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Nano-porous Membrane Process for Brackish Groundwater Treatment: Efficiency Analysis Using Response Surface Methodology

Yuzheng Lv*, Jihao Zhou, Zhengjun Mai** and Jie Liu**†**

*Research Institute for National Defense Engineering for Academy of Military Science PLA, Beijing, 100085, China
**Department of Military Facilities, Army Logistics University, Chongqing, 401331, China
†Corresponding author: Jie Liu

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ABSTRACT

Excessively high concentration of inorganic salts in the groundwater is the main threat for residents to drink directly in the remote areas of northwestern China. In this paper, nano-porous membrane process was proposed to removal of diverse ions in such raw water. Through the response surface methodology (RSM), the effects of multiple factors on permeate flux and ion rejection rates were analysed, and the application scope of nanofiltration for various water resource was evaluated. It was found that the factors affecting permeate flux, chloride removal and nitrate removal (response value) followed some typical sequences, and the operating pressure was always the most influential factor. Besides, nano-porous membrane process showed predominant performance in the removal of sulphate, chloride and fluoride; the rejection rates were over 99%, 97% and 95%, respectively, and the produced water could completely satisfy the relevant national standards for drinking water. However, nitrate removal rate was seldom over 80%, and it reduced obviously with the increasing initial concentration of nitrate, thus the nitrate content of raw water should be controlled within 40 mg.L^{-1}.

INTRODUCTION

Compared with traditional surface water, the groundwater resource is considered more abundant in most remote rural areas in northwest China. However, the groundwater is often not suitable for residents to drink directly due to its excessive levels of inorganic salts (Greenlee et al. 2010). It is necessary to desalt this brackish groundwater so that it can be utilized without threats from the high salinity. Conventional brackish groundwater treatment methods include ion exchange (Fox et al. 2014), adsorption (Zhang et al. 2016), electrodialysis (Onorato et al. 2017), distillation (Plattner et al. 2017) and reverse osmosis (Pérez-González et al. 2012), which have several disadvantages such as high investments and operation costs, low efficiency and recontamination problems (Pangarkar et al. 2011).

In the northwest rural areas of China, the phenomena that inorganic salt concentration among groundwater outnumber the standard are mainly embodied in indicators like sulphate, chloride, fluoride, nitrate and hardness. Compared with the seawater, salt concentration is lower in the groundwater, but both the ratios of $m_{SO_4^{2-}}/m_{TDS}$ and $m_{Ca^{2+}}/m_{TDS}$ are higher. Thus, these water quality characteristics make nanofiltration an alternative method for brackish groundwater desalination and purification. With a nominal pore size of 1~2 nm, nanofiltration falls between reverse osmosis and ultrafiltration in its separation characterization and becomes a new type of separation technology in recent years. Sieving and Donnan repulsion are the two main separation mechanisms for nanofiltration, they are separation of uncharged solutes due to size effects and separation of charged species like ions because of electrical repulsion, respectively (Bouranene et al. 2008). Possessing the advantages of high permeate flux, high divalent ion removal efficiency, low operating pressure and low investment, nanofiltration technology is gradually being applied in the fields of desalination of groundwater, softening of seawater, reuse and treatment of wastewater. At present, the reverse osmosis process with the separation feature of broad-spectrum has been partly applied in the northwest of China for brackish groundwater desalination. However, the shortcomings of low recovery rate, high energy consumption and strict pretreatment originate from the reverse osmosis process have a serious impact on the economics for the groundwater treatment systems. Compared with reverse osmosis, choosing nanofiltration cannot only avoid these defects, but also obtain a satisfactory desalting effect with some elements retained which are beneficial to the human body (Strathmann 2010). In addition, low operating pressure is the further superiority to promote the application of nanofiltration at remote locations with limited electrical supply (Padilla & Saitua 2010).

Nowadays, it has been confirmed that the groundwater source with higher pollutant concentrations may exist in the remote areas of Northwest China (Ma et al. 2011). Howev-

er, the application scope of raw water and the competitive relationship of ions removal during nano-porous membrane process are not completely understood. In this way, there is seldom a completely theoretical model to accurately describe the dynamic process for inorganic salts removing in brackish groundwater through nanofiltration membrane. The purification efficiency of the nanofiltration membrane is mainly measured by the water flux and ion rejection rate. A large number of studies have shown that the main factors affecting the water purification efficiency of nanofiltration are the raw water quality (the initial concentration of pollutants) and operating conditions (operating pressure and the inlet flow) (Han et al. 2013, Diawara 2008).

This work investigated the efficiency of nano-porous membrane as a potential technique for groundwater advanced treatment by satisfying the standard for drinking water quality of GB5749-2006. The aim of this study was to better understand the purification mechanism for removing inorganic salts in the brackish groundwater by nanofiltration, and to analyse various factors that influence the membrane flux and ion rejection rate, thus to evaluate the application scope of raw water quality based on the produced water quality. Response surface methodology (RSM), a critical tool for experimental design and parameters optimization, was utilized in this research, and the results obtained could provide technical support for the practical demonstration projects in the remote areas of Northwest China.

