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Study of membrane fouling in cross-flow vacuum membrane distillation

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ABSTRACT

Membrane fouling is one of the main obstacles to membrane distillation (MD) applications in desalination and other fields. Membrane scaling influences the efficiency and performance of vacuum membrane distillation (VMD). In this study, the process of a periodic membrane scaling experiment was investigated in detail by using a cross-flow hollow fiber membrane module. In the experiment, water flux significantly decreases from 42.5 kg/(m^2 h) to 4.1 kg/(m^2 h) because of membrane scaling; by comparison, water flux decreases from 42.7 kg/(m^2 h) to 30.4 kg/(m^2 h) in the blank experiment which is only affected by concentration and polarization. The blank experiment is performed under the same operating conditions as the periodic membrane scaling experiments, in which pure NaCl solution is used as feed. Scaling deposits form on/in membrane pores. Gas permeability experiments indicate that the membranes exhibit poorer transport properties as a result of aggravation of fouling and have smaller yield of MD. The scaling layer negatively affects heat and mass transfer in the feed near the evaporation surface. Membrane scaling further enhances temperature and concentration polarization, thereby decreasing the permeate flux. Experimental results further indicate that the overall heat transfer coefficient is reduced from 4569.4 W/(m^2 K) to 2346.6 W/(m^2 K) and the mass transfer coefficient in the membrane is reduced from 3.88 kg/(m^2 Pa h) to 2.18 kg/(m^2 Pa h) as scaling increases. Scanning electron microscopy (SEM) coupled with energy dispersion spectrometry (EDS) was employed to analyze the morphologies and compositions of the deposits formed on/in the membrane. The major component of the deposits is Ca; small amounts of Mg and S are also detected. The different morphologies of the deposits are significantly determined by various feed compositions.

Using Bohai seawater, we investigated membrane fouling on the basis of VMD. The results are important for VMD application in seawater desalination.

1. Introduction

Membrane distillation (MD) was proposed in the mid-1960s [1–3] and was considerably developed further in the early 1980s. In recent years, it has emerged as one of the most promising approaches to membrane separation [4–7]. The separation mechanism of the MD process is based on the vapor/liquid equilibrium of liquid mixtures [7–12]. The volatile components of the feed evaporate through the pores of a membrane [13,14]. In vacuum membrane distillation (VMD), a membrane separates water vapor molecules from the hot feed. The driving force for mass transport is the difference in pressure resulting from the temperature and composition of the solutions in the layer adjacent to the membrane on the hot feed side and pressure on the other side of the membrane [15–17].

However, membrane scaling has become one of the main obstacles to MD applications in desalination and other fields. The deposit formed on the hydrophobic surface of membrane causes that the pores adjacent to the deposit can be filled with liquid, which will result in a wetting of this part of the membrane and a leakage of feed to the permeate side. Therefore, membrane scaling result in the deterioration of the quality and the quantity of the water produced [18–22]. In the MD desalination process, the effect of polarization increases with feed concentration, making the potential for membrane scaling more serious. Membrane scaling is closely related to the composition of the feed. Various studies have been performed to determine the reason and factors affecting membrane fouling [18,21–31].

Membrane fouling is mainly caused by the deposition of insoluble ions during the desalination of seawater. The concentration/temperature of the solution in boundary layers adjacent to the

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Nomenclature

SQ	overall heat from the heat feed
Q_f	heat across membrane surface in thermal boundary layer
Q_m	heat across the membrane
V_{feed}	feed flow rate
S	available area of membrane module
n	number of hollow fiber membranes in the module
l	available length of a hollow fiber membrane
T_{fin}	inlet temperature of membrane module
T_{fout}	outlet temperature of membrane module
c_p	feed heat capacity
Q_v	heat taken by vapor across membrane
h_f	convective heat transfer coefficient of boundary layer in feed side
T_f	feed bulk temperature
T_{fm}	temperature of membrane surface in feed side
A_{rf}	area ratio of feed side
A_{rln}	logarithmic mean average area ratio
d_i	Inner diameter of hollow fiber (i.d.)
d_0	outer diameter of hollow fiber (o.d.)
d_{rln}	logarithmic mean diameter of i.d. and o.d. of hollow fiber
Nu_f	Nusselt number of feed flow in shell side of the module
k_o	Feed thermal conductivity
Re_o	Reynolds number based on o.d. of hollow fiber
u	feed linear velocity
ρ	feed density
μ	feed dynamic viscosity
Pr_o	Prandtl number of feed flow on shell side of the module
Pr_w	Prandtl number based on fiber-wall temperature
F_c	fiber-row correction factor
N_V	permeate flux
ΔH	latent heat of water at evaporation temperature
K	trans-membrane mass transfer coefficient
ΔP	difference in vapor pressure across the membrane
p_{fm}	water vapor partial pressure at the membrane surface on feed side
p_{pm}	vapor pressure of membrane surface on permeate side
P_{Vacuum}	vacuum of permeate side
p^o_{fm}	vapor pressure of water at the membrane surface on feed side
x_{fm}	molar ratio of water molecules on membrane surface
γ_{fm}	the activity coefficient of water molecules on membrane surface
H_f	overall heat transfer coefficient
K_f	overall mass transfer coefficient
H'_f	heat transfer coefficient in the feed side
$h_{f\text{-}fouling}$	heat transfer coefficient in fouling layer
α	model parameter in membrane fouling model
β	model parameter in membrane fouling model
TPC	temperature polarization coefficient of feed side

