

Article

Reverse Osmosis Membrane Combined with Ultrasonic Cleaning for Flue Gas Desulfurization Wastewater Treatment

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Abstract: Flue gas desulfurization (FGD) wastewater treatment is currently of interest, as stringent standards have been released in order to limit the pollution emissions from the energy industry, and concerns about water scarcity are also increasing. Reverse osmosis (RO) membrane is a promising alternative for highly efficient FGD wastewater treatment. However, membrane fouling strongly limits its application. This study developed a suitable treatment system by combining RO membrane with ultrasonic cleaning. The introduction of low-frequency and high-intensity ultrasonic cleaning improved the cleaning efficiency of membrane fouling, as the permeate flux recovered 49% of the reduced value within 10 min of cleaning. The lifespan of the membrane was also extended, as the time of permeate flux declined to the same level, increasing from 2 h to 4 h after ultrasonic cleaning. The effluent of the system could meet the standard of desulfurization wastewater treatment. The treatment system is feasible for FGD wastewater treatment at a laboratory scale. These findings proved that the combination of RO membrane and ultrasonic cleaning could be applied to FGD wastewater treatment. The study provided an efficient, cost-saving, and convenient way to develop the FGD wastewater treatment system.

Keywords: reverse osmosis membrane; ultrasonic cleaning; membrane fouling; flue gas desulfurization wastewater; wastewater treatment



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1. Introduction

Coal dominates the energy structure of China, and about 63.22% of electricity is generated by coal-fired power plants [1]. The consumption of coal directly increases the emissions of dust, sulfur dioxide, and nitrogen, causing severe atmospheric pollution. From 2011 to 2014, several national standards and plans were released to limit the pollution emissions from the energy industry, and flue gas desulfurization (FGD) systems have become mandatory for ultra-clean flue gas treatment in coal-fired power plants [2]. The most widely applied treatment method is limestone gypsum wet flue gas desulfurization, which accounted for about 69% and 80% of market shares worldwide and in China [3]. This process generates gypsum saturated FGD wastewater, which needs further treatment to avoid environmental pollution. The content of total dissolved solids in FGD wastewater is relatively high, including large amounts of SO_4^{2-} , SO_3^{2-} and Cl^- . Therefore, treatment for FGD wastewater is necessary to improve water quality and reduce environmental concerns [4].

Technologies for FGD wastewater treatment include surface impoundments, chemical precipitation, biological treatments (anoxic/anaerobic), evaporation systems, constructed

wetlands, zero-discharge systems, membrane separation, and others [5,6]. FGD wastewater is mostly treated via chemical precipitation in the world [7]. This method possesses deficiencies of significant investment, high maintenance cost, and harmful elements, which make it physically unable to meet the ever-increasing stringent standard for pollution emissions [7].

Considerable work was carried out in membrane separation technologies to realize the zero liquid discharge process, as it is broadly selected for FGD wastewater treatment [8]. High-performance technologies, like membrane distillation, forward osmosis, reverse osmosis, and high-efficiency reverse osmosis, have been investigated and reported. Among these technologies, pressure-driven membranes like reverse osmosis (RO) membranes are promising alternatives for FGD wastewater treatment with the potential to meet the standards [6]. RO membrane has been considered for a wide range of wastewater treatments and reuses, from the steel industry to the food industry to personal care products, and almost all the core reuse technologies are based on reverse osmosis [9–12]. It is also one of the most widespread methods for water purification and seawater desalination [13]. By applying external pressure, the RO membrane could overcome the osmotic pressure, separate solutes (i.e., micro-pollutants, organic-inorganic matter colloids, salt, and pathogens) from liquid streams, and produce high-quality water [14,15]. The simple design, convenient operation, and other merits have cut down the energy consumption when producing freshwater with RO membranes [16,17]. In the revised Steam Electric Power Generating Effluent Guidelines released by U.S. EPA, a combination of microfiltration (pretreatment) and RO membrane technologies is listed as a voluntary incentive program to achieve the discharge limits [18]. RO membranes are also the main membrane processes that have been widely applied for FGD wastewater advanced treatment [3]. However, the mechanism of the RO membrane has brought a performance limitation. As the RO process proceeds, the solute particles will potentially accumulate on the feed side of the membranes, leading to a more severe concentration polarization phenomenon and membrane fouling [19]. Membrane fouling is also the main obstacle that limits the application of membrane separation technologies in FGD wastewater treatment [20].

Physical and chemical methods are widely applied to membrane cleaning, but these methods have both advantages and limitations [21]. Physical cleaning methods, like backwashing, are environmentally friendly. The interruption to the membrane filtration process brings inconvenience and has further limited its practical application [22]. Although chemical cleaning is more effective in permeability recovering and irreversible fouling movement, the consumption of chemicals like acids and alkalis has increased the operation cost and possibly the secondary pollution [23]. Frequent chemical cleaning may also destroy the membrane structure and reduce the membrane lifetime [24]. In addition, the above membrane cleaning methods both require suspending operation, lowering the efficiency of membrane cleaning and the whole process of wastewater treatment.

Recently, new technologies for membrane cleaning, such as membrane cleaning using saturated CO₂ solution, CO₂ nucleation, steam cleaning, air bubbles, and ultrasonic cleaning have been investigated and reported [25–33]. Among these methods, ultrasonic cleaning has been paid more attention to in recent investigations due to the consistency of the membrane filtration process and no consumption of chemicals. Ultrasound application provides an alternative technique for membrane fouling control and membrane cleaning in desalination and wastewater treatment.

