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SEPARATION OF LIQUID SOLUTIONS BY CONTAINED LIQUID MEMBRANES

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ABSTRACT

The technique of contained liquid membranes (CLM) for liquid solution separation is discussed. The CLM is obtained by confining the membrane liquid between two sets of microporous hollow fibers (MHF). The lumen of the hollow fiber carries the feed or the strip solution under proper phase pressure condition vis-a-vis the membrane phase. Various possible structural configurations of the CLM are illustrated with respect to the nature of microporous hollow fiber substrate, the feed solution and the liquid membrane. The contributions of different resistances to the solute transport rate are identified. Some basic experimental data obtained in small CLM permeators are presented for two systems with organic liquid membranes to illustrate how steady state separation is achieved after an initial unsteady period. The considerable advantages of the CLM structure over more traditional liquid membrane techniques such as supported liquid membrane (SLM) with respect to membrane stability, membrane regeneration and feed equilibration are pointed out.

INTRODUCTION

Supported liquid membranes (SLM) are thin layers of pure liquids or liquid solutions immobilized in microporous inert supports (1,2). They have extraordinary capabilities of removing solutes from a feed solution to a strip solution (3). Their major advantages include: high separation factor per stage, low capital

and operating costs due, amongst others, to a very low inventory of extractant, modular and compact separators when hollow fibers are used, low energy cost and elimination of extractant loss resulting from inadequate coalescence in conventional dispersion-based solvent extraction. Further, the ability to concentrate solute in the strip solution using coupled transport is a highly attractive feature of a SLM. Despite such advantages, SLM-s are not used in industry because of major concerns with their lifetime (4).

Liquid membrane instability has been ascribed to (3,4,5) the following: extractant loss into feed and strip solutions, progressive reduction of the hydrophobicity of hydrophobic supports (used for organic liquid membranes) by surface-active extractants, and the pressure difference between the two sides of the SLM. In coupled transport having a large transmembrane osmotic pressure gradient, Danesi et al. (6) have further concluded that significant transfer of osmotically driven water displaces organic liquid from pores leading to membrane instability.

We describe here a novel contained liquid membrane (CLM) structure that has the potential to eliminate the shortcomings of SLM-s while retaining the latter's basic advantages. We identify it as the hollow fiber contained liquid membrane (HFCLM) technique when microporous hollow fibers are used to contain the liquid membrane in a permeator. The HFCLM technique for gas separation has been investigated elsewhere (7).

The HFCLM can be used for either an aqueous feed/organic membrane system, or an organic feed/aqueous membrane system. Each of these two systems can employ either hydrophilic microporous hollow fibers or hydrophobic microporous hollow fibers. We first describe these four possible configurations. We then present a first-order mass transport analysis adopting the resistances-in-series approach to identify the role of various mass transfer resistances for non-reactive situations. The HFCLM separation behavior is illustrated next by studying the removal of phenol and acetic acid from aqueous solutions using different organic liquid membranes. Both steady state and initial time dependent observations are reported. Steady state performances are compared with the values predicted by first order estimates from the resistance model. A more detailed comparison vis-a-vis the boundary layer resistances, etc. has been carried out in (8) for aqueous feeds.

HOLLOW FIBER CONTAINED LIQUID MEMBRANE CONFIGURATIONS

Aqueous Feed/Organic Membrane

Consider two sets of microporous hydrophilic hollow fibers intimately mixed together in a permeator shell (Fig. 1). Fibers marked 'F' have the aqueous feed flowing in the lumen; fibers marked 'S' have an aqueous strip solution flowing in the lumen. The fiber wall pores are filled by the respective aqueous solutions

