Application of internal reflux in the raffinate phase for membrane extraction in cross-flow rectangular modules

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Abstract

The effect of internal reflux in the raffinate phase for membrane extraction through a cross-flow rectangular module was investigated. Theoretical analysis of mass transfer in cross-flow devices with or without recycle was analogous to heat transfer in cross-flow heat exchangers. In contrast to a device without reflux, considerable improvement in mass transfer is achievable if cross-flow membrane extractors are operated with reflux which provides the increase of fluid velocity, resulting in reduction of mass-transfer resistance. It is concluded that reflux can enhance mass transfer, especially for large flow rate and feed-concentration solution operated under high reflux ratio.
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Keywords: Membrane extraction; Cross-flow; Rectangular modules; Internal reflux

1. Introduction

Application of recycle to the design and operation of a mass or heat transfer equipment can effectively enhance the effects on mass or heat transfer, leading to improved performance (Dussap and Gros, 1982; Jones, 1985; Marquart and Blenke, 1980; Marquart, 1981; Miyahara *et al.*, 1986; Siegel *et al.*, 1986; Teramoto *et al.*, 1994; Yeh *et al.*, 1987, 2000). The application of internal reflux to membrane extraction through parallel-flow rectangular modules have been studied (Yeh and Chen, 2001). The purpose of this work is to investigate the effect of internal reflux in the raffinate phase for solvent extraction through a cross-flow rectangular membrane module.

Recently, the mass transfer for solvent extraction in hollow-fiber modules was investigated both theoretically and experimentally (Lipnizki and Field, 2001; Schlosser *et al.*, 2001; Viegas *et al.*, 1998). Actually, performance of membrane solvent extractors is kind of mass transfer in mass-exchangers, which can be analogized the heat transfer in heat exchangers with a microporous membrane used in place of the heat-transfer medium (Yeh and Hsu, 1999). Like heat exchangers, mass exchangers of membrane extraction may be extremely different in design and construction, but in principle the only differences are those of relative direction of the two fluids flowing on the opposite sides of the membrane. Accordingly, distinction is made between parallel flow (cocurrently and countercurrently) and cross-flow. 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 (Jakob, 1957).

2. Theory in the module of type A

Fig. 1 shows the schematic diagram of a recycled cross-flow rectangular membrane extractor of type A. This system consists of two flow 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 are filled with another fluid (phase c) which is immiscible with these two fluids. The solute is extracted from phase a to phase c and then to phase b, or vice versa. Further, an impermeable plate with negligible thickness is placed in vertical to the upper plate and the membrane sheet, at the centerline of channel a (phase a) to divide the raffinate phase into subchannels a_1 (operation channel) and a_2 (reflux channel) of equal width, $B/2$, and that a pump is installed for recycle with reflux ratio of R.

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Nomenclature

B width of membrane sheet (cm)

$C_a(x)$, $C_b(y)$ bulk solute concentrations in raffinate phase (phase a), and in extract phase (phase b) (mol/cm^3)

$C_{a,e}$, $C_{b,e}$ outlet solute concentrations in phase a, and in phase b (mol/cm^3)

$C_{a,i}$, $C_{b,i}$ inlet solute concentrations in phase a, and in phase b (mol/cm^3)

$C_{a1}(x)$, $C_{a2}(x)$ bulk solute concentrations in subchannel a_1, and in subchannel a_2 of phase a (mol/cm^3)

$C_{a,1m}$, $C_{a,2m}$ average solute concentrations in phase a of region 1 defined by Eq. (A-1), and in phase a of region 2 defined by Eq. (A-2) (mol/cm^3)

$C_{b,1m}$, $C_{b,2m}$ average solute concentrations in phase b of region 1 defined by Eq. (A-3), and in phase b of region 2 defined by Eq. (A-4) (mol/cm^3)

$C_{b,1e}$ outlet solute concentration in phase b of region 1 (mol/cm^3)

$C'_{a,e}$ outlet concentration in subchannel a_1 (mol/cm^3)

$C^0_{a,i}$ mixed inlet concentration in phase a (mol/cm^3)

h half height of parallel channel, or distance between flat plate and membrane sheet (cm)

H_{ab} distribution coefficient between phase a and phase b

I improvement of performance defined by Eq. (32)

