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Reduction of concentration polarization in pervaporation using vibrating membrane module

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Abstract

A vibrating membrane module currently marketed for filtration applications was evaluated for the separation of volatile organic compounds (VOCs) from aqueous solutions by pervaporation. Preliminary screening experiments with three VOCs, three silicone membranes, and in the presence and absence of a surfactant were performed to determine if further consideration of the vibrating module for a field demonstration project was warranted. The primary process variables studied were vibrational amplitude and liquid flow rate. The vibrations greatly reduced concentration polarization in the system as inferred from an order of magnitude increase in the overall mass transport coefficient. Mass transfer coefficients for the vibrating module compared favorably with those for traditional spiral wound modules. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Concentration polarization; Modules; Pervaporation; Water treatment; Volatile organic compounds

1. Introduction

Since the early 1990s, the EPA's National Risk Management Research Laboratory (EPA-NRMRL) has been investigating the use of pervaporation to remove volatile organic compounds (VOCs) from aqueous matrices [1–3]. Most recently, EPA-NRMRL has been collaborating with the Department of Defense's Naval Facilities Engineering Service Center on a field demonstration project to recycle surfactant solutions which have been used to remove chlorinated solvents from contaminated soils. An early step in the

surfactant recycling process is to separate the VOCs from the surfactant solution. Subsequently, the surfactant solution can be concentrated utilizing micellar enhanced ultrafiltration. EPA-NRMRL has proposed that pervaporation be used to separate the VOCs from these solutions. To this end, EPA-NRMRL has evaluated traditional spiral wound and hollow fiber pervaporation modules for this purpose.

The impact of concentration polarization on the performance of pervaporation processes is well documented [4–12]. The polarization observed during the separation of VOCs from aqueous solutions by pervaporation is particularly severe [4–10,12]. Often, the rate of mass transport of the VOC from the feed solution is controlled solely by the rate of diffusion through the liquid boundary layer next to the mem-

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brane surface. As a result, a significant amount of effort has been expended attempting to understand the role of the boundary layer and to engineer systems to minimize the magnitude of concentration polarization.

For the traditional pervaporation modules (spiral wound, hollow fiber with lumen feed, hollow fiber with crossflow shell-side feed, and plate and frame), the liquid boundary layer mass transport coefficient (k_{bl}) is a direct function of the liquid bulk velocity (u). In the cases of laminar lumen liquid flow in hollow fibers and laminar open channel flow in plate and frame systems, L ev eque's correlation usually provides reliable values for k_{bl} [13]:

$$k_{bl} = 1.6 \frac{D}{d_h} Re^{1/3} Sc^{1/3} \left(\frac{d_h}{L} \right)^{1/3} = 1.6 \left(\frac{uD^2}{d_h L} \right)^{1/3}, \quad (1)$$

the Reynolds and Schmidt numbers are defined as

$$Re = \frac{u\rho d_h}{\eta}, \quad Sc = \frac{\eta}{\rho D}, \quad (2)$$

where D (diffusivity), ρ (density), and η (viscosity) are physical properties of the fluid, u is the superficial velocity of the fluid in the feed flow channel, d_h and L are hydraulic diameter and length of the cell. Turbulence generating flow spacers can be added to spiral wound and plate and frame systems to increase k_{bl} . In addition, in systems with spacers, k_{bl} can be a somewhat stronger function of u than in open channel systems (representative constants

obtained from [14]):

$$k_{bl} \cong 0.5 \frac{D}{d_h} Re^{0.4} Sc^{1/3} = 0.5 \frac{D}{d_h} \left(\frac{d_h u \rho}{\eta} \right)^{0.4} \left(\frac{\eta}{D\rho} \right)^{1/3}, \quad (3)$$

where d_h is the thickness of spacer and u is the average velocity if spacer were replaced by open slit with thickness d_h .

Realistic design and operating parameters for several different membrane modules in common use and calculated mass transfer coefficients for those modules are listed in Table 1 as well as the membrane area required to remove 99% of trichloroethylene (TCE) from a 2 gpm (126 cm³/s) water stream at 20°C. Higher temperatures would only marginally increase the mass transport coefficients. Table 1 is certainly not an exhaustive analysis of mass transfer coefficients, rather it should be used for illustrative purposes. However, the trend is not atypical. Open channel flow systems tend to have the lowest pervaporation k_{bl} values while spiral wound systems can be more easily designed and operated so that k_{bl} approaches the membrane mass transfer coefficient (k_M). In all cases, however, the liquid velocity must be manipulated to effect k_{bl} .

