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Effects of reflux and reflux-barrier location on solvent extraction through cross-flow flat-plate membrane modules with internal reflux

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Abstract

The influence of reflux as well as reflux-barrier location on cross-flow membrane extraction through the flat-plate module with internal reflux has been investigated. The recycle barrier is placed in the raffinate phase to divide the flow channel of width B into an operating subchannel of width ΔB and a reflux subchannel of width $(1 - \Delta)B$. Considerable improvement in performance is obtainable if cross-flow membrane extraction is operated with internal reflux which provides the increase of fluid velocity, resulting in reduction of mass-transfer resistance. It was further found that suitably adjusting the recycle-barrier location in raffinate phase such that $0.75 < \Delta < 0.9$, is beneficial to total mass-transfer rate and thus, the reflux ratio can be reduced for achieving the same performance with the reflux barrier located at the centerline, $\Delta = 0.5$. However, the hydraulic dissipated energies though are small, they increase rapidly with reflux ratio as well as when the recycle barrier goes far from the centerline for improving performance. Therefore, the increase of operating cost due to the friction loss of fluid flow should be also taken into consideration.

Keywords: Membrane extraction; Reflux; Recycle-barrier location; Cross flow

1. Introduction

Membrane solvent extraction is an unconventional extraction process which can overcome the application limitations of conventional solvent extraction, such as flooding, intimate mixing, limitations on independent phase flow rate variations, requirement of density difference and inability to handle particulate [1–3]. The performance of membrane solvent extraction through flat-plate mass exchangers has been analyzed under parallel-flow (cocurrent and countercurrent flows) and cross-flow operations [4,5]. Under comparable conditions, most of the solute is extracted in the countercurrent-flow arrangement and the least in cocurrent flow. It was reported, however, that from secondary effects or for large aspect ratio of the module, cross flow may extract more solute than countercurrent flow [6]. The theory of membrane extraction in cross-flow system is rather complicated than that in parallel-flow device since the concentration over the cross sections of flow channel are nonuniform. Nevertheless, the simpler but still precise equations for predicting the total mass-transfer rate in cross-flow membrane extractors have been derived with the assumption that the concentration variation in the cross sections of flow channel was negligible [5], and the results confirmed well with the exact solution [4].

The reflux indeed has much influence on the heat and mass transfer [7–17], which in turn plays a significant role on the design, calculation, and operation of the equipment. The effects of recycle on membrane extraction through flat-plate modules have been studied both theoretically and experimentally [18–21]. It was shown that recycle can enhance mass transfer due to the increase of fluid velocity, especially for large feed-concentration solution with high distribution coefficient operated under high reflux ratio. However, operation at high reflux ratio might not compensate for the loss of hydraulic dissipated power. A modified method of suitably adjusting the reflux-barrier location in a parallel-flow membrane extractor with external reflux has been investi-

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gated [22]. Instead of a parallel-flow device with external reflux, here we investigate the influence of reflux as well as reflux-barrier location on membrane extraction in a cross-flow flat-plate module with internal reflux.

2. Theory

Unlike the computation of mass transfer in parallel-flow systems (either cocurrent or countercurrent flow), the theory of mass exchanger in cross-flow system is rather complicated because that the flow directions of the two fluids cross each other and the concentrations over the cross-section of flow are nonuniform. The assumptions made in this analysis are: steady state, no chemical reaction, uniform concentration, $C_a(x)$ and $C_b(y)$, and uniform velocities over the cross-section of flow, constant rates of flows, constant mass-transfer coefficients and constant distribution coefficients. Further, here we only consider the simplest type of cross-flow systems in which the flow directions of the two fluids are perpendicular, instead of being oblique, to each other. The schematic diagrams in Figs. 1 and 2 may serve to explain the nomenclature to be employed for the cross-flow device with internal reflux. This system consists of two channels for the fluids a and b, respectively, which are separated by a microporous membrane sheet through which solute is extracted and transferred perpendicularly to its exposed surfaces. In the case that fluids a and b are miscible, then the pores of the membrane filled with another fluid (phase c) which is immiscible with these two fluids. The solute is extracted from phases a to c and then to phase b, or vice versa.

