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Review

Development of lower cost seawater desalination processes using nanofiltration technologies — A review

Dong Zhou [a,b], Lijing Zhu [a,*], Yinyi Fu [a], Minghe Zhu [b], Lixin Xue [a,*]

[a] *Polymer and Composite Division, Key Laboratory of Marine Materials and Related Technologies, Zhejiang Key Laboratory of Marine Materials and Protective Technologies, Ningbo Institute of Material Technology & Engineering, Chinese Academy of Sciences, Ningbo, Zhejiang 315201, PR China,*

[b] *Ningbo University, Ningbo, Zhejiang 315211, PR China*

HIGHLIGHTS

- The available data for the commercial NF membranes were listed for comparison.
- The integrating of NF with various types of desalination technologies was reviewed.
- The perspectives of lower cost seawater desalination were provided in the future.

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ABSTRACT

The implementation of seawater desalination, a key strategy to secure fresh water supply in arid and coastal regions, is greatly thwarted by its high cost relating to high energy and equipment cost associated with pressure and the high system or membrane fouling associated with the bi-valence ions in the sea water. Nanofiltration (NF), a lower pressure membrane process with high rejection for divalent ions, had been identified as a key component to reduce the costs relating to both pressure and fouling in the desalination process. Lower cost seawater desalination processes had been developed by integrating NF with various types of desalination technologies including reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED), multistage flash (MSF), multieffect distillation (MED), membrane distillation (MD) and ion exchange (IX). In this paper, after comparing the performance of currently available NF membranes, we attempt to review the recent progresses made in the development of lower cost seawater desalination processes using NF technologies and provide future perspectives for NF technologies.

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* Corresponding authors at: No. 1219, West Zhongguan Road, Zhenhai District, Ningbo, Zhejiang Province 315201, PR China.
E-mail address: xuelx@nimte.ac.cn (L. Xue).

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1. Introduction

Only about 0.5% of the overall global water is available as fresh water while seawater accounts for about 97% of them. Approximately 41% of the world population live in the arid regions, thus, fresh water shortage is becoming a worldwide problem [1–2]. Seawater desalination has become an important way to secure freshwater supply for lots of countries, such as the Gulf States, Spain and China [3–4], whose capacity is expected to reach about 100 million cubic meters per day in 2015 [5].

Thermal and membrane based processes have been developed for sea water desalination, including multistage flash (MSF), multieffect distillation (MED) and reverse osmosis (RO) [6–7]. Recently, the capacity of membrane based desalination processes (mainly RO) had surpassed thermal based processes (mainly MSF and MED), because of their lower operating and investment costs [5–10]. In the MSF and MED processes, plants usually cannot operate at more effective Top Brine Temperature (TBT) because of reactor scaling [15–16]. Although, great efforts have been conducted to improve the efficiency and reduce the energy consumption of desalination technology [2], the worldwide implementation of sea water desalination is still thwarted by its high operating costs associated with high system pressure and bivalent ionic fouling [11–16].

Nanofiltration (NF), an effective pressure-driven membrane process, has the pore size and cut off ability between RO and ultra-filtration [18–20]. Compared with RO, it operates not only under lower operation pressures, higher water fluxes, and lower investment, but also with high rejection rates for scale formation bivalent ions, especially anions [21–23]. With these characters, it is gaining its yards quickly in the seawater desalination field [25]. This paper compared the performance of currently available NF, reviewed the progresses made in the uses of NF in developing lower cost seawater desalination processes, and attempted to provide future perspectives for NF techniques in sea water desalination.

