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Study on nanofiltration for purifying fructo-oligosaccharides II. Extended pore model

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Abstract

Based on the basic pore model and steric hindrance pore model, the extended pore model was founded to predict and optimize the nanofiltration processes for purifying fructo-oligosaccharides. In this model, the factors on which the rejection properties depended were summed up in pressure gradient, steric hindrance and wall friction. Correspondingly, the previous pore models were extended to different combinations for different factors. The relatively suitable model combination was determined through the comparison between the results of calculation and experiment. Then, all transport parameters of FOS were obtained based on the extended pore model. It also showed that the main factors influencing the transport property in nanofiltration membranes might be different considering different sugars.

Keywords: Extended pore model; Fructo-oligosaccharides; Nanofiltration

1. Introduction

Nanofiltration (NF) membrane separation technology has been applied to the purification of fructo-oligosaccharides (FOS) in lab-scale successfully [1–5]. It is important to predict the results of purification under different operation conditions for the industrial design, including FOS purity, yield, dilute consumption and operation time. For the technical prediction, the quantitative analysis of saccharide molecules transport through NF membranes is necessary.

At present, the phenomenological equations derived by nonequilibrium thermodynamics have been generally used for analyzing the membrane transport process [6]. In this "black box" model, membrane characteristics are expressed by three transport parameters [7,8], pure water permeability L_P, reflection coefficient σ and solute permeability P. For the quantitative prediction of these transport parameters, different models for transport mechanism in the membranes were presented, such as friction model [6,9,10] and pore model [6,11–14]. As for the porous membrane processes, the pore model is more important.

According to pore model, the transport parameters can be calculated as long as the ratio q of the molecular radius r_s and the membrane pore radius r_p is acquirable. But in the previous study, the pore model has not been applied to the prediction of transport parameters directly, because it was difficult to characterize the membrane pore. Contrarily, the pore radius of ultrafiltration (UF) membranes have been calculated successfully base on pore model by Nakao and coworkers [6,15]. For the most appropriate prediction, Nakao and Kinura [6] eliminated the wall correction factors from the modified pore model, and proposed the steric hindrance pore model. As for uncharged solutes, the application of pore models for predicting the membrane transport parameters directly in nanofiltration processes was rarely reported.

The FOS mixture contains two kinds of sugars, one is small molecular weight sugar, including glucose (G) and sucrose (GF), another is large molecular weight sugar, namely, oligosaccharide, including 1-kestose (GF_2), nystose (GF_3) and 1-β-fructofuranosyl nystose (GF_4). As for the former, its transport parameters can be determined by

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experiments, since there is enough high purity small molecular weight sugar. Whereas the transport parameters of oligosaccharides can not be measured by experiments directly for the lack of high purity oligosaccharides.

In the present work, the transport parameters of G and GF were determined by linear fitting base on the transport experiment data. With these results, the extended pore model was proposed and applied to the prediction of oligosaccharides' transport parameters. In this model, the factors on which the rejection properties depended were summed up in pressure gradient, steric hindrance and wall friction. The corresponding equations were obtained, and the results of FOS rejection experiments verified that the extended pore model was applicable for FOS system in NF processes.

2. Theory

2.1. Transport equations and transport parameters

Pure water permeability L_p, reflection coefficient σ and solute permeability P were defined in the transport equations based on nonequilibrium thermodynamics [9,10]:

$$J_V = L_p(\Delta p - \sigma\,\Delta\Pi) \tag{1}$$

$$R = \frac{(1-F)\sigma}{1-\sigma F} \tag{2}$$

where

$$F \equiv e^{-J_V A} \tag{3}$$

$$A \equiv \frac{1-\sigma}{P} \tag{4}$$

In terms of Eqs. (1) and (2), the linear relationships can be obtained:

$$\frac{J_V}{L_p} = \Delta p - \sigma\,\Delta\Pi \tag{5}$$

$$(\sigma-1)J_V = P\,\ln\frac{R-\sigma}{\sigma(R-1)} \tag{6}$$

Considering the concentration polarization, the sugar concentration near the membrane surface was calculated by the concentration polarization equation [12] and transport equation out of the membranes [14]:

$$\frac{C_m - C_p}{C_b - C_p} = \exp\left(\frac{J_V}{k}\right) \tag{7}$$

In Eq. (7), k is the mass transfer coefficient outside membranes, and it can be calculated by Eq. (8), which considered the effects of spacer materials between membranes and was suitable when $100 < Re < 1000$ [16].

$$Sh = 0.065 Re^{0.875} Sc^{0.25} \tag{8}$$

where Sh is Sherwood number, Re is Reynolds number, and Sc is Schmidt number, they were defined as:

$$Sh = \frac{k d_h}{D} \tag{9}$$

$$Re = \frac{\rho u d_h}{\eta} \tag{10}$$

$$Sc = \frac{\nu}{D} \tag{11}$$

d_h was the hydraulic diameter of the spacer-filled channel in the spiral wound module. Solution properties were also important for the calculation of theses dimensionless numbers. It was difficult to obtain FOS solution properties for the same reason. Considering limited length, the methods for FOS solution properties were proposed in next paper [17] of this series.

2.2. Previous pore model

Considering sugars are uncharged solutes, the electric force can be negligible. So the solute flow per unit cross-sectional pore area and unit time j_s was expressed as [14]

$$j_s = -Df(q)\frac{dC}{dx} + u_w C g(q) - \frac{\bar{V}_s}{f_{sw}^0} C f(q)\frac{dp}{dx} \tag{12}$$

The functions $g(q)$ and $f(q)$ were defined as wall correction factors, and they related to wall friction. Haberman and Sayre gave their expressions as q [13]:

$$f(q) = \frac{1 - 2.105q + 2.0865q^3 - 1.7068q^5 + 0.72603q^6}{1 - 0.75857q^5} \tag{13}$$

$$g(q) = \frac{1 - (2/3)q^2 - 0.20217q^5}{1 - 0.75857q^5} \tag{14}$$

If the pressure gradient could be neglected, the classic pore model was obtained [14]:

$$\begin{cases} \sigma = 1 - g(q)S_F \\ P = Df(q)S_D\dfrac{A_k}{\Delta x} \end{cases} \tag{15}$$

S_D and S_F were the steric hindrance factors for diffusion and filtration flow, respectively, they related to steric hindrance. They were also functions of q:

$$S_D = (1-q)^2 \tag{16}$$

$$S_F = (1-q)^2(1+2q-q^2) \tag{17}$$

Considering the effects of pressure gradient, Nakao gave the modified pore model [6]:

$$\begin{cases} \sigma = 1 - S_F[g(q) + \frac{16}{9}q^2 f(q)] \\ P = Df(q)S_D\dfrac{A_k}{\Delta x} \end{cases} \tag{18}$$