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Removal of Benzene/Toluene from Water by Vacuum Membrane Distillation in a PVDF Hollow Fiber Membrane Module

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Abstract: Asymmetric polyvinylidene fluoride (PVDF) hollow fiber membranes were prepared by a phase inversion method using dimethylacetamide (DMAc) and a mixture of water/LiCl as solvent and a nonsolvent additive, respectively. The prepared membranes were characterized by scanning electron microscopy (SEM) for observing its microstructures and by a gas permeation method for measuring its surface porosity, pore size, and pore size distribution. Wetting pressures of the dry hollow fiber membranes were also measured. Using the prepared PVDF hollow fiber membranes, a membrane module was fabricated for removal of benzene/toluene from water. Effects of various operating parameters such as downstream vacuum

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levels, feed temperatures, and feed flow rates on performances of the module were investigated experimentally. The benzene/toluene removal was achieved over 99% under an optimal operating condition. Mass transfer of benzene or toluene removal is controlled not only by the liquid phase resistance but also by the membrane and gas phase resistances. Benzene and toluene can be removed from water simultaneously with no adverse coupling effects.

Keywords: Benzene/toluene, hollow fiber membrane, PVDF

INTRODUCTION

Contamination of water supply by volatile organic compounds (VOCs) is recognized as a major water supply problem in many countries (1). The VOCs commonly found in water/wastewater include benzene, toluene, xylene, naphthlene, acetone, and a wide range of chlorinated hydrocarbons (2). The presence of these organic compounds in receiving systems such as rivers, ponds, reservoirs, etc., poses serious detrimental effects to our natural environment and ecosystems. Moreover, some of these VOCs especially benzene and chlorinated compounds are known to be carcinogenic and present great danger to human health. Therefore, development of efficient methods to remove VOCs from water/wastewater is of great importance to both human health and environmental protection.

For removal of a trace amount of VOCs from water, conventional separation technologies such as distillation, liquid-liquid extraction, carbon adsorption, and air stripping are not economically suitable because they consume a large amount of energy (for distillation), produce a large volume of byproducts (for carbon adsorption and liquid-liquid extraction) that need a high costly post-treatment or generate extra pollution (for air stripping) (3, 4). Alternatively, membrane processes such as pervaporation (PV) and vacuum membrane distillation (VMD) are able to avoid the previously mentioned problems (5–8). For example, in a VMD process, the aqueous VOC containing solution is brought into contact with one side of a hydrophobic microporous membrane (so-called membrane contactor), where the hydrophobic nature of the membrane prevents the penetration of the aqueous solution into the pores of the membrane, forming a vapor-liquid interface at each pore entrance, while a vacuum is applied to the other side of the membrane. As a result, VOCs evaporate from the liquid-vapor interface and permeate across the membrane under a partial pressure gradient into the downstream side where they can be condensed in cold traps. Therefore, the energy consumption in the VMD process is much less than that in distillation processes due to much lower operating temperature required. Furthermore, the VOCs condensed in the cold traps can be easily recovered without any additional pollution. In addition, using hollow fiber membrane contactors, many other advantages over conventional mass-transfer equipment can also be expected, for instance, very high gas-liquid interfacial area per unit volume; independent variation of gas/vapor and liquid flow rates without problems such as flooding, loading, weeping, etc.; no entrainment of drops in the exiting gas thus eliminating demisters; much higher volumetric mass-transfer coefficient; known gas-liquid interfacial area and modular nature (8, 9).

Along with the advantages of membrane contactors, limitation of the membrane contactors particularly in the VMD mainly involves pore wetting and capillary condensation, which may lead to an increase in mass-transfer resistances. For this reason, hydrophobic membranes such as polytetrafluoroethylene (PTFE) and polypropylene (PP) (10–13) have been so far used in VMD processes because the hydrophobic nature of the membrane prevents the penetration of aqueous solutions into the membrane pores, resulting in a lower mass-transfer resistance. However, the commercial PP and PTFE membranes are limited to their restricted pore size range and porosity as well as their symmetric structures. Alternatively, polyvinylidene fluoride (PVDF) has become a new membrane material in recent years not only due to its good hydrophobicity but also the feasibility of forming asymmetric hollow fiber membranes via a phase inversion method (14)–(18). Obviously, the asymmetric structure is particularly favorable to reduce the mass-transfer resistance to VOC permeation since the resistance mainly exists in the skin layer of the asymmetric membranes. Furthermore, PVDF has good mechanical properties, and the hollow fiber geometry can provide much larger surface area per unit volume compared to the fleet membranes (PTFE is difficult to process into the hollow fiber form). This paper presents an experimental study on preparation, characterization, and performances of the PVDF hollow-fiber membranes as VMD for removal of benzene and toluene from water.

