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Study on seawater nanofiltration softening technology for offshore oilfield polymer solution preparation

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ABSTRACT

Nanofiltration (NF) is suitable for softening seawater and providing permeates with excellent quality for oilfield water injection. However, the industrial application of aqueous polymer solution prepared by NF softened seawater for oilfield polymer flooding has not been reported yet. In this work, a pilot-scale ultrafiltration (UF)–NF integrated membrane system (IMS) has been investigated as a method of removing divalent ions from seawater and providing softened water for oilfield polymer flooding. The performance of the selected NF 4040 spiral membrane module was investigated under different operating conditions. In addition, the performance of the NF membrane module at high system recovery was also investigated to simulate the practical situation. Finally, NF permeation waters were used to prepare HPAM polymer solutions to evaluate the possibility of preparing polymer solution with NF permeation water for polymer flooding in offshore oilfield. The results showed that, with the properly selected NF membrane, the operation factors and the order of membrane modules had little effect on its permeate quality, which could keep more than 90% removal rate for Ca^{2+} and Mg^{2+}. And NF2 membrane modules could provide good quality permeate for preparing polymer solution for polymer flooding in offshore oilfield.

Keywords: Nanofiltration seawater softening; Integrated membrane system; Offshore oilfield; Polymer solution preparation

1. Introduction

The limited life span of offshore platforms challenges operators to more effectively develop oil, thus various technologies including water injection, polymer flooding, and micellar polymer flooding, etc., should be adopted to enhance oil recovery (EOR) in offshore oilfield. Polymer flooding is an EOR method that uses water-soluble polymers to increase the crude oil recovery due to the improved sweep efficiency and displacement efficiency [1–3]. Polymer could reduce the mobility of aquifer phase to displace the remaining heavy oil [4].

As a mature EOR technology, polymer flooding is suitable for operation on offshore platform, because it does not require complex and additional surface facilities in the relatively limited platform spacing. The first

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offshore oilfield polymer flooding field trail in China was conducted in Bohai oilfield. It is estimated that about 70% crude oil in Bohai Bay, China, is heavy oil, and currently, the oil recovery by water flooding is around 20% of the original oil in place (OOIP) [5], and most of oil still remains in the reservoir. Polymer flooding has been studied for more than 10 years and has been designed and conducted in the early stage of oilfield development of the Bohai oilfield for improving heavy oil recovery since 2003. During the successful implementation of polymer flooding in a single-well injection, a hydrophobic associating polymer was applied as the driving agent and significant increment of oil was obtained [5]. The research results indicate that polymer flooding at the early development stage of the Bohai Oilfield is feasible [7] and could effectively drive oil recovery up. Based on the encouraging result of oil recovery increment in single-well pilot test, the polymer flooding was expanded to a larger pattern in October 2005 [6].

Seawater is the most convenient and abundant water resource for offshore oilfield. However, there is very high salinity and hardness (calcium and magnesium ions) in seawater, which could greatly reduce the viscosity of the polymer solution, especially for the commonly used anionic hydrolyzed polyacrylamide (HPAM) polymer in oilfield [8]. So the viscosity of the polymer solution prepared by seawater cannot meet the requirement of polymer flooding. This has long been confirmed by the investigation on polymer solutions prepared by seawater to enhance oil displacement efficiency in North Sea oil reservoirs, during which over 140 polymers have been evaluated for viscosity retention and porous media flow performance under high temperature (90˚C), high salinity, and high pressure, and the results showed that using polymers to enhance seawater injection processes is not practical [9].

Water quality has a direct impact on the performance and success of polymer flooding to enhance oil recovery. Salinity of the water greatly impacts the viscosity of polymer solution used in EOR application [10]. As a result, seawater softening is the key to the success of polymer flooding for effective oil recovery. Recent studies have shown that by using low-salinity feed water, the polymer consumption in polymer EOR projects required to achieve an ideal viscosity can be 5–10 times lower than when compared to seawater [11]. A high-level facility engineering study has been performed to assess the cost savings associated with low-salinity water in offshore polymer flooding [12]. The results of the study show that polymer flooding with low-salinity water is economically more beneficial compared with seawater polymer flooding. It could be possible to pay out the incremental desalination costs within a 4-year project time frame due to the large savings associated with chemical costs and polymer facilities costs in low-salinity polymer flooding. It indicates that low-salinity water flooding can synergize well with polymer flooding to drive down the cost and drive up the oil recovery. However, conventional seawater desalination methods provide almost fresh waters that could be incompatible with resident reservoir clays and hence may not be suitable for direct injection into the reservoir. In addition, the common methods used for seawater softening such as ion exchange and chemical softening are complicated to operate and require too much space, as well as consuming a lot of acid and alkali and producing large amount of sludge, which is very inconvenient in the oil production platforms [13].

Nanofiltration (NF) is a relatively new membrane technology that has unique selective separation characteristic of divalent ions as well as multivalent ions; and therefore, it is suitable for seawater softening and can provide permeate with excellent quality for oilfield with very low content of scaling forming ions [14,15]. There have been reports on research and applications of NF membrane technology to soften seawater for water flooding. For example, Marathon Oil has successfully applied NF membrane as a possible means to solve scaling problem for water flooding on the Brae Field [16,17]. However, the industrialized application of aqueous polymer solution prepared by using NF softened seawater has not been reported yet.

