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TECHNICAL NOTE

Microporous Membrane Solvent Extraction in Multiple-Fiber Passes and One-Shell Pass Hollow-Fiber Modules

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ABSTRACT

The performance for solvent extraction in microporous membrane hollow-fiber modules with various fiber passes, but with a specified total number of hollow fibers, has been calculated. Increasing the fiber passes, as well as decreasing the total cross-section area of flowing channels inside the hollow fibers, will increase the fluid velocity, thereby leading to an increased mass-transfer coefficient. Considerable improvement in the mass-transfer rate is obtainable if multiple-fiber passes, instead of a one-fiber pass, are arranged in a hollow-fiber module with a total number of fixed hollow fibers.

Key Words. Solvent extraction; Multipass hollow-fiber modules

INTRODUCTION

Recently, extensive studies on dispersion-free solvent extraction with the use of microporous membranes have been carried out (1–19). This technique not only overcomes the limitations of conventional liquid extraction, such as flooding, intimate mixing, limitations on independent phase flow rate variations, requirement of density difference, and inability to handle particulates

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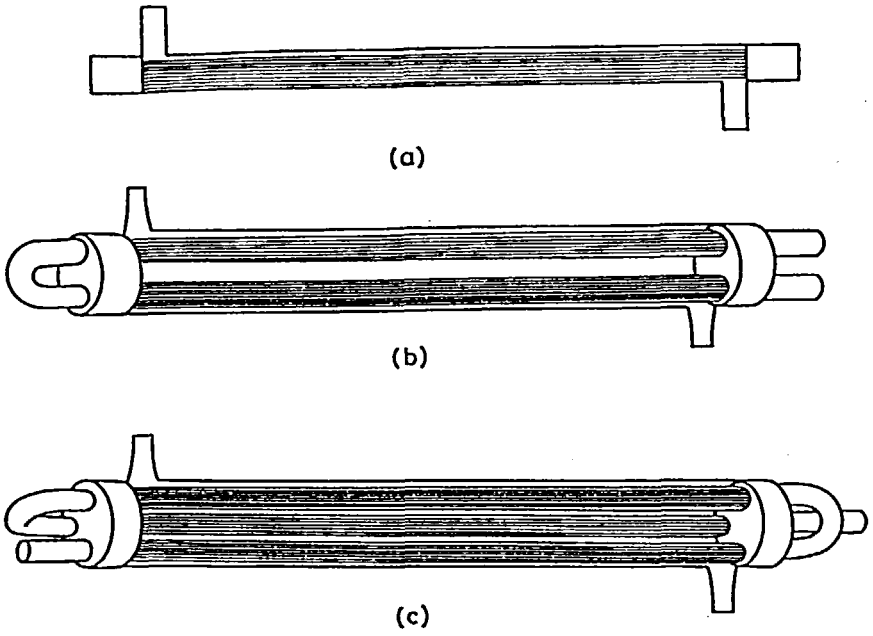

FIG. 1 Microporous hollow fiber (MHF) modules. (a) One-fiber pass system; (b) Two-fiber passes system; (c) Three-fiber passes system (20).

(1), but also provides a large surface area of mass transfer if the membrane resistance is significant. The hollow-fiber membrane modules used for membrane solvent extraction are like small tube-and-shell heat exchangers but with microporous hollow fibers (MHF) replacing tubes, as shown in Fig. 1. Typically, feed solution containing the solute of interest flows through the lumen of the fibers, and extractant flows outside the fibers on the shell side. Since solute usually diffuses out at a rather lower mass-transfer rate, an analogy between the theory of mass transfer in fiber-and-shell mass exchangers and that of heat transfer in tube-and-shell heat exchangers can be achieved (20).

