Plasma-Grafting of Fluoroalkyl Methacrylate onto PDMS Membranes and Their VOC Separation Properties for Pervaporation

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ABSTRACT: A polydimethylsiloxane (PDMS) membrane was improved by graft polymerization of 1H,1H,9H-hexadecafluorononyl methacrylate (HDFNMA) by plasma, which had the effect of increasing the selectivity for volatile organic compounds (VOCs). The use of an easy quantitative analysis for the pervaporation through plasma-grafted PDMS membranes was investigated. The degrees of grafting on the inside and reverse side of the grafted PDMS membranes were lower than on the surface. Only part of the HDFNMA sorbed into the PDMS membrane was grafted onto the PDMS membrane. The relationship between the feed concentration and the permeate concentration was observed to be linear. The pervaporation through the grafted PDMS membrane could be used for easy quantitative analysis. The solubility of VOCs for the grafted PDMS membrane was high when compared with the solubility for the PDMS membrane. The grafted PDMS membrane that had high VOC concentrations of the sorbed solution showed an excellent separation performance. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 73: 1835–1844, 1999

Key words: plasma graft polymerization; volatile organic compounds; 1H,1H,9H-hexadecafluorononyl methacrylate; permselectivity; method of quantitative analysis

INTRODUCTION

Pervaporation with organophilic membranes is an interesting alternative process to distillation or solvent extraction for the separation and the concentration of diluted organic compounds.¹ An example of this kind of separation is the treatment of process water, which is a side stream in the technical production of isocyanates containing aniline as a minor component and which usually has to be handled by biological treatment.^{2–6} Recently, it was found to be a social problem that ground water and soil are contaminated with vol-

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atile organic compounds (VOCs). Pervaporation is an attractive and potentially cost-competitive alternative to traditional methods (e.g., aeration, adsorption on activated carbon, photolysis, and ozonization) for removing low concentrations of organic solvents from waste water and has been expected to remove a number of organic components including trichloroethylene (TCE), tetrachloroethylene (PCE), chloroform, 1,1,2-trichloroethane, benzene, and toluene from dilute aqueous feed solutions.¹ This process is suited for the extraction of temperature-sensitive volatiles like aroma compounds²⁻⁴ and has shown many advantages in the bioindustry fields.

The method of quantitative analysis for VOCs is also expected to be studied. When the relationship between the feed concentration and the per-

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meate concentration is observed to be linear, the pervaporation membranes can be used for the value for quantitative analysis. For such a membrane, the feed concentration is able to be evaluated from the permeate concentration. In this case, the permselectivity for VOCs of the membrane is desired for water treatment.

The ability of pervaporation to remove VOCs from water with very high separation factors has been recognized as a result of several early studies.^{5–23} During the extraction of VOCs from an aqueous solution, the separation performances, in terms of flux and selectivity, are achieved by the difference in the membrane solubility and permeability of the feed-solution components. The study of the pervaporation of VOCs from water has focused on the use of organophilic and elastomeric (rubbery) polymers, including polydimethylsiloxane (PDMS) and its copolymers.²⁴⁻²⁷ Up to now, silicone rubber has been the most widely used and studied material to perform VOC extractions because of its high permeability, ease of preparation into different shapes, and relatively little thickness.²⁴⁻²⁷ The synthesis of PDMS copolymers and its improvement by the incorporation of fillers such as silicates and zeolites^{9,15} have been studied. The hydrophobic nature of fluorinated polymers was exploited to promote the selective adsorption and transport of the organic component of an organic/water feed solution.²⁸⁻³⁰

Graft polymerization is a method of extending the graft chain by polymerization that starts from the reactive radicals in the membrane.^{31,32} Generally, a vinyl monomer has been used in graft polymerization. The irradiation by gamma rays, electron beams, ultraviolet light, and plasma are well known as radical formation methods.^{31,32}

In previous studies,^{33,34} we modified the PDMS membrane with fluoroalkyl methacrylate (FALMA). The modified PDMS membrane showed the best separation performance due to introduction of a hydrophobic polymer, poly-(FALMA).