In this study, a treatment system was developed by combing the RO membrane with ultrasonic cleaning, and the system was applied to FGD wastewater treatment. The optimal operating conditions of the system were examined for better treatment effect. The actual FGD wastewater was also induced to the system to test the feasibility for its actual application. The design of the treatment system provided an efficient, cost-saving, and convenient way for FGD wastewater treatment.

2. Materials and Methods

2.1. Materials

All chemicals were of analytical reagent grade. The Na_2SO_4 solution was freshly prepared with deionized water.

2.2. Design of Laboratory-Scale Membrane System with Ultrasonic Cleaning

The experimental system combined a commercial reverse osmosis membrane with an ultrasonic cleaning apparatus. The membranes were commercial household reverse osmosis (RO) membranes (HP18122-50, Vontron Membrane Technology Co., Ltd., Guiyang, China), with a membrane area of 0.18 m^2 . The ultrasonic cleaning apparatus consisted of six ultrasound transducers (KMDcsb, Shenzhen, China) and a resonance cell. The transducers were connected to an ultrasound generator (KMDcsb, KMD-K1, Shenzhen, China) to precisely adjust the frequency and intensity of ultrasound. The feed for the pilot system was Na_2SO_4 solutions with specific concentrations for operating conditions optimization experiments and actual flue-gas desulfurization (FGD) wastewater for cleaning performance experiments. The feed was induced to the RO membrane via a high-pressure pump. A schematic of the system is shown in Figure 1a and photograph is shown in Figure 1b.

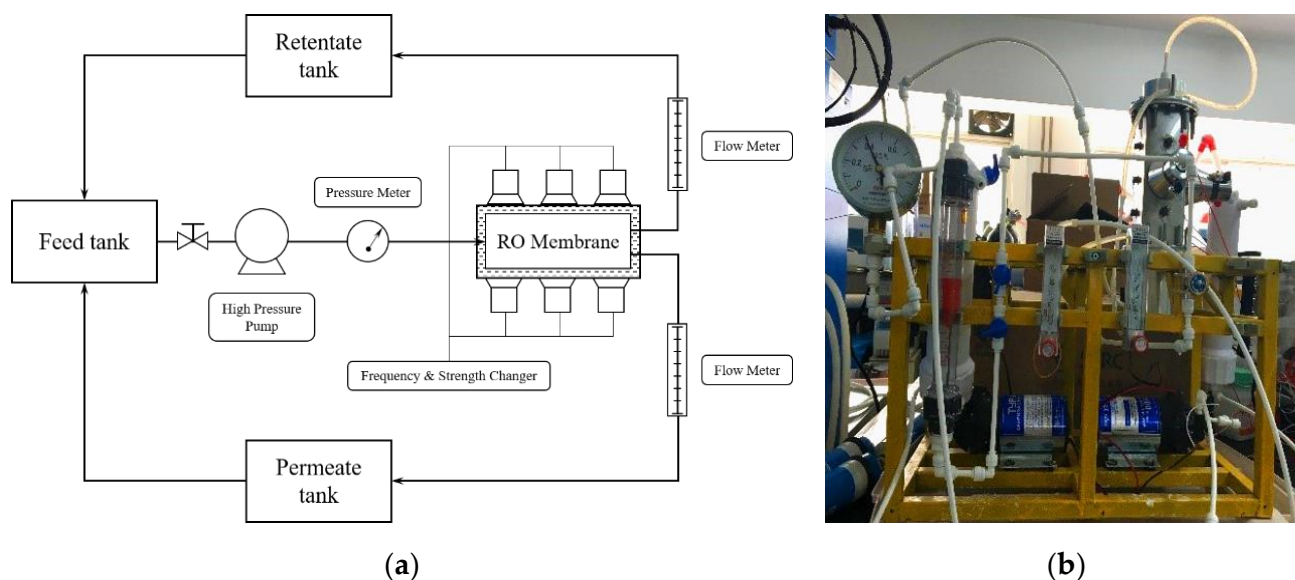


Figure 1. Schematic (a) and photograph (b) of the laboratory-scale membrane system.

2.3. Optimization Experiments for RO Membrane Operation

Five parameters (feed flow rate, operating pressure, feed concentration, temperature, and pH) were evaluated separately to obtain the optimal operating conditions for the RO membrane. In each experiment, four factors were maintained constant to evaluate the effect of the remaining factor on RO membrane performance. The membranes were operated for 10 h under different operating conditions. Permeate flux and rejection were calculated according to the following equations to evaluate the performance of the RO membrane process:

$$J = \frac{Q_p}{S}, \quad (1)$$

$$R = \left(1 - \frac{C_p}{C_f}\right), \quad (2)$$

where J = permeate flux, Q_p = permeate flow rate, S = membrane surface area, R = rejection, C_p = ions concentration in permeate flow, and C_f = ions concentration in feed flow.

2.4. Optimization Experiments for Ultrasound Generation Conditions

The optimal generation conditions for ultrasound were also examined to achieve better cleaning effects. As in the above experiments, frequency and intensity were adjusted separately by the ultrasound generator to evaluate the influence of the two parameters on ultrasonic cleaning. The membranes were also operated for 10 h under optimal operating conditions and then cleaned for 10 min under different ultrasound generation conditions. Permeate flux and rejection after cleaning were also calculated according to the above equations to evaluate the cleaning effect.

2.5. Ultrasonic Cleaning Performance of RO Membrane after Actual FGD Wastewater Treatment

After determining the optimal conditions of membrane operation and ultrasound generation, the laboratory-scale membrane system was fed with actual FGD wastewater to evaluate the cleaning effect of ultrasonic cleaning. As the actual ion concentration was too high for the commercial household RO membrane treatment, the actual FGD wastewater was diluted 10 times to avoid membrane fouling. The system was operated for 10 h and cleaned for 10 min. The permeate flow was sampled and measured every 15 min in the first 2 h and then measured every 30 min. The ions concentrations in feed wastewater were measured before membrane filtration. Moreover, the concentrations of the ions were measured before ultrasonic cleaning and after cleaning.