In this work, a pilot-scale Ultrafiltration (UF)–NF integrated membrane system (IMS) has been investigated as the method of removing divalent ions from Jiaozhou Bay seawater and providing softening water for offshore oilfield polymer flooding. The performance of the selected NF−4040 spiral membrane module has been investigated under different operating conditions. In addition, to simulate the practical situation in industrial applications, the performance of the NF membrane module has been investigated at high system recovery. And the viscosity value of polymer solutions prepared with different NF permeate at different temperature have also been investigated.

2. Materials and methods

2.1. Membranes

The UF device consists of two commercial hollow fiber membrane modules in parallel, with the molecular weight cutoff (MWCO) of 20 k Dalton (Da) and 100 k Da, respectively. Two types of 4-inch commercial spiral wound NF membrane modules which

Table 1
Performance parameters of the UF modules used in the test

Items	UF1	UF2
Membrane material	Polyether sulfone (PES)	Polysulfone (PS)
Effective membrane area (m^2)	8	8
Molecular weight cutoff (kDa)	100	20
Pore size (μm)	0.025	0.01
Highest inlet water temperature (℃)	50	50
Highest operating pressure (MPa)	0.2	0.2
pH range	2−11	2−11

Table 2
Performance parameters of the NF modules used in the test

Items	NF1-4040	NF2-4040
Membrane module	Spiral wound	Spiral wound
Separation layer material	Polyamide	Polyamide
Effective membrane area (m^2)	7.9	7.6
Rejection rate (%)	>25%	>97%
Highest inlet water temperature (℃)	45	45
pH range	3−10	2−11
Highest operating pressure (MPa)	4.14	4.14
Highest inlet water turbidity (NTU)	1	1
Highest inlet water SDI	5	5

numbered as NF1 and NF2 were tested, respectively. The characteristics of the UF and NF membranes according to the membrane manufactures are shown in Tables 1 and 2, respectively.

2.2. Experimental procedure

UF is compact of space, simplicity of operation, and ease of maintenance. And most of all, it could continuously provide water with low turbidity and SDI value for NF membrane. So that UF was selected as the pretreatment process of NF for offshore platform application. The schematic process flow diagram of the IMS and pictures of the setup are shown in Figs. 1 and 2, respectively.

Seawater from Jiaozhou Bay after pretreated by sand filter and cartridge filter was fed to the UF module, and then, the UF filtrate was pumped into the NF setup to obtain NF permeate for further investigation on the feasibility of water and polymer flooding.

2.3. Polymer solution preparation

A commonly used partially HPAM with the average molecular weight of 23–26 million Da was provided by the CNOOC Energy Technology and Services Co., and was selected to investigate the viscosity of the polymer solution prepared by different NF permeate water. The HPAM solution is prepared at a concentration of $1,500\,\mathrm{mg\,L^{-1}}$ under 25℃ with stirring velocity of $200\,\mathrm{r\,min^{-1}}$.

2.4. Analytical methods

The turbidity was measured by turbid meter. The silt density index (SDI) value was measured by SDI monitor. The content of all kinds of ions in water was analyzed by Ion Chromatography. The conductivity and pH were measured by conductivity meter and precision acidity meter, respectively.

The rejection, R_{ej}, and the flux, J_v, are calculated using Eqs. (1) and (2):

$$R_{ej} = (1 - c_p/c_f) \times 100\% \quad (1)$$

$$J_V = \frac{Q}{A} \quad (2)$$

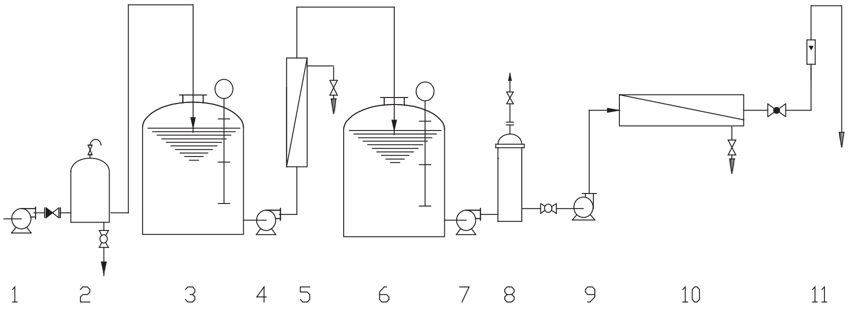

Fig. 1. Schematic flow diagram of the IMS for NF softening seawater preparation: 1, 4, 7–low-pressure pump; 2–sand filter; 3, 6–water tank; 5–UF module; 8–cartridge filter; 9–high-pressure pump; 10–NF module; 11–flowmeter.