When we modified the PDMS membrane with FALMA by UV irradiation, the partition coefficient of chlorinated hydrocarbons into the membrane increased. However, in this method, increase in the membrane weight by poly(FALMA) was low. For pervaporation through the modified PDMS membrane, the relationship between the feed concentration and the permeate concentration was observed to be linear as well as that for the PDMS membrane. The pervaporation through the modified PDMS could be used for easy quantitative analysis. We improved the PDMS membrane by graft polymerization of 1H,1H,9H-hexadecafluorononyl methacrylate (HDFNMA) using a ⁶⁰Co source and then applied pervaporation. The grafted membrane had a microphase-separated structure, that is, a separated structure of PDMS and grafted-polymerized HDFNMA. At low feed concentrations of the TCE solution, the diffusivity of the TCE molecules must be much lower than that of water due to the larger molecular size of TCE. At high concentrations of the TCE solution, TCE was sufficiently sorbed into the membrane, and the diffusion of water was prevented by the TCE molecules; therefore, the permselectivity of TCE was significantly increased. Hence, for the pervaporation through the grafted membrane, the relationship between the feed concentration and the permeate concentration was observed not to be linear.

The plasma technique does not require a high installation cost for the energy source. The radical formation is easily performed on the surface of the polymer. The treatment time is short, within a few minutes. In this study, we improved the PDMS membrane by graft polymerization with HDFNMA using a plasma preirradiation method, which had the effect of increasing the selectivity for chlorinated hydrocarbons. When the pervaporation is used as an analytical method, it is expected that the relationship between the feed concentration and the permeate concentration is linear. The easy quantitative analysis of the pervaporation through plasma-grafted PDMS membranes was then investigated.

EXPERIMENTAL

Materials

Commercial PDMS membranes (Fuji Systems Corp. Tokyo, Japan), 50 μ m thick, were used throughout this work. HDFNMA (Daikin Fine Chemical Laboratory Corp. Tokyo, Japan) was used as received to avoid homopolymerization. TCE, PCE, benzene, toluene, isopropanol, and acetone (special grade, Waco Pure Chemical Industries, Ltd. Tokyo, Japan) were used as received.

Graft Polymerization of HDFNMA by Plasma

The plasma graft polymerization was performed as reported by Hiritsu et al.^{35,36} and a schematic



Figure 1 Apparatus for the graft polymerization by plasma.

diagram of the apparatus is shown in Figure 1. PDMS membranes with 7×7 -cm dimensions were placed in a flask under a vacuum overnight. Ar gas was then introduced into the flask. The flask was next evacuated. The introduction of Ar gas and evacuation was repeated several times. The membrane was treated by 13.56-MHz plasma and fixed powers (W), for fixed time intervals. The membranes then came into contact with the HDFNMA in the liquid phase at 60°C. After the polymerization stopped, the membranes were rinsed in acetone overnight to remove the homopolymers and any nonreacted monomers, then dried for 48 h in an evacuated vessel.

The degree of grafting was calculated as

Degree of grafting (%) = $(W_1 - W_0)/W_0 \times 100$, (1)

where W_0 and W_1 denote the weight of the PDMS membrane and the grafted PDMS membrane, respectively.

Characterization of the Grafted PDMS Membrane

X-ray photoelectron spectroscopy (XPS) spectra were obtained using an IPS-9000SX (JEOL, Ltd.) with MgK α exciting radiation (1253.6 eV). The X-ray gun was operated at 10 eV with a sample chamber vacuum of less than 5 × 10⁻⁹ Torr. The XPS spectra were recorded at two electron emission angles (ϑ) of 30 and 90°.

Pervaporation Experiment

The pervaporation experiments were performed in a previous study^{33,34} using the continuous-feed type at 25°C. The feed solution was circulated through the cell and the feed tank. The effective membrane area in the cell was 19.6 cm². The pressure on the permeation side was kept below 10 Torr by vacuum pumps. Upon reaching steadystate flow conditions, the permeate was collected in traps cooled by liquid nitrogen (-196°C) at timed intervals, isolated from the vacuum system, and weighed. The permeation rate, flux (*J*), was obtained using eq. (2):

$$J = Q/At \tag{2}$$

where Q is the amount that permeated during the experimental time interval, t, and A is the effective surface area.

