO_2 emission and global warming potential, which adds up to the values of this work and all studies on energy optimization areas [22–25].

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