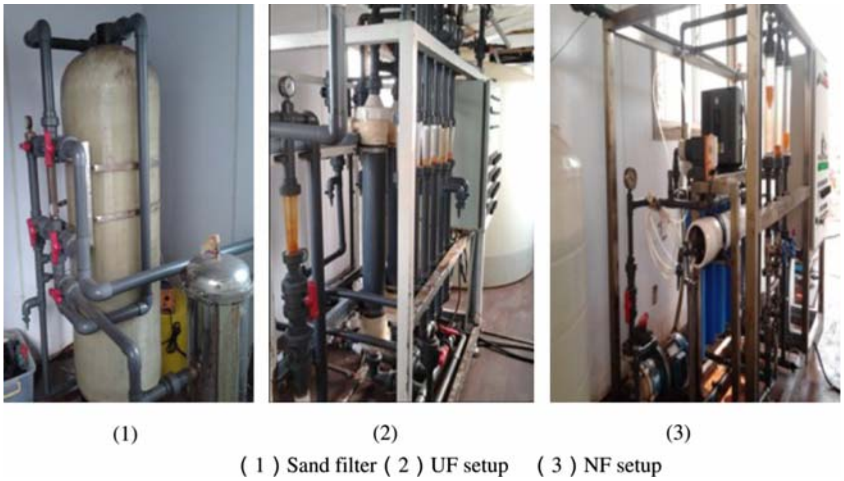

Fig. 2. Photos of the pilot integrated membrane system.

where c_p and c_f are the solute concentrations in the permeate and feed sides, respectively. Q is the volume flow rate of the permeate water, and A is the effective membrane area of the membrane module.

Two different water recovery rates termed as the system water recovery rate (R_{ec}) and the actual membrane module water recovery rate (R'_{ec}), are calculated using Eqs. (3) and (4):

$$R_{ec} = \frac{V_P}{V_F} \tag{3}$$

$$R'_{ec} = \frac{Q_P}{Q_F} \tag{4}$$

where V_p is total volume of permeate water, and V_F is the original volume of feed water in tank; Q_P is the volume flow rate of the permeate water, and Q_F is the volume flow rate of the influent water into the membrane module.

3. Results and discussion

3.1. Quality of UF permeate

During the whole experiment period, the turbidity range of original seawater was 5.1–14.9 NTU, with an average turbidity value about 9.3 NTU, the UF operating pressure was kept at 0.1 MPa and the UF system recovery was about 80%. The variation of the UF filtrate turbidity and SDI_{15} with time is shown in Figs. 3 and 4, respectively. All the turbidity values of the UF permeate are nearly 0 NTU, as shown in Fig. 3, which demonstrates that the UF membrane had excellent turbidity removal efficiency. Excellent

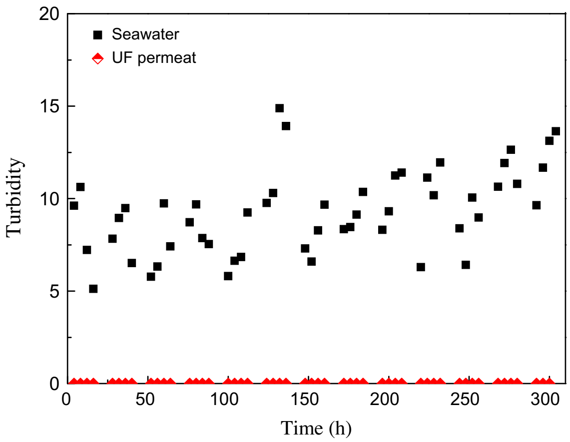

Fig. 3. Turbidity of the seawater and UF permeate at different operating time.

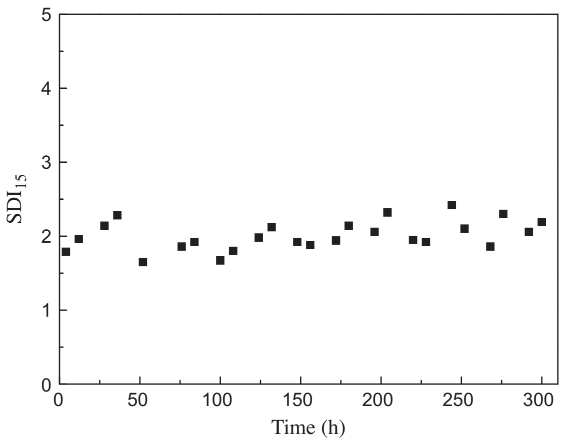

Fig. 4. SDI_{15} of the UF permeate at different operating time.

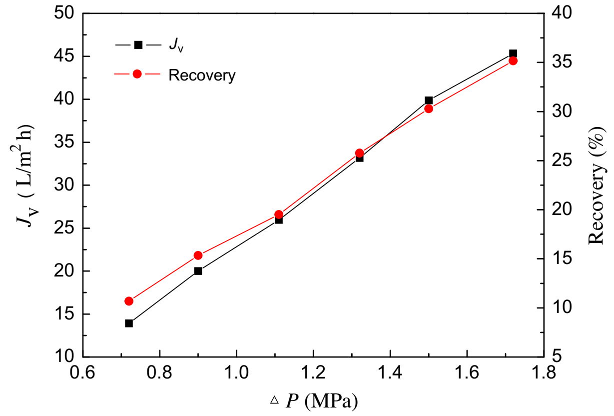

Fig. 5. Effect of operating pressure on NF1 flux and recovery (influent flow: 1,000 L h^{-1}).

quality of the UF filtrate could also be reflected by SDI_{15}. All the SDI_{15} values of the UF filtrate were less than 2.5, as can be seen from Fig. 4, which could meet the NF feeding requirement of $SDI_{15} < 5$. It can be seen that the UF pretreatment system could continuously and steadily provide qualified filtrate for NF system, despite of the original seawater quality.