EXPERIMENTAL

Preparation and Characterization of PVDF Hollow Fiber Membranes

The PVDF hollow fiber membranes were prepared by a wet-phase inversion method using dimethylacetamide (DMAc, from Merk, >99%) (a) as solvent and a mixture of water and LiCl (Analysis Grade, Merck) as an additive. Polyvinylidene fluoride (Kynar grade 760, MW = 444,000) in pallet form was purchased from Elf Atochem (USA). The dope solution has a composition of 15 wt% PVDF, 5.22 wt% LiCl, 1.95 wt% H_2O, and 77.84 wt% DMAc. The viscosity of the dope solution is 2540 cp, measured using a falling ball viscometer (HAAKE) at the room temperature (25 ± 1)°C. The fibers were spun through a spinneret with the orifice diameter of 0.8 mm and the tube inner diameter of 0.22 mm. Water was used as both internal and external coagulants at ambient conditions (25 ± 1°C, RH = 60–65%). Other spinning conditions include: zero air gap (wet-phase inversion), internal coagulant rate of 1.1 mL/min and take-up velocity of 4.5 m/min. During spinning, the take-up velocity was kept as the same as the free-falling velocity of the nascent fiber to prevent in stretching the membrane. The hollow fiber spinning apparatus and detailed spinning procedures can be found elsewhere (14).

The resulting PVDF hollow fiber membranes were characterized in terms of their morphology, permeability, and hydrophobicity. Scanning electronic microscopy (SEM) (JSM 5600LV) was used to examine the morphology of the spun PVDF hollow fiber membranes. The hollow fiber was firstly immersed in liquid nitrogen. After about 10 min, the frozen membranes were slowly flexed in the liquid nitrogen so that a clear cross-sectional fracture occurred. These membrane samples were then positioned on a metal holder and gold coated using a sputter coating operated under vacuum. The SEM micrographs of cross-section of the hollow fiber membranes were taken at various magnifications.

Gas permeation tests were carried out to determine pore structures of the hollow fiber membranes. The apparatus and the detailed procedures of measurements were described elsewhere (19). In this work, nitrogen with purity of 99.99% (supplied by SOXAL Singapore) was used as the test gas. Operating pressures were increased stepwise from 15 to 105 cmHg at room temperature (25 ± 1°C). The membrane's pore structural parameters in terms of effective porosity, mean pore radius, and standard deviation were obtained by regression of the nitrogen permeance data as a function of average pressure with a log-normal distribution function and are reported in Table 1.

Hydrophobicity of the membranes was evaluated in terms of the critical entry pressure (CEP), which is defined as the transmembrane pressure difference at which liquid penetrates pores of the membrane. It was measured in this work as follows: (1) a test module containing three hollow fibers was prepared with one end blocked with epoxy resin and the other connected to a swagelok, (2) deionized water was fed into the lumen side of the fibers initially under a pressure of 2 bar, maintaining 30 min to observe whether or not water penetrated through the membranes to the outer membrane surface, (3) the pressure was then increased in a stepwise of 0.1 bar until the water was observed on the outer membrane surface.

Benzene/Toluene Removal in the PVDF Hollow Fiber Membrane Module

A PVDF hollow fiber membrane module was prepared for removal of benzene/toluene from water. The module was made of a stainless steel tube with a length of 55 cm and OD of 3/4 inch connected to a swagelok on

Table 1. Properties of the PVDF hollow fiber membrane and the membrane module

Membrane material	PVDF
Effective porosity of the membrane, ε/Lp (m^{-1})	118
Mean pore radius of the membrane, r_m (m)	1.62×10^{-7}
Standard deviation of the membrane pores, σ	1.306
ID of the hollow fibers (mm)	0.52
OD of the hollow fibers (mm)	0.90
Effective length of the module, L (m)	0.51
Number of the hollow fibers, n	143
Specific interfacial area (m^2/m^3)	2000
Total membrane area (m^2), A_m	0.159^a
Housing material	Stainless steel

[a] $A_m = n\pi(OD - ID)/\ln(OD/ID)$.

each end. A total of 143 hollow fibers were randomly packed in the tube and then sealed with an epoxy resin (UKR-135 resin with UKH-136 hardener, supplied by UK Epoxy Resins). The effective length of hollow fibers and the effective membrane area for permeation are therefore around 0.51 m and 0.12 m^2, respectively. The properties of the hollow fiber module are also summarized in Table 1.

