Journal of Membrane Science 443 (2013) 201–209

Contents lists available at SciVerse ScienceDirect

Journal of Membrane Science

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

Evaluation of scaling potential in a pilot-scale NF–SWRO integrated seawater desalination system

Yuefei Song, Xueli Gao*, Congjie Gao

Key Laboratory of Marine Chemistry Theory and Technology of Ministry of Education, College of Chemistry & Chemical Engineering, Ocean University of China, 238 Songling Road, Qingdao 266100, China

ARTICLE INFO

Article history:
Received 11 January 2013
Received in revised form
23 April 2013
Accepted 24 April 2013
Available online 2 May 2013

Keywords:
Scaling evaluation
Nanofiltration
Integrated membrane system (IMS)
Concentration polarization
Supersaturation index (*SI*)

ABSTRACT

Pilot-scale experiments were carried out on a nanofiltration (NF)–seawater reverse osmosis (SWRO) integrated membrane system (IMS) to evaluate scaling potential on NF and SWRO membrane surface using a kind of loosen NF membrane and costal seawater. The effect of NF permeate recovery (R_{NF}) increasing on the occurrence of scaling in the NF and SWRO module was investigated in term of concentration polarization modulus (*CP*) of scalant ions, Stiff and Davis Stability Index (*S&DSI*), as well as Supersaturation Index (*SI*) of $CaCO_3$ and $CaSO_4$. The results show that the salt rejection by the loosen NF module is only about 10%, while the rejection of SO_4^{2-} is higher than 95%; *S&DSI* is always less than zero, indicating that $CaCO_3$ scaling could not form on the NF membrane surface when R_{NF} was less than 35%. $CP_{SO_4^{2-}}$ is much higher than $CP_{CO_3^{2-}}$; and at R_{NF} of higher than 30%, *SI* of $CaSO_4$ on NF membrane surface increased gradually higher than 1.0, which indicated that $CaSO_4$ scale is more apt to form on the NF membrane surface than $CaCO_3$ at that NF permeate recovery. This scaling sequence in the loose NF module was different from that in traditional SWRO desalination processes.

1. Introduction

Water recovery of seawater reverse osmosis (SWRO) desalination process usually lies between 30% and 40% [1], and it is one of key design parameters which determine the scale and cost of SWRO desalination system. Higher water recovery will result in smaller installation size of the desalination system and less capital and operating costs. However, the increase of water recovery may cause severe scaling of inorganic substances on membrane surface and thus SWRO systems require much frequent membrane cleaning and replacement [2,3].

Many efforts have been made recently to increase the water recovery of SWRO process while avoiding membrane scaling. Shammiri and Dawas [4] found that when adjusting the feed pH from 7.2 down to 7.0, although no scale inhibitor was dosed, the water recovery of SWRO plant could safely increase from 22.5% up to 34.2%, without any danger of scaling on membrane surface. Kurihara and coworkers [5–7] adopted a brine conversion system (BCS) in a two-stage SWRO desalination system and they achieved an overall water recovery of above 60%. Kim et al. [8] applied a two-stage RO process for seawater desalination on a 5 m^3 h^{-1} pilot plant with MF as pretreatment and they successfully increased the water recovery from 30% up to 50%.

With the increase of SWRO water recovery, the concentration of scale-forming species may beyond their solubility limits, and precipitation (scaling) may form on RO membrane surface [9]. The most common constituents of these scales are $CaCO_3$ and $CaSO_4$ [10]. Scaling not only reduces permeate flux of SWRO membranes, but also increases pressure drop along the membrane element. In addition, severe scaling may damage SWRO membranes due to irreversible plugging of membrane surface. Therefore, avoiding scaling is an important consideration in the operation of SWRO processes.

Scaling can be prevented by several methods [11,12]. When the main scaling ingredient is $CaCO_3$, the feed water should be acidified in advance to convert part of carbonate and bicarbonate to carbon dioxide, until a negative Stiff and Davis Stability Index (*S&DSI*) is achieved in the SWRO brine. Another method is by using scale inhibitor to alter the physico-chemical nature or the growth mechanisms of the precipitation and prevent the formation of scaling, until the brine stream leaves the RO system.

Currently, advance in membrane technology and increasing requirements on water quality have stimulated the investigation and application of nanofiltration (NF) for seawater softening. NF membrane is usually negatively charged and has unique separation characteristics of preferentially rejecting divalent ions which are prone to scaling. Much research work has been carried out to use NF membrane for seawater softening recently. Saline Water Conversion Corporation (SWCC) of Saudi Arabia had carried out profound pilot and demonstrative investigation on application

* Corresponding author. Tel./fax: +86 532 66782017.
E-mail address: gxl_ouc@126.com (X. Gao).

0376-7388/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.memsci.2013.04.048

of NF membranes for seawater softening to supply feed water to SWRO, and they concluded that NF membranes exhibited excellent performance in seawater softening process [3]. SWCC further investigated on the application of NF as pretreatment to a power/RO/MSF hybrid system to reduce energy requirements and operating costs [2,3,13]. Drioli et al. [14] also investigated seawater softening pretreatment using NF300 membrane and they successfully increased the water recovery of a single RO vessel up to 50%.

However, with the operation of NF seawater softening process, there is also scaling potential of inorganic substances on NF membrane surface due to the supersaturation of some scalant ions in NF retentate. Performance of NF membranes would be limited due to the scaling problems of these ions on the membrane surface. Nevertheless, until now, relatively few research work was focus on this subject [15], and almost all the designers followed the manufacturer recommended recovery which was usually limited to below 15% for a single NF membrane element.

