Desalination 326 (2013) 19–29

Contents lists available at ScienceDirect

Desalination

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

A novel Forward osmosis membrane pretreatment of seawater for thermal desalination processes

Ali Altaee [a,*], Abdelnasser Mabrouk [b], Karim Bourouni [c]

[a] Faculty of Engineering and Physical Sciences, University of West of Scotland, Paisley, PA1 2BE, UK
[b] Engineering Science Department, Faculty of Petroleum & Mining Engineering, Suez University, Suez, Egypt
[c] Maître Assistant à l'ENIT, Département de Génie Industriel, 1012 Tunis, Tunisia

HIGHLIGHTS

- FO pretreatment of SW to thermal desalination was suggested.
- FO–MSF/MED design was optimized.
- Model for FO process was developed.
- $CaCO_3$ scale model was developed.
- FO model coupled with VDS program to calculate thermal plant performance.

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form 9 July 2013
Accepted 10 July 2013
Available online 3 August 2013

Keywords:
FO membrane softening
Seawater pretreatment
Thermal desalination
Scale removal

ABSTRACT

The present work introduced a novel conceptual design of integrating Forward Osmosis (FO) membrane with the Multi Stage Flashing (MSF) or Multi Effect Distillation (MED) thermal desalination processes. A simple mathematical model was developed here to estimate the performance of the FO membrane system. A previously developed program, VDS, for estimating the performance of thermal processes was updated to include the FO system. The verified VDS program [1] was applied to simulate the performance of the FO–MSF/MED hybrid system at different recovery rates varied from 16% to 32%. Brine reject from the thermal desalination processes was recycled and used as a draw solution to reduce the cost of FO membrane pretreatment. Seawater was used as the donor solution in the FO membrane. The simulation results showed that the FO pretreatment, successfully, reduced the concentration of multivalent ions in the feed solution to the MSF and MED. It was found that the concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} ions, which are responsible for scale problem in MSF, decreased with increasing the recovery rate of FO membrane. In case of FO–MED hybrid system, the thickness of the $CaCO_3$ scale layer was calculated at different FO recovery rates. The estimated thickness of $CaCO_3$ scale layer was 74 μm, 43 μm, and 39 μm for 0%, 20%, and 32% FO recovery rate respectively. It was also found that the thickness of $CaCO_3$ scale layer decreased in the direction from effect 1 to effect 6 due to temperature drop. Finally, the study demonstrated the feasible application of FO membrane in the pretreatment of seawater to reduce the concentration of multivalent ions which are responsible for the scale problem in the thermal desalination processes.

1. Introduction

Thermal desalination processes have been used in seawater desalination in the region of the Middle East since the early sixties of the last century [1]. The current worldwide market share of the thermal desalination processes is about 35% while RO membrane technology represents 61% [2]. However, the market share in Gulf Cooperation Council (GCC) countries showed that thermal technologies represent 70% and RO membrane technology covers the remaining cake. This situation reflects the thermal process maturity for large capacity production with high purity. The harsh gulf seawater property (high temperature, high salinity, high impurity and sometimes red tide) increases the cost of RO membrane replacement and pretreatment cost [2].

Multi stage flushing (MSF) and Multi Effect Distillation (MED) are the major thermal technologies for seawater desalination and fresh water supply in a number of countries in the Middle East. Despite the high efficiency of the thermal processes, they suffer from an essential drawback represented in the deposition and accumulation of scale materials on the surfaces of heat exchangers [3–5]. Normally, none-alkaline scale is deposited on the internal pipe surfaces in the MSF while alkaline scale deposit was reported on the external surface of heat exchangers in

* Corresponding author. Tel.: +44 7986517994.
E-mail address: ali.altaee@uws.ac.uk (A. Altaee).

0011-9164/$ – see front matter.
http://dx.doi.org/10.1016/j.desal.2013.07.008

the MED [4–6]. Scale deposition in thermal processes is renown of reducing the heat transfer efficiency in the evaporator and hence the process efficiency [4,6]. To avoid this problem, antiscalants are normally dosed into the feed water to the thermal processes. In real life scale deposition can't be completely avoided even when antiscalants is used and hence mechanical and chemical cleaning is often applied to clean the fouled parts. Furthermore, scale deposition restricts the Top Brine Temperature (TBT) increase beyond the precipitation point of the inversely soluble metal ions. Accordingly, the TBT's of MSF and MED cannot exceed 112 °C and 65 °C respectively [4,7,8].

In the nineties of past century, Ata and co-workers suggested the application of Nanofiltration membranes (NF) for the removal of multivalent ions from feed water to the thermal desalination processes [3,4]. NF membranes have the ability to remove divalent ions from seawater which are responsible for scale deposition in thermal units such as Ca^{2+}, Mg^{2+}, and SO_4^{2-}. Pilot and bench scale experiments showed the feasibility of NF pretreatment in the removal of scale ions from seawater and hence it was possible for the MSF unit to operate at TBT's over 112 °C [3,4]. At higher TBT's, the Gain Output Ratio (GOR) of MSF was increased over 8. Further research on NF pretreatment proposed a partial dilution of the feed solution to the thermal desalination processes with NF permeate in order to reduce the pretreatment cost. The pilot plant tests demonstrated more than 75% removal of scale ions from the seawater feed to the thermal desalination processes. After scrutiny, however, it was found that the cost of NF was uneconomical even at NF recovery rate more than 65% [7]. Technical problems were also reported with the NF pretreatment of seawater in Sharjah pilot plant test, UAE [7]. Therefore, the divalent ions removal from seawater by NF would only be possible if the cost of membrane pretreatment is reduced.

