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Comparison between Forward Osmosis-Reverse Osmosis and Reverse Osmosis processes for seawater desalination

Ali Altaee [a,1], Guillermo Zaragoza [b], H. Rost van Tonningen [c]

[a] Faculty of Engineering and Physical Sciences, University of West of Scotland, Paisley PA1 2BE, UK
[b] CIEMAT-Plataforma Solar de Almería, Ctra. de Senés s/n, 04200 Tabernas, Almería, Spain
[c] Malmok Vision, Waterschapslaan 15, 1261JR Blaricum, The Netherlands

HIGHLIGHTS

- RO–FO and RO seawater desalination processes were compared using developed software.
- Total power consumption (Est) in FO–RO was higher than that in RO.
- Water flux in the RO process was higher than in the FO–RO process.
- Power consumption in FO process was 2%–4% of total power consumption in the FO–RO.
- The efficiency of FO–RO process was higher at higher seawater salinities.

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ABSTRACT

The combination of Forward Osmosis (FO) and Reverse Osmosis (RO) was evaluated for seawater desalination. RO process was suggested for the draw solution regeneration because of its high efficiency and applicability for a wide range of ionic solution treatments. Two different salts, NaCl and $MgCl_2$, were used as a draw solution. The performance of FO and RO regeneration processes was simulated using pre-developed software. A comparison between the RO and FO-RO processes was carried out. The simulation results showed that the total power consumption in the RO was lower than that in the FO-RO process. But, the difference in total power consumption between the RO and 0.65 mol $MgCl_2$ FO-RO processes was insignificant. The results also showed that the power consumption in the FO process was only 2%-4% of the total power consumption in the FO-RO process. However, the difference in total power consumption between the RO process and the FO-RO process decreased with a higher seawater salinity. In the FO-RO process, the results showed that the permeate TDS was increased with increasing the concentration of draw solution. The lowest permeate TDS was achieved in the 0.65 mol $MgCl_2$ FO-RO process and it was attributed to the high rejection rate of $MgCl_2$ by the RO regeneration unit.

1. Introduction

Membrane-based seawater desalination processes are one of the practical solutions for fresh water supply in arid and semi-arid areas [1–6]. A wide range of membranes were developed for the treatment of seawater and fresh water production from feed water of different salinities. Nowadays, the most popular membrane processes for saline water treatment are Reverse Osmosis (RO), Nanofiltration (NF), and Membrane Distillation (MD) [2,5.7,8]. Dual stage NF process was suggested for seawater desalination but it required a very exacting method for membrane operation [5]. Instead dual stage NF-BWRO process was proposed for seawater desalination to overcome the operating complexity in the dual stage NF process. MD has the potential to reduce the power consumption for seawater desalination because it does not require high pressure for membrane operation [9]. However, the low recovery rate and high thermal consumption make the MD process less attractive for seawater treatment in large desalination plants [10]. Unlike the other technologies, RO process enjoys a number of advantages which make it an attractive technology for seawater desalination because of its reliability, high water recovery rate and salt rejection rate, and its ability to treat a wide range of seawater concentrations [1,11]. At present, more than 50% of the world's desalination water is produced by RO process. Additionally, the RO membranes have found application in wastewater reuse and the production of ultra-pure water [12,13]. Although RO process has a number of advantages, the high power consumption is the process's main disadvantage. With the Energy Recovery Instrument (ERI), an average of 3.5 kWh/m^3 is required for seawater desalination (seawater TDS 35,000 mg/L) [14]. Indeed, reducing power consumption in the process of reverse osmosis was the objective of many research studies [5,9,15].

E-mail address: ali.altaee@uws.ac.uk (A. Altaee).
[1] Tel.: +44 7986517994.

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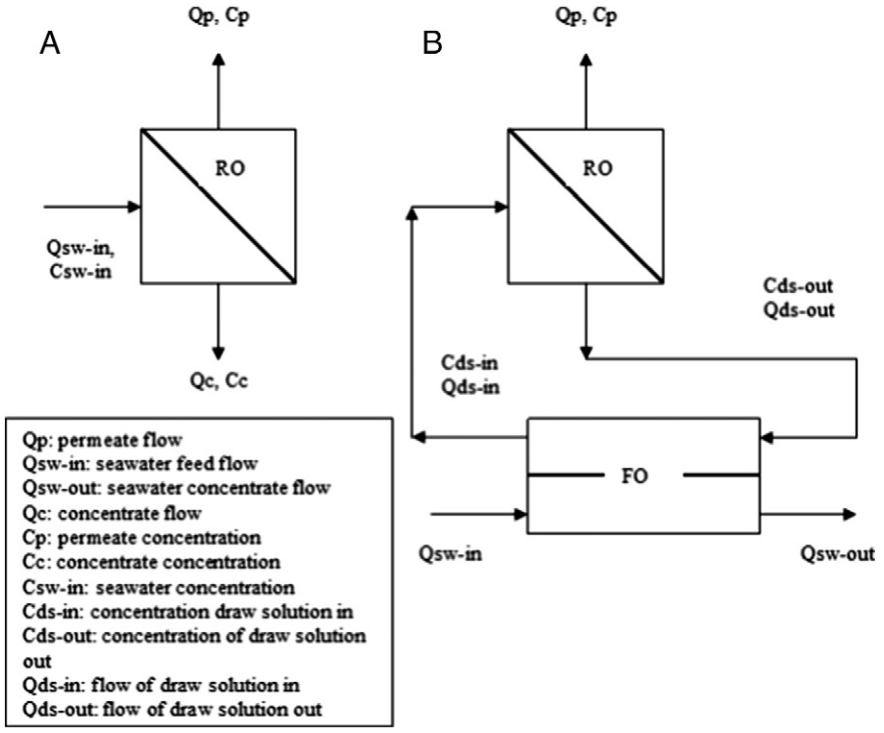