The VOC and water flux were calculated from the total flux and the permeate composition. The concentration of VOC in the feed and permeate solution was determined by gas chromatography using an FID detector. The VOC concentration in the permeate was high, which is far beyond its solubility limit in water. The phase separation took place in the permeate, and isopropanol was added to the permeate solution. The permeate solution was homogenized and analyzed to determine the VOC concentration. The separation factor, α_{pv} , was calculated as

$$\alpha_{pv} = \{Y(1-X)\}/\{(1-Y)X\},\tag{3}$$

where *X* and *Y* denote the concentrations of VOC in the feed and permeate solutions, respectively.

Sorption Measurement

The dried and weighed membrane was immersed in the VOC solution and sealed at 25°C until equilibrium was reached. The membrane was then taken out of the vessel, wiped quickly with filter paper, and weighed. The degree of sorption



Figure 2 Apparatus for the composition measurement in the membrane: (A) cold trap for membrane; (B) valve; (C) cold trap for collecting samples.

of the VOC solution into the membranes was measured as

Degree of sorption (%)

$$= (W_1 - W_0)/W_0 \times 100, \quad (4)$$

where W_0 and W_1 denote the weights of the dried membrane and the swollen membrane, respectively.

The concentration of the VOC solution soaked into the membrane was determined using the apparatus shown in Figure 2. The membrane, upon reaching equilibrium, was taken out of the vessel, quickly wiped with filter paper, and placed in the cold trap (A). The trap was connected to the apparatus and quickly cooled by liquid nitrogen. After the apparatus was sufficiently evacuated, the valve (B) was closed and the VOC solution soaked into the membrane was vaporized by heating with a drier and collected in the cold trap (C).

The concentration of the VOC solution in the feed and the soaked membrane was determined by gas chromatography. The separation factor, α_s , was calculated as

$$\alpha_s = \{Y'(1-X)\}/\{(1-Y')X\},\tag{5}$$

where X and Y' denote the concentrations of VOC in the feed solution and the swollen membranes, respectively.

RESULTS AND DISCUSSION

Graft Polymerization of HDFNMA by Plasma

The dependence of the degree of grafting on polymerization time, that is, the immersion time, is shown in Figure 3 for plasma preirradiation at 50W for 180 s. The degree of grafting increased with increasing polymerization time and leveled off in 60 min. The polymerization time was determined to be 60 min. The obtained degree of grafting was around 7.5 wt %. The degree of sorption of HDFNMA in PDMS is 13 wt %. Only a part of the HDFNMA sorbed into the PDMS membrane was grafted onto the PDMS membrane.

Characterization of the Grafted PDMS Membrane

The surface morphologies of the grafted PDMS membranes were analyzed using their XPS spectra. The ratio of fluorine, oxygen, carbon, and silicon atoms were analyzed and calculated for \sim 9 nm beneath the surface on the grafted



Figure 3 Dependence of the degree of grafting on polymerization time for plasma preirradiation at 50 W for 180 s.

Plasma Graft Condition			Atomic Ratio ^a			
Power (W)	Exposure Time (s)	Electron Emission Angle (°)	F/Si	O/Si	C/Si	
	30	30 90	$0.0584 \\ 0.0174$	$\begin{array}{c} 1.18\\ 1.36\end{array}$	$\begin{array}{c} 1.63 \\ 1.74 \end{array}$	
	60	30 90	$0.0355 \\ 0.0512$	$\begin{array}{c} 1.80\\ 2.61\end{array}$	$2.86 \\ 4.39$	
10	(Reverse side)	30 90	$0.0109 \\ 0.0106$	$1.19 \\ 1.35$	1.78 1.86	
	180	30 90	$0.110 \\ 0.101$	$\begin{array}{c} 1.80\\ 2.15\end{array}$	$\begin{array}{c} 3.34\\ 4.82\end{array}$	
	(Reverse side)	30 90	$0.0288 \\ 0.0268$	1.29 1.36	1.83 1.80	
	300	30 90	$0.0590 \\ 0.0869$	$\begin{array}{c} 1.71\\ 3.00 \end{array}$	$2.88 \\ 5.07$	
10		30 90	$\begin{array}{c} 0.110\\ 0.101 \end{array}$	$\begin{array}{c} 1.80\\ 2.15\end{array}$	$\begin{array}{c} 3.34\\ 4.82\end{array}$	
30	180	30 90	$0.136 \\ 0.102$	$\begin{array}{c} 1.88\\ 2.93\end{array}$	$3.37 \\ 6.20$	
50		30 90	$0.0958 \\ 0.154$	2.02 3.69	$3.29 \\ 6.97$	
10 Under air a PDMS	180 fter plasma exposure: not gr	90 afted 90	_	1.60 1.42	1.21	