As if concentration polarization were not enough of a technical hurdle to overcome, previous pervaporation pilot experiments performed with groundwaters and actual surfactant-based soil remediation fluids indicated that spiral wound modules can suffer from plugging of the flow spacer due to secondary con-

Table 1
Comparison of liquid boundary layer mass transfer coefficients for several common pervaporation modules

Module type	Governing equation	Hydraulic diameter (d_h) (cm)	Velocity u (cm/s)	Mass transfer coefficient k (cm/s)	Membrane area for 99% TCE removal (m ²)
<i>Plate and frame</i> : open channel, twenty 1/16 in. slits in parallel, 8 in. wide, 30 in. long	Eq. (1)	0.159	1.95	3.8×10^{-4}	153
<i>Hollow fiber</i> : laminar flow, 10 000 fibers, 250 micron ID, 30 in. long	Eq. (1)	0.025	25.7	1.7×10^{-3}	34
<i>Spiral wound</i> : 1 mm thick spacer, 30 in. wide flow path (similar to 2 in. OD module)	Eq. (3)	0.1	16.5	3.6×10^{-3}	16
<i>No liquid boundary layer</i> : membrane resistance for 127 �m silicone membrane	$k_M = P^M/T$	–	–	Est. 2×10^{-2}	5

Assumed properties for a TCE-water system at room temperature: D =diffusivity= 0.93×10^{-5} cm²/s; η =water viscosity= 0.01 g/cm s; ρ =water density= 1 g/cm³; P^M =TCE permeability in silicone $\approx 3 \times 10^{-4}$ cm²/s (from [14]); T =membrane thickness.

taminants present in the solutions, such as soluble or colloidal iron and oils [15]. Hollow fiber modules with lumen-side feed did not display plugging problems, but did display mechanical problems due to the effects of the VOCs and surfactant on the selective layer, support, and tube-sheet materials. The low interfacial tension surfactant solutions tend to wet even the smallest defect and may contribute to the propagation of minor adhesion defects resulting in leakage of solution into the permeate chamber. Leakage is a significant problem when dealing with surfactant solutions, since the solution will foam immediately when exposed to vacuum.

As a result, EPA-NRMRL has been attempting to identify pervaporation membrane systems which are less susceptible to module plugging, more resistant to the process chemicals studied, and which still have reasonably high mass transfer coefficients. This search led us to consider a new type of membrane module originally developed for filtration applications [16]. The module is similar to a plate and frame system with open channel flow. The main difference is that the entire stack of membrane “plates” vibrates rotationally about the axis of the stack at approximately 60 Hz. The edge of the stack moves a maximum distance of 1 in. (2.54 cm) per cycle (approx. 10° rotational amplitude for an 11 in. (28 cm) OD disk). Because the membrane is actually moving at the same rate as the plate, high shear rates are developed at the membrane surface. In addition, because the plate vibrates back and forth, a high level of turbulence results. In filtration applications, the high surface shear rates will reduce the buildup of materials on the membrane surface, thereby increasing membrane fluxes. EPA-NRMRL was attracted to the system because these same surface shear rates would greatly reduce concentration polarization in pervaporation thereby dramatically improving mass transport rates. Further, the open flow channel between the membrane plates combined with high shear rates would significantly reduce the tendency of the module to plug with precipitates.

The experiments described herein represent an attempt to obtain sufficient information to determine if the vibrating membrane system was worthy of further consideration for the EPA-NRMRL surfactant field demonstration project. They were not meant to be a complete analysis of the system. To the best of our

knowledge, this is the first pervaporation research conducted with this type of vibrating membrane system.