The VOC aqueous solution was prepared by transferring a desirable amount of VOC into deionized water in a covered 2-L volumetric flask and being stirred by a magnetic stirrer for at least 3 h until the VOC was totally dissolved. After that, the VOC solution was quickly transferred into a 3-L stainless steel pressure feed tank and sealed. At the beginning and the end of each run, the concentration of the solution inside the feed tank was measured by taking samples through a sample valve. Figure 1 shows a flow diagram of the experimental setup. The water containing trace amounts of benzene, toluene, or both was pressurized through a mass flow controller (Brooks Instrument 0151E), which can finely control the feed flow rate, by pure nitrogen gas from a gas cylinder. The pressure of the gas cylinder was controlled by a gas regulator and set at 0.6 bar to provide enough pressure for the mass flow controller to work. The feed solution was preheated through a stainless-steel coil and then fed into the lumen side of the module. Both the preheating coil and membrane module were immersed in a water bath where temperature was controlled by a thermo controller (Techne Tempette TE-8D) with a stability of $\pm 0.1°C$. A Büchi Vacuum system B-178 with Büchi vacuum controller B-720 was applied to the shell side on the exit end of the module. The water and benzene (toluene or both) permeated through the membranes were condensed in an ice-cold trap (Quickfit) and a liquid-nitrogen trap (Quickfit cold trap partially immersed in liquid nitrogen) in series. At the end of each run of VMD experiments,

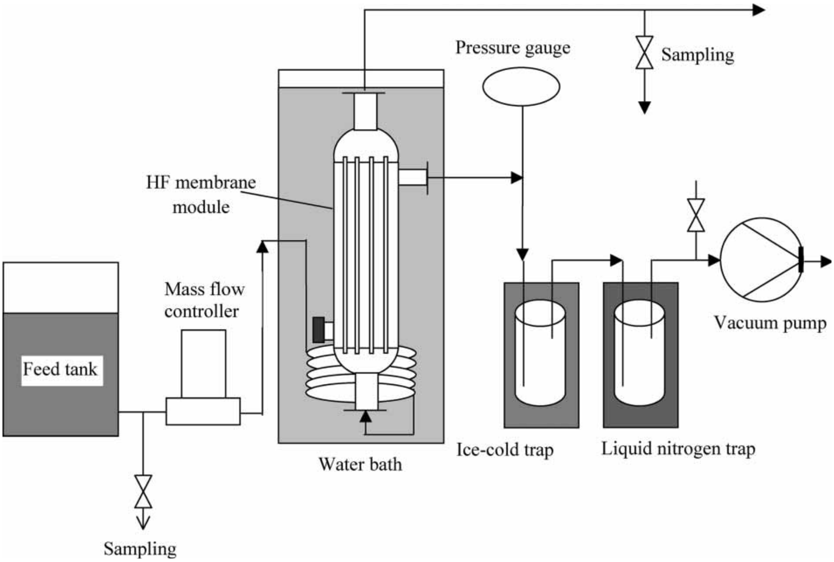

Figure 1. Schematic diagram of the experimental setup.

the condensed water and VOC were unfrozen if necessary and weighted at the room temperature. The benzene or toluene concentration in the feed, retentate and permeate solutions, which were diluted if necessary, were monitored using a Total Organic Carbon analyzer (TOC-5000A) and a GC (HP6890) equipped with a HP7694E headspace sampler. During the transfer, dilution and measurement of the VOC solution, all the containers used must be capped or sealed properly to prevent the vaporization of the VOC into atmosphere.

