



# Effect of high salinity on the performance of forward osmosis: Water flux, membrane scaling and removal efficiency



Pin Zhao<sup>a</sup>, Baoyu Gao<sup>a</sup>, Qinyan Yue<sup>a,\*</sup>, Sicheng Liu<sup>a</sup>, Ho Kyong Shon<sup>b</sup>

<sup>a</sup> Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University, Jinan 250100, China

<sup>b</sup> School of Civil and Environmental Engineering, University of Technology, Sydney (UTS), Post Box 129, Broadway, New South Wales 2007, Australia

## HIGHLIGHTS

- FO was applied in treating the high-salinity feed water.
- The role of temperature is less than velocity in high-salinity feed treatment.
- The operation efficiency dropped gradually with the salinity of feed water.
- The membrane scaling aggravated with the increasing FS salinity in the PRO mode.
- The removal efficiency of Ni(II) was high in the FO process.

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## ABSTRACT

In this study, the performance of forward osmosis (FO) in treating the high-salinity feed water was investigated under different temperatures, membrane orientations and flow cross velocities in terms of water flux, membrane scaling and removal efficiency of Ni (II). The results showed that, the enhanced temperature cannot, while the increased cross flow velocity can promote the water flux effectively in treating the high-salinity feed water. The optimal operating conditions were determined to be 35 °C and 10 cm/s, in which the operation was energy-efficient. The water flux declined gradually with the salinity of feed water. It was more than 10 LMH in treating 50 g/L NaCl solution, while was 5 LMH when the FS salinity increased to 100 g/L. The application became unfeasible in the salinity of 100 g/L. The membrane scaling was slight in the FO mode; on the contrary, it was severe in the PRO mode and aggravated with the FS salinity. But fortunately, the membrane scaling can be removed effectively by simple physical cleaning. The removal efficiency of Ni(II) in the FO mode was higher than that in the PRO mode, and both of them were higher than 95%. Moreover, the rejection efficiency increased with FS salinity.

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## 1. Introduction

Reverse osmosis (RO) combines process stability with excellent effluent quality, and is becoming a standard technology for desalination and wastewater treatment for water reuse in decades [1]. However, its sustainable development is severely limited by RO concentrate disposal due to the high salinity and fouling potential. RO concentrate is characterized by high concentrations of organic and inorganic, such as heavy metals, viruses, colloids, bacteria, particulates, acid and antiscaling agents [2–4]. The traditional treatment of RO concentrate is direct discharge into the natural water body with or without dilution, or evaporation. However, neither of them is environmentally-friendly. With increasing awareness to the environmental protection, the limitation on disposal of RO concentrate has become increasingly stringent [5]. It

is crucial and urgent to find an efficient way to treat the RO concentrate, which can not only bring advantages to the environment but also improve the development of RO process.

Nowadays, many novel methods have been applied to treat the RO concentrate. Greenlee et al. [6] investigated a treating scheme consisting of ozonation, precipitation and microfiltration steps, and found that the overall recovery increased from 80 to 94%. Zhou and his colleagues [7] studied a simple integrated method (coagulation and photocatalysis) which achieved a high organics removal in RO concentrate. Zhang et al. [8] reported that, electro-dialysis (ED) received good effect in RO concentrate treatment using the decarbonation process as pretreatment. These treatments achieved high salt and organics removal, but the energy consumption was proportional to the permeate water quality and quantity, which made the application uneconomical in treating massive high-salinity solutions. As anticipated, the consumed energy would be minimized if the RO concentrate was further concentrated and the total volume was reduced.

\* Corresponding author.

E-mail address: [qyyue58@aliyun.com](mailto:qyyue58@aliyun.com) (Q. Yue).

Forward osmosis (FO) is an emerging separation/desalination technology. Water transports from feed to draw side driven by the osmotic pressure difference between the two solutions separated by a special semi-permeable membrane [9]. FO can be operated at low or none pressures and has additional advantages such as high rejections to a variety of contaminants, relatively lower fouling propensity and higher fouling reversibility [10,11]. It is expected that FO can be used to treat high-salinity feed waters. During the process, the high-salinity feed water is further concentrated and then the concentrated feed water can be further treated by evaporation or ED. The useful resource of RO concentrate can be recovered. At the same time, the diluted draw solution (DS) will still have relatively high osmotic pressure, which can be applied in the other FO process to treat the wastewater of low osmotic pressure. This way not only saves a lot of energy, but also realizes the recovery of useful resources.

Up to now, applying FO technology for treatment of the RO concentrate is not well investigated. Therefore, in this work, the performance of FO process in treating the high-salinity feed waters (simulative RO concentrate) in the various salt concentrations was measured under different temperatures, membrane orientations and velocities. The objective of this research was to study the feasibility of applying FO to treat the high-salinity feed waters of different levels and choose the optimum operating condition. Moreover, the removal efficiency of Ni (II) was evaluated under the optimum condition. It is envisioned that this study may support the fundamentals to the further development of FO in treating the high-salinity feed waters.