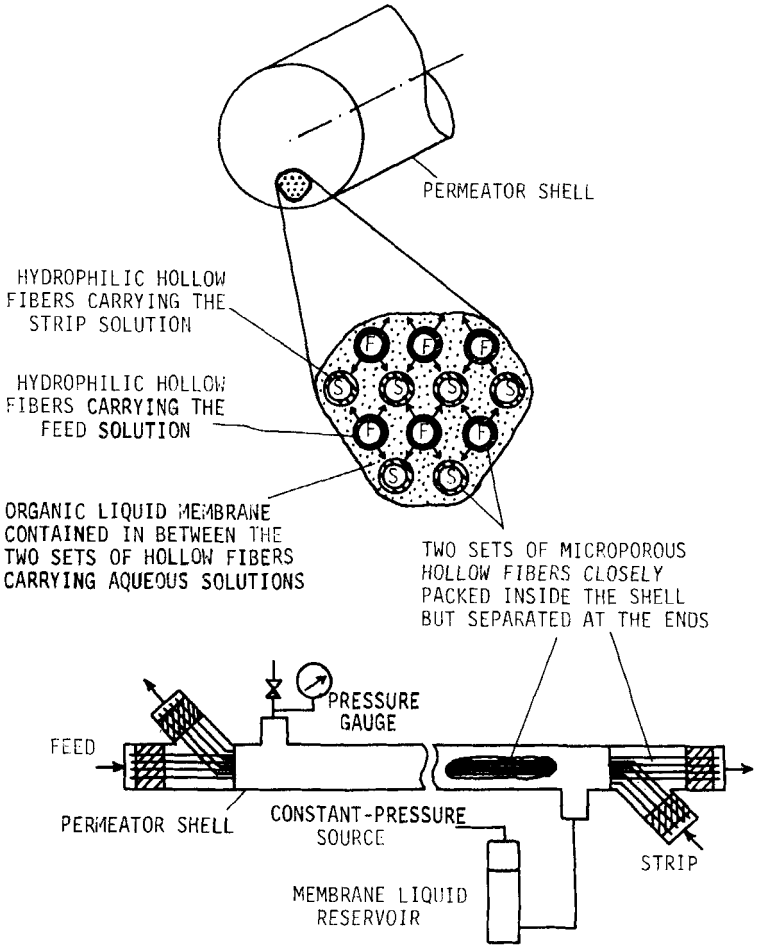


Fig. 1. Hollow fiber contained liquid membrane (HFCLM) *permeator*: concept and schematic for aqueous solution separation with hydrophilic microporous fibers.

because the fibers are hydrophilic (Fig. 2). The shell side space between these hollow fibers contains the organic liquid selected as the membrane. This liquid should obviously be immiscible with the aqueous phases.

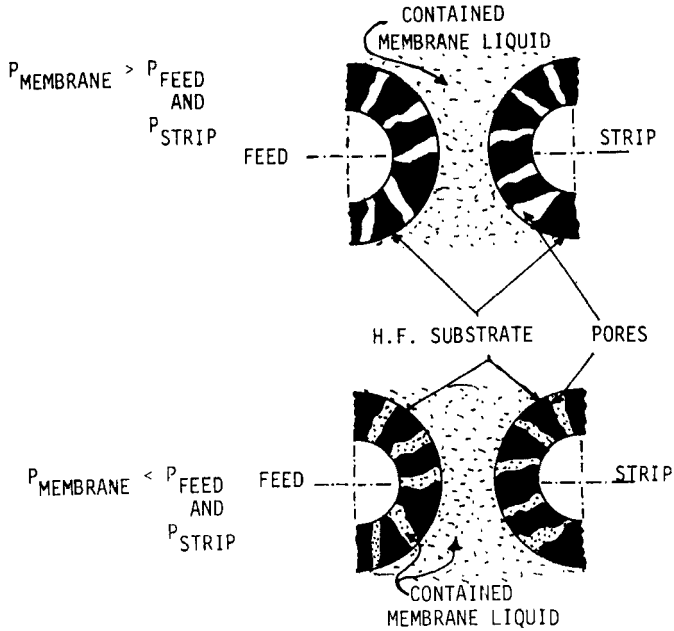
There are two aqueous-organic interfaces in this configuration. One interface is at the outside diameter of the feed fiber where solute is extracted into the organic membrane liquid; the second interface is at the outside diameter of the strip fiber for back extraction of the solute into the strip solution. Guided by extensive previous studies on nondispersive solvent extraction using hydrophilic microporous flat membranes and hollow fibers (9,10,11), we stabilize both the interfaces by maintaining the organic membrane liquid at a pressure higher than the two aqueous phase pressures. The organic membrane liquid in the shell is connected to an external reservoir pressurized independently (Fig. 1).

This configuration has several benefits. Two differential pressures (feed-membrane and strip-membrane) can now be independently controlled; in SLM-s only one differential pressure (between the feed and strip) can be controlled. Secondly, the organic membrane liquid is automatically replenished from the external reservoir to counteract any loss, eliminating the need for any prior equilibration. These features lead to extraordinary liquid membrane stability. Further, using fine hollow fibers, the effective liquid membrane thickness in the interstices of the tightly packed hollow fiber assembly can be kept at a very low value (7,8). The organic membrane liquid contained between the hollow fibers (the HFCLM) thus retains the traditional advantages of a SLM.