Permeation fluxes ($g/m^2 \cdot h$) of water, benzene, and toluene were calculated from the mass and concentrations of the condensate collected in the ice-cold trap and in the liquid-nitrogen cold trap:

$$J_i = \frac{P_1 w_{1,i} + P_2 w_{2,i}}{A_m t}, \quad (i = B, T\, or\, W) \tag{1}$$

The benzene or toluene removal, R_i ($i = B$ or T) is generally defined as

$$R_i = 1 - c_{i,out}/c_{i,in} \times 100\% \tag{2}$$

At steady state, the mass conservation equation for benzene/toluene in the hollow fiber membrane module is given by

$$-Q dc_i = K_{L,i} \cdot 2n\pi R_m dz \cdot \left(c_i - \frac{p_v Y_i}{H_i} \right) \tag{3}$$

where H_i is the Henry constant for benzene/toluene in water:(20)

$$H_B = \exp[8.3387 - 4018.1/T] \quad \text{for benzene} \tag{4a}$$

and

$$H_T = \exp[10.092 - 4512.3/T] \quad \text{for toluene} \tag{4b}$$

Integration of Eq. (3) gives an expression of the overall mass-transfer coefficient for benzene/toluene permeation in the hollow fiber membrane module as

$$K_{L,i} = \frac{Q}{A_m} \ln\left(\frac{c_{i,in} - P_v Y_i / H_i}{c_{i,out} - P_v Y_i / H_i}\right) \tag{5}$$

The symbols in these equations are defined in the notation section at the end of this paper.

RESULTS AND DISCUSSION

Characteristics of the PVDF Hollow Fiber Membranes

The morphology of the prepared PVDF hollow fiber membranes was examined by SEM and is shown in Fig. 2. It can be seen that a highly asymmetric structure is formed in the hollow fiber membrane wall. The hollow fiber is composed of an inner porous layer that exhibits a finger-void structure and an outer layer that is relatively denser, as shown in Fig. 2(a). Furthermore, a very thin skin layer on the outer surface is supported on a sponge-like structure with interconnecting pores, as shown in Fig. 2(b). For such asymmetric membranes, the porous supporting layer generally provides negligible resistance, and the permeation process is mainly controlled by the outer skin layer. Therefore, it is mainly the pores on the outer skin layer that should be

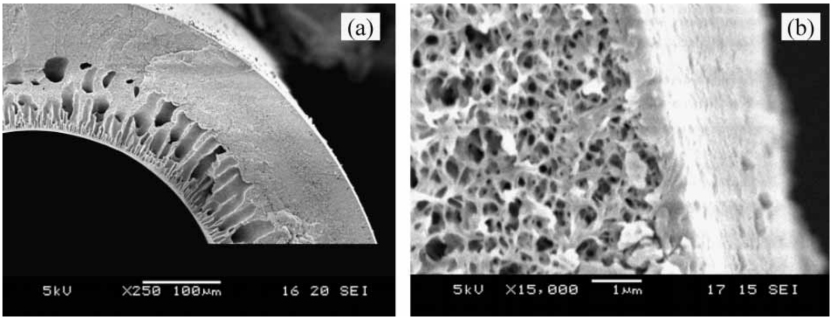

Figure 2. SEM photographs of the PVDF hollow fiber membrane (a) membrane wall; (b) outer edge.

characterized, preferably using a gas permeation method (19). By regressing the permeance data with the log-normal distribution function, the membrane's pore structural parameters including the effective porosity, mean pore radius, and standard deviation have been obtained as $118\,m^{-1}$, 1.62×10^{-7} m, and 1.306, respectively.

In addition to the pore structural parameters, another important parameter is the critical entry pressure (CEP) of the membrane that is related to the surface tension of liquid, the contact angle of the liquid on the membrane surface, and the size and shape of membrane pores (21). For the prepared PVDF hollow fiber membranes, it was measured to be about 7 bars using water as the test liquid. This value is much higher than the operating pressures applied in the benzene/toluene removal experiments, which will be presented in the following section. Therefore, the PVDF membrane is considered non-wetting and may be suitable for removing VOCs such as benzene/toluene from water.

REMOVAL OF BENZENE/TOLUENE IN THE PVDF MEMBRANE MODULE

Influences of several important parameters such as downstream pressures, feed solution temperatures, and feed flow rates on removal of benzene/toluene have been investigated experimentally. In these experiments, all the experimental parameters, except the specified parameter to be studied, were kept constant and are given in Table 2.