2.1. Governing equations

As shown in Fig. 1, an impermeable plate with negligible thickness is placed in vertical to the upper plate and the membrane sheet, at a certain line of channel a (phase a) to divide the raffinate phase into subchannels a_1 (operation channel) and a_2 (reflux channel) of widths ΔB and $1-\Delta B$, respectively, and that a pump is installed for internal reflux. Thus, in the raffinate phase (phase a), the inlet fluid of volume rate Q_a mixed with the outlet reflux fluid of volume rate RQ_a, flows steadily through subchannel a_1, and recycle internally through channel a_2 with volume flow rate RQ_a. The extract phase (phase b) with inlet volume rate Q_b flows steadily through channel b and firstly across subchannel a_2 and then subchannel a_1. The overall mass balances are

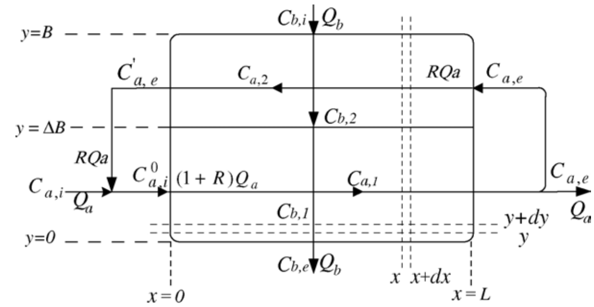

Fig. 2. Flow sheet of cross-flow parallel-plate membrane extractor with internal reflux.

$$Q_a(C_{a,i}-C_{a,e})=Q_b(C_{b,e}-C_{b,i}) \tag{1}$$

The impermeable plate divides the raffinate phase into two flow regions, subchannels a_1 and a_2. Let K_1 and K_2 are the overall mass-transfer coefficients in regions 1 and 2, respectively, while H_{ac} and H_{bc} are the distribution coefficients between two different phases, as defined by

$$H_{ac}=\frac{\text{solute concentration in phase c}}{\text{solute concentration in phase a}} \tag{2}$$

By taking the mass balances through a differential area $\mathrm{d}x\,\mathrm{d}y$ in flow region 1, one obtains

$$-(1+R)Q_a\,\mathrm{d}C_{a,1}=K_1(\Delta B)\,\mathrm{d}x(H_{ac}C_{a,1}-H_{bc}C_{b,1}) \tag{3}$$

$$-Q_b\,\mathrm{d}C_{b,1}=K_1L(H_{ac}C_{a,1}-H_{bc}C_{b,1})\,\mathrm{d}y \tag{4}$$

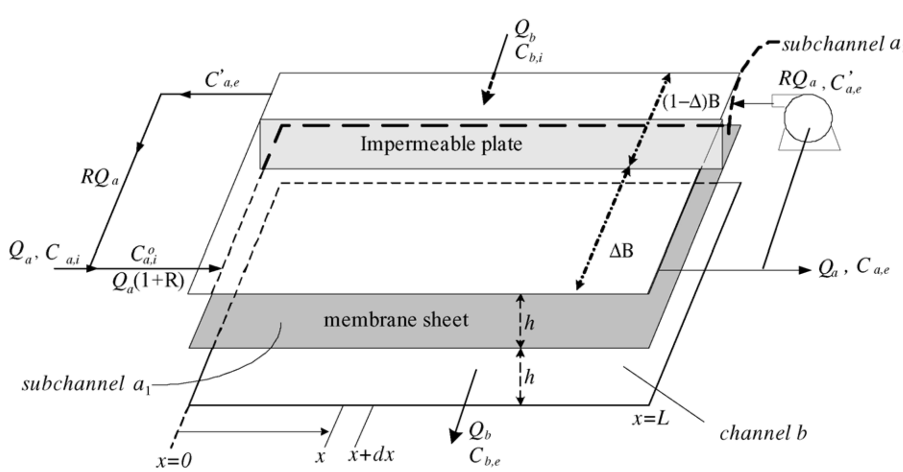

Fig. 1. Schematic diagram of cross-flow parallel-plate membrane extractor with internal reflux.