## 2. Materials and methods

### 2.1. Feed and draw solutions

There were three pairs of DS and feed solution (FS) applied in our study. Specifically, 117, 155 and 194.5 g/L NaCl were chosen as DS, while 0, 50 and 100 g/L NaCl were chosen as the corresponding FS. NaCl was obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai). It was chemically pure. The basic properties of DS such as osmotic potential, diffusion coefficient, conductivity, viscosity and density were determined using OLI Stream Analyzer 3.1 (OLI Systems Inc., Morris Plains, NJ, USA). The osmotic pressure differences between DS and FS were held constant. 50 and 100 g/L NaCl represented the different levels of high-salinity wastewater.

Heavy metal Ni (II) was chosen as the representative pollution of RO concentrate. NiCl<sub>2</sub> 6H<sub>2</sub>O was obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai). The initial concentration of Ni (II) in the FS was 100 mg/L. The amount of Ni (II) in the draw side was determined by atomic absorption spectrophotometer (Beijing Purkinje General Instrument Co., China). The rejection efficiency of FO process (%) was calculated by the retention coefficient:

$$R = \frac{C_F - C_D}{C_F} \times 100\% \quad (1)$$

where  $C_F$  is the initial concentration of Ni (II) in the FS and  $C_D$  the final concentration of Ni (II) in the DS.

### 2.2. Forward osmosis membrane

The membrane applied in this work was a commercial flat-sheet cellulose triacetate (CTA) FO membrane, which was provided from Hydration Technology Innovations or HTI, Albany, USA. It had been widely used for FO process in wastewater reclamation applications. The CTA-FO membrane shared the general characteristics of asymmetric structure. It was made from cellulose acetate embedded in a polyester woven mesh, containing a thick mechanical support layer and a thin

active layer. The contact angles of active layer and support layer were 76.6° and 81.8°, respectively. The operation pH range was 3–8. Moreover, the zeta potential of active layer at pH 6 was –2.1 mV [12,13]. The pure water permeability coefficient of CTA-FO membrane was measured under hydraulic pressure (RO mode) and determined to be 0.98 L / (m<sup>2</sup> h bar).

Since the absence of hydraulic pressure, there are two modes of membrane orientation in FO process. When the mechanical support layer faces the FS and the dense active layer faces the DS, this membrane orientation is referred to be the pressure retarded osmosis (PRO) mode; when the mechanical support layer faces the DS and the dense active layer faces the FS, this membrane orientation is referred to be the FO mode.

### 2.3. Forward osmosis system

The FO experimental setup in this study was similar to that in our previous studies [14,15]. FO was conducted using a lab scale unit with an effective membrane area of 20.0 cm<sup>2</sup> (7.7 cm length, 2.6 cm width and 0.3 cm depth). The FS and DS were circulated by two peristaltic pumps (BT300-2J, Baoding Longer Precision Pump Co., Ltd., China. Pump head: YZ1515x) and flowed concurrently through the lumen and shell sides at the flow rates of 5, 10 or 15 cm/s. The performance at temperatures of 25 ± 0.5, 35 ± 0.5 or 45 ± 0.5 °C was measured. A weighing balance (Satorius weighing technology GmbH, Gottingen, Germany) was used to record automatically the variation in the DS weight for water flux computation.

### 2.4. Theoretical water flux

In an optimal situation, the standard water flux is obtained by the following equation:

$$J_w = A\sigma[\pi_D - \pi_F] = A\sigma\Delta\pi \quad (2)$$

where  $J_w$  is the ideal water flux across the FO membrane, L / (m<sup>2</sup> h) (LMH);  $A$  is the membrane permeability coefficient, L / (m<sup>2</sup> h bar);  $\sigma$  is the reflection coefficient;  $\pi_D$  and  $\pi_F$  are the osmotic pressure of the DS and FS, respectively, and  $\Delta\pi$  is the net osmotic gradient, bar. Especially, the value of  $\sigma$  can be assumed to be 1 when the water permeation is low and FS is dilute completely in the FO process, (i.e., complete rejection of the feed solution).

However, all the FO membrane contains a thick mechanical support layer which causes the lower  $\sigma$  value. The concentration polarization (CP) effect hampers the FO performance severely. In the PRO mode, water is diffused from the feed to draw side, resulting in the external CP (dilutive) in the active layer and the internal CP (concentrative) in the porous support layer, while in the FO mode, dilutive internal CP and concentrative external CP occur on the porous support layer and active layer, respectively [16–18].

Considering negative effects of CP on the actual water flux, Eq. (1) can be modified to the form of Eqs. (3) and (4) in the PRO and FO mode, respectively [19,20].

$$J_w = A\sigma[\pi_{D,m} - \pi_{F,m}] = A\sigma \left[ \pi_D \exp\left(-\frac{J_w}{k_D}\right) - \pi_F \exp\left(\frac{J_w}{k_F}\right) \right] \quad (3)$$

$$J_w = A\sigma[\pi_{D,m} - \pi_{F,m}] = A\sigma \left[ \pi_D \exp(-J_w/k) - \pi_F \exp\left(\frac{J_w}{k_F}\right) \right] \quad (4)$$

where  $\pi_{D,m}$  and  $\pi_{F,m}$  are the osmotic pressure of the DS and FS on the membrane surfaces, respectively (bar).  $k$  is the solute resistance to diffusion within the membrane support layer.  $k_D$  and  $k_F$  are the mass transfer coefficient on the draw and feed side, respectively.

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