In case of microporous hydrophobic hollow fibers and aqueous feed and strip solutions, the organic liquid membrane will penetrate the pores in the wall of both the feed and strip fibers (Fig. 2). The aqueous-organic interfaces are stabilized at the internal diameter of both types of hollow fibers. Extensive investigations on nondispersive solvent extraction using microporous hydrophobic membranes (11,12,13,14) suggest maintaining the organic membrane phase at a pressure lower than those of the two aqueous streams.

Organic Feed/Aqueous Membrane

To remove a solute from an organic solvent, one can use an aqueous solution (15) or a polar organic phase as the liquid membrane as long as the membrane is immiscible with the feed and the receiving phase (Fig. 2). For example, toluene and n-heptane can be separated using a polar organic membrane liquid e.g. sulfolane or n-methyl pyrrolidone (NMP) with or without water in the HFCLM configuration. Toluene preferentially permeates through the membrane and can be removed by a strip hydrocarbon phase like kerosene.



HOLLOW FIBER SUBSTRATE NATURE	FEED & STRIP SOLUTION	MEMBRANE LIQUID	PORE LIQUID
HYDROPHOBIC	AQUEOUS	NONPOLAR ORGANIC	NONPOLAR ORGANIC
	NONPOLAR ORGANIC	AQUEOUS AND/OR POLAR ORGANIC	NONPOLAR ORGANIC
HYDROPHILIC	AQUEOUS	NONPOLAR ORGANIC	AQUEOUS
	NONPOLAR ORGANIC	AQUEOUS AND/OR POLAR ORGANIC	AQUEOUS AND/OR POLAR ORGANIC

Fig. 2. Hollow fiber contained liquid membrane (HFCLM) structures for different porous substrates, feeds and membranes.

If the support is hydrophobic, it is preferentially wet by the hydrocarbon feed and strip phases, whereas if it is hydrophilic, it will be preferentially wet by the membrane phase. The phase interface locations will be similar to those shown in Fig. 2, except that the role of the support will be reversed here. The organic feed/aqueous membrane/hydrophobic support system will appear similar to the aqueous feed/organic membrane/hydrophilic support system, and vice versa. For hydrophobic support, the aqueous (or polar organic) membrane will be at a pressure higher than the feed/strip phases (9), and for hydrophilic support, it would be just the opposite.

The four HFCLM configurations described above are not exhaustive. There can be additional configurations. Further, we have shown both the feed and the strip fibers to be of the same dimensions. This is not necessary; we have actually made HFCLM permeators with different size fibers. In addition, different types of fibers can also be used in the same permeator. They are studied elsewhere.

In real situations, some fibers in a permeator may be defective. This causes breakthrough of one phase into another. When the membrane phase is at a higher pressure than the feed and strip phases, the membrane liquid may leak into the mobile phases. However, small leaks do not seriously undermine the separation capability of the HFCLM. When the membrane phase is at a lower pressure, the feed or strip may leak into the membrane. However, it is always possible to periodically charge fresh liquid membrane from the reservoir, and/or to recycle the contaminated membrane liquid after adequate phase separation. These are additional advantages of the CLM over the conventional SLM-s where fiber defect directly connects the feed to the strip phase.

SOLUTE TRANSFER RATES AND COEFFICIENTS IN HFCLM PERMEATORS

A detailed mass transfer model in a HFCLM permeator should consider differential mass transport in all three spatial directions, the curved boundary surfaces, and the different probabilities of location of a feed fiber vis-a-vis the strip fibers. However, at this early stage it is more appropriate to adopt a first order analysis in order to identify the role of the major factors, and to focus on the advantages and disadvantages of the various possible HFCLM configurations. As such, we use a resistances-in-series approach employing simple mass transfer coefficients.