3.2. Effect of operating factors on NF performance of the seawater softening process

3.2.1. Effect of operating pressure on NF performance

The flux and the R_{ec} of two types of NF membrane modules were investigated, respectively, under different operating pressure with the water inflow remaining unchanged. The results are shown in Figs. 5 and 6, respectively.

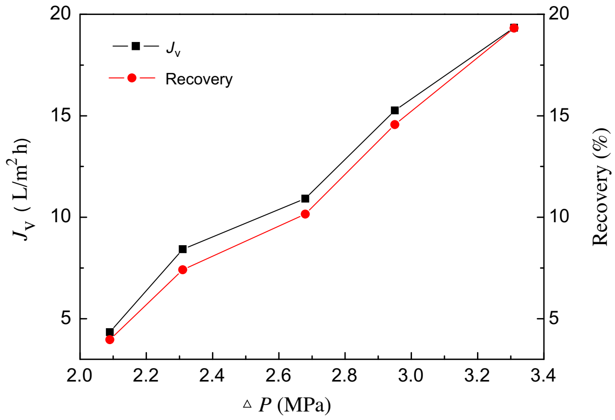

Fig. 6. Effect of operating pressure on NF2 flux and recovery (influent flow: 800 L h^{-1}).

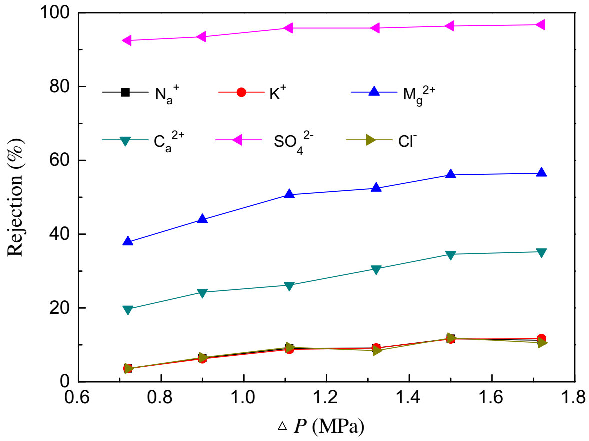

Fig. 7. Effect of operating pressure on ions rejection of NF1 (influent flow: 1,000 L h^{-1}).

It can be seen from Figs. 5 and 6 that both the flux and the R_{ec} increased linearly with the increase in the operating pressure. As shown in Fig. 5, with water inflow remaining 1000 L h^{-1}, when the operating pressure increased from 0.7 to 1.7 MPa, NF1 membrane flux increased from 13.92 to 45.32 L m^{-2} h^{-1}, and the R_{ec} increased from 10.7% to 35.2%. However, the increase in the operating pressure could also cause the increase in energy consumption and running costs of the system significantly.

As shown in Fig. 6, with water inflow remaining 800 L h^{-1}, when the operating pressure rose from 2.1 to 3.3 MPa, NF2 membrane flux increased from 4.18 to 18.6 L m^{-2} h^{-1}, and the R_{ec} increased from 3.96% to 19.32%. Compared with NF1 membrane, NF2 membrane had lower flux and recovery, which resulted in relatively high-energy consumption. It can also be seen that the flux and the R_{ec} of NF2

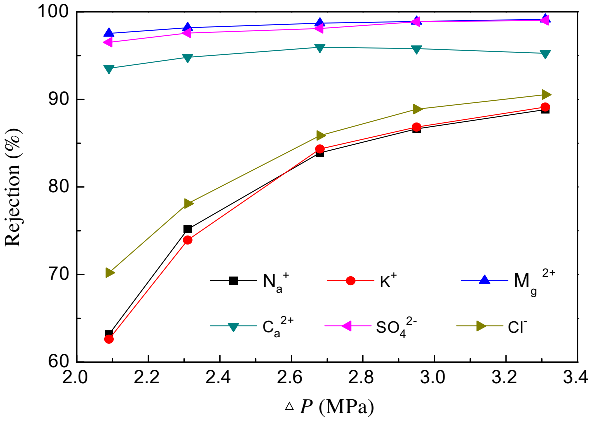

Fig. 8. Effect of operating pressure on ions rejection of NF2 (influent flow: 800 L h^{-1}).