2. Performance of commercially available NF membranes

Due to the unique separation ability, NF technology has been developed for removing scaling ions and low-molecular-weight organics as well as part of the NaCl from seawater [26,27]. A lot of efforts have been devoted to evaluate their performance under different application conditions. Some of the currently available data for the commercial NF membrane are listed in Table 1 for comparison. It is obvious that the ionic rejection ratios of NF membranes varied greatly among the brands. Hilal et al. [28] investigated the desalination performance of three kinds of nanofiltration membranes NF90, NF270 (Dow Filmtec), and N30F (MICRODYN-NADIR) and found that the flux and salt rejection rate of NF90 and NF270 agreed well to the Spigler–Kedem model. It was suggested that NF90 might be the best choice for NaCl removal, having the highest rejection but medium permeates flux. Llenas et al. [29] evaluated the performance of six commercial NF membranes, NF270, NF200, NF90 (Dow Filmtec), K-SR2 (Koch), ESNA1-LF2 (Hydranautics), and NF99HF (Alfa Laval) and found all of them showed high rejection to divalent ions, especially sulfate ions. They suggested that NF270, K-SR2 and NF99HF membranes were more suitable for pretreatment in RO desalination. Song et al. [30] suggested that ESNA3 membrane was quite suitable for softening sea water while Pontié et al. [31–32] found that the use of NF200 membrane could bear potential system flaws under the conditions of high pressure and high salt concentration. Llenas et al. [33] also suggested that NF270, K-SR2 and NF99HF be suitable for removing scaling ions in seawater.

A lot of detailed studies were carried out for hardness ion concentration polarization, membrane scaling and organic fouling on the surface of NF membranes. It was found that organic fouling mostly occurred on the lead elements while inorganic scaling mostly occurred on the last elements [34]. A1-Amoudi et al. [35] successfully restored NF permeate flux after scaling using SDS (sodium dodecyl sulfate) cleaning and PH swinging methods. Song et al. [36] observed that ion rejection and permeate flux of ESNA3 declined with time due to inorganic fouling on the surface of NF membranes, and found that $CaSO_4$ scaling could form but $CaCO_3$ could not at high recovery rate. By scale inhibitor addition and pH adjustment, NF water recovery rates reached 60% without $CaSO_4$ scaling [37–38]. NF technology was an effective treatment process for removing most of divalent ions and reducing the TDS of seawater. Their stronger separation power for organics provides better protection for the safe operation of the next process.

3. Integration of NF in membrane based desalination processes

3.1. Dual stage NF desalination process

Asymmetric NF membranes with tight polyamide separating layer (such as NF90 and ESNA1) possessed high rejection ratios for both monovalent and bivalent ions. Based on this, Vuong [39–40] developed two stage NF–NF seawater desalination systems, effectively removing ions from seawater with 20% to 30% lower energy cost than conventional one-stage RO. It was reported that a fully operational NF–NF process has been established in a facility in Long Beach, United States with a daily water production of 1135 m^3 [41]. Harrison et al. [42] found that the average permeate TDS was less than 400 mg/L when the high rejection NF-90 was used in both stages. Altaee et al. [43] studied the performance of NF–NF desalination process with ROSA simulation software. At 35,000 mg/L feed salinity, the pressure of the first and second stages was 37 bar and 19 bar, and the recovery was 59% and 67%, respectively. The permeate TDS and energy consumption of the NF90–NF90 system was 254 mg/L and 3.35 kWh/m^3, respectively. Liu et al. [44] found that the operation pressure had the greatest effects on flux and TDS of permeate water in the NF90–NF90 system. In consideration of water quality and energy consumption, the dual-stage NF seawater desalination process was a promising seawater desalination technology.

3.2. Integrated NF and RO desalination processes

Integrating NF with RO desalination process may increases the complexity and cost of desalination plant. However, NF pretreatment had shown effectiveness in removing divalent ions and reducing osmotic pressure from the RO feed water, and integrated NF with RO could join the advantages from both kinds of membranes [45–46]. Hassan et al. [27,48] and Uhlinger [47] proposed the NF–RO low cost seawater desalination process, and showed that, at the low pressure of only 22 bar, the Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^- and total hardness rejection of NF were 89.4%, 94.0%, 97.8%, 96.6% and 93.3%, respectively, and the rejection rate of monovalent ions (Cl^-, Na^+) was 40.3%, achieving about 27% reduction in the net water production cost from one-stage SWRO.

It was also found that the permeate quality of NF was significantly affected by operating pressure, recovery rates, feed water quality, feed water temperature, and the number and combination of membrane element [49]. Hassan et al. studied a pilot device of 8 NF and NF–RO

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