2.6. Analytical Methods for Evaluation Parameters

Grab samples of permeate were collected and analyzed for inorganic constituents three times during each experiment. According to National Standard, the analyses were performed (GB/T 5750.5-2006, GB/T 15453-2008, GB/T 15452-2009, HJ 535-2009). The ion concentrations were analyzed via UV spectrophotometer. In optimization experiments for RO membrane operation and ultrasound generation conditions, sulfate was the only anion of interest. In the experiment of ultrasonic cleaning effect of RO membrane after actual FGD wastewater treatment, the anions of interest were calcium, magnesium, and ammonium and the cations of interest were sulfate and chloride.

3. Results and Discussion

3.1. Effects of Operating Conditions on Membrane Performance

Five parameters (feed flow rate, operating pressure, feed concentration, temperature, and pH) were studied to optimize the operating conditions, as they influence the wastewater treatment effect of the reverse osmosis (RO) membrane [34]. Feed flow rate, operating pressure, temperature, and pH are the essential parameters that directly determine the overall operating conditions. The optimization experiment on feed concentration was to testify the concentration range of wastewater that the system can handle. The experiment results (permeate flux and rejection) could also testify the feasibility of using the RO membrane for FGD wastewater.

Permeate flux and rejection versus feed flow rate are shown in Figure 2. Both permeate flux and rejection increased with feed flow rate and reached maximum ($36.19 \text{ L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ and 96.15%, respectively) at a feed flow rate of $35.00 \text{ L} \cdot \text{h}^{-1}$, representing the best performance of wastewater treatment. The improvement of membrane performance was related to the mitigation of membrane fouling. Higher feed flow rate increased the flow velocity and provided a better mass transfer coefficient [35]. The improved flow velocity and mass transfer coefficient further reduced the ion concentration near the membrane surface and diminished the concentration polarization and membrane fouling.

High operating pressure increased the permeate flux and rejection (Figure 3). The increment of permeate flux was expected, as RO membranes are pressure-driven membranes. An increase in the rejection with increasing pressure was achieved until a constant and steady rejection of ca. 96.10% at 0.35 MPa was obtained. The trend of rejection variation was similar to the experimental results of Gur-Reznik Shirra [36]. The variation of rejection may be attributed to the path change of the high content of salts with the permeate, which

decreases the salt rejection efficiency [37]. The maximum permeate flux and rejection were obtained at 0.50 MPa ($37.25 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and 96.16%, respectively). In this study, 0.50 MPa was applied to the membrane system for higher experimental efficiency, while 0.35 MPa could be applied for cost-saving purpose.

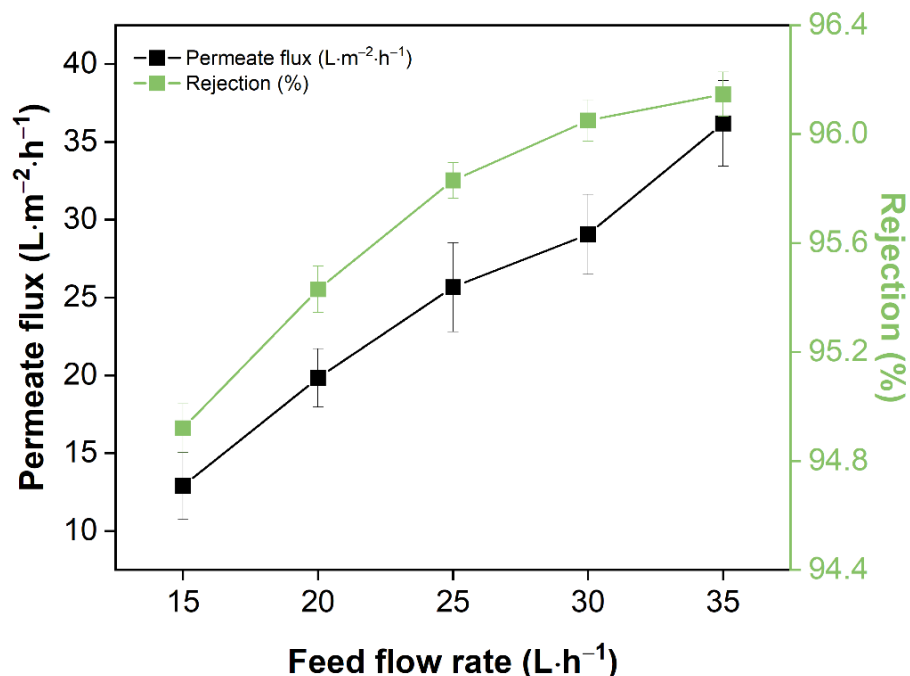


Figure 2. Permeate flux (black dot line) and rejection (green dot line) of reverse osmosis (RO) membrane after 10 h running at different feed flow rates ranging from 15 to 25 $\text{L}\cdot\text{h}^{-1}$. Operating conditions: feed solution, Na_2SO_4 ; feed concentration, $2500 \text{ mg}\cdot\text{L}^{-1}$; operating pressure, 0.5 MPa; temperature, 18°C ; pH, 7.