Table I	Fluorine-to-Silicon	, Oxygen-to-Silicon,	and Carbon-	-to-Silicon	Atomic	Ratios for
the Surf	ace of PDMS and G	rafted PDMS Memb	ranes by XPS	8 Analysis		

^a F/Si: fluorine atomic ratio (%)/silicon atomic ratio (%). O/Si: oxygen atomic ratio (%)/silicon atomic ratio (%). C/Si: carbon atomic ratio (%)/silicon atomic ratio (%). —, not detected.

PDMS membrane at 30 and 90° photoelectron emission angles and are characterized in Table I. In this spectra, the composition of the atoms are determined up to a depth of 4.5 and 9 nm from the surface at the photoelectron emission angles of 30 and 90°, respectively.³⁷ On the surface of the PDMS membrane exposed to the air after irradiation, the O/Si and C/Si ratios increased. The surface of the membrane was oxidized by oxygen or water vapor in the air.

Figure 4 shows the effect of the plasma power on the F/Si, O/Si, and C/Si ratios for the 180-s plasma graft polymerization. The F/Si and C/Si ratios on the surface of the grafted PDMS membrane increased with increasing plasma power, due to the graft polymerization of HDFNMA by the plasma. The radical produced on the surface significantly increased with increasing plasma power. Hence, the degree of grafting increased with increasing plasma power. After the graft polymerization, the residual radicals on the surface of the membrane reacted with oxygen or water vapor in the air.

Figure 5 shows the effect of the plasma irradiation time on the F/Si and C/Si ratios for the 10-W plasma graft polymerization. The F/Si and C/Si ratios on the surface of the grafted PDMS membrane increased with increasing plasma irradiation time due to the graft polymerization of HDFNMA by the plasma. The O/Si ratio on the surface of the grafted PDMS membranes leveled off in the irradiation time of 60 s.

For a long irradiation time, the probability of radical bonding reciprocally increased.³⁷ The radical produced on the surface gradually increased with increasing plasma irradiation time. The degree of grafting and hydrophobicity then gradually increased with increasing plasma irradiation



Figure 4 Effect of plasma power on F/Si, O/Si, and C/Si of the membrane surface grafted for 180-s plasma preirradiation: (\Box) F/Si; (\diamond) O/Si; (\bigcirc) C/Si at electron emission angle of 90°.

time. The residual radicals after graft polymerization did not exist for a long time. The residual radicals on the surface of the membrane did not significantly react with oxygen or water vapor in the air.

The F/Si, O/Si, and C/Si ratios on the reverse side of grafted PDMS membranes were lower than on the grafted surface. After the irradiation, the degassed HDFNMA was placed in the reactor and the PDMS membranes were soaked and



Figure 5 Effect of plasma irradiation time on F/Si, O/Si, and C/Si of the membrane surface grafted at 10-W plasma preirradiation: (\Box) F/Si; (\diamond) O/Si; (\bigcirc) C/Si at electron emission angle of 90°.



Figure 6 Effect of plasma power on the flux and separation factor (α_{pv}) for TCE–water mixtures in pervaporation through grafted PDMS membrane for 180-s plasma preirradiation: (\Box) 0.005 wt % feed concentration; (\bigcirc) 0.01 wt %; (open) flux; (closed) separation factor.

grafted. The graft polymerization was promoted in the grafted PDMS membrane.³⁷ The quantity of the radicals on the inside and reverse side of the grafted PDMS membrane was lower than that on the surface. Hence, the degree of grafting on the inside and reverse side of the grafted PDMS membrane was lower than that on the surface.