THEORY

Mass Transfer Coefficients

When solvent extraction is carried out in a microporous hollow-fiber module, each hollow fiber is generally contacted with two kinds of fluid at the two sides of the membrane and fills the pores of the membrane with another fluid which is immiscible with these two fluids. The first fluid flowing through

the fiber forms phase a and the second fluid flowing outside the fiber forms phase b, while the third fluid, which fills the pores of the membrane, establishes phase c. The solute is extracted from phase a to phase c and then to phase b, or vice versa.

Yeh and Huang (20) derived an expression for calculating the total mass-transfer rate W for solvent extraction in multipass hollow-fiber modules by following the procedure of Underwood (21). The results is really analogous to Underwood's equation as

$$W = K_i S F (\Delta C)_{lm} \tag{1}$$

where the logarithmic mean of solute concentration difference $(\Delta C)_{lm}$ and the total mass-transfer area S of a hollow-fiber module having fiber length L, fiber inside diameter d_i, and fiber number N, are defined, respectively, as

$$(\Delta C)_{lm} = \frac{(H_{bc}C_{b,e} - H_{ac}C_{a,i}) - (H_{bc}C_{b,i} - H_{ac}C_{a,e})}{\ln\left(\frac{H_{bc}C_{b,e} - H_{ac}C_{a,i}}{H_{bc}C_{b,i} - H_{ac}C_{a,e}}\right)} \tag{2}$$

$$S = N\pi d_i L \tag{3}$$

while the correction factors F, which are functions of the fluid concentrations and the distribution coefficients, are presented graphically in a previous paper (20). These graphical representations are exactly the same as those obtained in Bowman's work (22), except that the temperatures in Bowman's results are replaced here by the products of concentrations and distribution coefficients. Yeh and Huang (20) found that F is nearly equal to unity in their experimental systems. In Eq. (2), $C_{a,i}$ and $C_{a,e}$, as well as $C_{b,i}$ and $C_{b,e}$, denote the inlet and outlet concentrations of solute in phases a and b, respectively; H_{ac} and H_{bc} are the distribution coefficients between two different phases, as defined by Eq. (4):

$$H_{ac} = \frac{\text{solute concentration in phase c}}{\text{solute concentration in phase a}} \tag{4}$$

When solvent extraction is carried out only between an aqueous solution (say phase a) and an organic solution (say phase b) without the third fluid filling the membrane of a microporous hollow fiber (MHF) module, the membrane is called a hydrophilic MHF if the aqueous solution wets the membrane, and thus $H_{ac} = 1$. On the other hand, the membrane is called a hydrophobic MHF if the organic solution wets the membrane, and thus $H_{bc} = 1$.

The relation between the overall mass-transfer coefficient K_i, based on the inside diameter of the hollow fiber, and three other mass-transfer coefficients k_a, k_b, and k_m in the fiber side, in the shell side, and within the membrane, respectively, can be obtained with the concept of resistances in series as

$$\frac{1}{K_i} = \frac{H_{ac}}{k_a} + \frac{1}{k_m(d_{lm}/d_i)} + \frac{H_{bc}}{k_b(d_o/d_i)} \tag{5}$$

where d_o and d_m denote the outside and logarithmic-mean diameters of a hollow fiber, respectively. Since mass transfer in both the fiber side and shell side is convective, k_a and k_b are functions of fluid properties, flow pattern, etc. Prasad and Sirkar (6), Dahuron and Cussler (7), and Yang and Cussler (19) gave empirical equations for estimating k_a and k_b for microporous membrane solvent extraction. Let us take Dahuron and Cussler's equations as an example. Then

$$(k_a d_i/D_a) = 1.5[(d_i/L)(v_a d_i \rho_a/\mu_a)(\mu_a/D_a)]^{1/3} \tag{6}$$

$$(k_b d_e/D_b) = 8.8[(d_e/L)(v_b d_e \rho_b/\mu_b)(\mu_b/D_b)]^{1/3} \tag{7}$$

where d_e denotes the equivalent diameter of the shell, D_a and D_b are the diffusivities of the solute in phases a and b, ρ_a and ρ_b are fluid densities in phases a and b, μ_a and μ_b are the fluid viscosities in phases a and b, while v_a and v_b are fluid velocities in tube side and in shell side, respectively. Further, since mass transfer within the membrane is due to ordinary diffusion alone, the following expression may be used for calculating the mass-transfer coefficient in the membrane:

