Available online at www.sciencedirect.com
SCIENCE DIRECT®

Journal of Membrane Science 271 (2006) 38–46

journal of MEMBRANE SCIENCE

www.elsevier.com/locate/memsci

A numerical study on concentration polarization and system performance of spiral wound RO membrane modules

Wenwen Zhou, Lianfa Song *, Tay Kwee Guan

Division of Environmental Science & Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore

Received 7 December 2004; received in revised form 1 July 2005; accepted 8 July 2005
Available online 15 August 2005

Abstract

The development of concentration polarization in a spiral wound reverse osmosis membrane channel and the depolarization effect of spacers are important concerns for understanding the performance of membrane processes. However, an accurate quantification of these effects derived from fundamental principles is impractical due to the complexity of the processes. In this study, a macroscopic method was developed to estimate the effect of concentration polarization on the performance of the spiral wound membrane modules. Concentration polarization in a channel filled with spacers was described as a combination of two extreme cases, namely the undisturbed concentration polarization and complete depolarization (uniform distribution across the channel height). With the introduction of a polarization factor for the degree of concentration polarization, a mathematical model was developed for the permeate flux in the spiral wound modules. The proposed model was solved numerically to simulate the performance of a long membrane channel under various operation conditions. The simulation results demonstrated that the model developed in this study was a feasible way to estimate concentration polarization in spiral wound modules. Excellent fitness was found between the numerical simulations and experimental observations of the average permeate fluxes in along membrane channel of spiral wound membrane modules.

Keywords: Concentration polarization; Spiral-wound module; Reverse osmosis; Mathematical modeling; Spacers

1. Introduction

Reverse osmosis (RO) processes have been widely used for separation and concentration of solutes in many fields, such as chemical and biomedical industry, food and beverage processing, as well as water and wastewater treatment [1,2]. With the shrinkage of water sources and the more stringent standards for drinking water quality, the applications of RO membrane in water reclamation and seawater desalination will continue to grow in the near future. Thus, a better model for describing RO process performance is highly desirable for designing and optimizing the system to further improve its cost-effectiveness.

The performance of an RO process is generally governed by membrane properties, operating conditions and feed solution [3]. The behavior of a small piece of RO membrane can be described with fundamental transport theories and models [2,4–6]). However, it becomes questionable when these models are directly applied to describe the performance of long membrane filtration channels as employed in full scale RO filtration systems. For example, according to the membrane transport theories, permeate flux is linearly related to driving pressure, which has been well demonstrated with laboratory-scale RO systems and small flat-sheet membrane processes. However, it is observed in full-scale RO processes that the average permeate flux does not always increase linearly with driving pressure. Because the process parameters may vary substantially along a long membrane channel, the average permeate flux in the membrane channel cannot be adequately described with the basic membrane transport theories [7–9].

Many studies have been conducted to investigate the mechanisms that control the performance of full-scale RO

* Corresponding author. Tel.: +65 874 8796; fax: +65 6779 1635.
E-mail address: eseslf@nus.edu.sg (L. Song).

0376-7388/$ – see front matter
doi:10.1016/j.memsci.2005.07.007

processes, among which concentration polarization is usually considered as a major factor for the deviation of the average permeate flux from being linearly increasing with driving pressure. For a better description of RO system, considerable efforts have been made to estimate the mass transfer coefficient in RO processes affected by concentration polarization [10–12]. Recently, Song et al. [7] suggested that salt accumulation along a long membrane channel might lead to an equilibrium state under certain circumstances. At the equilibrium state, the osmotic pressure of brine at some point in the membrane channel becomes equal to the driving pressure and permeate flux would therefore vanish from that point onwards. It was further demonstrated that the increase of salt concentration along the channel length could lead to a strong non-linear relationship between the average permeate flux and the driving pressure. Model simulations were compared and agreed with experimental observations in a full-scale RO plant [7]. However, concentration polarization in the spiral wound modules was assumed negligible in these studies without much in-depth delineation.

