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CFD analysis of tracer response technique under cake-enhanced osmotic pressure

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ABSTRACT

A cake-layer mass transfer model applicable for RO, that incorporates the cake-enhanced osmotic pressure (CEOP) effect of a particulate fouling layer, is presented. This model includes the effect of a variable dissolved solute concentration on the specific cake resistance and porosity of the cake layer. The model is based on one-dimensional diffusion of the dissolved solute through the cake layer, and uses the solute concentration at the cake surface and the cake mass per unit area to calculate the solute concentration at the membrane surface and the trans-membrane osmotic pressure. The cake-layer mass transfer model is incorporated into a commercial Computational Fluid Dynamics (CFD) software package. Simulations are validated against experimental data, and the model predictions are within $\pm 7\%$ for permeate fluxes and within $\pm 14\%$ for measured concentration polarisation.

The model is used to interpret and assess tracer response test results for estimating concentration polarisation and fouling resistance. Model predictions confirm the assumption for the tracer experiment that the average concentration polarisation along the membrane wall does not change significantly after a step change in the feed concentration of the tracer solute. However, it was found that the tracer experiment over-estimates the concentration polarisation index and under-estimates the fouling resistance, particularly under fouled conditions. The sources of error are discussed and a multiple tracer response test is proposed to minimise estimation error.

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1. Introduction

Concentration polarisation and fouling represent two of the biggest challenges faced by membrane separation operations such as Reverse Osmosis (RO). Concentration polarisation reduces the separation performance of membrane systems by adding an extra layer of resistance [1,2] and/or reducing the driving force in the region near the membrane [3]. Moreover, an increased concentration of solutes near the membrane will also increase the likelihood of precipitation and fouling. A fouled membrane will present a higher resistance to the passage of solvent, or even prevent it altogether, further decreasing the performance of the membrane system.

Since concentration polarisation occurs due to solute rejection, it is inevitable and inherent to membrane separation processes. For these reasons, various mathematical models have been proposed for predicting the extent of concentration polarisation [4–8]. However, most of these models do not take into account the effect of a fouling layer, which hinders back diffusion and increases

concentration polarisation, an effect referred to as “cake-enhanced osmotic pressure” (CEOP) [9–11] (see Fig. 1). Neglecting to take CEOP into consideration results in an over-estimation of the fouling resistance.

Incorporation of the CEOP effect into models for the performance of membrane systems can potentially lead to better agreement with experimental data [12]. However, the development of fouling models that take CEOP into consideration also face validation difficulties. This is because fouling occurs within the boundary layer at the membrane surface. Many experimental techniques are too “coarse” and lack the sensitivity required to measure flow variables inside this thin layer, resulting in experimental measurement errors [13]. In addition, these techniques are generally more suited for laboratory scale measurements than for routine use in an industrial plant.

Chong et al. [14] proposed a simple technique for assessing the effect of fouling on concentration polarisation, by measuring the response to the introduction of a sodium chloride tracer in a RO system. This tracer response technique can be used for online fouling monitoring. The objective of this paper is to develop a cake-layer mass transfer model that takes CEOP into account and to incorporate this model into a commercial CFD software package. The CFD model is then used to interpret data obtained from the

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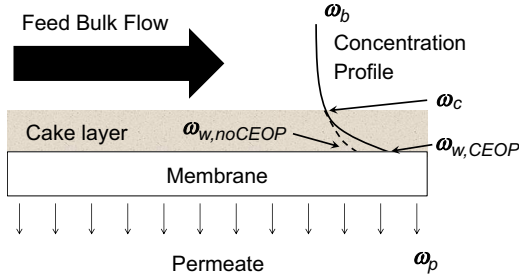


Fig. 1. Schematic of solute concentration (ω) profile with and without the effect of cake-enhanced osmotic pressure (CEOP).

tracer technique. Simulation predictions are compared against experimental data and the accuracy of the tracer response test is assessed.

2. Background

The tracer response technique proposed by Chong et al. [14] employs sodium chloride as a tracer. The tracer is injected into the feed stream of the membrane separation unit as an extended pulse, while monitoring permeate flux and trans-membrane pressure (TMP), as well as the concentration of solute in the permeate. This information is then used to calculate the degree of fouling and concentration polarisation.

