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Discussion on calculation of maximum water recovery in nanofiltration system

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HIGHLIGHTS

- A method has been proposed to calculate the maximum recovery for NF2 system.
- Water recovery for a NF element should be lower than 25% to maintain it stable.
- The CP degree was recommended to be 1.15 at the recovery of 25% in NF system.

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ABSTRACT

In desalination process, the effect of concentration factor (CF) and concentration polarization degree (CP degree) on water recovery in nanofiltration (NF) system displays a significant difference from that in reverse osmosis (RO) system due to their different salt rejections. In this work, the relationship between CF, salt rejection and water recovery was firstly discussed in a single NF element. In order to keep a stable performance, a spiral NF2 membrane was taken as an example, and water recovery for the single NF2 element should be about 25% instead of 15%, which is generally considered suitable for the single RO element. Then, the CP degree was calculated according to the theoretical model and experimental test, and the ultimate value was pointed out to be below 1.2. Thus, when calculating the scaling tendency of the sparingly soluble salts, the salt concentration near the membrane surface was recommended to be 1.15 times as high as that in bulk solution. Finally, a calculation method for maximum recovery was proposed for NF system. Because of the varied rejection with different NF membranes for the same feed water, which is significantly different from that in RO system, the pre-test is very necessary for NF system design.

1. Introduction

In water treatment process, water recovery is one of the most important indexes for system design of the pressure-driven membrane, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) membrane. It affects not only the pretreatment capacity and equipment investment but also the membrane fouling and operating costs [1].

Since MF and UF membranes are incompetent of retaining the soluble salt, water recovery is not limited by the scaling fouling and osmosis pressure from salts [2,3]. The normal water recovery for MF and UF system is up to 90–96%, and even greater than 99% if recycling the backwashing water by cross flow.

In RO system, water recovery was mainly restricted by the scaling fouling and osmosis pressure (only for high salt concentration feed water) [4]. The concentration polarization (CP) of the salt ions on membrane surface will accelerate the irreversible scaling fouling, reduce the transport efficiency, and thus lessen water recovery [5]. In a small size RO system (less than 18 membrane elements and not enough for a two-stage system with a flow path of 12 m), water recovery was limited lower than 15% to maintain a low CP [6,7]. In a large-scale RO system, the flow path is quite long, and water recovery is mainly limited by scaling fouling [8]. Under the reasonable arrangement of membrane elements, the saturation degree of the sparingly soluble salt near the membrane surface is usually related to the system recovery, CP and feed water quantity. However, it almost had no obvious relation with RO membrane itself because of its nearly total rejection against all ions. Consequently, the maximum system recovery can be calculated by the solubility of sparingly soluble salt, the CP degree and ion concentration in the feed water [9]. In fact, the CP degree is controlled lower than 1.2 to avoid the severe membrane fouling [6].

However, research efforts have barely focused on how much the CP degree in NF system membrane should be controlled. Sutzkover et al. [10] introduced a simple technique to measure the CP degree in RO system based on evaluation of the permeate flux decline induced by

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the addition of a salt solution to an initially salt-free water feed. Wang et al. [11] have reported that under laminar state the CP degree for flat NF membrane system turned to be stable as the cycle flow increased during the removal of high-molecular weight organic matters. Zhang et al. [12] have provided a real rejection calculation on commercial spiral NF membrane in the rejection testing of NaCl solution. Bader et al. [13] have calculated the various ion concentrations close to the surface of commercial spiral NF membrane in the sea water desalination.

The NF membrane came after RO membrane for more than two decades [14], and also the real application of NF membrane in water treatment is not much as RO membrane. Hence, the service experience for NF application is not adequate yet, and lots of NF design ideas follow RO service. However, the calculation of the maximum water recovery in NF system is quite different from that in RO system due to their different range of salt rejection. The scaling tendency of sparingly soluble salt and the CP degree of salt ions, which are absent in UF and MF process, change a lot with the salt rejection of NF membranes.

In this work, a NF2 membrane was taken as an example, and the differences of the concentration factor and the CP degree between NF and RO membranes will be discussed. Then a calculation method of the concentration factor and the CP degree on the NF membrane surface was analyzed. Finally, a theoretical model to estimate the maximum system recovery in NF system was proposed.