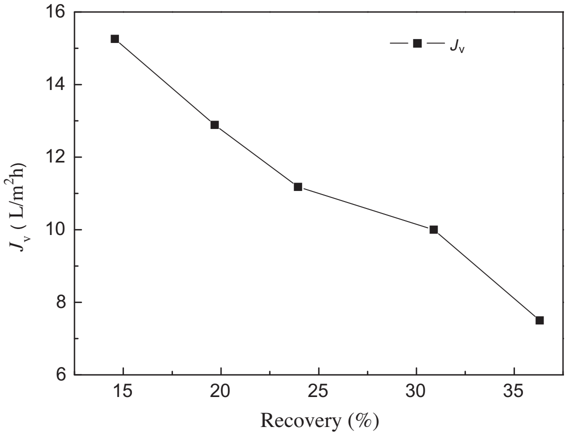

Fig. 9. Effect of recovery on NF1 flux (operating pressure: 3.0 MPa).

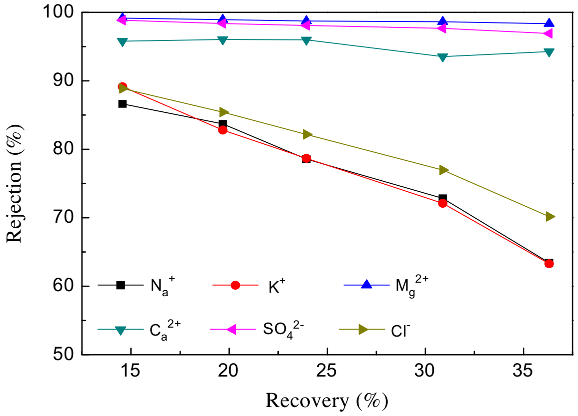

Fig. 10. Effect of recovery on ions rejection of NF1 (operating pressure: 3.0 MPa).

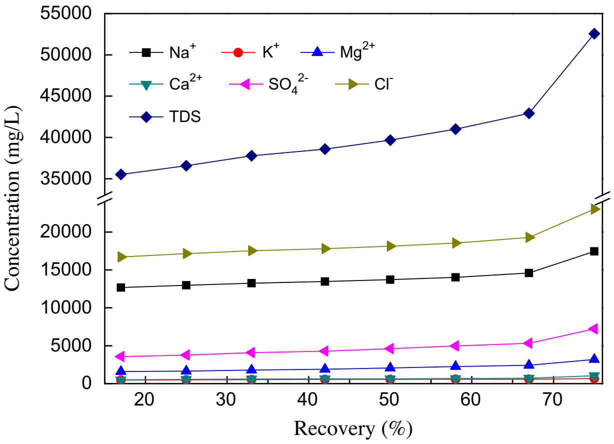

Fig. 11. Concentrated solution quality of the NF2 membrane module at different R_{ec} (operating pressure: 2.6 MPa).

membrane was too low under lower operating pressure, which could hardly meet the water production quantity requirement. As a result, NF2 membrane should be operated at higher operating pressure, which was better more than 2.7 MPa.

The effect of operating pressure on ions rejection of the two NF elements was investigated, respectively, with the water inflow rate remaining unchanged. The results are shown in Figs. 7 and 8.

It can be seen that the ions rejection rate of NF membrane increased with the increase in operating pressure, and the growth rate gradually slowed down. This might be caused by concentration polarization at higher operating pressure. With the rise of operating pressure, the water flux increased, causing ions rejection rate increasing accordingly. Meanwhile, the concentration gradient across the membrane also increased, resulting in the increase in the ions flux. Eventually, the trend of ions rejection rate tended to be stable.

Fig. 7 shows that for NF1 membrane, within the experimental operating pressure range, the rejection of SO_4^{2-}, Mg^{2+}, and Ca^{2+} was 92.46–96.73%, 37.84–56.53%, and 19.71–35.21%, respectively, while the rejection of monovalent Na^+, K^+, Cl^- was 3.62–11.68%, 3.57–11.70%, and 3.59–11.87%, respectively. There was high limit for the concentration of Ca^{2+}, Mg^{2+} in softened water used to prepare polymer solution [6]. The concentration of total calcium and magnesium ions in NF1 production water was above 820 mg L^{-1}, and therefore, NF1 permeate was not suitable for offshore oilfield polymer solution preparation.

Fig. 8 shows that within the experimental operating pressure range, NF2 membrane had high removal rate for bivalent ions, with SO_4^{2-}, Mg^{2+}, and Ca^{2+} rejection in the range of 96.52–99.02%, 97.52–99.15%, and 93.55–95.25%, respectively. It indicates that NF2 membrane had high removal efficiency for bivalent ions and was hardly affected by operating pressure. However, for monovalent ions, the rejection rate is affected by operating pressure obviously, and there was relatively high fluctuation in the rejection rate, with the rejection rate for Na^+, K^+, Cl^- in the range of 63.17–88.84%, 62.61–89.13%, and 70.20–90.53%, respectively. As the concentration of total calcium and magnesium ions in NF2 production water was very low, NF2 permeate was applicable for polymer solution preparation for offshore oilfield.