MATERIALS AND METHODS

Raw Water and Membrane

With reference to the characteristics of groundwater quality in all regions of Northwest China, the raw water was prepared by mixing the tap water and inorganic salts. The tap water was allowed to stand still for about 24 h so that most of the residual chlorine could be removed, which ensured that it had met the inflow chlorine control standards before the membrane treatment. According to the measured data from five representative sampling points (Table 1), the test raw water quality parameters are given in Table 2. Meanwhile, NF90 (The Dow Chemical Company. USA), a commercial nano-porous membrane, was selected as the experimental membrane in the nanofiltration process. The main characteristic parameters of the membrane NF90 are given in Table 3.

Experimental Method and Procedure

Aiming at the groundwater with excessive salt content, a desalination process with the core technology of nanofiltration was constructed. The schematic diagram of the experimental filtration setup is shown in Fig. 1. It is a cross-flow membrane system, which mainly includes the water tank (1000L), the security filter, the pump unit, the membrane module and the ancillary equipment. The test raw water passes through the security filter first and then enters into

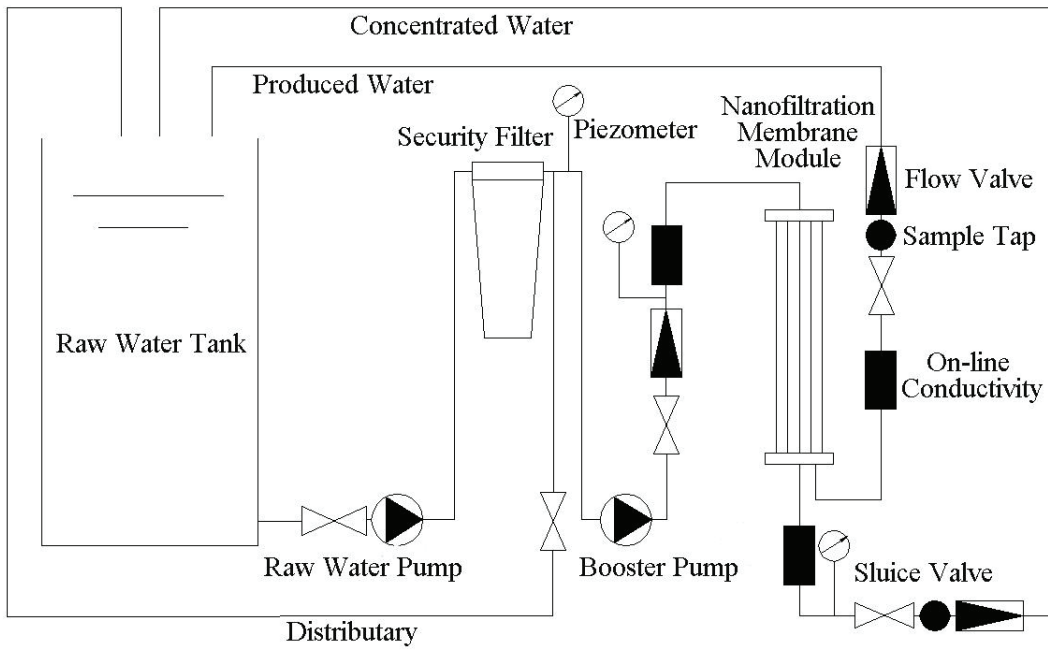

Fig. 1: The schematic diagram of the experimental filtration setup.

Table 1: The quality data of typical water samples.

Sampling points	Mass concentration, $mg \cdot L^{-1}$			
	SO_4^{2-}	Cl^-	F^-	NO_3^-
P1	622.03±8.35	70.97±2.14	0.36±0.09	2.69±0.08
P2	145.01±3.41	104.93±2.56	0.25±0.04	23.09±1.12
P3	464.66±5.27	103.61±1.98	0.99±0.03	3.32±0.17
P4	460.91±6.38	100.58±2.77	0.82±0.08	3.64±0.75
P5	25.10±1.36	28.07±0.69	2.03±0.04	2.68±0.30

Table 2: The main quality parameters of raw water.

Parameter		Unit	Value
Temperature		°C	19.5±1.0
pH		-	8.00+0.05
Redox Potential		mV	110~150
Mass Concentration	TDS	$mg \cdot L^{-1}$	1351~1372
	Ca^-	$mg \cdot L^{-1}$	136.17~142.21
	Mg^{2+}	$mg \cdot L^{-1}$	58.55~60.76
	Na^-	$mg \cdot L^{-1}$	184.04~191.85
	K^-	$mg \cdot L^{-1}$	31.67~33.32
	HCO_3^-	$mg \cdot L^{-1}$	187.90~208.41
	SO_4^{2-}	$mg \cdot L^{-1}$	611.86~629.35
	NO_3^-	$mg \cdot L^{-1}$	25.83~26.71
	F^-	$mg \cdot L^{-1}$	2.13~2.18
	Cl^-	$mg \cdot L^{-1}$	96.67~101.03
	CO_3^{2-}	$mg \cdot L^{-1}$	1.03~1.15

Table 3: The main characteristics of the test membrane NF90.

Material	Molecular Cut Off (Da)	Effective Area (m^2)	Zeta Potential (pH=7，mV)	Surface Roughness (nm)	Highest Temperature (°C)	Applicable pH	Highest Pressure (MPa)
polyamide	200	2.6	-30	70~129	40	2~11	4.1

the nanofiltration membrane module for desalination treatment. In this experiment, a permeate full circulation mode of operation was used, which required all the producing water and the concentrated water to flow back into the raw water tank. The rate of inflow and operating pressure were adjusted by simultaneously changing the valves for both inlet and the concentrated water outlet. The water samples under a special working condition were detected when a steady on-line conductivity value corresponding to the produced and concentrated water was observed respectively.