2. Theoretical backgrounds

2.1. Calculation of the concentration factor in NF system

In RO system, the concentration factor (CF) has been widely involved to determine water recovery (R) and the ion concentration (C_c) in the concentrated stream with a given ion concentration (C_f) in feed water under the hypothesis that the salt permeability is zero [15]. The simplified formula is as following:

$$\mathrm{CF} = \frac{C_c}{C_f} = \frac{1}{1-R}. \tag{1}$$

However, the above simplified formula is not suitable to NF system because salt permeability in NF is not zero, that is, the hypothesis is not applicable. Therefore, a rigorous deducing process is needed to obtain a more suitable formula for NF system.

In steady state, there are the mass balance Eq. (2) and mass conservation Eq. (3):

$$Q_f \cdot C_f = Q_p \cdot C_p + Q_c \cdot C_c \tag{2}$$

$$Q_f = Q_p + Q_c \tag{3}$$

where Q_f, Q_p and Q_c denote the fluxes of feed water, permeate water and concentrated water, respectively, and C_f, C_p and C_c denote the salt concentrations in feed water, permeate water and concentrated water, respectively.

Water recovery (R) and the observed rejection (r_o) are described as Eqs. (4) and (5), respectively:

$$R = \frac{Q_p}{Q_f} \times 100\% \tag{4}$$

$$r_o = 1-\frac{C_p}{C_f} \times 100\%. \tag{5}$$

The integration of Eqs. (2), (3) and (5) leads to (see Supplementary information):

$$\mathrm{CF} = \frac{C_c}{C_f} = \frac{1-R(1-r_o)}{1-R}. \tag{6}$$

Obviously, in NF system the CF is related to water recovery (R) and the observed rejection (r_o), both of which are mainly affected by the membrane performance, feed water quality, operating parameter and membrane arrangement.

2.2. Calculation of concentration polarization degree and recovery in NF system

The concentration polarization (CP) is quantified by the concentration polarization degree (CP degree), which is defined as the ratio of the solute concentration at the membrane surface and the solute concentration in the bulk solution [16,17].

Since the direct measurement of CP degree near the NF membrane surface is infeasible, the CP degree can be approximately estimated based on the theoretical model and experimental test. On the other hand, the CP degree varies with different NF membranes because of the different salt rejections under same operating condition. In the following discussion, CP degree in the optimum NF system design will be determined.

As is well known, the film theory is based on the assumption that the membrane surface is separated from the bulk stream by a thin film (ion-water) and axial solute convection near the membrane surface is negligible [18,19].

The real salt rejection (r_r, which means the theoretical rejection calculated from the conventional model as described below) and the CP degree can be denoted as:

$$r_r = 1-\frac{C_p}{C_m} \times 100\% \tag{7}$$

$$\text{CP degree} = \frac{C_m}{C_f} \tag{8}$$

where C_f, C_p and C_m are the solute concentration in the feed flow, the permeate flow and the vicinity of membrane surface, respectively.

In order to describe the relationship between CP and permeate flux, a well-established equation has been deduced as [8,10]:

$$\ln\frac{(1-r_o)}{r_o} = \ln\frac{1-r_r}{r_r} + \frac{J}{\beta U^{\alpha}} \tag{9}$$

where J, U, β and α are the net permeate flux, the velocity of crossing flow, a constant related with the membrane configuration and the solution characteristic and the velocity index that is equal to 1/3 (laminar flow) or 7/8 (turbulent flow), respectively [20,21,10].

If $\ln\left(\frac{1-r_o}{r_o}\right)$ and $\frac{J}{U^{\alpha}}$ are the linear relationship for certain solution quality and membrane module, the real rejection (r_r) and $1/\beta$ can be obtained by linear regression and thus the salt concentration near the membrane surface can be also calculated. In the Eq. (9), the observed rejection (r_o), the permeate flux (J) and the velocity of crossing flow (U) can be obtained from the NF membrane test.

3. Materials, methods and experimental

3.1. Materials

Spiral NF membrane (NF2-2540 type, see supplementary information) was provided by VONTRON, Beijing, China. Spiral reverse osmosis (RO) membrane (ESPA2 type) was provided by Hydranautics, Oceanside, USA. Sodium chloride and magnesium sulfate (analytical grade) were purchased from Sinopharm Chemical Reagent Co., Ltd., China.