2. Experimental

Reagents. All chemicals were used as received (the mention of trade names or commercial products does not constitute an endorsement or recommendation for use):

- 1,1,1-trichloroethane (TCA): 99+%, ACS reagent, Aldrich Chemical.
- trichloroethylene (TCE): 99.5+%, spectrophotometric grade, Aldrich Chemical.
- tetrachloroethylene (PCE): 99.9+%, HPLC grade, Aldrich Chemical.
- Methyl alcohol: 99.9+%, ACS HPLC grade, Aldrich Chemical.
- Calcium Chloride Dihydrate (CaCl₂): USP/FCC grade, Fisher Scientific.
- Sodium Chloride (NaCl): 99+% ACS reagent grade, Aldrich Chemical.
- Sodium dihexyl sulfosuccinate, Aerosol MA 80-I Surfactant (Cytec MA 80-I): Cytec Industries.
- Dow Corning Antifoam C emulsion: food grade, Dow Corning.

All experiments were carried out with the bench unit shown in Fig. 1. The feed stream was circulated by a magnetic drive centrifugal pump (Tuthill Model TCM53MC) between the 20 l stainless steel feed tank and the membrane cell in a loop via stainless steel tubing. The temperature of the feed liquid was controlled by passing the feed stream through a counter-current tube-in-tube heat exchanger. The liquid on the shell side of the heat exchanger was recirculated to a constant temperature water bath (Cole-Parmer Polystat 12101-10). Two float-type flowmeters (Gilmont) of different flowrate specifications were installed in parallel, monitoring the feed flowrate. The temperatures of the feed liquid, residual liquid, and the permeate vapor were measured by thermistor thermometers (YSI no. 703). Vacuum was provided via a belt-driven pump (Welch Model 1380) and monitored with an active strain gauge (Edwards high vacuum model D35726000). All experiments were performed at 30°C with an applied vacuum of 1–2 torr. Permeate vapor was condensed in glass cold traps immersed in liquid

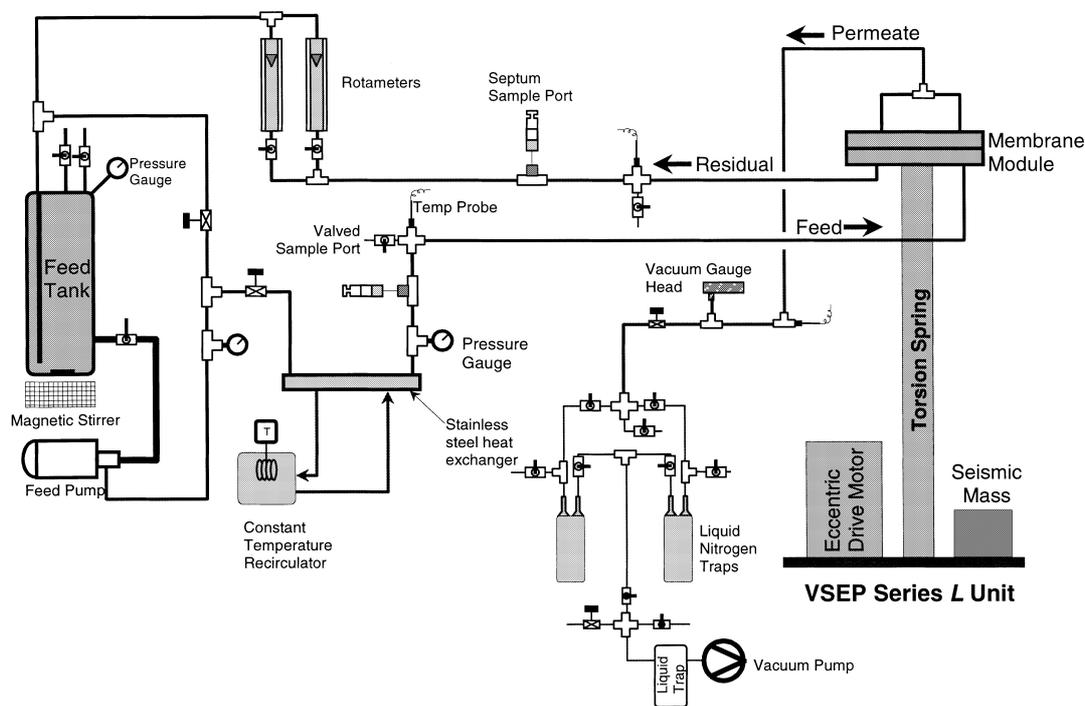


Fig. 1. Schematic diagram of EPA bench-scale pervaporation unit with vibrating membrane module.

nitrogen. The size of these traps, combined with the larger than normal bench-scale membrane area caused the feed temperature to be limited to 30°C. At the end of each day, additional VOC was added to the feed tank to compensate for the VOCs removed.