Analytical Methods

The mass concentration of TDS, and pH were determined by Hach portable multi-spectrometer (HQ 40d). The concentrations of cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) in water were determined by ICP-OES (Agilent 715 model), and the concentrations of anions (SO_4^{2-}, Cl^-, F^-, NO_3^-) were determined by ion chromatography (Metrohm 881 Compact IC pro). The concentrations of HCO_3^- and CO_3^{2-} were calculated via the law of electric charge conservation and the ionization balance formula.

Design of Experiments by RSM Model

In the current study, RSM has been used for the determination of the relation between the input variables and output responses over numerous experimental processes (Salahi et al. 2013; Maher et al. 2014). The Design-Expert 8.0.6 software was used in this study to design experiment schemes, analyse experimental data and plot. There were six independent variables considered in the process of NF90 nanofiltration for the brackish groundwater treatment, which included operating pressure, inlet flow, and the concentrations of sulphate, chloride, fluoride and nitrate. According to the results of the pre-experiments and the possible groundwater quality conditions, the selected level-value of each factor is given in Table 4. These six factors were coded at three levels between -1 and +1, where -1 corresponded to the minimum and +1 corresponded to the maximum value of each variable. The response values used for results analysis included permeate flux, removal rates of chloride as well as nitrate. Besides, the sulphate and fluoride removal rates were measured at the same time. Afterwards, 52 groups of related experiments (Table 5) were designed through RSM based on the central composite design (CCD).

RESULTS AND DISCUSSION

Response Surface Analysis with Permeate Flux as the Response Value

A quadratic regression model was constructed by means of Design-Expert 8.0.6 software with regarding permeate flux as the response value. The results of Anova in this model are

Table 4: The selected level-value of each factor.

Factor	Unit	Level-value		
		Minimum（-1）	Central Point（0）	Maximum（1）
Operating pressure（X_1）	MPa	0.3	0.5	0.7
Inlet Flow（X_2）	$L{\cdot}h^{-1}$	300	400	500
Sulfate Concentration（X_3）	$mg{\cdot}L^{-1}$	500	750	1000
Chloride Concentration（X_4）	$mg{\cdot}L^{-1}$	100	250	400
Fluoride Concentration（X_5）	$mg{\cdot}L^{-1}$	2	4	6
Nitrate Concentration（X_6）	$mg{\cdot}L^{-1}$	20	35	50

Table 5: Experimental design and response values.

No.	Factor						Response Value				
							Permeate Flux（$L{\cdot}h^{-1}{\cdot}m^{-2}$） X_2	Ion Rejection Rate（%）		SO_4^{2-} Rejection Rate（%）	F^- Rejection Rate%）
	X_1		X_3	X_4	X5	X_6		Cl^-	NO_3^-		
1	0.5	400	500	250	4	35	33.3	95.8	78.2	99.91	98.3
2	0.7	500	500	100	6	50	54.1	97.3	81.7	99.93	98.8
3	0.5	400	1000	250	4	35	29.9	96.2	78.0	99.90	98.6
4	0.5	400	750	250	4	20	32.2	96.3	79.8	99.92	98.5
5	0.7	300	1000	400	2	50	39.7	96.7	79.2	99.99	97.8
6	0.7	400	750	250	4	35	46.5	96.8	81.5	99.93	98.6
7	0.3	300	1000	100	6	20	14.5	94.6	72.3	99.67	95.1
8	0.3	500	500	100	6	20	19.6	94.9	71.5	99.89	98.0
9	0.7	300	500	400	6	50	48.3	96.1	76.2	99.91	98.6
10	0.7	500	500	400	2	50	44.5	97.5	84.3	99.92	98.9
11	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.4
12	0.5	400	750	250	2	35	31.2	95.6	76.4	99.92	97.3
13	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6

Table Cont....