Effect of Vacuum Level

The effect of downstream vacuum level on the water and VOC permeation fluxes, the VOC removal, and the overall mass-transfer coefficient are shown in Fig. 3 where the vacuum level in terms of absolute pressure varies from 20 to 120 mmHg. As can be seen in Fig. 3(a), the water fluxes are less than 11.3 and $3.2\,g/m^2 \cdot h$ in the benzene-water and toluene-water systems,

Table 2. Experimental conditions for benzene/toluene removal

Variable	Value
Temperature, °C	50
Downstream pressure (absolute), mmHg	80
Feed flow rate, m^3/h	10^{-3}
Feed concentration, ppm	1070, for benzene in water 320, for toluene in water 1050/200, for benzene/toluene in water

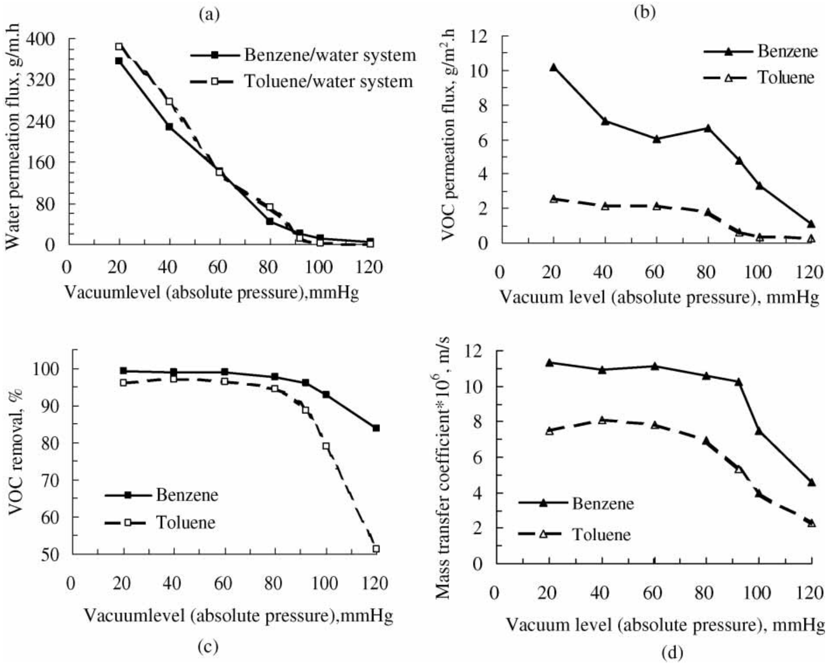

Figure 3. Effect of vacuum levels on the benzene/toluene removal (operating conditions: temperature = 50°C, feed flow rate = $10^{-3}\,m^3/h$, benzene feed concentration = 1070 ppm, toluene feed concentration = 320 ppm).

respectively, when the downstream pressure is higher than 100 mmHg. A critical point around 90 mmHg is observed, below which the water flux increases drastically as the vacuum level is increased. It should be noted that the saturated vapor pressure of water at 50°C is 92.5 mmHg. Therefore, it suggests that the operating pressure of the VMD process should not be much lower than the water vapor pressure at the given operating temperature, otherwise permeation of a large amount of water vapor may occur. A little difference between the water permeation fluxes of benzene-water and toluene-water systems is observed because the driving force for water permeation is not noticeably changed.

Figure 3(b) shows that permeation flux of benzene (or toluene) decreases as the downstream pressure is increased since the driving force for the VOC permeation is reduced. The higher benzene permeation flux than that of toluene is because of the higher feed concentration, which is due to their solubility difference in water. The experimental result also indicates that the benzene (or toluene) removal [Fig. 3(c)] is strictly dependent on the downstream pressure. When the downstream pressure is decreased from 120 to 80 mmHg, the benzene (or toluene) removal can be promoted remarkably. However, further decrease of the downstream pressure from 80 to 20 mmHg, the benzene (or toluene) removal is remained relatively unchanged. For example, the benzene removal of 99% can be achieved at the vacuum level of 60 mmHg while only additional 0.4% of the benzene (or toluene) removal can be further expected if the downstream pressure is further decreased to 40 mmHg. Under the vacuum level of 40 mmHg, much more water permeates through the membrane than benzene (or toluene) as shown in Fig. 3(a) and (c) and thus, the benzene (or toluene) concentration in the permeate phase is greatly reduced. Although the permeated benzene (or toluene) is mainly collected in the liquid-nitrogen cold trap and is easily recovered because of partial miscibility of benzene (or toluene) in water, considerable energy is required for the water permeation during the operation. Moreover, the high water permeation flux may also lead to the membrane wetting and capillary condensation problems, which result in a higher mass-transfer resistance and affect in improving the VOC removal efficiency by VMD processes. It is interesting to note that the final VOC removal in the VMD process seems to be related to the type of VOCs, for example, the final removal for benzene may be 99.2%, whereas for toluene it is always lower than 97%.