3.2.2. Effect of R_{ec} on NF performance

Effect of the R_{ec} on NF2 membrane flux and ions rejection rate were investigated at constant operating

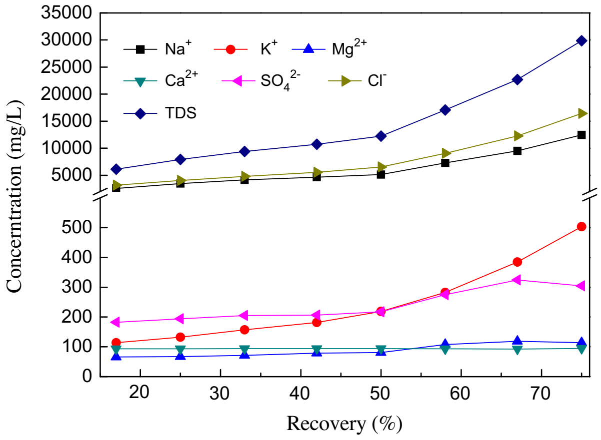

Fig. 12. Permeate quality of the NF2 membrane module at different R_{ec} (operating pressure: 2.6 MPa).

pressure of 3.0 MPa. Results are shown in Figs. 9 and 10.

It can be seen from Fig. 9 that with the R_{ec} increased from 14.57% to 36.31%, the NF2 membrane flux decreased from 14.68 L m^{-2} h^{-1} to 7.22 L m^{-2} h^{-1}, reducing by 50.82%. It indicates that NF2 membrane flux was affected by the R_{ec} greatly.

Fig. 9 shows that, within the whole experimental recovery range, NF2 membrane kept high removal rate for bivalent ions, with rejection of SO_4^{2-}, Mg^{2+}, and Ca^{2+} in the range of 98.85–96.92%, 99.15–98.35%, and 95.79–93.55%, respectively, while there was relatively high fluctuation in the monovalent ions rejection rate of NF2 membrane, with the rejection rate for Na^+, K^+, Cl^- in the range of 86.64–63.42%, 89.13–63.30%, and 88.88–70.16%, respectively. It indicates that the monovalent ions rejection rate of NF2 membrane was affected by the R_{ec} obviously, while NF2 membrane could keep high removal efficiency for bivalent ions, which maintained above 90% and was hardly affected by the R_{ec}.

3.3. Performance of NF membrane module at high R_{ec}

In practice, NF membrane modules are connected in series in a pressure container to improve the R_{ec}. Performance of the NF membrane modules varies according to the orders in the pressure container. With the increase in the R_{ec}, the influent flow is concentrated continually along the pressure container and the effective operating pressure gradually decreases, which affect the flux and permeate quality of the NF membrane modules.

The variation of permeate quality, concentrate quality, membrane flux, the actual membrane module water recovery rate (R'_{ec}), and ions rejection of NF2 with system recovery were investigated at constant operating pressure to simulate and investigate the performance of different NF2 membrane modules along the pressure container. The operating pressure was kept at 2.6 MPa. The R_{ec} was changed through total recycling of the concentrate.

3.3.1. Concentrate and permeate quality of NF2 membrane modules with system recovery

The concentrate and permeate quality of the NF2 membrane module at different R_{ec} are shown as Figs. 11 and 12, respectively.

It can be seen from Fig. 11 that with the increase of the system recovery, concentration of all ions in the concentrate became higher. TDS increased from 35,000

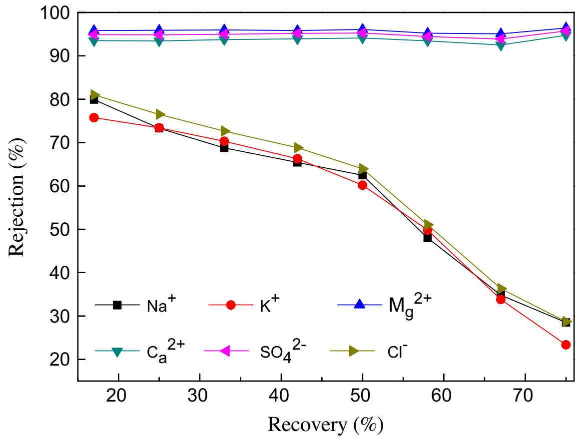

Fig. 13. Ions rejection of the NF2 membrane module at different R_{ec} (operating pressure: 2.6 MPa).

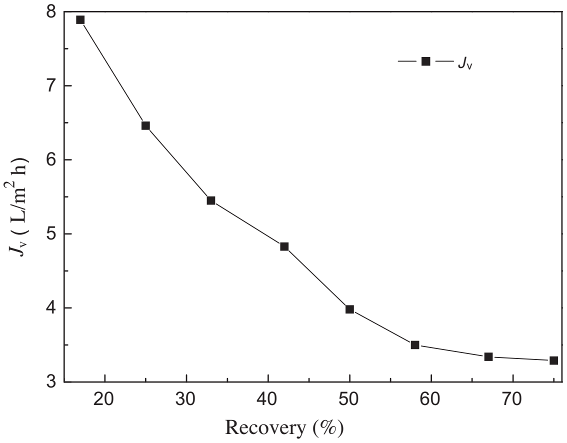

Fig. 14. Flux of NF2 membrane module at different R_{ec} (operating pressure: 2.6 MPa).