No.	Factor						Response Value				
							Permeate Flux ($L \cdot h^{-1} \cdot m^{-2}$) X_2	Ion Rejection Rate (%)		SO_4^{2-} Rejection Rate (%)	F^- Rejection Rate%
	X_1		X_3	X_4	X5	X_6		Cl^-	NO_3^-		
14	0.3	500	500	400	6	50	16.4	93.3	60.4	99.90	97.8
15	0.3	500	1000	400	6	20	12.5	93.9	63.4	99.86	97.8
16	0.3	300	500	100	6	50	18.5	94.3	61.6	99.89	97.9
17	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6
18	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6
19	0.7	500	1000	100	2	50	44.5	97.1	83.0	99.92	98.4
20	0.3	500	1000	100	6	50	14.7	94.2	64.9	99.87	98.1
21	0.5	300	750	250	4	35	31.1	95.4	74.7	99.89	98.3
22	0.7	500	1000	400	2	20	37.9	98.0	87.8	99.93	98.7
23	0.7	300	1000	400	6	20	39.7	96.5	80.3	99.59	98.3
24	0.3	300	500	100	2	20	19.1	93.3	65.8	99.59	99.7
25	0.7	500	500	100	2	20	56.6	97.1	83.4	99.92	98.6
26	0.3	300	1000	100	2	50	12.4	92.5	54.3	99.81	97.5
27	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6
28	0.7	300	1000	100	2	20	40.8	97.4	83.5	99.91	97.9
29	0.7	300	500	100	6	20	53.9	96.5	80.8	99.91	98.6
30	0.3	300	500	400	2	50	14.1	93.9	62.6	99.85	97.6
31	0.3	300	1000	400	2	20	11.4	94.3	67.9	99.81	97.3
32	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6
33	0.3	400	750	250	4	35	15.5	93.3	63.9	99.88	97.9
34	0.7	500	1000	400	6	50	45.4	96.5	78.0	99.94	98.6
35	0.7	500	1000	100	6	20	42.2	98.2	88.3	99.94	99.0
36	0.7	300	500	400	2	20	45.3	96.9	84.0	99.81	98.4
37	0.5	500	750	250	4	35	31.7	96.4	79.3	99.94	98.6
38	0.3	500	1000	400	2	50	12.3	93.5	60.2	99.87	97.6
39	0.5	400	750	250	4	50	31.2	95.9	75.7	99.92	90.6
40	0.5	400	750	100	4	35	33.1	96.7	79.8	99.92	98.1
41	0.3	500	1000	100	2	20	15.2	95.9	73.6	99.89	97.8
42	0.5	400	750	400	4	35	30.5	95.5	76.5	99.91	98.0
43	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6
44	0.7	300	1000	100	6	50	41.9	96.4	79.3	99.82	98.7
45	0.3	500	500	400	2	20	15.4	94.6	72.1	99.87	97.5
46	0.3	500	500	100	2	50	17.2	95.2	71.8	99.87	97.9
47	0.7	500	500	400	6	20	45.0	97.6	84.9	99.89	98.9
48	0.7	300	500	100	2	50	46.9	96.4	82.2	99.66	98.4
49	0.3	300	500	400	6	20	14.3	94.4	66.4	99.83	97.8
50	0.5	400	750	250	4	35	31.1	96.2	78.0	99.92	98.6
51	0.5	400	750	250	6	35	31.1	96.2	77.2	99.92	98.5
52	0.3	300	1000	400	6	50	13.7	90.6	45.3	99.87	97.2

given in Table 6. Meanwhile, combined with the analysis results from Design-Expert 8.0.6, it could be found that the P-value was less than 0.0001, the determination coefficient (R^2) was 99.54%, and the correction coefficient (Adj R^2) was 99.01%, all of which indicated that the model is very significant. In addition, the coefficient of variation (C.V.) of the model was 4.16%, which was less than 10%, indicating that the model possessed high accuracy and reliability. The signal-to-noise ratio (Adeq-Precision), which was 46.498 (greater than 4), suggested that the model's precision was reasonable.

Through the software Design-Expert 8.0.6, the P-value of each factor was investigated. According to the significance level, three factors influencing permeate flux (operating pressure, sulphate concentration and chloride concentration) were selected. Taking permeate flux as the response value, the response surface diagrams revealing the influences by each factor are presented in Fig. 2. As can be seen from Fig. 2a, under the condition of a constant concentration of sulphate ions at inflow, permeate flux increased linearly with the increase of operating pressure. In the experiment, when the operating pressure increased from 0.3 to 0.7MPa, permeate flux increased from 17.44 to 49.66 $L \cdot h^{-1} \cdot m^{-2}$ at the influent sulphate concentration of

Table 6: The results of Anova for permeate flux.

Item	Sum of Squares	Degrees of Freedom	Mean Square	F-value	Prob > F
Model	8366.49	27	309.87	190.63	< 0.0001
Residual	39.01	24	1.63	-	-
Lack of Fit	38.55	17	2.27	34.62	< 0.0001
Pure Error	0.46	7	0.066	-	-
Cor Total	8405.50	51	-	-	-