The effect of vacuum level on the mass-transfer coefficient of VOCs in the PVDF hollow fiber membrane module is illustrated in Fig. 3(d). It can be seen that the overall mass-transfer coefficients generally decreases with increasing the downstream pressure. Since the overall mass-transfer coefficient can be expressed as (22, 23)

$$\frac{1}{K_{iL}} = \frac{1}{K_{il}} + \frac{1}{H_i k_{im,g}} + \frac{1}{H_i k_g} = \frac{\delta_i}{D_{il}} + \frac{1}{H_i D_{ig}} \left(\frac{\tau_M L_p}{\varepsilon_p} f(r_p, \sigma) + \delta_g \right) \qquad (6)$$

in which the gas/vapor diffusivity is dependent on the operating pressure. As the downstream pressure increases, the gas diffusivity is decreased leading to the increase in the membrane and gas phase resistances to VOC permeation. Therefore, it may be concluded that the membrane and gas phase resistances play an important role in the benzene and toluene removal when the downstream operating pressure is low.

Effect of Feed Temperature

Figure 4(a) shows the effect of feed temperature on the removal of benzene (or toluene) in the PVDF hollow fiber membrane module, where the downstream pressure was kept constant at 80 mmHg and feed flow rate is at 0.001 m^3/h. As pointed out, the amount of water permeation flux strictly depends on the water vapor pressure at a given operating temperature. At the pressure of 80 mmHg, the corresponding saturated temperature of water is 47.1°C. As a result, the water permeation flux increases remarkably as the temperature increases beyond 47.1°C. When the feed temperature is 60°C, the water permeation fluxes of the benzene-water and toluene-water systems reach to 229 and 267 g/m^2h, respectively.

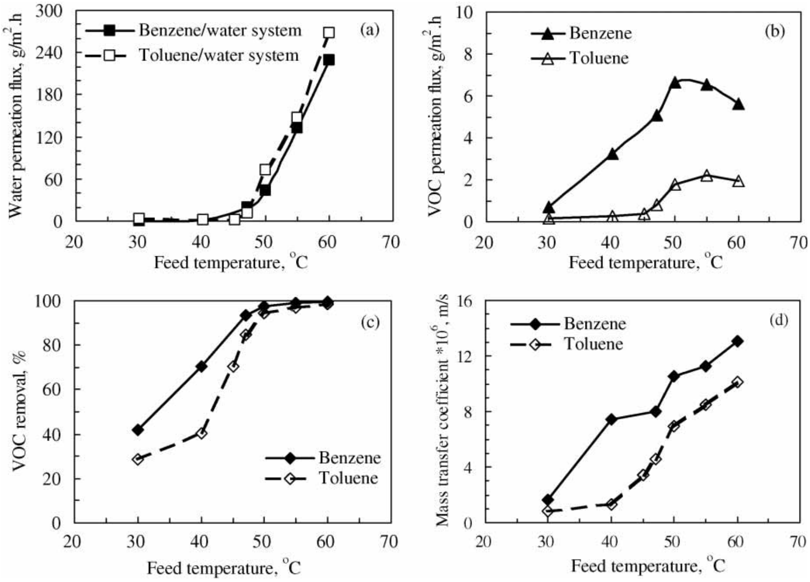

Figure 4. Effect of feed temperatures on the benzene/toluene removal (operating conditions: downstream pressure = 80 mmHg, feed flow rate = 10^{-3} m^3/h, benzene feed concentration = 1070 ppm, toluene feed concentration = 320 ppm).

The removal of benzene (or toluene) increases drastically with the feed temperature as shown in Fig. 4(c). This is because the driving force for benzene (or toluene) permeation is increased by both the increase in the saturated vapor pressure of benzene/toluene (due to higher temperature) and the decrease in downstream partial pressure of benzene/toluene (resulted from the permeation of much more water). In addition, the mass-transfer coefficients of benzene and toluene in both the liquid and gas phases are also increased as temperature increases, giving further enhancement in the VOCs removal. The higher permeation flux of benzene than toluene as shown in Fig. 4(b) is naturally expected because of the higher benzene feed concentrations. Note that a slightly lower permeation flux of benzene at 60°C may be due to the loss of the VOC during the dilution and transition of solution samples for analysis.