The techno-economic analysis of integrating NF pretreatment for the existing multi stage flash-brine recirculation (MSF-BR) and newly developed MSF-DM configurations was evaluated [8]. The cost analysis showed the unit product cost was 5 % higher than that conventional MSF (at 110 °C) due to the additional capital cost of NF system. When NF system was integrated in a new desalination plant configuration NF-MSF-Deaeration and Brine Recycle (NF-MSF-DM) at TBT = 130 °C, the gain output ratio was as high as 16, i.e. double the convention MSF-BR. The new NF-MSFDM configuration significantly reduced the unit's input thermal energy to suit the use of (the relatively expensive) solar energy as a desalination plant driver. On the other hand, the levelized water cost of NF-MSF-DM (at TBT = 130 °C) is 14% lower than conventional MSF (at 110 ° C) at the current oil price 104 $/bbl [8].

In light of the recent development in the membrane filtration technologies, the cost of seawater pretreatment can be reduced if FO membranes were used instead of NF. The novel application of FO membrane for seawater filtration requires; firstly, retrofit FO system to the thermal desalination unit in a hybrid system. Secondly, to find a suitable draw solution that would maintain the low cost of FO pretreatment and reduces waste discharge to sea. Fortunately, the current FO membranes exhibit high water permeability and rejection rate which make them an ideal solution for seawater pretreatment. The objective of the current paper is to introduce a hybrid FO-thermal desalination system which is designed to remove scale elements from sweater to the thermal units and hence reduces scale deposition. The performance of the thermal evaporator will be evaluated after introducing the FO pretreatment. The scale deposition on the thermal unit will be estimated by using special software to predict the precipitation on inversely soluble metal ions on the heat exchangers.

2. Conceptual design of FO-thermal hybrid system

The main purpose of FO-Thermal hybrid system is to alleviate the scale problem in the thermal desalination plants and hence reduces the system shutdown period. In the pretreatment process, FO membrane is in charge of seawater softening i.e. the removal of divalent ions which are responsible of scale deposition on the heat exchangers. As discussed before, the driving force in FO is the osmotic pressure gradients between the draw and feed solutions. Different compounds such as ammonium carbon dioxide, magnesium sulfate, magnesium chloride, sodium chloride and many other chemicals were used as draw solutions. The cost of the draw solution will be added to the overall cost of FO treatment. Reverse ions diffusion and osmotic agent losses during the regeneration process will increase the cost of FO treatment [9,10]. The regeneration process can't guarantee a complete recycle of the osmotic agent and residue of ionic species, such as ammonium, in the product water is extremely undesirable [9]. Therefore, a careful selection of the draw solution will determine the success of FO seawater pretreatment from thermal desalination processes. Accordingly, it is proposed here to use the brine reject from the thermal desalination plants as a draw solution for the following reasons:

1. to reduce the cost and chemicals use in the FO process;
2. to reduce the amount of brine waste to discharge to sea; and
3. to reduce the intake seawater feed.

The implementation of the new FO–MSF/MED design concept will increase the attractiveness of the FO pretreatment process. In the present paper, a two novel configurations of hybrid FO with MSF and MED respectively are developed and proposed as shown in Figs. 1 and 2.

In case of FO–MSF hybrid system, it should be noted here that most of the MSF plants are operated in brine recycle mode. In such design, the brine reject is recycled back to the evaporated after mixing with the make-up from seawater feed. The make-up ratio depends on the MSF capacity, TBT, and recovery rate. For example, for seawater feed has 3.5 g/L TDS, 110 °C TBT, and recovery rate 31% the estimated make-up ration is about 10% of the total feed flow. These data were estimated by the VDS program for seawater desalination [2,8]. Typically, the concentration of the brine solution from the MSF plant is 30% higher than the seawater; this provides enough osmotic pressure gradients for FO operation. Usually, the temperature of brine reject is higher than the seawater. This will increase the osmotic pressure of the draw solution according to the following equation:

$$\Pi = nCRT \tag{1}$$

Π is the osmotic pressure (bar), n number of ions, C is the molar concentration of solution, R is the gas constant, and T is the temperature (Kelvin). Fig. 1 shows a schematic diagram of the FO–MSF system. There are two options to feed seawater into the FO–MSF hybrid system. In the first option; seawater goes to FO first then to the heat rejection unit in MSF while the second option is to feed seawater into the heat rejection unit before it goes into the FO membrane system. The former option suits our design better because the feed temperature of seawater will be higher after leaving the heat rejection unit and this will increase its osmotic pressure according to Eq. (1). Therefore, Seawater is fed into one side of the FO membrane while the MSF brine reject is fed on the other side of the membrane in a concurrent flow mode. Due to the osmotic pressure difference across the FO, fresh water will cross the membrane from the seawater to the brine reject (draw solution) side. After leaving the MSF, seawater is sent to the heat rejection unit in the MSF plant before it is discharge to the sea. The diluted draw solution from the FO system will be the feed to the MSF. Inside the MSF, the feed solution is heated up to 110 °C and fresh water is extracted by evaporation while the concentrated brine is recycled to the FO membrane.

Fig. 2 shows a novel hybrid FO–MED configuration. The brine of the last effect is recycled and diluted with FO membrane permeation. The diluted brine is then used as make up feed to the evaporator. The