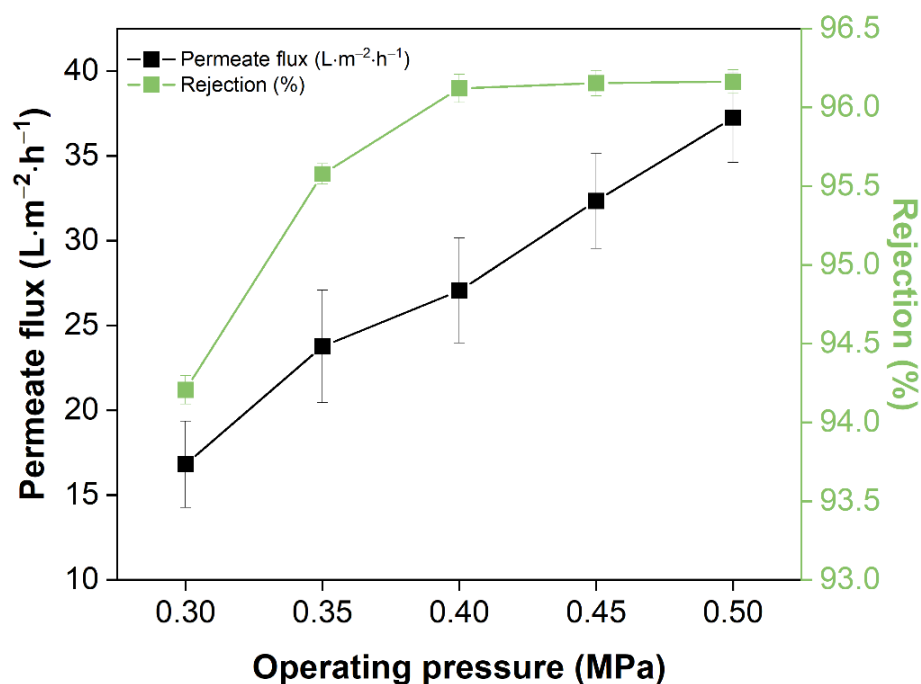


Figure 3. Permeate flux (black dot line) and rejection (green dot line) of RO membrane after 10 h running under different operating pressure from 0.30 to 0.5 MPa. Operating conditions: feed solution, Na_2SO_4 ; feed concentration, $2500 \text{ mg}\cdot\text{L}^{-1}$; feed flow rate, $35 \text{ L}\cdot\text{h}^{-1}$; temperature, 18°C ; pH, 7.

The high concentration feed resulted in reducing the wastewater treatment effect (Figure 4). Compared with other experiments under the same operating conditions, both the value of permeate flux and rejection declined to the minimum ($30.15 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and 85.44%) under high concentration. The highly concentrated feed contained more polluting particles at fixed feed flow. These particles will deposit on the surface or the pores of the membrane, resulting in membrane scaling and the decrease of permeate flux and rejection [34]. The feed concentration suitable for RO membrane treatment was 1000.00 to $3500.00 \text{ mg}\cdot\text{L}^{-1}$ in this study, as the rejection value remained at ca. 95.00%.

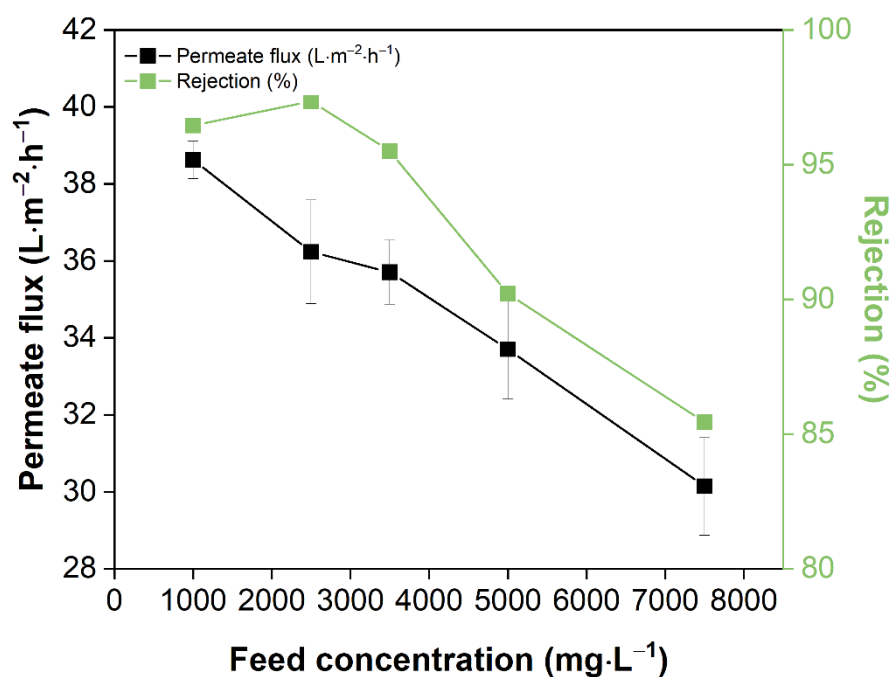


Figure 4. Permeate flux (black dot line) and rejection (green dot line) of RO membrane after 10 h running under different feed concentrations from 1500 to $7500 \text{ mg}\cdot\text{L}^{-1}$. Operating conditions: feed solution, Na_2SO_4 ; feed flow rate, $35 \text{ L}\cdot\text{h}^{-1}$; operating pressure 0.5 MPa ; temperature, 18°C ; pH, 7.

Since this study evaluates the feasibility of simplifying desulfurization wastewater treatment by combining RO membrane treatment with ultrasonic cleaning, the laboratory-scale experimental system was built with commercial RO membranes to save on experimental costs. The results above indicate that the commercial RO membranes showed inadequacy to high concentration (above $3500.00 \text{ mg}\cdot\text{L}^{-1}$) wastewater. The actual FGD wastewater ($25,000.00 \text{ mg}\cdot\text{L}^{-1}$) was diluted 10 times to avoid poor membrane treatment effects under high feed concentrations. In future research, this deficiency could be made up when applying the industrial RO membrane to the system.