The vibrating membrane module was obtained from New Logic International (Emeryville, CA). This module is designated as the VSEP (vibrational shear enhanced process) Series *L*. The VSEP Series *L* consists of a circular membrane module connected to a torsion spring which transmits the oscillations of a lower plate vibrated by an eccentric drive motor to the membrane module. As detailed in Fig. 2, the module itself consists of polypropylene upper and lower clamshell chambers. Liquid enters the lower clamshell along a radial groove on one side and exits along a similar groove on the opposite side of the same clamshell. A 3 mm deep recess in the lower clamshell serves as the feed channel. The membrane is placed on top of o-rings at the inner and outer perimeters of the lower clamshell. The region of membrane exposed to the feed liquid has an inner diameter of 9.5 cm and an outer diameter of 26.7 cm. The exposed membrane

area was estimated to be 510 cm². One or two sheets of a melt spun polypropylene permeate spacer (Tytar) and a 0.4 mm thick woven polypropylene spacer were placed on the vacuum side of the membrane. Vacuum was supplied at two points of the upper clamshell. Gland seal o-rings in the upper clamshell separated the vacuum in the upper clamshell from the outside atmosphere. The clamshells and membrane were bolted together and bolted to the top of the torsion spring. The entire membrane assembly vibrates together.

The VSEP Series *L* was equipped with a vibration controller. The frequency of vibrations of the module could be adjusted to the nearest 0.01 Hz. As the frequency of oscillations was increased, the angular displacement also increased. A gauge was provided to determine the “travel distance” of a point on the perimeter of the module. As the natural harmonic of the mass-torsion system was approached, small changes in the frequency yielded large changes in the angular displacement. Most experiments were performed in the vicinity of 54 Hz. Specific travel distances were monitored and maintained for a given experiment.

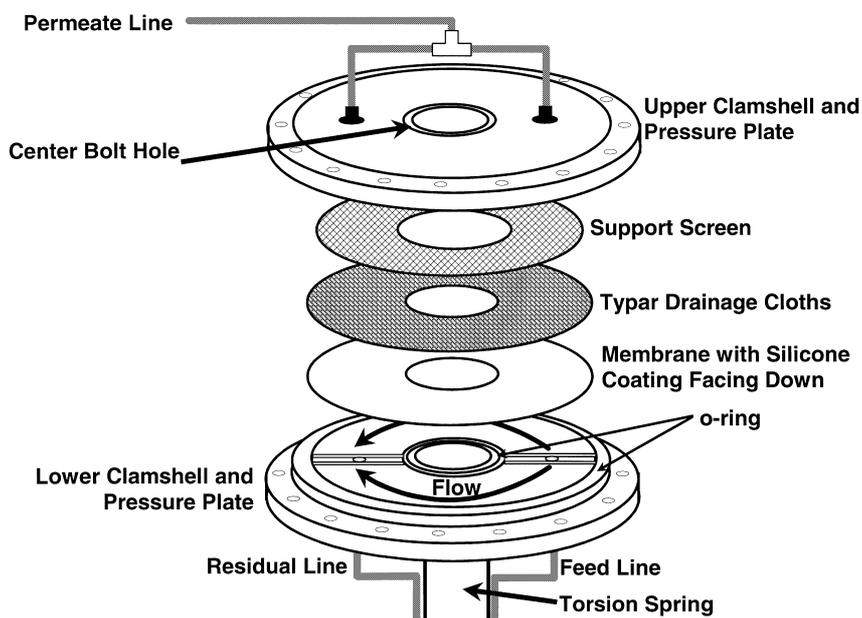


Fig. 2. Assembly diagram for VSEP Series *L* module.

Three separate membranes were evaluated with the VSEP Series *L*:

- 76 μm silicone sheeting: Specialty Manufacturing (Dow Corning Silastic Q7-4840),
- 127 μm silicone sheeting: Specialty Manufacturing (same as above),
- 20 μm silicone on porous support: Membrane Technology and Research (MTR).