Figure 4(d) shows the effect of the feed temperature on the overall mass-transfer coefficient of benzene (or toluene) in the PVDF hollow fiber membrane module. As is expected, the overall mass-transfer coefficients of both benzene and toluene increase with increasing temperature. In addition, the mass-transfer coefficient for benzene permeation is higher than that for toluene at the same temperature because the diffusivity of benzene either in liquid or in gas phase is higher than that of toluene. On the other hand, exceptionally high feed temperature is not always desirable as it would result in a great increase in water permeation flux with negligible improvement of the benzene/toluene removal. As mentioned, this would not favor the VMD process since it would cause the membrane wetting with the result of increasing mass-transfer resistance and also would consume extra energy.

Effect of Feed Flow Rate

The effect of feed flow rates on the water and VOC permeation fluxes, the VOC removal, and the overall mass-transfer coefficient are shown in Fig. 5. As is expected, the permeation fluxes of benzene (or toluene) and water increase with increasing the feed flow rate, because the higher the liquid flow rate (high velocity), the less the boundary layer resistance and thus the higher the mass-transfer coefficient. Of course, the increase of water vapor permeation flux is not so remarkable compared to the increase in either the vacuum level or in the feed temperature. On the other hand, the benzene (or toluene) removal is decreased as the feed flow rate increases. When the feed flow rate is lower than 0.4 L/h, the removal of benzene and toluene can reach up to 99% and 97%, respectively, as shown in the figure.

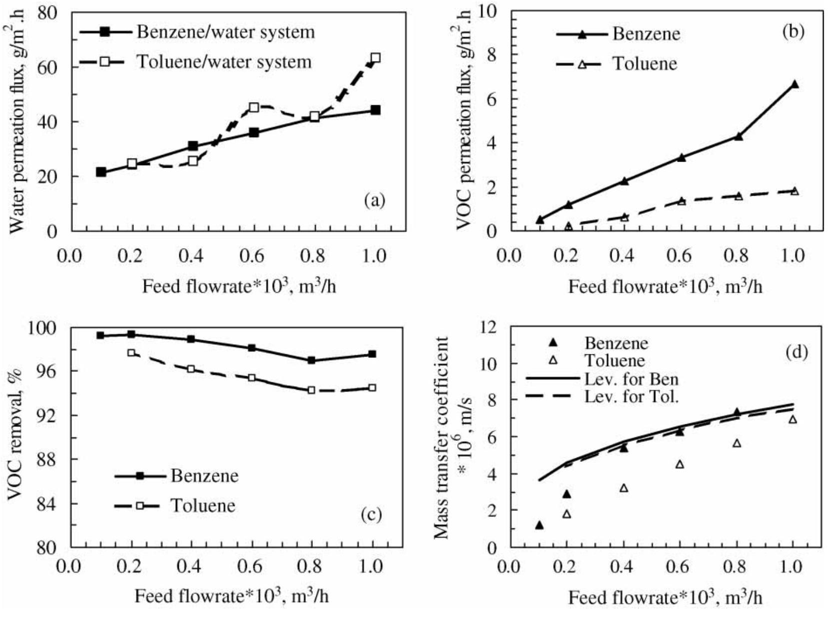

Figure 5. Effect of feed flow rates on the benzene/toluene removal (operating conditions: temperature = 50°C, downstream pressure = 80 mmHg, benzene feed concentration = 1070 ppm, toluene feed concentration = 320 ppm).

It is known that the Leveque expression, which is the relation between Sherwood number (defined as $Sh = k_{il}d_eD_{il}$) and Graetz number (defined as $G_z = ud_e^2/D_{il}L$), is usually used to describe the mass-transfer coefficient in a tube/fiber lumen (22):

$$Sh = 1.615G_z^{1/3} \tag{7}$$

The estimated values of the mass-transfer coefficients based on the Leveque equation is also plotted in Fig. 5(d) with lines. It can be seen that the experimental results are somewhat lower than the predicted ones. This suggests that the membrane and/or the gas phase resistance also make some contributions to the overall mass-transfer resistance. Since the Leveque equation generally predicts the mass-transfer coefficient with reasonable accuracy for Gz $>$ 4 but overestimates for Gz $<$ 4 due to the nonuniform flow caused by polydispersity in the hollow fiber diameter (8), as a result, the difference between the experimental data and the Leveque prediction gradually becomes smaller as the feed flow rate increases. It follows that for a more accurate analysis, other resistances, especially the diffusional resistance in the membrane, should be taken into consideration.