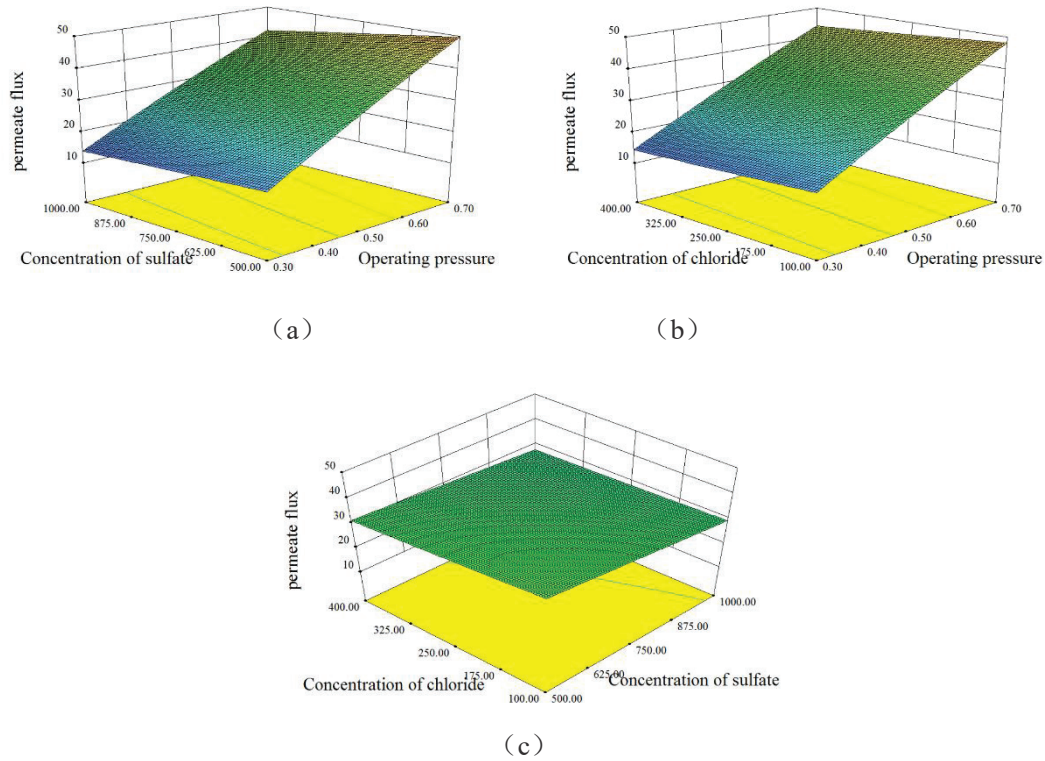

Fig. 2: Analysis of each factor's influence on permeate flux by RSM: (a) concentration of sulphate and operating pressure; (b) concentration of chloride and operating pressure; (c) concentration of chloride and sulphate.

500 mg·L^{-1}. In contrast, the permeate flux increased from 14.06 to 42.00 L·h^{-1}·m^{-2} when the influent sulphate concentration became 1000 mg·L^{-1}. This showed that under low salinity influent conditions, the effect of operating pressure on permeate flux was more pronounced, and the increase of permeate flux could be more dramatic. The same variation trend between permeation flux and operating pressure could also be seen in Fig. 2b, which may be explained by the non-equilibrium thermodynamic model. This is, under conditions of constant water quality, the net driving pressure on both sides of the nanofiltration membrane increased linearly with increasing inlet pressure. In addition, under low operating pressure conditions, permeate flux was less affected by changes in ion concentration in the influent water than under high operating pressure conditions (Figs. 2a, 2b). A comprehensive analysis of Fig. 2 showed that operating pressure, initial sulphate concentration and chloride concentration all affected permeate flux in the nanofiltration process, and the effect of these factors were operating pressure, initial sulphate concentration, initial chloride concentration in turn.

Response Surface Analysis with Chloride Rejection Rate as the Response Value

A quadratic regression model was also constructed with regard to removal rate of chloride as the response value, and results of the Anova are presented in Table 7. It indicated that the P-value was less than 0.0001, the R^2 was 96.02%, and the Adj R^2 was 91.54%, all of which indicated that the model is very significant. In addition, the C.V. of 0.46% (less than 10%) indicated that the model possessed high accuracy and reliability. The Adeq-Precision of 23.163 (greater than 4) suggested that the model's precision was reasonable.

Table 7: The results of Anova for chloride rejection.

Item	Sum of Squares	Degrees of Freedom	Mean Square	F-value	Prob > F
Model	111.00	27	4.11	21.45	< 0.0001
Residual	4.60	24	0.19	-	-
Lack of Fit	4.58	17	0.27	101.89	< 0.0001
Pure Error	0.019	7	2.645×10^{-3}	-	-
Cor Total	115.60	51	-	-	-

Chloride removal rate was used as the response value. Analysis by Design-Expert 8.0.6 software found that the P-values of the five factors of operating pressure, inlet flow, sulphate concentration, chloride concentration, and nitrate concentration were all less than 0.01. Therefore, it could be considered that all these five factors had a significant effect on the removal of chloride. The influence of each factor on chloride removal rate is shown in Fig. 3. It could be seen that the rejection of chloride increased continually as the operating pressure increased from 0.3MPa to 0.6MPa under a certain influent quality (Figs. 3a, 3b). However, when the operating pressure exceeded 0.6MPa, the chloride rejection did not increase and remained substantially constant. As shown in Figs. 3a and 3e, the increase of the initial sulphate concentration could reduce the removal rate of chloride because of the competitive relationship between the two coexisting ions. A similar situation occurred in Fig. 3b, with the increase of the initial concentration of chloride, the rejection rate of chloride also decreased slightly. But when the system was under a higher operating pressure condition, the influence of the initial chloride concentration on chloride rejection in produced water significantly reduced. Figs. 3c, 3d indicated that the increase of inlet flow rate was conducive to the removal of chloride. When the operating condition was kept at the centre point, the chloride rejection rate increased from 95.56% to 96.46% within the inflow range of 300-500 L/h, though the growth rate was relatively slow. The influence of initial nitrate concentration on chloride removal rate is shown in Figs. 3d, 3f. When the influent nitrate concentration was increased from 20 to 50 mg·L^{-1}, the chloride rejection rate decreased from 96.44% to 95.95%, which suggested that the increase of nitrate concentration was not conducive to the removal of chloride. A comprehensive analysis of Fig. 3 showed that these five factors affecting the removal of chloride were as follows: operating pressure, inlet flow, initial sulphate concentration, initial nitrate concentration, initial chloride concentration.

Response Surface Analysis with Nitrate Rejection Rate as the Response Value

With regard to removal rate of nitrate as the response value, the quadratic regression model was constructed. As given in Table 8, the Anova results indicated that the P-value was less than 0.0001, the R^2 was 97.67%, and the Adj R^2 was 95.05%, all of which indicated that the model is very significant. Meanwhile, the C.V. was less than 10%, which showed high accuracy and reliability. The Adeq-Precision (reached 29.386 and exceed 4) suggested that the model's precision was reasonable.