$$k_m = \frac{D_c \epsilon}{[(d_o - d_i)/2]\tau} \tag{8}$$

where D_c is the diffusivity of the solute in phase c, ϵ denotes the porosity of the membrane, and τ is the pore tortuosity of the membrane.

Calculation Procedure

A mass balance for solute over the whole mass exchanger gives the total mass-transfer rate in a mass exchanger as

$$W = Q_a(C_{a,i} - C_{a,e}) = Q_b(C_{b,e} - C_{b,i}) \tag{9}$$

The procedure for calculation of theoretical values of W is described as follows. First, with the given apparatus conditions and system properties, the overall mass-transfer coefficient K_i for specific flow rates, Q_a and Q_b (as well as v_a and v_b), is determined from Eqs. (5)–(8) while the distribution coefficients are determined experimentally from Eq. (4). Next, with known inlet concentrations $C_{a,i}$ and $C_{b,i}$, a temporary value of $C_{a,e}$ (or $C_{b,e}$) is estimated from Eq. (9) once $C_{b,e}$ (or $C_{a,e}$) is assumed; accordingly, $(\Delta C)_{lm}$ can be determined from Eq. (2). Further, the total mass-transfer rate W is calculated from Eq. (1), in which F is determined from the charts provided by Yeh and Huang (20). With this calculated value of W, new values of $C_{a,e}$ and $C_{b,e}$ are

then calculated from Eq. (9). If the calculated values of $C_{a,e}$ and $C_{b,e}$ are different from the assumed values, continuous calculation by iteration is needed until the last assumed values of outlet concentrations meet the finally calculated values.

THE IMPROVEMENT IN PERFORMANCE

In order to accomplish as much transfer of mass in as small a space as possible, it is desirable to utilize multiple passes of fluids as shown in Figs. 1(b) and 1(c). Further, with a specified total number of hollow fibers, increasing the fiber passes as well as decreasing the total cross-section area of flowing channels inside the hollow fibers will increase the fluid velocity, thereby leading to improved mass transfer. It is the purpose of this work to investigate the effect of fiber passes on the performance of solvent extraction in multiple-fiber passes and one-shell pass hollow-fiber modules, with the total number of hollow fibers fixed.

For a specific system, mass-transfer coefficient k_a in a fiber side is a function only of the fluid velocity v_a in that side. It is seen from Eq. (6) that k_a increases when v_a increases. For m-fiber passes and a one-shell pass device with total fiber number N, the fluid velocities in the fiber side and the shell side as well as the equivalent diameter d_e of the module chamber are, respectively,

$$v_a = \frac{Q_a}{(N/m)(\pi d_i^2/4)} \tag{10}$$

$$v_b = \frac{Q_b}{(\pi/4)(d_s^2 - Nd_o^2)} \tag{11}$$

$$d_e = 4\frac{(\pi/4)(d_s^2 - Nd_o^2)}{\pi(d_s + Nd_o)} = \frac{d_s^2 - Nd_o^2}{d_s + Nd_o} \tag{12}$$

where m denotes the fiber-pass number while d_s is the shell diameter.

Numerical Example

The improvement in performance resulting from operating at more than a one-fiber pass, with both the fiber length and total fiber number kept unchanged, may be illustrated by assigning some numerical values as follows.