Fig. 1. RO and FO–RO processes diagram.

With the emergence of Forward Osmosis technology, scientists conceived the idea that the cost of desalination could be reduced. However, the cost of desalination by FO process is affected by a number of factors such as type of FO membrane, concentration of the draw solution, type of draw solution, and the regeneration process [16,17]. Elimelech and co-workers proposed using ammonium carbon dioxide as a draw solution for seawater desalination [17,18]. The MD process, then, was used for the regeneration of the draw solution because of the lower evaporation temperature of ammonium carbon dioxide compared to water. The impact of concentration polarization on the efficiency of the FO was investigated and found to be more serious when the draw solution was facing the support layer while the feed solution is facing the membrane active layer [19]. Abdulsalam and Adel suggested a two-stage seawater desalination process using FO process in the first stage and NF process in the second stage [20]. In this case, multivalent chemical compounds such as $MgCl_2$, Na_2SO_4, or $MgSO_4$ were proposed as the draw solution due to their high rejection by the NF membranes. Shung and co-workers used magnetic nano-particles coated with hydrophilic polymers as a draw solution in the FO process. Although the magnetic nano-particles exhibited high osmotic pressure, regeneration was a problem due to the agglomeration of nano-particles [21]. Hydrogel polymers were proposed as a draw solution in the FO process because of their high osmotic pressure. Water flux across the FO membrane increased when carbon nano-particles were added but the excessive addition of carbon nano-particles resulted in a flux reduction [22]. It should be noted here that the cost of draw solution must be added to the total cost of the desalination. Regeneration is the most expensive stage in the FO process for seawater desalination regardless of the type of draw solution used and hence it will determine the overall cost of the desalinated water.

Most of the previous studies were focused on the evaluation and optimization of the FO process through the membrane, while little attention was paid to the performance of the entire desalination system which includes the FO and the regeneration processes. In principle, FO only produces a concentrated solution which requires further treatment before it can be used for human applications. Fresh water is extracted from the draw solution in the regeneration process, which has been identified as the most expensive stage in the FO desalination. The specific power consumption in the regeneration process should be added to the total power consumption of seawater desalination by FO. In the current study, RO was chosen for the regeneration of draw solution because of its high efficiency and suitability to treat different types of draw solutions. A comparison between the RO and RO-FO systems was carried out using developed RO and FO software models [23,24]. Reverse Osmosis System Analysis (ROSA6.1) was used to model the RO process. The effect of seawater TDS on the RO and FO-RO processes was evaluated. Typically, the recovery rate in RO does not exceed 50% for low salinity seawater because of the scaling problems. However, this is not an issue in FO because of the high purity of the draw solution. Thus, the recovery rate of the RO in the FO-RO process can be increased over 50%. NaCl and $MgCl_2$ were used as draw solutions because of their high solubility in water, high osmotic pressure, and high rejection by RO membranes.

2. Methodology

FO seawater desalination is a multistage process. In the first stage seawater is treated by the FO process and generates a diluted draw solution while in the second stage fresh water is extracted from the draw solution in the regeneration process. In the current study, the performance of FO process was estimated from a developed model to

Table 1
Seawater composition.

SW TDS (mg/L)	Ion concentration mg/L							
	K	Na	Mg	Ca	HCO_3	Cl	SO_4	SiO_2
32,000	354	9854	1182	385	130	17,742	2477	0.9
35,000	387	10,778	1293	421	142	19,406	2710	1.0
36,000	398	11,086	1330	433	146	19,960	2787	1.0
38,000	419	11,663	1399	456	154	20,999	2932	1.0
40,000	441	12,278	1473	480	162	22,105	3086	1.1
45,000	496	13,812	1657	539	182	24,868	3472	1.2