The solute concentration profile from the feed to the strip solution is shown for each configuration in Fig. 3 for simple partitioning at each of the two interfaces. This figure does not show the curved surfaces of both kinds of hollow fibers. The organic or aqueous membrane always refer to the shellside space (and to the support pores wherever indicated) for simple

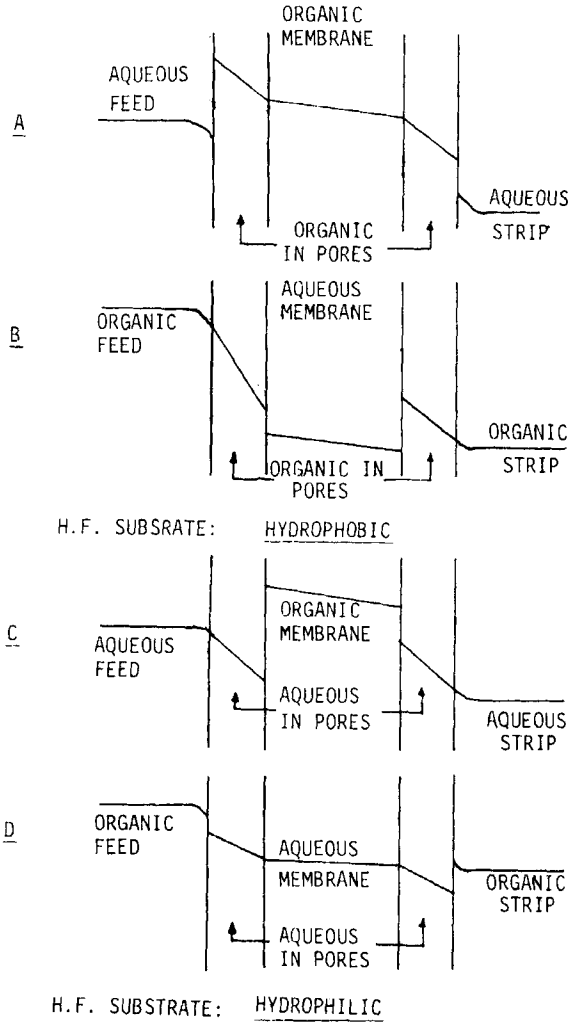


Fig. 3. Solute concentration profile in four different HFCLM configurations for separation from liquid solutions.

permeation without any reaction. The overall solute transfer resistance (1/K) is made up of the resistances of the feed side boundary layer ($1/k^F$), feed hollow fiber substrate ($1/k^F_s$), shell-side liquid membrane ($1/k_m$), strip side hollow fiber substrate ($1/k^S_s$) and the strip side boundary layer ($1/k^S$). The following assumptions are used: (1) no two-dimensional mass transfer effects exist between the pore liquid and the outside liquid; (2) resistances-in-series approach is valid with a permeator-averaged value for each of the five resistances; (3) hollow fiber substrate coefficient determined by the model of unhindered diffusion through a tortuous porous medium (9,10,11,12,14); (4) an effective thickness can be assumed for the shell side liquid membrane (7,8); (5) feed or strip boundary layer coefficients may be obtained from Graetz solutions (11).

If the feed and the strip hollow fiber substrates have identical dimensions, and the solute distribution coefficient m^F_D at the feed-membrane interface is equal to that at the strip-membrane interface, m^S_D, then we may show, for aqueous feed/strip, organic membrane and hydrophobic substrate, (configuration A, Fig. 3) that

$$\frac{1}{K_w} = \left(\frac{1}{k^F_w} + \frac{1}{k^S_w}\right) + \frac{d_i}{d_{lm}}\frac{1}{m_D}\left(\frac{1}{k^F_{so}} + \frac{1}{k^S_{so}}\right) + \frac{d_i}{d_o}\frac{1}{m_D}\frac{1}{k_{mo}} \qquad (1)$$

Here subscript w indicates aqueous phase, subscript o indicates organic phase and $m^F_D = m^S_D = m_D$ (defined as the equilibrium organic phase concentration divided by that in the aqueous phase) at both the aqueous-organic phase interfaces. The corresponding expressions for the other configurations in Fig. 3 are:

Configuration B (Organic feed/strip, aqueous or polar organic membrane, hydrophobic substrate)

$$\frac{1}{K_o} = \frac{d_o}{d_i}\left(\frac{1}{k^F_o} + \frac{1}{k^S_o}\right) + \frac{d_o}{d_{lm}}\left(\frac{1}{k^F_{so}} + \frac{1}{k^S_{so}}\right) + \frac{m_D}{k_{mw}} \qquad (2)$$