Simultaneous Removal of Benzene and Toluene from Water

Removal of benzene and toluene simultaneously from the benzene-toluene-water system was also investigated under various vacuum levels as shown in Fig. 6. It can be seen that both benzene and toluene in water can be simultaneously removed with the removal more than 99% at 50°C provided that the downstream pressure is 60 mmHg and the feed flow rate is 0.001 m^3/h. Similar to the binary systems, the benzene and toluene removal decreases as the downstream pressure is increased. Furthermore, the water permeation

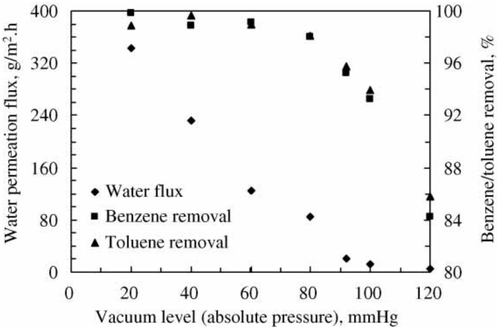

Figure 6. Simultaneous removal of benzene and toluene from water under different vacuum levels (operating conditions: temperature = 50°C, VOC solution feed flow rate = 10^{-3} m^3/h, benzene feed concentration = 1050 ppm, toluene feed concentration = 200 ppm).

flux was not affected significantly by the existence of both the benzene and toluene due to their low concentrations in water. However, compared with the binary system as shown in Fig. 3(c), the toluene removal in the benzene-toluene-water system is higher. This difference is resulted not only from the presence of benzene but also possibly from the difference in feed concentrations. More investigations should be carried out on the effect of VOC concentration on the removal in the VMD processes.

CONCLUSIONS

PVDF hollow fiber membranes have been prepared and proved to be suitable for the removal of benzene/toluene from water due to their excellent hydrophobicity, asymmetric structure, and hollow fiber geometry. The benzene/toluene removal of up to 99% may be achieved under an optimal operating condition in this study, i.e., the downstream vacuum level of 60 mmHg, the temperature of 50°C, and the feed flow rate $10^{-3}\,m^3/h$, respectively. The experimental results indicate that the liquid phase as well as the membrane (or even the gas phase) contributed the resistances in the benzene and toluene mass-transfer. The experimental study in a benzene/toluene/water ternary system shows that the benzene and toluene can be removed from water simultaneously with no adverse coupling effects.

NOTATION

A_m	effective membrane area, m^2
c	concentration of benzene or toluene in water solution, g/m^3
c_{in}	feed concentration of benzene or toluene, g/m^3
c_{out}	residual concentration of benzene or toluene, g/m^3
c_i^*	benzene or toluene concentration in equilibrium with permeate phase, g/m^3
D_l, D_g	benzene or toluene diffusivity in solution and gas phase, m^2/s
d_e	characteristic dimension of the hollow fiber, m
Gz	Graetz number, $G_z = ud_e^2/D_{il}L$
H_i	Henry's constant of benzene or toluene, $atm.m^3/mol$
J	permeation flux, $g/m^2 \cdot h$
K_L	overall mass-transfer coefficient in liquid phase, m/s
k_g	individual mass-transfer coefficient in gas phase, mol/m^2 atm s
k_l	individual mass-transfer coefficient in liquid phase, m/s
L	effective length of hollow fibers, m
L_p	effective membrane thickness
n	number of hollow fibers in the module

P_1, P_2	weight of condensate, g
p_v	absolute pressure on the vacuum side, atm
Q	volumetric feed flow rate of water solution, m^3/s
R_{in}	inner radius of the hollow fiber, m
R_m	log-mean radius of the hollow fiber, $R_m = (R_o - R_{in})/\ln(R_o/R_{in})$, m
R_o	outer radius of the hollow fiber, m
r_p	pore radius, m
R_B, R_T	removal of benzene and toluene, %
Sh	Sherwood number, $Sh = k_{il} d_e D_{il}$
T	operation temperature, K
w	weight percentage of benzene or toluene in the condensate, %
y	mole fraction of benzene or toluene in the permeate stream
z	length variable of the fiber, m
δ_l, δ_g	liquid or gas boundary thickness, m
τ_M	tortuosity of membrane
ε_p	surface porosity of a membrane
σ	dimensionless standard deviation of the membrane pore size

Subscripts

1	ice-cold trap
2	liquid-nitrogen cold trap
B	benzene
i	shortcut for B, T, and W
T	toluene
W	water

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