K_0 average overall mass-transfer coefficient in a device without reflux (cm/s)

K_1, K_2 average overall mass-transfer coefficients in region 1 and in region 2 (cm/s)

l constant defined by Eq. (A-5)

L the length of membrane sheet (cm)

n_1, n_2 constants defined by Eq. (A-6) and by Eq. (A-7)

Q_a, Q_b inlet volume flow rates in phase a and in phase b (cm^3/s)

R reflux ratio, reverse volume flow rate RQ_a divided by inlet volume rate Q_a

S overall mass-transfer area of a rectangular membrane module, LB (cm^2)

$v_{a,0}$ fluid velocity in channel a of the device without reflux (cm/s)

$v_{a,1}$, $v_{a,2}$ fluid velocities in subchannel a_1, and in subchannel a_2 (cm/s)

v_b fluid velocity in phase b (cm/s)

W total mass-transfer rate for reflux device (mol/s)

W_0 W for the device without reflux (mol/s)

W_1, W_2 W for reflux device in region 1 and in region 2 (mol/s)

x axis along the flow direction of raffinate phase (phase a) (cm)

y axis along the flow direction of extract phase (phase b) (cm)

Greek symbols

$\xi^0_{a,e}$, $\xi'_{a,e}$
            dimensionless constants defined by Eqs. (A-8) and (A-9)

2.1. Governing equations

Fig. 2 illustrates the flow sheet for the module of type A. The assumptions made in this analysis are: steady state, no chemical reaction, uniform velocities and uniform concentrations [$C_a(x)$ and $C_b(y)$] over the cross-section of flows, constant rates of flows, constant mass-transfer coefficients and constant distribution coefficients. The overall mass balance for total mass-transfer rate, W, is

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

By taking the mass balances through a differential area, dxdy, in flow region 1, we have

$$-(1 + R)Q_a\,dC_{a,1} = K_1\left(\frac{B}{2}\right)dx(H_{ac}C_{a,1} - H_{bc}C_{b,1}) \qquad (2)$$

$$Q_b\,dC_{b,1} = K_1 L(H_{ac}C_{a,1} - H_{bc}C_{b,1})\,dy \qquad (3)$$

Similarly, for region 2

$$RQ_a\,dC_{a,2} = K_2\left(\frac{B}{2}\right)dx(H_{ac}C_{a,2} - H_{bc}C_{b,2}) \qquad (4)$$

$$Q_b\,dC_{b,2} = K_2 L(H_{ac}C_{a,2} - H_{bc}C_{b,2})\,dy \qquad (5)$$

where K_1 and K_2 are 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

$$H_{ac} = \frac{\text{solute concentration in phase c}}{\text{solute concentration in phase a}} \qquad (6)$$

The boundary conditions for solving $C_{a,1}$, $C_{a,2}$, $C_{b,1}$ and $C_{b,2}$ from Eqs. (2)–(5) are:

$$\text{at } x = 0, \; C_{a,1} = C^0_{a,i} \qquad (7)$$

$$\text{at } x = 0, \; C_{a,2} = C'_{a,e} \qquad (8)$$

$$\text{at } x = L, \; C_{a,1} = C_{a,e} \qquad (9)$$

$$\text{at } x = L, \quad C_{a,2} = C_{a,e} \qquad (10)$$

$$\text{at } y = 0, \quad C_{b,1} = C_{b,i} \qquad (11)$$

$$\text{at } y = \frac{B}{2}, \quad C_{b,1} = C_{b,2} = C_{b,1e} \qquad (12)$$

$$\text{at } y = B, \quad C_{b,2} = C_{b,e} \qquad (13)$$

Inspection of Eqs. (7)–(13) show that the outlet concentrations, ($C_{a,e}$, $C'_{a,e}$, $C_{b,1e}$ and $C_{b,e}$) as well as the mixed inlet concentration, $C^0_{a,i}$, are not specified in a priori. Mathematically, more relations for mass-transfer rates, W_1 and W_2, in regions 1 and 2, as well as for the mixing effect at the inlet, are needed for determination of these values. With the definitions of mean concentration differences, $(\Delta C)_{1,m}$ and $(\Delta C)_{2,m}$, in regions 1