Taking the nitrate removal rate as the response value, analysis found that the operating pressure, inlet flow, sulphate concentration, chloride concentration, and nitrate concentration all had significant effects on nitrate rejection. The effects of each factor on nitrate removal is presented in

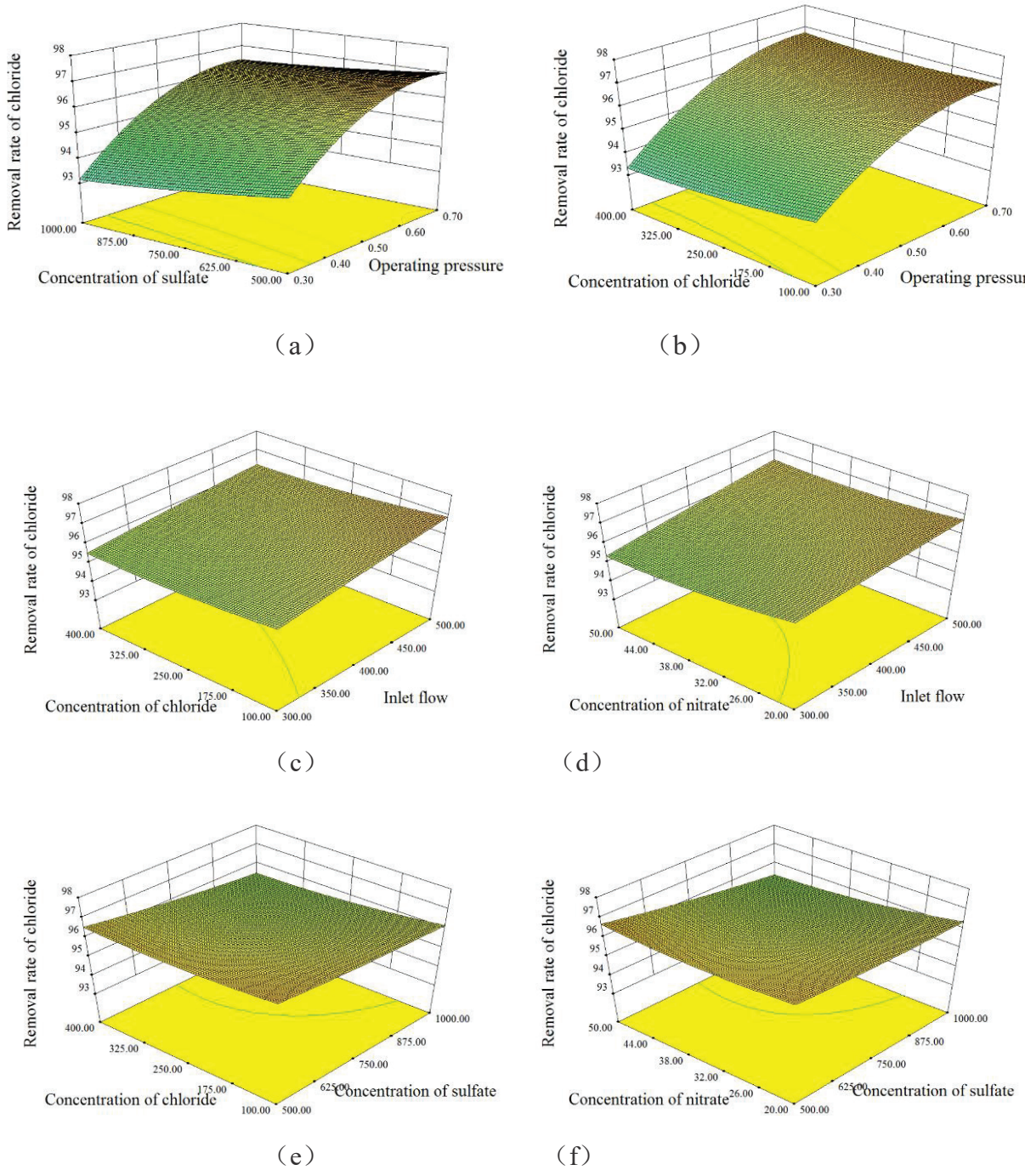

Fig. 3: Analysis of each factor's influence on the chloride rejection by RSM: (a) concentration of sulphate and operating pressure; (b) concentration of chloride and operating pressure; (c)concentration of chloride and inlet flow; (d) concentration of nitrate and inlet flow; (e)concentration of sulphate and chloride; (f) concentration of nitrate and sulphate.

Table 8: The results of Anova for nitrate rejection.