Feed temperature had the opposite effects on permeate flux and rejection (Figure 5). The permeate flux increased linearly with temperature, while the rejection declined slightly at high temperatures. The rising trend of permeate flux is similar to previous studies, with a 60% increase in the permeate flux when the feed temperature increased from 20 to 40°C [38]. The high temperature increased the pore size of the membrane because of thermal expansion, allowing more water to pass through. With the increment of temperature, the solubility of the solute also increased, and a higher diffusion rate of solute through the membrane is possible, causing the decrease of rejection at high temperature [39]. According to the experimental results, the optimal temperature for membrane operation was 25.00°C (maximum rejection value of 96.17%). Considering the heating cost, the operating temperature for the system was 18.00°C .

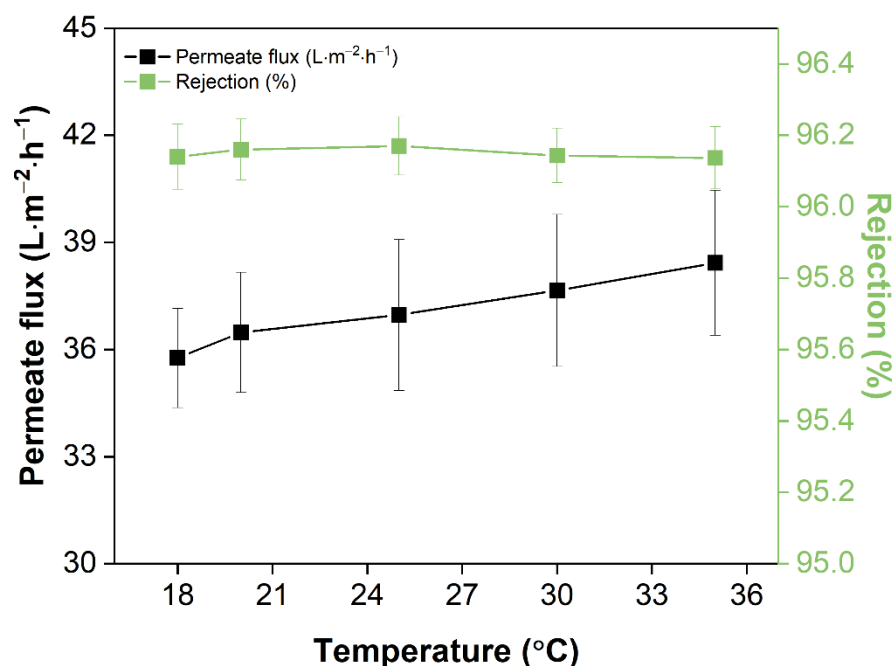


Figure 5. Permeate flux (black dot line) and rejection (green dot line) of RO membrane after 10 h running under different temperatures from 18 to 35 °C. Operating conditions: feed solution, Na₂SO₄; feed concentration, 2500 mg·L⁻¹; feed flow rate, 35 L·h⁻¹; operating pressure, 0.5 MPa; pH, 7.

The effect of feed pH on membrane performance was negligible, as the rejection value remained at about 96.00% (Figure 6). However, the variation trend of permeate flux and rejection is similar to Hoang's experiment [40]. Alkaline wastewater may cause membrane structure deformation or damage, leading to permeate flux decline at high pH values. The impact of feed pH on RO membrane structure may require further studies. Since the pH of actual FGD wastewater is often acidic, the RO membrane can treat it without membrane damage. In this study, the optimum operating condition of pH was 7 because of the maximum value of permeate flux and rejection (35.97 L·m⁻²·h⁻¹ and 96.14%).

To determinate optimal membrane operating conditions, permeate flux and rejection are the key factors. According to the experimental results above, the optimal conditions (feed flow rate, 35.00 L·h⁻¹; operating pressure, 0.50 MPa; feed concentration, 2500.00 mg·L⁻¹; feed temperature, 18.00 °C; feed pH, 7) for the RO membrane operation in this study were fixed. The permeate flux and rejection results also proved that the RO membrane was capable of FGD wastewater treatment.

3.2. Effect of Frequency and Intensity on Membrane Cleaning

Since RO membranes are vulnerable and have complex and composite structures, cleaning conditions are vital to membrane lifetime extension. Operational factors of ultrasound generation can influence the effectiveness of ultrasonic treatment [32]. This study examined the effect of frequency and intensity on the ultrasonic cleaning effect. All membranes ran for 10 h using 2500.00 mg·L⁻¹ Na₂SO₄ under optimal operating conditions (feed flow rate: 35.00 L·h⁻¹, operating pressure: 0.50 MPa, temperature: 18.00 °C, pH: 7). The time of ultrasonic cleaning was 10 min.

Both permeate flux and rejection reduced with increasing ultrasound frequency, indicating the cleaning efficiency decreased under high frequencies (Figure 7). This result is consistent with previously published literature, in which high-frequency treatment led to low permeate flux [41–44]. The findings further support that lower ultrasound frequencies have higher cleaning efficiencies [45]. The foulant on the membrane surface was removed by collapses of microbubbles generated by ultrasound [46]. Under high frequencies, the rarefaction and compression cycles of cavitation bubbles formation were reduced, lowering

the lifetime and the size of the microbubbles before collapse [47]. The energy contained in microbubbles was also reduced. The diminished energy cannot generate powerful collapses for pollutant cleaning, resulting in a poor membrane cleaning effect. The optimal frequency for ultrasonic cleaning is 25 kHz in this study, as the permeate flux and rejection reached the maximum ($45.26 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and 97.37%).