to 53,000 mg L^{-1} as the R_{ec} increases from 17% to 75%. In the permeation water of NF2 membrane module, concentration of monovale ions rose greatly with the increase in the R_{ec}. For example, the concentration of Na^+ and K^+ in NF2 permeate was even higher than that in original seawater when the R_{ec} increases to 67%, the concentration of Cl^- was almost as high as that in original seawater when the R_{ec} increases to 75%. It indicates that there was no practical significance for the monovalent ions rejection of the NF2 membrane module in such high R_{ec}. On the contrary, concentration of bivalent ions always maintained at a very low level according to the whole system recovery range. The concentration range of Ca^{2+}, Mg^{2+}, and SO_4^{2-} was 32.90−54.45 mg L^{-1}, 65.63−113.52 mg L^{-1}, and 182.26−304.80 mg L^{-1}, respectively. Even when the R_{ec} reached as high as 75%, the sum of the concentration of Ca^{2+} and Mg^{2+} ions was still less than 200 mg L^{-1}, which demonstrated that NF2 membrane module could provide permeate with very low concentration of bivalent ions even at high system recovery.

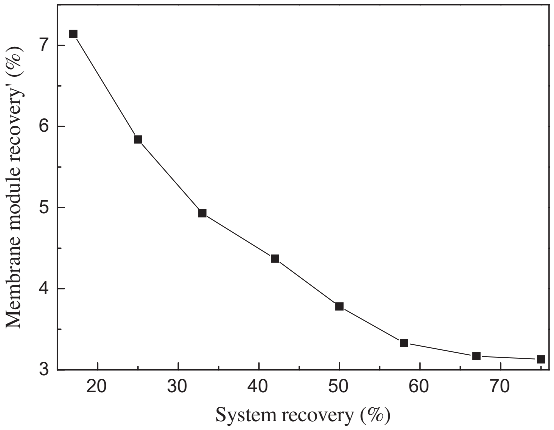

Fig. 15. Recovery rate of NF2 membrane module at different R_{ec} (operating pressure: 2.6 MPa).

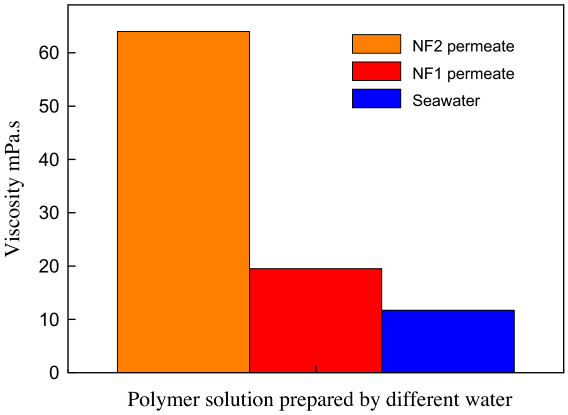

Fig. 16. Viscosity of polymer solution at 65℃ prepared by different water (concentration: 1,500 mg L^{-1}).

Thus, it can be seen that the concentration of monovalent ions in influent was almost the same as that in original seawater, when system recovery increasing to a certain level (67%). In this situation, it was meaningless for the monovalent ions rejection of the NF2 membrane modules at such high R_{ec}. However, the concentrations of bivalent ions in permeate could always maintain in a low level and increased only a little according to the order of NF2 membrane module. Therefore, all the NF2 membrane modules could provide good quality permeate with very low concentration of Ca^{2+} and Mg^{2+}.

3.3.2. *Performance of ions rejection, flux, and recovery with R_{ec}*

Fig. 13 shows the ions rejection of NF2 membrane modules at different R_{ec}. In the experimental recovery range, NF2 membrane module kept high removal rate for bivalent ions, with rejection rate of SO_4^{2-} 93.91–95.77%, Mg^{2+} 95.09–96.44%, and Ca^{2+} 92.49–94.74%, while the monovalent ions rejection rate of NF2 membrane module decreased greatly according to the increase in R_{ec}, with the rejection rate for Na^+ 79.89–28.51%, K^+ 75.74–23.35%, and Cl^- 81.01–28.71%, respectively. It indicates that the monovalent ions rejection rate of NF2 membrane module was affected by system recovery obviously, while the removal efficiency for bivalent ions of NF2 membrane module kept high, maintaining above 90% and hardly affected by system recovery. It can be seen that the monovalent ions rejection rate of the NF2 membrane modules decreased greatly according to their order, while the bivalent ions rejection rate remained stable and did not decrease according to the order of the NF2 membrane modules at all.

Fig. 14 shows that with the R_{ec} increased from 17% to 75%, the flux of NF2 membrane module decreased from 7.89 to 3.29 $L\,m^{-2}\,h^{-1}$, declining greatly by 58.30%. And the downtrend slowed significantly at higher R_{ec}. The actual membrane module water recovery rate of NF2 at different R_{ec} was shown in Fig. 15. In the system recovery range, the actual membrane module water recovery rate of NF2 drops greatly from 7.14% to 3.13%. And the decline slows down significantly at higher R_{ec}. It indicates that the flux and actual membrane module water recovery rate of NF2 decreased significantly according to their orders, and the decrease gradually slowed down.