Item	Sum of Squares	Degrees of Freedom	Mean Square	F-value	Prob > F
Model	3819.43	27	141.46	37.26	< 0.0001
Residual	91.11	24	3.80	-	-
Lack of Fit	90.28	17	5.31	44.56	< 0.0001
Pure Error	0.83	7	0.12	-	-
Cor Total	3910.54	51	-	-	-

Fig. 4. In general, nitrate removal was affected more than other ions removal. From Figs. 4a, 4d and 4e, it could be seen that the increase of the initial concentration of influent sulphate would cause the decrease of nitrate reject rate. Taking Fig. 4d as an example, in the range of the initial sulphate concentration of 500 to 1000 mg·L^{-1}, the nitrate rejection rate decreased from 79.14% to 77.49%. Figs. 4b, 4d illustrated the influence of initial concentration of influent chloride on nitrate rejection rate, that is, the increase of the initial chloride concentration hindered the removal

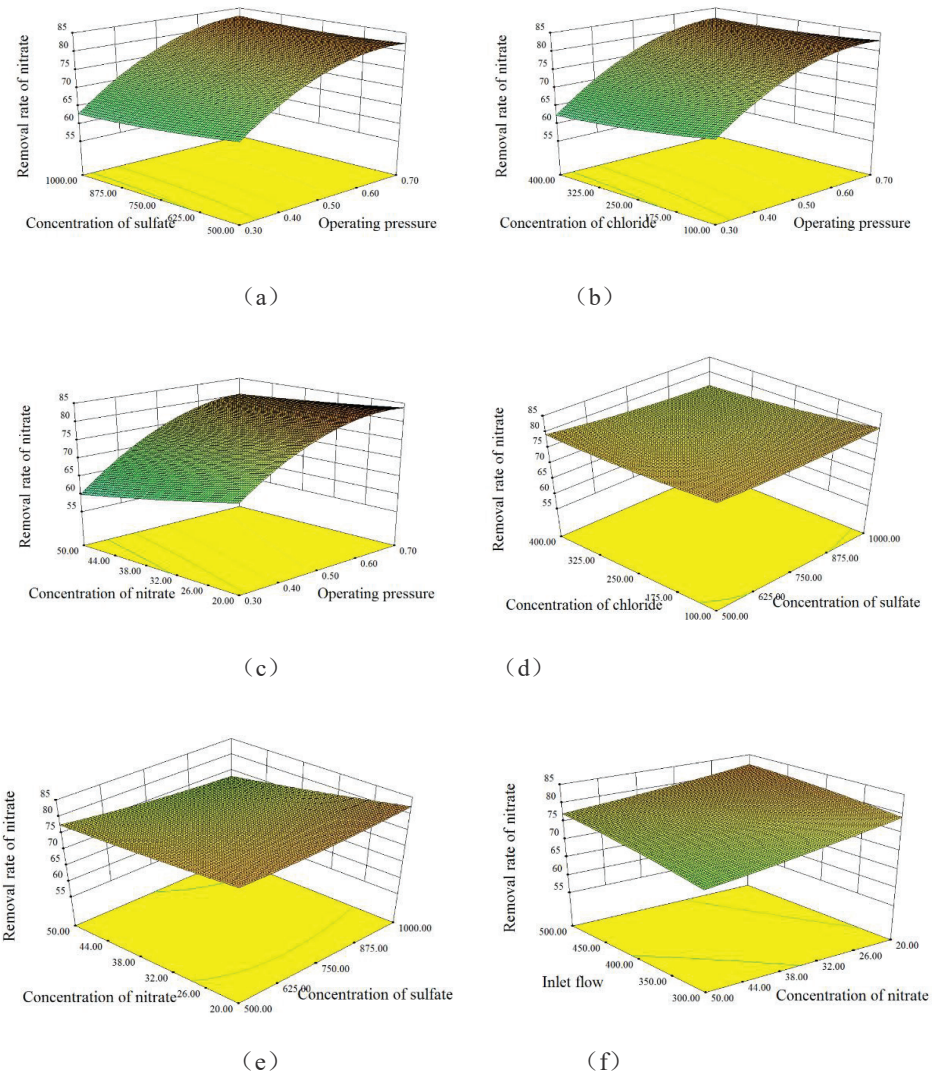

Fig. 4: Analysis of each factor's influence on the nitrate rejection by RSM: (a) concentration of sulphate and operating pressure; (b) concentration of chloride and operating pressure; (c) concentration of nitrate and operating pressure; (d) concentration of chloride and sulphate; (e) concentration of sulphate and nitrate; (f) concentration of nitrate and inlet flow.

of nitrate. Meanwhile, it could be seen from Fig. 4f that the increase of inlet flow would promote the rejection of nitrate. In the range of 300 to 500 L/h, the rejection rate increased from 76.11% to 79.69%. In addition, a major factor affecting nitrate removal was the initial nitrate concentration in the inflow water. As Figs. 4c, 4e and 4f illustrated, nitrate removal was greatly affected by the change of its own initial concentration. Taking Fig. 4e as an example, when the initial nitrate concentration was increased from 20 to 50 mg·L^{-1}, the rejection rate decreased from 81.01% to 75.05%. According to the saliency analysis by software, the factors affecting the nitrate removal were operating pressure, concentration of nitrate, inlet flow, concentration of sulphate and concentration of chloride in turn.