Configuration C (Aqueous feed/strip, organic membrane, hydrophilic substrate)

$$\frac{1}{K_w} = \frac{d_o}{d_i}\left(\frac{1}{k^F_w} + \frac{1}{k^S_w}\right) + \frac{d_o}{d_{lm}}\left(\frac{1}{k^F_{sw}} + \frac{1}{k^S_{sw}}\right) + \frac{1}{m_D}\frac{1}{k_{mo}} \qquad (3)$$

Configuration D (Organic feed/strip, aqueous or polar organic membrane, hydrophilic substrate)

$$\frac{1}{K_o} = \left(\frac{1}{k^F_o} + \frac{1}{k^S_o}\right) + \frac{d_i}{d_{lm}} m_D \left(\frac{1}{k^F_{sw}} + \frac{1}{k^S_{sw}}\right) + \frac{d_i}{d_o}\frac{m_D}{k_{mw}} \qquad (4)$$

If the dimensions and the number of the feed fibers are not identical to those of the strip fibers, and $m_D^F \neq m_D^S$, then the relations between K and the individual coefficients are much more complex. We illustrate such a relation below for Configuration B:

$$\frac{1}{d_o^F K_o} + \frac{\pi}{R_T}\left(1 - \frac{d_o^S m_D^F}{d_o^F m_D^S}\right) N_S C_o^S - \left(1 - \frac{d_o^S}{d_o^F}\right) N_S C_b^S$$

$$= \frac{1}{d_i^F k_o^F} + \frac{1}{d_{lm}^F k_{so}^F} + \frac{m_D}{d_o^F k_{mw}} + \frac{1}{d_{lm}^S k_{so}^S} + \frac{1}{d_i^S k_o^S} \qquad (5)$$

where R_T is the total molar rate of solute transfer in the permeator containing N_S number of strip fibers and N_F number of feed fibers. The corresponding expressions for aqueous feed/strip systems are available in (8). The direct relation between R_T, K_o, fiber numbers, dimensions and bulk concentrations for configuration B are

$$R_T = K_o \left[\pi d_o^F N_F C_b^F - \pi d_o^s N_S C_b^S\right] \qquad (6)$$

Here C_b^F and C_b^S represent the bulk solute concentrations in the feed and strip solutions respectively whereas C_o^S in relation (5) is the solute concentration in strip organic phase at the aqueous-organic interface located at the outer diameter of the hydrophobic hollow fiber.

EXPERIMENTAL

Solutes studied are phenol (Fluka Chemical, Ronkonkoma, NY) and acetic acid (glacial reagent, Electronic grade, DuPont, Wilmington, DE). Organic liquid membrane consisted of either MIBK (methyl isobutyl ketone, certified ACS grade, Fisher Scientific, Fairlawn, NJ) or decanol (Eastman Kodak Co., Rochester, NY). Hydrophobic hollow fibers used were of polypropylene (PP) X-10 type (Questar, Charlotte, NC; d_o = 150 microns; d_i = 100 microns; porosity 0.2). Hydrophilic hollow fibers of regenerated cellulose (RC) were obtained from CD Medical Inc., Miami Lakes, Fl. and CasChem Inc., Bayonne, NJ and were washed as recommended and dried before usage. The RC fiber dimensions from the two sources are d_o = 200 microns, 270 microns and d_i = 150 microns, 220 microns.

HFCLM permeators were prepared in a 10 cm long 1.27 cm I.D. stainless steel (s.s.) nipple acting as the shell. There was a teflon sleeve (0.61 cm I.D., 103 cm O.D.) epoxied to the s.s. nipple inside surface. The fibers passed through this sleeve which provided a smooth surface for the fiber bundle. The fiber bundle was prepared by taking two sets of fibers, placing one set on

another and carefully rolling them together in the middle while keeping the ends separated on the two sides. This two-set fiber bundle was put into the permeator from one side and was pulled from the other side. Ends of each set of fibers were taken out at each permeator end separately through the two arms of a Y-fitting (Fig. 1) and potted.

The permeator s.s. shell had openings for membrane liquid introduction and withdrawal. Although the actual fiber length in the permeator is longer than 10 cm, an effective permeation length of 10 cm was chosen since the two fiber sets were effectively separated beyond that distance. For potting, the Armstrong C4/D epoxy (Beacon Chemicals, Mount Vernon, NY) was used.