The objective of this study was to develop a macroscopic method to quantify the depolarization effect by spacers in the spiral wound modules so that the effect of concentration polarization on the performance of a long membrane channel can be better evaluated. The method treated concentration polarization as a combination of two extreme cases: undisturbed polarization and completely mixing in the direction of channel height. A mathematical model was then developed to investigate the effects of key operating parameters, such as driving pressure, feed salt concentration and feed velocity, on the performance of the long membrane channel. Finally, model simulations were compared with experiments of a long membrane channel of spiral wound modules.

2. Theoretical development

2.1. Governing equations

Spiral-wound module is the typical RO element used in water and wastewater treatment processes. It is a customary practice to employ several membrane modules in series (up to seven modules) held in a long pressure vessel for full-scale RO processes [13]. Fig. 1 shows schematically (a) a spiral wound RO module with (b) a feed channel sandwiched by two pieces of membranes. For convenience, a membrane channel in the following sections refers half of the channel shown in Fig. 1b with a membrane on one side and an impermeable wall on the other. The length and height of the membrane channel are indicated by L and H, respectively. Permeate flux, cross-flow velocity and salt concentration in the channel are denoted by $v(x)$, $u(x)$ and $c(x)$ with x being the distance from the entrance.

According to the principle of membrane transport, permeate flux at any point along the channel, $v(x)$, is determined by:

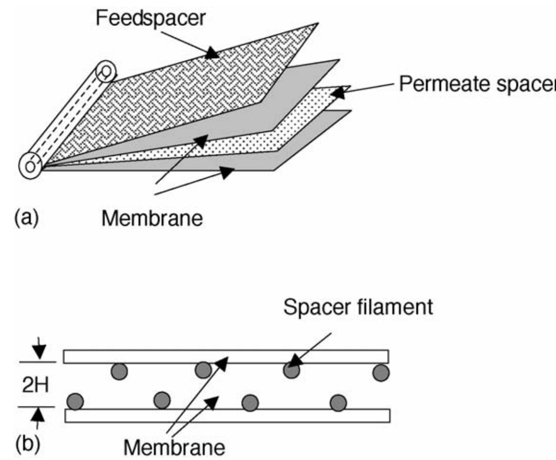

Fig. 1. Schematic drawings of (a) spiral-wound module and (b) cross-section of a feed channel.

$$v(x) = \frac{\Delta p(x) - \Delta\pi(x)}{R_m} \quad (1)$$

where R_m is the membrane resistance, $\Delta p(x)$ and $\Delta\pi(x)$ are the driving pressure and the osmotic pressure at x, respectively. The osmotic pressure can be determined with the modified van't Hoff formula by adding an ionization number N_{ion} to account for the effect of salt ionization in water,

$$\Delta\pi = \frac{N_{ion} R_g T\, \Delta c}{M_w} \quad (2)$$

where R_g is the ideal gas constant (=8.31 × 10^3 Pa/(K mol/l)), T the absolute temperature (K), Δc the salt concentration difference across the membrane (mg/l) and M_w is the molecular weight of the salt (mg/mol).

By applying the mass conservation principle on water, the cross-flow velocity along the membrane channel, $u(x)$, can be expressed as:

$$u(x) = u_0 - \frac{1}{H}\int_0^x v(\xi)\, d\xi \quad (3)$$

where u_0 is the feed velocity at the entrance and ξ is the dummy integration variable.

At steady state, the total longitudinal flux of the retained salt across the height of the channel at any point x is equal to the total amount of salt retained by the membrane from the inlet to the location x, which can be expressed by the following equation [14,15]:

$$\int_0^H uC\, dy = r_j c_0 \int_0^x v(\xi)\, d\xi \quad (4)$$

where c_0 is the feed concentration and r_j is the membrane salt rejection. C is the concentration of retained salt (the actual salt concentration $c = C + c_0$).

The distribution of salt concentration across the channel height is affected by both concentration polarization induced by permeate flow and the mixing facilitated by spacers in