Each membrane was used as delivered. Approximately half of the experiments were performed with water spiked with three VOCs: TCA, TCE, and PCE. The other half were performed with an aqueous surfactant solution consisting of 4 wt% active Cytec MA 80-I, 2.5 wt% NaCl, 0.1 wt% CaCl_2 , a trace amount of isopropyl alcohol (from the surfactant formulation), and the same three VOCs.

The system was allowed to operate for at least 1 h prior to sampling to allow the system to reach steady state conditions (other than feed concentration). Once the initial period had ended, a “run” was initiated by immersing an empty preweighed vacuum trap in liquid nitrogen. The feed and residual streams were then sampled by withdrawing 0.1–2.5 ml of liquid from a septum port via an airtight syringe. Care was taken to maintain a liquid pressure of at least 5 psig at both the feed and residual sample ports. This combined with

slow syringe plunger speeds ensured minimal volatilization of VOCs in the syringe by avoiding suction conditions in the syringe. The syringe fluid was immediately diluted in either 50 or 100 ml of water and transferred to a 40 ml vial capped with a Teflon-lined septum. When greater than a 10% difference in feed and residual concentrations was expected, duplicate samples of the feed and residual were obtained. Otherwise, the feed and residual samples were considered duplicates of each other.

At the end of each run, the feed and residual streams were sampled and the permeate trap removed. Before the permeate sample had thawed, a known mass of methanol was added to the trap (approx. 10 g) in order to reduce volatilization of VOCs upon melting. Once the outside of the trap had been dried, the trap was reweighed (approx. 5 min). Additional methanol was then added to fully dissolve the trap contents. The methanol solution was transferred to a volumetric flask and diluted to 50 ml with methanol. A sample of this final methanol solution (usually 10, 25, or 50 μl) was dissolved in 100 ml of water and transferred to a 40 ml vial capped with a Teflon-lined septum. Duplicate dilutions of the final methanol solution were always prepared and analyzed.

Samples were analyzed by purge and trap gas chromatography (GC) using a Dynatech Dynawaters purge and trap autosampler and a Tremetrics 9001 GC equipped with a flame ionization detector (FID). In general, EPA test method 601 was followed with the following modifications: (1) Vocarb 3000 trap containing Carbopack B / Carboxen 1000 & 1001, (2) FID detector, (3) J & W Scientific DB-624 megabore column 75 m×0.533 mm with film thickness of 3 μm, (4) 25 ml sparge tube. 1-Bromobutane (99+%, Aldrich Chemical) was used as an external standard to monitor purge efficiency and system operation. External standard recoveries of 80–120% were considered acceptable. A small amount of anti-foam agent was added to surfactant solutions to reduce foaming in the purge vessel. The antifoam and surfactant did not alter the analytical results for the VOCs as determined by acceptable matrix spike recoveries which were between 95% and 105%. The GC system was considered to be operating properly if calibration checks yielded VOC concentration values within 10% of the calibration standard concentrations. Water content of the permeate was determined as the difference between total permeate mass and the masses of VOCs determined from the GC analysis. Mass balance closures were calculated when VOC removals exceeded 25%. Closures of 80–100% were observed. In general, although repeated runs exhibited relative standard deviations of less than 10%, the calculated mass transport constants reported herein are more likely accurate to 20%.

All but one of the experiments consisted of at least two permeate collection periods, termed “runs”. VSEP travel distances of 0 and 7/8 in. (2.2 cm) and a flow rate of 0.94 lpm (15.7 cm³/s) were selected as reference conditions. The experiments for the reference conditions were often repeated, yielding as many as six separate runs. The data from all runs for each set of experimental conditions have been averaged.

3. Results and discussion

For simplicity, the performance of the vibrating pervaporation membrane system was quantified by calculating an overall mass transport coefficient for each VOC under each set of operating conditions, defined as

$$k_{\text{VOC}} = \frac{m_{\text{VOC}}}{AtC_{\text{lm}}}, \quad (4)$$

where k_{VOC} is the mass transport coefficient for a particular VOC (cm/s), m_{VOC} the mass of VOC collected in permeate (g), A the membrane area (cm²), t the accumulation time for permeate (s), and C_{lm} is the log-mean concentration of VOC in liquid stream averaged over both time and feed/residual sampling positions (g/cm³) (equivalent to 10⁶ mg/l).