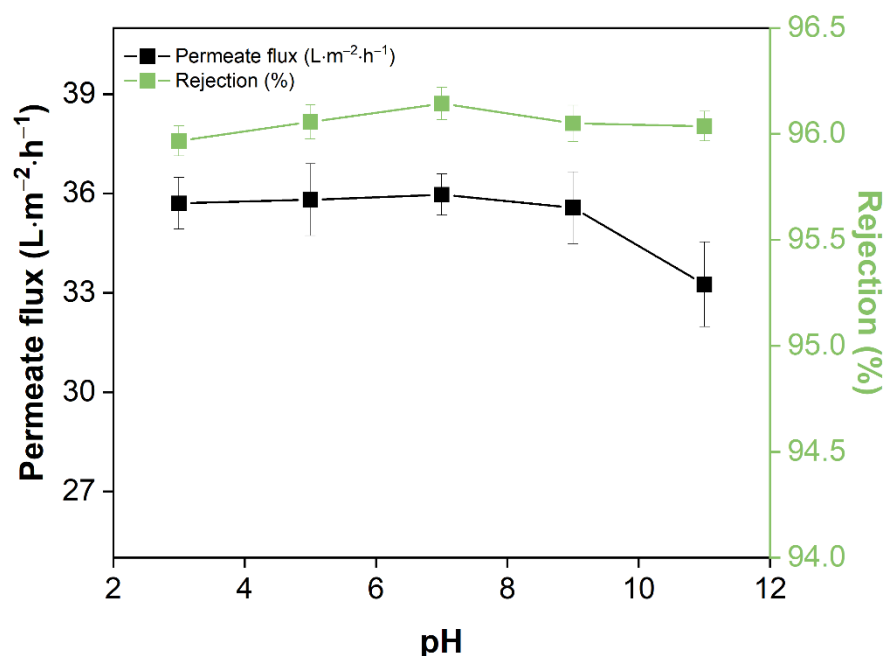


Figure 6. Permeate flux (black dot line) and rejection (green dot line) of RO membrane after 10 h running under different pH from 3 to 11. Operating conditions: feed solution, Na_2SO_4 ; feed concentration, $2500 \text{ mg}\cdot\text{L}^{-1}$; feed flow rate, $35 \text{ L}\cdot\text{h}^{-1}$; operating pressure, 0.5 MPa; temperature, 18°C .

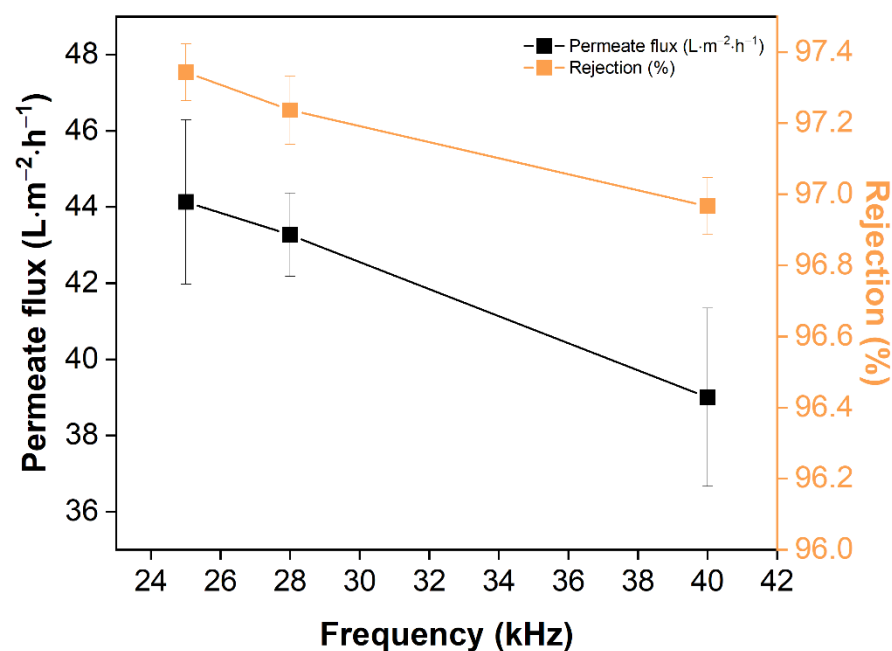


Figure 7. Permeate flux (black dot line) and rejection (orange dot line) of RO membrane after 10 min cleaning under different frequencies from 25 to 40 kHz. Before ultrasonic cleaning, the membrane had been running for 10 h under optimal operating conditions. Membrane operating conditions: feed solution, Na_2SO_4 ; feed concentration, $2500 \text{ mg}\cdot\text{L}^{-1}$; feed flow rate, $35 \text{ L}\cdot\text{h}^{-1}$; operating pressure, 0.5 MPa; temperature, 18°C ; pH, 7. Ultrasound generation conditions: intensity, $3.1 \text{ W}\cdot\text{cm}^{-2}$.

By increasing the intensity of ultrasound, the permeate flux and rejection after cleaning reached the maximum ($45.26 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and 97.37%), indicating that the cleaning effect improved (Figure 8). In accordance with the present results, previous studies have demonstrated that higher intensity will provide better cleaning effect and greater permeate flux, and the permeate flux increased nearly linearly with intensity [41–43,48]. Contrary to the influence of frequency on the cleaning effect, an increment of intensity will increase the acoustic pressure amplitude and generate more powerful ultrasonic bubbles [47]. More pollutants on the membrane surface can be removed under high intensities. The optimal intensity for RO membrane cleaning was $3.10 \text{ W}\cdot\text{cm}^{-2}$ in this study.