membrane should be higher/lower than the average value due to the polarization effect. However, the solubility of most salts increases with temperature. Thus, scale deposits are formed from those salts whose solubility is generally limited and, in the majority of the cases, decreases with increasing temperature. Stringent pretreatment of the feed solution before the MD process can effectively reduce the concentration of contaminants and can effectively inhibit membrane scaling [18,31].

Vacuum membrane distillation (VMD) is one of the most widely studied processes in membrane distillation (MD); VMD produces gases in the permeate side [5]; thus, studying the characteristics and polarizations are easily conducted compared with direct contact membrane distillation. For this reason, a system of periodic membrane scaling experiment was implemented in this study by using a cross-flow hollow fiber membrane module with simulated seawater to understand the process and characteristics of membrane scaling. Each periodic scaling membrane was investigated by conducting a gas permeability test to determine the transport properties. Important process parameters (T_{fm}; TPC; overall heat transfer coefficient, H_f; trans-membrane mass transfer coefficient, K) were calculated in VMD. The morphology and composition of the scaling layer on/in the membrane were analyzed by scanning electron microscopy (SEM) coupled with energy dispersion spectrometry (EDS). After the periodic membrane scaling experiment, different fouling experiments with Ca and Mg in the feed were investigated in detail to verify the scaling morphologies. Real BoHai seawater was used in VMD desalination. Different pretreatment processes and experimental results were obtained in this study.

2. Theoretical model

2.1. Heat and mass transport model in VMD

MD is a thermally driven process. Mass is transferred across the membrane due to differences in temperature and vapor/liquid equilibrium. We selected the internal diameter-based surface area of a hollow fiber in a cross-flow membrane module for the basis of our calculation [32–34].

Heat transferred on feed side:

$$\mathrm{SQ} = Q_f = Q_m \tag{1}$$

Here, SQ is the heat transferred from the hot feed to the membrane module; Q_f is the heat transferred from the hot feed to the membrane surface; and Q_m is the heat transferred across the membrane.

Heat from the hot brine:

$$\mathrm{SQ} = V_{feed,in}C_{p(t)}T_{fin} - V_{feed,out}C_{p(t)}T_{fout} \tag{2}$$

where V_{feed} is the flow of the feed and T_{fin} and T_{fout} are the inlet and outlet temperatures of the membrane module, respectively.

Heat from hot feed to membrane surface:

$$Q_f = h_f S A_{rf}(T_f - T_{fm}) \tag{3}$$

$$\text{where} \quad A_{rf} = \frac{d_o}{d_i}, \quad S = n\pi d_i l, \quad T_f = \frac{T_{fin} + T_{fout}}{2} \tag{4}$$

Here, T_{fm} is the temperature at the membrane surface; h_f is the heat transfer coefficient on the feed side; S is the effective area of the module; n is the number of hollow fibers; l is the effective length of one hollow fiber; and T_f is the average temperature in the bulk feed.

In this study, we employed the equation of Zukauskas to describe the observed variation in water vapor flux with brine flow velocity [32]:

$$Nu_f = \frac{h_f d_o}{k_o} = 1.04\mathrm{Re}_o^{0.4}\mathrm{Pr}_o^{0.36}\left(\frac{\mathrm{Pr}_o}{\mathrm{Pr}_w}\right)^{0.25} F_c \quad (\mathrm{Re}_0 < 40) \tag{5a}$$

$$Nu_f = \frac{h_f d_o}{k_o} = 0.71\mathrm{Re}_o^{0.5}\mathrm{Pr}_o^{0.36}\left(\frac{\mathrm{Pr}_o}{\mathrm{Pr}_w}\right)^{0.25} F_c \quad (\mathrm{Re}_o > 40) \tag{5b}$$