In developing Eq. (4), it was assumed that the permeate side concentration was negligible compared to the feed concentration so that the flux is proportional to the feed concentration. The water flux was calculated according to the following equation:

$$J_w = \frac{m_w}{At}, \quad (5)$$

where J_w is the water flux (g/cm² s) and m_w is the mass of water collected in permeate (g).

The main variables studied in this preliminary work included: amplitude of oscillation (travel distance), liquid flow rate, presence of surfactant, and membrane thickness. Although the VOC concentration was not the same between sampling events and separate experiments, it was not observed to have a measurable effect on mass transport coefficients. For example, concentrations ranging from 300 to 2000 mg/l VOC were used in the series of surfactant experiments with the 20 μm silicone membrane yielding TCA mass transport coefficients ranging from 2.1×10⁻³ to 2.5×10⁻³ cm/s. The high and low coefficients did not correspond to the extremes in concentration. As a result, VOC concentration will not be reported as a process variable. In general, however, the nonsurfactant solutions contained between 10 and 200 mg/l of each VOC while the surfactant solutions contained between 100 and 2000 mg/l of each VOC.

The effect of engaging the vibrations of the VSEP unit on VOC mass transport are displayed in Fig. 3 for the 127 μm membrane with and without surfactant. k_{VOC} was 9–12 times larger when the VSEP oscillated at 7/8 in. travel (circa 54.7 Hz) than when the unit was not oscillating. In order to achieve the same enhancement in k_{VOC} by increasing liquid flow alone (no vibrations), the flow rate would have to be increased by a factor of 1000, assuming that a laminar flow is maintained. Addition of the surfactant reduced k_{VOC} by a factor of 3 a result, primarily, of the reduction in

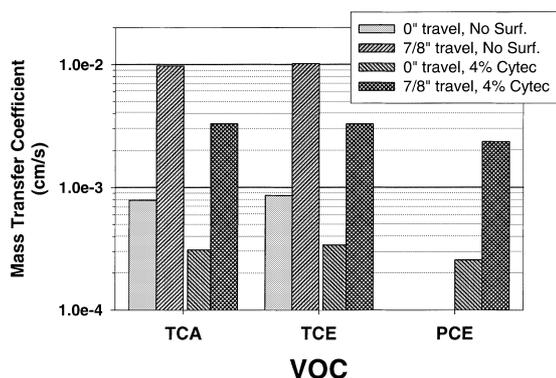


Fig. 3. Effect of surfactant and VSEP conditions on lumped mass transfer coefficient. Conditions: 127 μm thick silicone membrane; flow rate=0.94 lpm=15.7 cm^3/s ; temperature=30°C.

activity of the VOCs due to partitioning into the surfactant micelles (C_{lm} represents the bulk concentration, not just the extracellular concentration of VOC). The water flux averaged $1.0 \pm 0.2 \times 10^{-6} \text{ g}/\text{cm}^2 \text{ s}$ for the 7/8 in. travel and $0.5 \pm 0.1 \times 10^{-6} \text{ g}/\text{cm}^2 \text{ s}$ for no oscillations. The difference in water fluxes is most likely due to the enhanced heat transfer to the membrane surface resulting from the oscillations as well as the energy imparted to the fluid by the shear forces which would increase the fluid temperature. When no surfactant was present, the values of k_{VOC} observed without oscillations (circa $8 \times 10^{-4} \text{ cm}/\text{s}$) are consistent with values obtained from Eq. (1) for flow through the 3 mm open channel gap in the lower clamshell. The values of k_{VOC} observed with 7/8 in. oscillations (circa $1 \times 10^{-2} \text{ cm}/\text{s}$) exceed those displayed in Table 1 for traditional pervaporation modules and even approach the mass transport resistance of the membrane alone.