For an aqueous solution with phenol as the solute and flowing in the fiber side:

$$C_{a,i} = 5.31 \times 10^{-6}\ \text{gmol/cm}^3,\ Q_a = 0.05\text{–}1.6\ \text{cm}^3/\text{s},\ \rho_a = 1\ \text{g/cm}^3,$$
$$\mu_a = 0.89 \times 10^{-2}\ \text{g/cm·s},\ D_a = 9.98 \times 10^{-6}\ \text{cm}^2/\text{s} \quad (23)$$

For an organic solution with *n*-butyl acetate as the solvent and flowing in the shell side:

$$C_{b,i} = 0,\ Q_b = 1.6\ \text{cm}^3/\text{s},\ \rho_b = 0.882\ \text{g/cm}^3,\ H_{ab} = 71 \quad (24)$$
$$\mu_b = 6.8 \times 10^{-3}\ \text{g/cm·s},\ D_a = 2.38 \times 10^{-5}\ \text{cm}^2/\text{s} \quad (23)$$

For membrane modules made with the Celgard X-20 microporous polypropylene hollow fiber:

$$d_i = 0.024\ \text{cm},\ d_o = 0.029\ \text{cm},\ \epsilon = 20\%,\ \tau = 2.8 \quad (6)$$

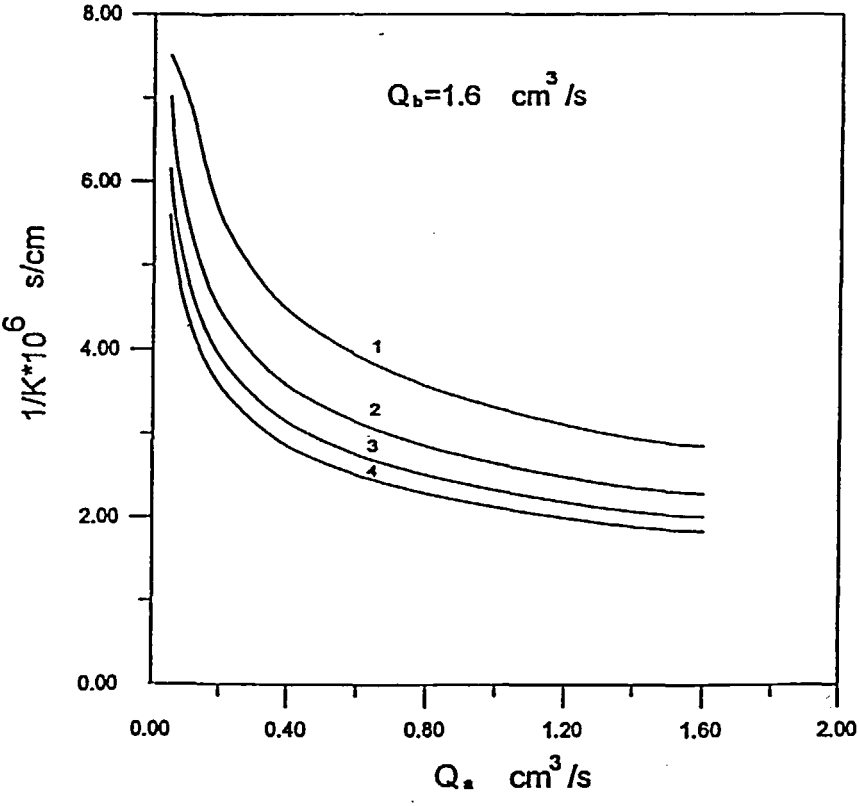

FIG. 2 Relation between K_i and Q_a for numerical Example 1. (1) One-pass MHF; (2) two-passes MHF; (3) three-passes MHF; (4) four-passes MHF.

$L = 15.8$ cm, $N = 180$, $d_s = 2$ cm, $S = N\pi d_i L = 214.433$ cm^2,
hydrophobic MHF ($H_{bc} = 1$, $H_{ac} = H_{ab} = 71$, $D_c = D_b$)

RESULTS AND DISCUSSION

Using the numerical values given, the total mass-transfer coefficients K_i and the total mass-transfer rates for one-fiber and multiple-fiber passes were calculated from the corresponding equations by following the procedure described in a previous section. The correction factors F were determined from Figs. 6 and 7 of a previous paper (20), and it was found that these values are also nearly equal to unity for the present numerical examples.