The experimental setup schematic is basically that indicated in the bottom of Fig. 1. The membrane phase pressure was controlled by the gas cylinder pressure imposed on the membrane liquid reservoir. Inlet and exit pressures of the feed and the strip streams were noted. Time varying concentration measurements were made initially to determine when steady state was achieved. The flow rates were measured using measuring cylinders and timers since their values were low. Experiments were conducted in the temperature range of 22-24°C.

Acetic acid concentrations in different streams were determined by NaOH-titrations (12,14). A Hewlett-Packard HPLC was used to determine phenol concentrations, using a reverse phase C-18 column with 35% acetonitrile-65% water carrier, and a UV detector at 280 nm.

RESULTS AND DISCUSSION

Hydrophobic HFCLM Permeator

We first present the initial time-dependent solute permeation behavior in a hydrophobic HFCLM permeator for two different systems; (1) transfer of acetic acid from a 29.7 mg/mL aqueous feed solution through a CLM of MIBK into water used as strip solution and (2) transfer of phenol from a 9.0 mg/mL aqueous feed solution through a CLM of MIBK into water used as strip solution. The hydrophobic PP hollow fiber permeator had 300 feed and 300 strip fibers (X-10) with a mass transfer area per unit volume of 32.2 cm^{-1}. The flow pattern was cocurrent.

Figure 4 shows that acetic acid concentrations at the hydrophobic permeator outlets on the feed side and the strip side have reached steady values within 2-4 hours. The strip side outlet concentrations of phenol are shown as a function of time in Fig. 5. A steady state concentration is reached around 11-12 hours. The difference in time to reach steady state in the two cases is primarily due to the difference in the values of the distribution coefficient of the two solutes, acetic acid and phenol, between water and MIBK.

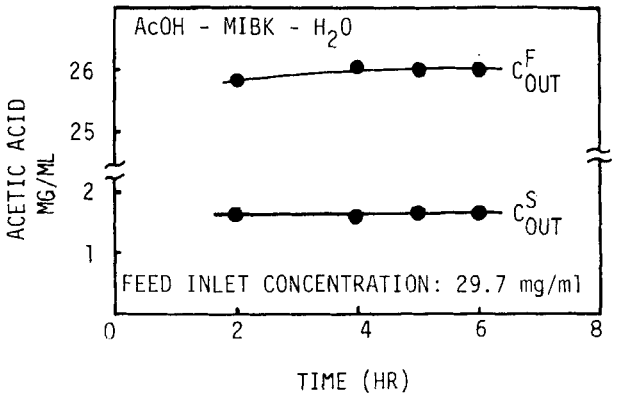


Fig. 4. Time dependent acetic acid concentrations in feed and strip outlet streams from hydrophobic HFCLM permeator with MIBK as CLM.

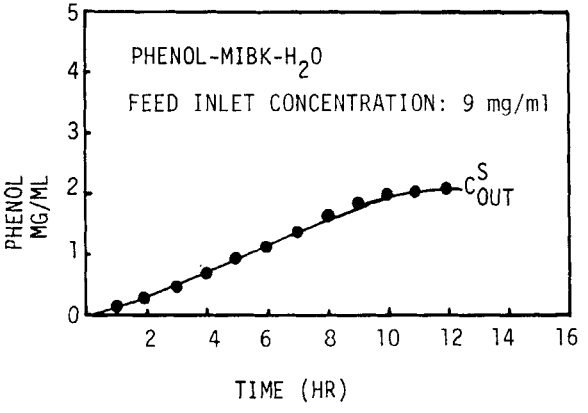


Fig. 5. Time dependent phenol concentration in strip outlet stream from hydrophobic HFCLM permeator with MIBK as CLM.

The value of m_D for acetic acid between water and MIBK is around 0.52 (14) while that for phenol varies strongly with phenol concentration in MIBK-water system (16). A value of 25-35 for the latter would be reasonable (8). Obviously, the time needed to raise the phenol concentration in CLM to this level would be considerably higher than that for acetic acid. The MIBK volume in the external membrane liquid reservoir would also influence the time needed to reach steady state.

Since the organic membrane liquid MIBK wetted the hydrophobic fibers in both the systems, the membrane pressure (between 6.9-10.2 kPa) was always kept lower than the pressure of the aqueous feed (inlet 34.5 kPa, outlet 13.8 kPa) and the aqueous strip (inlet $\sim$ 48.3 kPa, outlet $\sim$ 13.8 kPa). Feed and sweep flow rates were kept at low levels (feed $\sim$ 0.5 mL/min, sweep 0.79-0.9 mL/min) to artificially increase the time to reach steady state. We have also run this HFCLM permeator successfully at flow rates that are at least an order of magnitude larger.