Concentration polarisation refers to a concentration profile characterised by a higher concentration of solute at the membrane surface than in the bulk flow. This phenomenon can be quantified by the use of a concentration polarisation index or modulus (CP). Although there are many forms of the CP index used in the literature, Chong et al. [14] utilise a form derived from the solution of the one-dimensional mass balance differential equation within the boundary layer over the membrane surface [15]

$$CP_B = \frac{\omega_w - \omega_p}{\omega_b - \omega_p} = \exp\left(\frac{J_V}{k_{mt}}\right) \quad (1)$$

where CP_B is the local concentration polarisation index based on the local solute bulk concentration, J_V is the volumetric permeate flux and k_{mt} is the mass transfer coefficient. This concentration polarisation index can also be calculated by using the inlet bulk concentration, and it is expressed as

$$CP_{B0} = \frac{\omega_w - \omega_p}{\omega_{b0} - \omega_p} \quad (2)$$

One of the properties of this form of the concentration polarisation index is that, for one-dimensional diffusion, it only depends on the values for volumetric flux, diffusivity and boundary layer thickness. Therefore, for a constant flux and Reynolds number, the local CP_{B0} should remain constant. However, the assumption of one-dimensional diffusion from which CP_{B0} is derived is only an approximation for cross-flow membrane separation, particularly if spacers are present. Spacers promote the formation of vortices that disrupt the boundary layer [16,17] which results in regions of relatively high and low local CP_{B0} at the locations of boundary layer separation and reattachment respectively. Nevertheless, the average value of the CP_{B0} index over the membrane surface is still a useful approximation for predicting the permeate flux through a membrane.

2.1. Other concentration polarisation indices

The local permeate flux is usually calculated following the approach of Kedem and Katchalsky [18] and Merten [19] which, assuming a linear dependence between solute concentration and

osmotic pressure, yields the following expression:

$$J_V = \frac{TMP - \sigma\phi(\omega_w - \omega_p)}{\mu(R_m + R_f)} \quad (3)$$

where the trans-membrane pressure is defined as the pressure difference between the surface of the fouling layer and the permeate ($TMP = p_c - p_p$). Substituting the concentration polarisation index from Eq. (2) to Eq. (3) yields

$$J_V = \frac{TMP - \sigma\phi CP_{B0}(\omega_{b0} - \omega_p)}{\mu(R_m + R_f)} \quad (4)$$

It is important to note that Eqs. (3) and (4) are valid locally at every point on the membrane surface. They do not refer to the average permeate flux and permeate concentration measured by experiments. This means Eqs. (3) and (4) will not necessarily fit experimental data that has been averaged over the membrane surface and are, therefore, difficult to validate experimentally. The permeate flux typically measured by experiments is equal to the permeate flux given by Eqs. (3) and (4) averaged over the whole membrane area

$$\bar{J}_V = \frac{1}{L} \int_{x=0}^{x=L} J_V dx = \frac{\overline{TMP} - \sigma\phi(\bar{\omega}_w - \bar{\omega}_p)}{\mu(R_m + \bar{R}_f)} \quad (5)$$

From Eq. (5), it is important to note that the relevant fouling resistance when considering the area averaged permeate flux is the permeate-flux-averaged fouling resistance, \bar{R}_f . This variable is defined mathematically as the permeate flux weighted average of the local hydraulic resistance, such that the value of \bar{R}_f is biased towards the values of the local fouling resistance at locations where the permeate flux is larger (e.g. the channel inlet and places with relatively less local fouling resistance). In this sense, \bar{R}_f is representative of the average fouling resistance over the whole membrane surface and, as opposed to the simple area average, it can be used in Eq. (5) to calculate the average permeate flux for the whole membrane.

An alternative expression for the concentration polarisation can be defined by using an analogy to Eq. (4) for the area averaged permeate flux:

$$\bar{J}_V = \frac{\overline{TMP} - \sigma\phi \overline{CP}_{B0}(\omega_{b0} - \bar{\omega}_p)}{\mu(R_m + \bar{R}_f)} \quad (6)$$

The concentration polarisation index (\overline{CP}_{B0}) from Eq. (6) depends on area-averaged concentrations, and is given by

$$\overline{CP}_{B0} = \frac{\bar{\omega}_w - \bar{\omega}_p}{\omega_{b0} - \bar{\omega}_p} \quad (7)$$

This form of the concentration polarisation index is not to be confused with the area averaged CP_{B0} , which is given by

$$\overline{CP}_{B0} = \frac{1}{L} \int_{x=0}^{x=L} CP_{B0} dx = \frac{1}{L} \int_{x=0}^{x=L} \left(\frac{\omega_w - \omega_p}{\omega_{b0} - \omega_p} \right) dx \quad (8)$$

Generally speaking $\overline{CP}_{B0} \neq \overline{CP}_{B0}$, although under some practical operating conditions they may approach each other.

Although the permeate flux given by Eq. (6) can easily be measured experimentally, the same is not true for the area-averaged TMP and permeate concentration. Area-averaged concentrations generally cannot be determined from experimental measurements other than for some particular variables such as flux. A form of the area averaged flux equation based on experimental variables that are easy to measure is given when the inlet TMP (TMP_0) and permeate flux-averaged permeate concentration ($\bar{\omega}_p$) are used. This yields the following expression:

$$\bar{J}_V = \frac{TMP_0 - \sigma\phi CP_M(\omega_{b0} - \bar{\omega}_p)}{\mu(R_m + \bar{R}_f)} \quad (9)$$

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