In this study, we use an ultra-low-pressure and high-selectivity NF membrane element for seawater softening in a UF–NF–SWRO integrated membrane system (IMS), and we suggested that the manufacturer's recommendation of 15% recovery should be reconsidered for low-pressure membrane. The aim of this study is to investigate the effect of increasing NF permeate recovery on the scaling potential of the sparingly soluble $CaCO_3$ and $CaSO_4$ on membrane surface of NF element with the absence of NF retentate recirculation and chemical dosage. Meanwhile, the coupling scaling potential in RO membrane element was also investigated.

2. Material and methods

2.1. Experimental

Membrane scaling evaluation experiments were conducted from May to June 2011 with a pilot-scale UF−NF−SWRO integrated membrane system using costal seawater of Qingdao Jiaozhou Bay, the Yellow Sea of China. The raw seawater quality parameters such as SDI_{15}, turbidity, TDS, hardness, as well as the main ions concentration, were shown in Table 1. The pilot-scale unit with a capacity of 5 $m^3\,d^{-1}$ consists of a UF system, a NF system, and a SWRO system. As shown in Fig. 1, raw seawater was firstly pumped through a sand filter by diving pump to the UF system, then the UF filtrate was further pumped to the NF system by a high-pressure pump at 0.7–2.0 MPa. The NF softened water was then fed to the SWRO unit at 4.4 MPa during the IMS pilot experiments.

Once-through mode NF experiments were carried out at constant inlet cross-flow velocity of 0.05 $m\,s^{-1}$, while neither permeate nor retentate of the NF module was recirculated back to the feed tank, and neither acid nor antiscalant was dosed in the feed solution as well. All the operating conditions of the NF membrane were kept at temperature of 16 ± 1 °C and pH of 7.8 ± 0.1. And we enlarged the NF permeate recovery to 20%, 25%, 30% and 35%.

For clarification, the NF permeate recovery (R_{NF}), the SWRO water recovery (R_{RO}) and the overall IMS system recovery (R_{IMS}), were defined in Eqs. (1)–(3), respectively.

$$R_{NF} = \frac{Q_{p,NF}}{Q_{f,NF}} \tag{1}$$

$$R_{RO} = \frac{Q_{p,RO}}{Q_{p,NF}} \tag{2}$$

$$R_{IMS} = \frac{Q_{p,RO}}{Q_{f,Overall}} \tag{3}$$

where Q is the flow rate; subscripts p and f refer to the permeate and the feed stream of each system. R_{IMS} and R_{RO} are only used for understanding the recovery, and our research focus is just on R_{NF}.

Each pilot test lasted continuously for at least 2 h to reach a steady state and then the permeate, retentate and feed samples of the NF and SWRO modules were taken. Before each sampling, at least 1 l solution was discharged to assure sampling accuracy; and after that, another 2 l solution was sampled for each stream. Then operating parameters including pressure, temperature, pH, flow rate of feed water, retentate and permeate for UF, NF and SWRO modules, respectively, were recorded. After each sampling, NF membrane was flushed three times using SWRO water for 20 min at cross-flow velocity of 0.072 $m\,s^{-1}$ to remove any impurities on the membrane surface. Then, NF permeate recovery was adjusted to another certain value by regulating the frequency of high pressure pump and the flow rate of retentate stream for another pilot test. The pressure drop in the NF and SWRO module during the experimental process were lower than 0.05 MPa.

2.2. Membranes

The membranes used in this study include one tight UF membrane (HF-1500, Lanlu), one ultra-low pressure NF membrane (ESNA3, Hydranautics), and one SWRO membrane (SW30, Dow Filmtec).

HF-1500 UF membrane module with MWCO of 20,000 Da was used as pretreatment of NF to remove suspended solids and large molecular weight organic matter in raw seawater. All the operating parameters of the UF unit were optimized in our prior research work [16] and were kept constant in this study. The quality of the UF filtrate was shown in Table 2.

ESNA3 membrane is a kind of ultra-low-pressure NF membrane which has great advantage for the selectivity of divalent ions over monovalent ions. And according to our former investigation, the ions selectivity of ESNA3 membrane lies in the range of 3.9 and 4.8, which is higher than those of other commercial NF membranes [16]. This makes it a viable option for seawater softening treatment. Meanwhile, it could achieve high flux and high permeate recovery with considerably low feed pressure, which could reduce energy consumptions and operating costs as well.

SW30 membrane has high salt rejection and it is a suitable SWRO membrane. The pure water fluxes of the HF-1500 UF, ESNA3

Table 1
Quality of the raw seawater of Jiaozhou Bay.

Parameters	Values	Parameters	Values
Turbidity (NTU)	8–40	K^+ (mg L^{-1})	363–405
SDI_{15}	> 6	Na^+ (mg L^{-1})	9260–11451
TDS (mg L^{-1})	31,527–35,562	Ca^{2+} (mg L^{-1})	372–419
Fe and Al oxides (μg L^{-1})	8–10	Mg^{2+} (mg L^{-1})	1150–1325
Total hardness (mg L^{-1})	3190–3480	Cl^- (mg L^{-1})	17,500–19,565
Total alkalinity (10^{-3} mol L^{-1})	1.95–2.26	SO_4^{2-} (mg L^{-1})	2100–2396
Activity of SiO_2 (mg/L)	0.36–0.90	HCO_3^- (mg L^{-1})	118–139