Figures 2 and 3 show that the overall mass-transfer coefficient K_i as well as the total mass-transfer rate W increases not only when the flow rate Q_a of

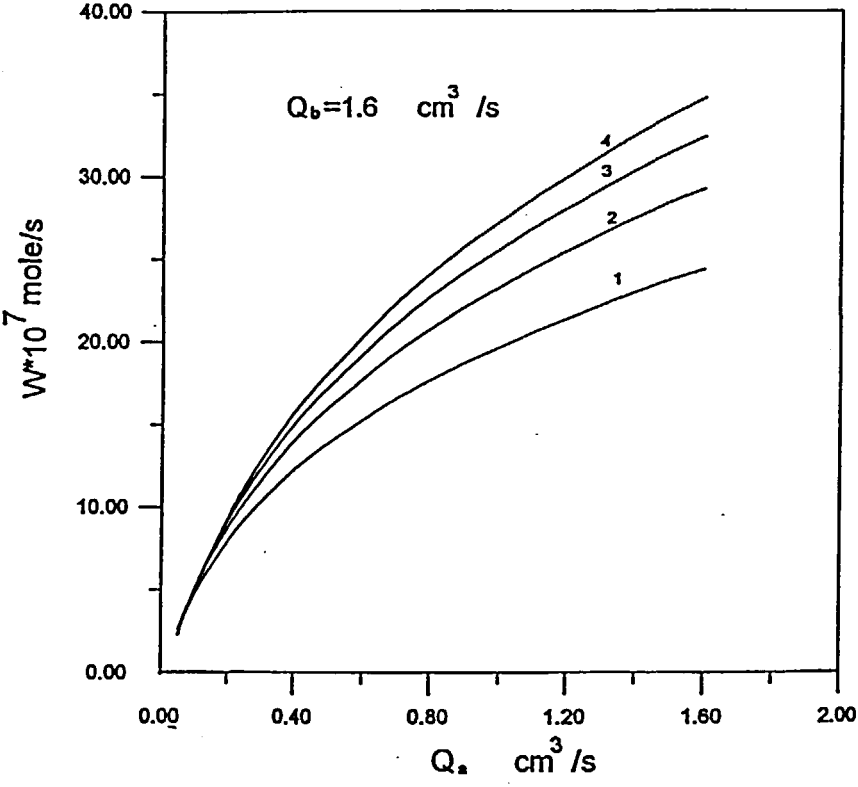

FIG. 3 Relation between W and Q_a for numerical Example 1. (1) One-pass MHF; (2) two-passes MHF; (3) three-passes MHF; (4) four-passes MHF.

the fiber-side fluid increases, but also when the number of fiber passes m increases. Considerable improvement in performance is obtained when the module of multiple-fiber passes (m) with (N/m) fibers in each pass, instead of the module of one-fiber pass with same total number of hollow fibers N, is employed, as shown in Fig. 3. The improvement in mass-transfer rate also increases when the number of fiber passes increases, as well as when the flow rate Q_a of the fiber-side fluid increases.

CONCLUSION

The effect of flow velocity of tube-side fluid on the overall mass-transfer coefficient as well as on the total mass-transfer rate has been investigated. When a microporous hollow-fiber module of N hollow fibers with one-fiber pass and one-shell pass is rearranged to become a device of multiple-fiber passes (m) with an equal number of hollow fibers N/m in each fiber pass, the fluid velocity v_a in the fiber side increases, thereby leading to increased mass-transfer coefficients as well as increased total mass-transfer rate if the mass transfer is dominated by the external films and not by the membrane resistance. Since this velocity increases as the number of fiber passes m increases, the improvement in the total mass-transfer rate also increases when m increases.

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