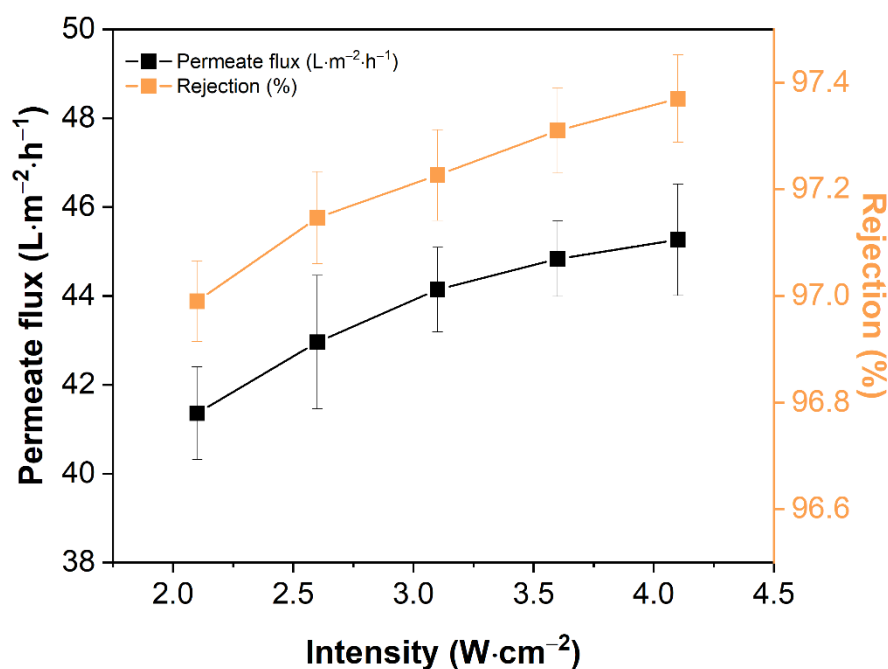


Figure 8. Permeate flux (black dot line) and rejection (orange dot line) of RO membrane after 10 min cleaning under different intensities from 2.1 to $4.1 \text{ W}\cdot\text{cm}^{-2}$. Before ultrasonic cleaning, the membrane had been running for 10 h under optimal operating conditions. Membrane operating conditions: feed solution, Na_2SO_4 ; feed concentration, $2500 \text{ mg}\cdot\text{L}^{-1}$; feed flow rate, $35 \text{ L}\cdot\text{h}^{-1}$; operating pressure, 0.5 MPa ; temperature, 18°C ; pH, 7. Ultrasound generation conditions: frequency, 25 kHz.

According to the experimental results above, the optimal conditions (frequency, 25 kHz; intensity, $3.10 \text{ W}\cdot\text{cm}^{-2}$) for ultrasound generation in this study were also fixed. In summary, for ultrasonic cleaning of the membrane module, the optimal conditions for ultrasound generation should be low frequency and high intensity. This could be guiding advice when applying the ultrasonic cleaning technology to other membrane technologies.

3.3. Treatment of Actual FGD Wastewater and Ultrasonic Cleaning of the Fouled Membrane

After determining the optimal conditions for membrane operation and ultrasound generation, the system was fed with actual FGD wastewater (diluted 10 times) to evaluate the treatment effect of RO membrane combined with ultrasonic cleaning. The flux data during the experimental process were examined and presented in Figure 9. After 6 h of filtration, the flux decreased from 47.78 to $34.55 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Then the flux increased to $41.07 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ after 10 min of ultrasonic cleaning. The permeate flux recovered for 49% of the reduced value within 10 min of cleaning, suggesting that ultrasonic cleaning can efficiently remove pollutants on the membrane surface. Although the recovery rate of permeate flux (49%) was only about half of the physical cleaning (ca. 93%), the cleaning time (10 min) was only one-third of physical cleaning (30 min) [49]. The ultrasonic cleaning was more efficient than physical cleaning without consuming a large amount of clean water. The recovered flux was also higher than the chemical cleaning of sugar-fouled reverse

osmosis membrane with some chemical agents (i.e., 1% HNO_3 , 1% NaOH , 1% HCl , 1% CTAB) [50]. After another 4 h of filtration, the flux declined to $36.40 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. The decline rate of flux slowed down, as the flux declined to $36.41 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ within only 2 h in the first 6 hours of filtration. This result indicated that ultrasonic cleaning extended the lifetime of the membrane. The cleaning may loosen the foulant layer on the membrane surface and diminish the speed of layer formation. Table 1 shows the variation of permeate concentration and rejection before and after ultrasonic cleaning. Rejections increased by 2–3% after cleaning, suggesting that the ultrasonic cleaning slightly improved the treatment effect. As the rejection value was at a high level (ca. 95.00–97.00%) after cleaning, ultrasonic cleaning was beneficial to maintain wastewater treatment performance. The effluents also met the standard of desulfurization wastewater treatment during the whole experimental process. These results proved that ultrasonic cleaning is an efficient method for fouled RO membrane. Furthermore, combining RO membrane treatment with ultrasonic cleaning can extend the lifetime of the membrane and improve the wastewater treatment effect.