Initial trials with the VSEP Series L determined that 7/8 in. was the maximum reproducible travel distance for the unit tested. Therefore, 7/8 in. travel was selected as the reference point. In order to determine the effect of other oscillation travel distances on mass transport, additional experiments were performed at 1/4 in. (53.7 Hz) and 1/2 in. travel (54.3 Hz). The results of these experiments for TCA are displayed in Fig. 4. As seen in the figure, even a 1/4 in. travel has a marked effect on mass transport, raising k_{VOC} by a factor 4–10 times the value with no oscillations. Fig. 4 further indicates that additional gains could be achieved by

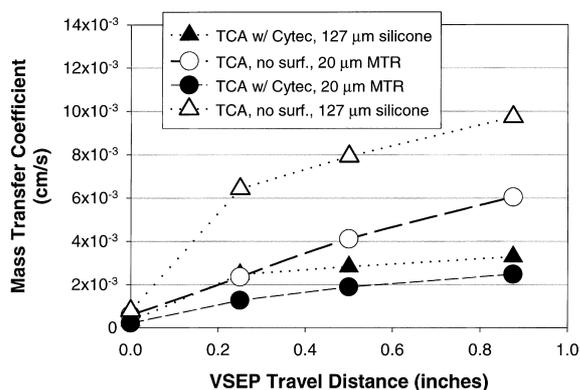


Fig. 4. Effect of VSEP travel distance and membrane on lumped mass transfer coefficient for 1,1,1-trichloroethane. Conditions: flow rate=0.94 lpm=15.7 cm^3/s ; temperature=30°C.

increasing oscillations beyond 7/8 in.. The k_{VOC} curves for the surfactant systems appear to be leveling off more than the no-surfactant systems, indicating that further increases in oscillation amplitude may not have as significant an effect. It should be noted that the mass transport coefficients calculated for the 20 μm supported silicone membrane were lower than those observed with the 127 μm silicone unsupported membrane. It is possible that the microporous support material of the 20 μm membrane presented a mass transport resistance. Further, there may be a difference in the exact form of the silicone in each material. Finally, it is possible that secondary vibrations developed in the unsupported membrane, yielding additional turbulence next to the membrane surface. The water flux was: 1.0×10^{-6} and $2.1 \times 10^{-6} \text{ g}/\text{cm}^2 \text{ s}$ for the 127 μm unsupported and 20 μm MTR membranes, respectively.

A unique aspect of a vibrating pervaporation module is that the liquid shear rate in the module is relatively independent of the liquid flow rate. Therefore, the liquid-side mass transport constant should be relatively insensitive to the feed flow rate. A series of experiments was performed with the VSEP Series L to determine the effect of flow rate on k_{VOC} . The results of these experiments are shown in Fig. 5 for TCA. It is apparent from Fig. 5 that the bulk liquid flow rate did not have a significant impact on k_{VOC} . A seven-fold increase in flow rate (0.254–1.88 lpm) resulted in 10–30% increase in k_{VOC} . The data for the other VOCs followed similar trends. As noted earlier, in traditional

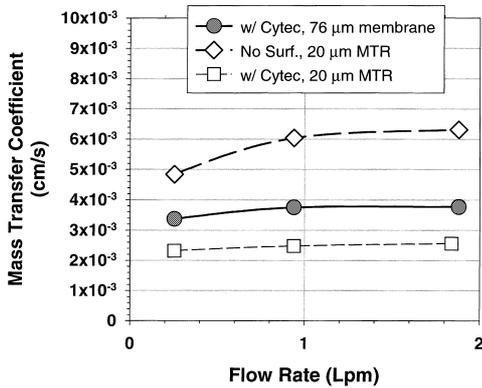


Fig. 5. Effect of flow rate on mass transfer coefficient for 1,1,1-trichloroethane. Conditions: temperature=30°C; VSEP travel of 7/8 in.; 4 wt% cytec MA 80-I surfactant when present.

pervaporation systems, the liquid boundary layer mass transport coefficient is a direct function of the liquid bulk velocity or flow rate. A similar increase in flow rate would result in a 95% increase in k_{VOC} for laminar open channel flow and an even greater improvement for systems with flow spacers. As evidenced by the data presented in Fig. 5, the vibrating pervaporation system effectively decouples k_{VOC} from the liquid flow rate.