Hydrophilic HFCLM Permeator

Some results of HFCLM permeation are presented next for two hydrophilic hollow fiber (RC) permeators (modules A and B). The solute is phenol in aqueous feed/strip system and the organic liquid membrane is either decanol or MIBK. Table 1 shows the time-dependent experimental mass transfer rates of phenol in both modules. These rates have been calculated with respect to both the feed stream and the strip stream.

Data groups 1 and 2 show that the mass transfer rate based on feed is considerably larger than that based on the strip, indicating phenol accumulation in the membrane liquid. Data groups 3 and 4 taken for longer time periods indicate that both mass transfer rates become essentially same; further, they do not change with time, indicating steady state. In fact, the overall mass transfer coefficient shown in the last column has not only become constant but is essentially independent of the two modules even though the fiber dimensions and effective areas are different in the two modules.

This last result follows directly from equation (3) for configuration C. Since phenol-water-decanol is a high m_D ($\sim$ 25) system (8), the membrane resistance term is negligible. The quantity K_w is controlled by k_w^S, k_w^F, k_{sw}^S and k_{sw}^F. As the two flow rates are very similar, k_w^S and k_w^F are quite close; so are the substrate coefficients (8,11).

Equation (3) indicates that for two different liquid membranes with high m_D-S, K_w values should be identical for the same aqueous flow rates in a given permeator. Table 2 provides a

Table 1. Experimental mass transfer rates with time

Substrate : Hydrophilic (Regenerated Cellulose)
Feed : Phenol-water; Strip : Water; Membrane : Decanol
Temperature : 22-24°C; Flow Pattern : Cocurrent
Module A : Effective area 126 sq cm; Fiber id/od = 150/200 microns
Module B : Effective area 170 sq cm; Fiber id/od = 220/270 microns

Data Group No.	Module No.	Feed inlet conc. mg/mL	Avg. feed flow mL/min	Avg. strip flow mL/min	Expt. time hours	Mass Transfer rate (mg/hr) based on feed	Mass Transfer rate (mg/hr) based on strip	$K_w \times 10^5$ cm/sec
1	A	9.0	1.73	2.88	1.5	3.50	1.47	6.02
					3.0	3.55	1.51	6.19
					4.5	4.00	1.68	7.20
					6.0	4.37	1.74	7.76
2	B	9.3	1.15	1.55	5.0	4.56	2.16	6.91
					7.0	4.29	2.48	7.05
3	A	9.0	0.59	1.93	15.0	1.77	-	-
					19.0	1.32	1.39	2.34
					23.0	1.53	1.29	2.82
					39.0	0.94	1.46	2.52
4(*)	B	9.3	0.66	1.48	2.0	2.53	2.24	3.86
					5.0	2.52	2.32	3.86
					6.5	2.31	2.34	3.56
					9.0	1.89	2.93	2.82
					.			
					.			
					29.0	1.73	2.04	2.52
					32.0	1.52	1.38	2.23

*Between data groups 2 and 4, the membrane liquid was equilibrated, giving rise to faster response time for data group 4.

Table 2. Mass transfer characteristics and pressure conditions

Substrate: Hydrophilic (Regenerated Cellulose)
Feed : Phenol-water; Strip : Water
Temperature : 22-24°C
Module : A; Flow pattern : Cocurrent
Feed Inlet Conc. : 5.4 mg/mL (5400 ppm)

Membrane	Average strip flow rate mL/min	Feed flow rate, mL/min	Phenol removal rate from feed mg/hr	Percent phenol removed from feed (1)
Decanol	6.5	0.7	101	44%
		3.0	180	19%
		9.4	338	11%
MIBK	7.7	0.7	84	37%
		1.4	101	23%
		8.0	288	11%

(1) 100 * (Feed inlet conc. - Feed outlet conc.)/(Feed inlet Conc.)