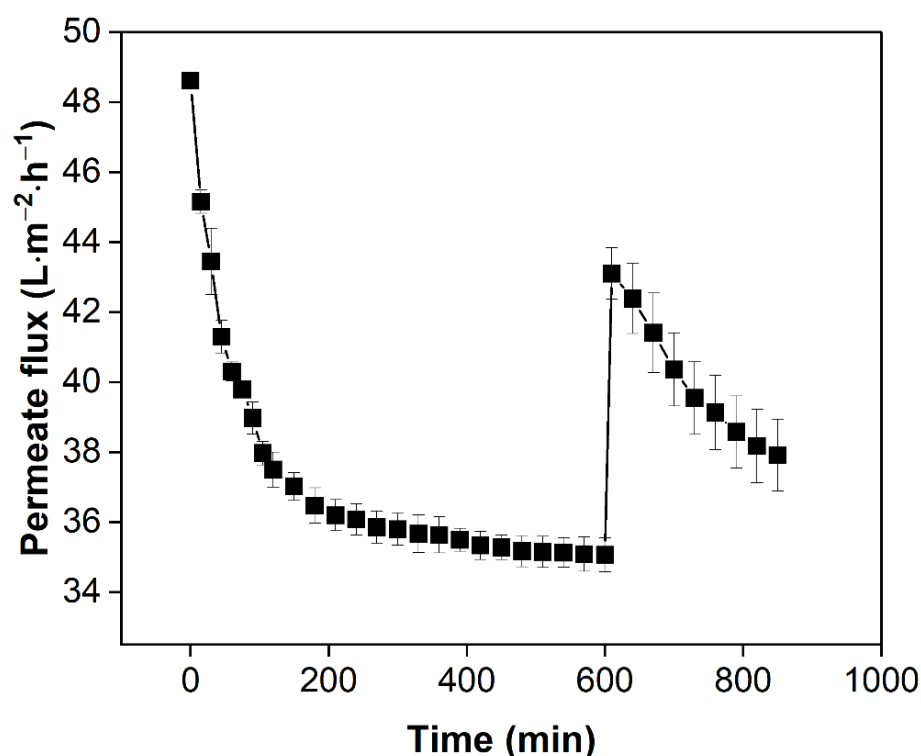


Figure 9. Permeate flux variation during the membrane running process. Before ultrasonic cleaning, membranes had been running for 10 h. After 10 min of ultrasonic cleaning, the membrane was kept running for another 4 h. Membrane operating conditions: feed solution, actual desulfurization wastewater diluted 10 times; feed flow rate, $35 \text{ L}\cdot\text{h}^{-1}$; operating pressure, 0.5 MPa; temperature, 18°C ; pH, 7. Ultrasound generation conditions: frequency, 25 kHz; intensity, $3.1 \text{ W}\cdot\text{cm}^{-2}$.

Table 1. Permeate concentration and rejection variation before and after ultrasonic cleaning.

Ion	Initial Concentration (mg/L)	Permeate Concentration before Cleaning (mg/L)	Rejection before Cleaning (%)	Permeate Concentration after Cleaning (mg/L)	Rejection after Cleaning (%)
SO_4^{2-}	2333.90	119.86	94.86%	94.86	95.94%
	2400.00	120.20	94.99%	70.41	97.07%
	2499.90	119.11	95.24%	69.34	97.23%
Ca^{2+}	48.32	2.50	94.83%	1.46	96.98%
	53.87	2.73	94.93%	1.56	97.10%
	59.55	2.61	95.62%	1.47	97.53%

Table 1. Cont.

Ion	Initial Concentration (mg/L)	Permeate Concentration before Cleaning (mg/L)	Rejection before Cleaning (%)	Permeate Concentration after Cleaning (mg/L)	Rejection after Cleaning (%)
Mg ²⁺	792.70	43.60	94.50%	26.32	96.68%
	806.74	43.60	94.60%	25.04	96.90%
	836.51	42.77	94.89%	24.33	97.09%
Cl [−]	1350.00	83.97	93.78%	66.69	95.06%
	1388.48	85.15	93.87%	67.84	95.11%
	1440.30	84.33	94.14%	54.46	96.22%
NH ₄ ⁺	309.58	18.82	93.92%	15.06	95.14%
	320.63	19.10	94.04%	14.60	95.45%
	350.67	18.22	94.80%	13.62	96.12%

4. Conclusions

In this work, flue gas desulfurization (FGD) wastewater was treated by a laboratory-scale treatment system with the combination of reverse osmosis (RO) membrane and ultrasonic cleaning. The optimization experiments on operating parameters proved that the commercial RO membrane was capable of FGD wastewater treatment. The investigation of optimal ultrasound generation conditions has shown that ultrasound generated under low frequency and high intensity had the best cleaning effect on the fouled membrane. These findings provide the optimal conditions for RO membrane operation (feed flow rate, 35.00 L·h^{−1}; operating pressure, 0.50 MPa; feed concentration, 2500.00 mg·L^{−1}; feed temperature, 18.00 °C; feed pH, 7) and ultrasound generation (frequency, 25 kHz; intensity, 3.10 W·cm^{−2}). The feasibility of the system was also tested.

The introduction of ultrasonic cleaning improved the cleaning efficiency of membrane fouling. The permeate flux recovered 49% of the reduced value within 10 min of cleaning, which is more efficient and cost-saving than physical cleaning and some chemical cleaning methods. Furthermore, the time for permeate flux decline after cleaning had doubled (from 2 h to 4 h), suggesting that the ultrasonic cleaning can delay the formation of membrane fouling and extend the lifespan of the RO membrane. The treatment effects were maintained as the rejection values were high (95.00–97.00%). The effluent of the system also met the standard of FGD wastewater treatment.

Overall, the study indicated that the treatment system is capable of FGD wastewater treatment at a laboratory scale. The combination of RO membrane and ultrasonic cleaning sheds new light on building a system for FGD wastewater treatment in a more efficient, cost-saving, and convenient way. Further research should focus on applying this system at a factory-scale experiment by changing the commercial membrane to industrial membrane.

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