Evaluation of the Application Scope of Nanofiltration for Various Raw Waters

Combined with the previous experimental design and results, in the NF90 nanofiltration membrane system, variation laws of the ion concentration at outlet with the inlet concentration changing are shown in Fig. 5. As shown in Fig. 5a, sulphate rejection was less affected by the initial concentration in raw water, increasing initial sulphate concentration from 500 to 1000 mg·L^{-1} only caused a small increase in sulphate in the produced water. During the whole process of NF90 nanofiltration membrane system, sulphate removal rates were all over 99.9%, but the concentrations were all below 1.5 mg·L^{-1}, which were far below the standard limit of 250 mg·L^{-1}. Fig. 5b showed that increasing initial chloride concentration decreased the rejection rate. Chloride concentration increased from 3.3 to 18 mg·L^{-1} as the initial ion concentration increased from 100 to 400 mg·L^{-1}, the quality parameter chloride content always met the standard limit of 250 mg·L^{-1}. For the fluoride ion from Fig. 5c, it could be seen that the rejection rate increased first and then slightly reduced with increasing the initial fluoride concentration from 2 to 6 mg·L^{-1}. During this process, the fluoride concentration in outlet increased from 0.05 to 0.09 mg·L^{-1} and the rejection rate was all above 97.3%, which completely met the standard limit of 1.0 mg·L^{-1}. Therefore, it is feasible to use nanofiltration membrane process for purifying brackish groundwater with sulphate, chloride and fluoride exceeding the standard in northwest China, and the produced water can completely satisfy the drinking water hygiene standard of GB5749-2006. Fig. 5d showed the same trends for nitrate rejection, when the concentration

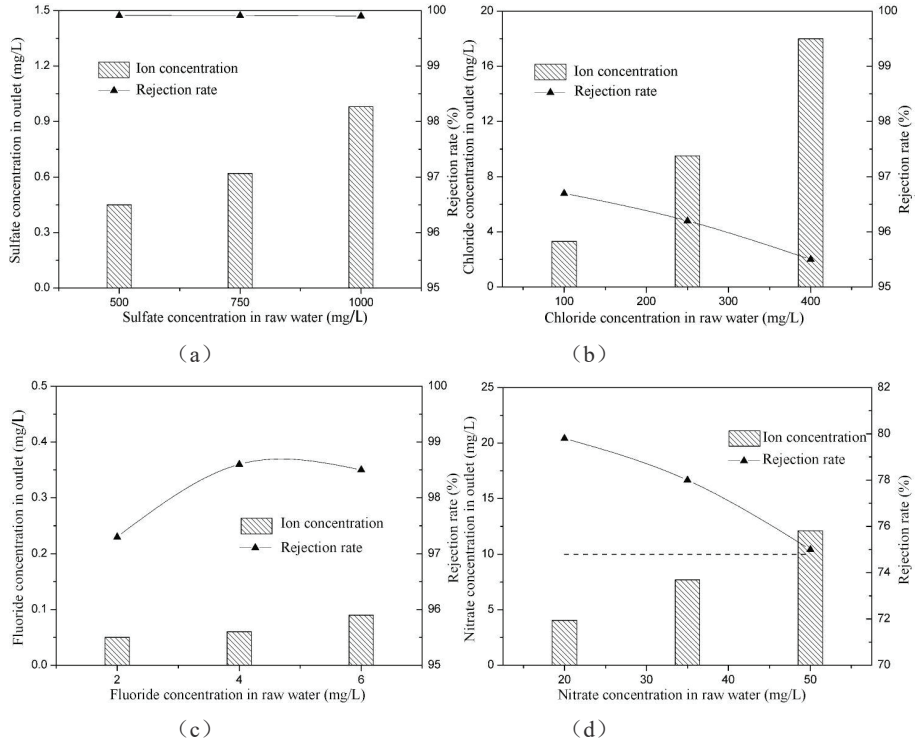

Fig. 5: The variation of ion concentration in outlet in the NF90 nanofiltration membrane system: (a) SO_4^{2-}, (b) Cl^-, (c) F^- and (d) NO_3^-.

of nitrate in raw water increased from 20 to 50 $mg \cdot L^{-1}$, the concentration in outlet increased from 4.05 to 12.1 $mg \cdot L^{-1}$, and the rejection rate decreased from 79.8% to 75%. It suggested that the produced water cannot meet the standard limit of 10 $mg \cdot L^{-1}$ in the case where the raw water possesses a high level of nitrate concentration. Thus, the nitrate concentration in raw water should be controlled within 40 $mg \cdot L^{-1}$ to ensure a safe residual.

CONCLUSION

In view of the possible existence of anion pollution for groundwater resource in the remote areas of northwestern China, through RSM, the effects of various factors on flux and ion rejection rates in the nano-porous membrane process were analysed, and its application scope for diverse water resource was evaluated. Under the test parameters, the main factors influencing permeate flux are operating pressure, initial sulphate concentration as well as chloride concentration, and the effect of operating pressure on membrane flux is most obvious. Secondly, chloride rejection affects in the order of operating pressure, inlet flow, initial sulphate concentration, initial nitrate concentration, initial chloride concentration. On the other hand, the factors affecting the nitrate removal are operating pressure, concentration of nitrate, inlet flow, concentration of sulphate, concentration of chloride in turn. In the aspect of evaluation in water quality adaptability, nano-porous membrane process puts up predominant performance in the removal of sulphate, chloride and fluoride, and the residual can abundantly satisfy the national standard (GB5749-2006) for drinking water. In particular, the nitrate content of raw water should be controlled within 40 $mg \cdot L^{-1}$. In summary, it appears that nanofiltration can be very promising in producing ion-free safe drinking water with a wide range of water quality adaptation. This study is expected to raise scale up confidence in the backdrop of rare implementation of nano-porous membrane process in removing diverse ions from brackish groundwater at an affordable cost in the vast affected areas.

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