EPA-NRMRL has performed similar experiments with other pervaporation systems. Results of selected actual experiments with 2 in. OD spiral wound modules (Hoechst Celanese), lumen-side feed hollow fiber modules (Applied Membrane Technology), and the VSEP Series *L* are shown together in Fig. 6. Module design and operating parameters for the spiral and hollow fiber modules are the same as those for the hypothetical modules described in Table 1. In all cases, the selective layer was silicone rubber. The hollow fibers were microporous polypropylene plasma-coated on the shell side with silicone. The spiral wound modules were constructed with membrane similar to the MTR 20 μm supported membrane used for some of the VSEP Series *L* experiments. The operating conditions were selected to represent those which would likely be used in practice for each of the modules. The results, therefore, should be representative of what could be expected if each type of module were used in a real application. In such an application, however, flow rate and temperature could be adjusted to tweak the mass transport coefficient.

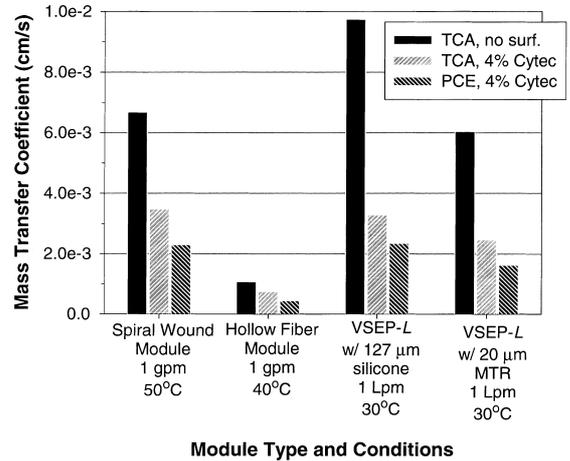


Fig. 6. Comparison of mass transfer coefficients measured for two commercial pervaporation membrane modules to those observed with VSEP module.

As expected and predicted in Table 1, the hollow fiber system with lumen-side feed exhibited the lowest values of k_{VOC} . The spiral wound modules and the VSEP system delivered similar values of k_{VOC} . It should be noted that the spiral wound experiments were performed at 50°C and the hollow fiber experiments at 40°C while all VSEP experiments were performed at 30°C. The primary effect of temperature on boundary layer mass transport is through viscosity which is also manifested in the diffusivity terms in Eqs. (1) and (3). Raising the temperature from 30°C to 50°C would likely result in a 30% increase in k_{VOC} for a boundary layer limited situation. As a result, if the spiral wound data in Fig. 6 are adjusted for temperature, the measured values of k_{VOC} for the VSEP Series *L* would be mostly greater than those for the spiral wound modules.

4. Conclusions

This paper introduces a new application of an existing vibrating membrane system ordinarily used for microfiltration, ultrafiltration, nanofiltration, or reverse osmosis. The use of the VSEP system in pervaporation offers several notable features. First, the vibrating membrane produces high surface shear rates which greatly enhance the boundary layer mass transport. In this work, as little as 1/4 in. travel dis-

tance (approx. 3° rotational amplitude) yielded as much as a 10-fold increase in the rate of VOC mass transport. Levels of k_{VOC} observed with the VSEP Series *L* reached and generally exceeded those observed with spiral wound modules for characteristic operating conditions. Of equal significance is the decoupling of k_{VOC} from liquid flow rate in the VSEP system, since the shear energy is not provided by the feed fluid. A seven-fold increase in fluid flow rate resulted only in 10–30% increase in k_{VOC} . If k_{VOC} could be completely decoupled from flow rate, then any configuration of a given set of membrane modules (i.e. all in series vs all in parallel) would yield the same level of removal. Another feature is that the vibrating system can be designed to contain only mechanical O-ring seals, no epoxies or adhesives should be required. Further, no rotating seals are needed since the amplitude of vibrations is small enough that flexible hoses can be used for liquid and vacuum connections.

Since this module was originally designed for pressure filtration applications, several design issues will need to be addressed before it can be scaled-up for pervaporation applications. First, seals which work under high positive pressures may not be acceptable for vacuum systems. Second, the permeate flow path may need to be redesigned to minimize vacuum pressure drops. Finally, the current VSEP may have to be modified to accept the existing pervaporation membrane materials or new membranes developed to work specifically with a vibrating membrane unit. A field unit fabricated with up to 20 m² of 250 μm thick silicone-coated fiberglass fabric is currently under consideration.

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