Table 3
Quality of different water

Water sample	TDS (mg L^{-1})	Ca^{2+} and Mg^{2+} (mg L^{-1})
Seawater	33,148	1,660
NF1 permeate	28,626	930
NF2 permeate	3,210	24

3.4. The possibility of preparing polymer solution with NF permeation water

The softening and demineralization of seawater are the keys to successfully implement of preparing polymer solution with NF permeate water for polymer flooding. Viscosity of the polymer solution prepared by permeate water of NF1 and NF2 membrane at the system recovery of 15% as well as seawater and was investigated at formation temperature (65℃), as shown in Fig. 16. The quality of the different water samples was shown in Table 3.

TDS, especially the divalent cation ions in the injection water had contributed greatly to the viscosity of the HPAM polymer solution. As shown in Table 3, the TDS and concentration of Ca^{2+} and Mg^{2+} in NF2 permeate water was significantly lower, so that the curling of the polymer molecular chain could be effectively prevented and viscosity of the polymer solution was as high as 64 MPa·s, as shown in Fig. 16. It was much higher than that of the crude oil which was usually below 30 MPa s for moderate viscosity crude oil. On the contrary, the TDS and concentration of Ca^{2+} and Mg^{2+} of the seawater and NF1 permeate water was relatively high, which may cause the curling of HPAM molecular chain and finally reduce the viscosity of the polymer solution greatly. It can be seen in Fig. 16 that the viscosity of the polymer solution prepared by NF1 permeate water and seawater was 20 and 12 MPa s respectively, both of which was less than 30 MPa s. Therefore, it was obvious that not all the NF softened seawater was suitable for preparing polymer solution for polymer flooding. In our experiment, only the NF2 permeation water could be used for preparing polymer solution.

Viscosity of the polymer solution prepared by permeate water of NF2 membrane at different system recovery was further investigated at 65℃, as shown in Fig. 17. The quality of the different water samples was shown in Table 4.

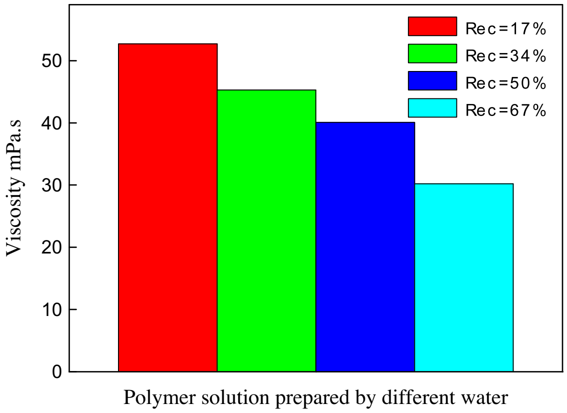

Fig. 17. Viscosity of polymer solution at 65℃ prepared NF2 permeate at different R_{ec} (concentration: 1,500 mg L^{-1}).

Table 4
Quality of NF2 membrane module permeate at different R_{ec}

R_{ec} (%)	TDS (mg L^{-1})	Ca^{2+} and Mg^{2+} (mg L^{-1})
17	6,117	98.5
34	9,397	109.7
50	12,233	118.5
67	22,675	172.0

From Fig. 17 we can see that viscosity of the polymer solution prepared by permeate water of NF2 membrane at system recovery of 17%, 34%, 50%, and 67% was 53, 45, 40, and 30 MPa s, respectively, all of which was above 30 MPa s. When system recovery increased to a high degree (e.g. 67%), the TDS of the NF2 permeate water reached as high as more than 20,000 mg L^{-1}, as shown in Table 4. However, the concentration of the Ca^{2+} and Mg^{2+} of the NF2 permeate water was still low, less than 200 mg L^{-1}. And the viscosity of the polymer solution prepared by NF2 permeate water at such high R_{ec} could still be high as more than 30 MPa s. It indicates that NF2 membrane modules could provide good quality permeate for preparing polymer solution for polymer flooding in offshore oilfield.

4. Conclusions

(1) The concentration of total calcium and magnesium ions in NF1 permeate was too high to be used to prepare polymer solution for offshore oilfield. On the contrary, NF2 membrane could keep very high removal efficiency for bivalent ions which was hardly affected by operation factors and provide good quality permeate with very low concentration of total calcium and magnesium ions.

(2) The NF2 membrane module could provide good quality permeate with very low concentration of Ca^{2+} and Mg^{2+} even at very high R_{ec}. In actual

production that NF membrane modules are connected in series in a pressure container, the concentration of bivalent ions including Ca^{2+} and Mg^{2+} in permeate of NF2 membrane modules keeps at very low level.

(3) The viscosity of the polymer solution prepared with NF2 softened seawater could reach 64 MPa s, which is much higher than that of the ordinary crude oil in the reservoir. Seawater nanofiltration softening technology is viable for application in oilfield polymer solution preparation for polymer flooding in offshore oilfield.

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