Membrane phase pressure kPa	Feed inlet pressure kPa	Feed outlet pressure kPa	Strip inlet pressure kPa	Strip outlet pressure kPa
48-65	28-48	14-48	28-41	17-24

verification for this. We observe, that, for two different organic membrane liquids (decanol, $m_D \sim 25$; MIBK, 25-35), at similar feed and sweep flow rates, the phenol removal rates are quite similar. This table also gives the pressure conditions used with hydrophilic fibers; the organic membrane pressure is higher than those of the feed as well as the strip. The interfacial areas per unit volume in these hydrophilic permeators are 43-58 cm^{-1}.

We provide now a glimpse into the usefulness of equations 1-4 for predicting K in a HFCLM permeator. We select equation 1 for hydrophobic substrate and aqueous feed/strip in the phenol-MIBK

water system. Consider the behavior partially shown in Fig. 5. The experimentally obtained value of K_w is 9.32×10^{-5} cm/sec. Using Graetz solution and substrate information about these fibers from reference (11), we find that the predicted K_w is 10.3×10^{-5} cm/sec, indicating how this analysis can be employed for a useful order-of-magnitude prediction.

Membrane Stability

Unless the fibers are defective, we have found that the HFCLM is quite stable. We have run systems where MIBK was the membrane with aqueous feed/strip for as long as 60 hours without observing any membrane instability. We have also run the hydrophilic fiber permeator with small defects for long periods of time, without affecting steady state.

Role of the Distribution Coefficients in Overall Mass Transfer

For systems having simple permeation and no complexities due to interfacial reactions, facilitated or coupled transport, we can suggest conditions that lead to increased K in HFCLM permeator. We consider specifically the role of m_D. In the case of hydrophobic fibers in aqueous feed/strip systems, with $m_D >> 1$, equation (1) suggests that only the aqueous boundary layer coefficients k_w^F and k_w^S control transport. If the system has $m_D << 1$, the substrate and the membrane resistances become very large. For the same fibers in organic feed/strip systems, $m_D << 1$ will eliminate the CLM resistance allowing the substrate and boundary layer resistances to control transport. A $m_D >> 1$ system on the other hand, will mean that CLM resistance may become controlling.

For hydrophilic fibers and aqueous feed/strip systems having $m_D << 1$, equation (3) suggests that the CLM resistance may control. For a $m_D >> 1$ system, boundary layer and substrate resistances (rather than the CLM resistance) will control. For the same fibers and organic feed/strip systems, with $m_D << 1$, equation (4) suggests that only the boundary layer resistances control. For $m_D >> 1$ systems, however, the CLM and the substrate resistances determine the transport rate.

CONCLUSIONS

The hollow fiber contained liquid membrane (HFCLM) can be used effectively for separation or purification of liquid solutions. The CLM structure is physically very stable and can be operated for long times without any operational problem. CLM-s can be used for a variety of systems. Operations with both aqueous feed/organic membrane, and organic feed/aqueous membrane are possible, by maintaining the correct phase pressure conditions, and using the right substrates. Based on a first order theoretical model presented here, it is possible to identify the various mass transfer

resistances to solute transport, and predict the optimum configuration for systems without chemical reactions.

NOTATION

C_b^F, C_b^S	solute concentration in the bulk phase for feed and strip, respectively, mg/mL
C_o^F, C_o^S	solute concentration at the fiber outside wall surface in the feed and the strip phases, mg/mL
d_i, d_o, d_{lm}	hollow fiber inside diameter, outside diameter, and the log-mean diameter, respectively, cm
k_w^F, k_w^S	boundary layer coefficients in the feed and the strip phase, respectively, for aqueous feed, cm/sec
k_o^F, k_o^S	boundary layer coefficients in the feed and the strip phase, respectively, for organic feed, cm/sec
k_{sw}^F, k_{sw}^S	substrate coefficients for water-filled substrate on the feed and the strip side, respectively, cm/sec
k_{so}^F, k_{so}^S	substrate coefficients for organic-filled substrate, on the feed and the strip side, respectively, cm/sec
k_{mo}, k_{mw}	liquid membrane transfer coefficient, for organic and aqueous membranes, respectively, cm/sec
K_w	overall mass transfer coefficient based on water phase, cm/sec
K_o	overall mass transfer coefficient based on organic phase, cm/sec
m_D	solute distribution coefficient, organic phase concentration to aqueous phase concentration, (mg/L)/(mg/L)
N_F, N_S	total number of feed and strip fibers, respectively, in the module
R_T	solute transfer rate per unit permeator length, relation 6, mg/cm-sec

subscripts and superscripts

F,S	feed or strip

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