Pervaporation of Grafted PDMS Membrane

We show the effect of the plasma power on the flux and separation factor for the TCE solution during pervaporation through the PDMS membrane for a 180-s plasma treatment in Figure 6. The flux of the grafted PDMS increased with increasing plasma power. The separation factor showed a maximum at 10 W and then decreased with increasing plasma power. The radical produced on the surface significantly increased with increasing plasma power. The degree of grafting and oxidation were simultaneously increased. The membrane grafted at a weak power, 10 W, was not significantly oxidized. The hydrophobicity of the grafted membrane was maximum when the membrane was irradiated at 10 W and grafted.

We show the effect of the plasma irradiation time on the flux and separation factor for the TCE solution during pervaporation through the PDMS membrane at 10-W plasma power in Figure 7. The flux of the grafted PDMS membrane was



Figure 7 Effect of plasma irradiation time on the flux and separation factor (α_{pv}) for TCE–water mixtures in pervaporation through grafted PDMS membrane at 10-W plasma preirradiation: (\Box) 0.005 wt % feed concentration; (\bigcirc) 0.01 wt %; (open) flux; (closed) separation factor.

constant regardless of the plasma irradiation time. The surface of the grafted PDMS membrane was not significantly oxidized. The separation factor of the grafted PDMS membranes increased with increasing irradiation time and the maximum was for the 180-s plasma treatment. The degree of grafting increased with increasing plasma irradiation. The hydrophobicity of the grafted PDMS membranes was effectively increased due to introducing the hydrophobic polymer, poly(HDFNMA).

The flux as a function of the TCE concentration in the feed solution is shown in Figure 8 for the grafted PDMS membranes. For the PDMS and the grafted PDMS membranes, the water flux decreased with increasing feed TCE concentration. In a previous study, for the PDMS membranes grafted using HDFNMA by ⁶⁰Co irradiation, the water flux decreased with increasing feed concentration. In this study, a similar phenomenon was observed.

The TCE flux increased with increasing feed concentration. For the grafted PDMS membranes, this tendency was significant. The total flux that consisted of TCE and water for the grafted PDMS membrane increased with increasing feed concentration while the total flux for PDMS membrane decreased with increasing feed concentration. The PDMS membranes that were grafted with HDFNMA and simultaneously oxidized by plasma graft polymerization had a high selectivity for TCE.

The relationships between the TCE concentration in the feed and permeate are shown in Figure



Figure 8 Effect of feed concentration on the flux for TCE–water mixtures in pervaporation through PDMS membrane and plasma-grafted PDMS membrane at 10 W for 180 s: (\Box) total flux; (\diamond) water flux; (\bigcirc) TCE flux; (open) grafted membrane; (closed) PDMS membrane.



Figure 9 Relationship between TCE concentration in feed and permeation in pervaporation through PDMS and grafted PDMS membranes: (\bigcirc) membrane irradiated at 10 W for 180 s and grafted; (\triangle) membrane irradiated at 10 W for 300 s and grafted; (\Diamond) membrane irradiated at 10 W for 180 s and exposed in the air; (\Box) PDMS.

		Composition (wt %)			
VOC	Membrane	Feed	Permeate	$\begin{array}{c} Flux \\ (g \ m^{-2} \ h^{-1}) \end{array}$	Separation Factor α_{pv}
TCE	Grafted membrane PDMS	$0.015 \\ 0.015$	20 7.0	30 64	$\begin{array}{c} 1700 \\ 520 \end{array}$
PCE	Grafted membrane PDMS	$0.0070 \\ 0.0079$	$\frac{14}{5.6}$	40 37	$\begin{array}{c} 2300 \\ 740 \end{array}$
Benzene	Grafted membrane PDMS	$0.017 \\ 0.016$	$31 \\ 7.5$	31 65	$\begin{array}{c} 2600 \\ 500 \end{array}$
Toluene	Grafted membrane PDMS	$\begin{array}{c} 0.014\\ 0.014\end{array}$	22 6.8	28 57	$\begin{array}{c} 2000\\ 530 \end{array}$

Table IIPervaporation Data for Various VOCs Through PDMS Membrane andPlasma-grafted PDMS Membrane at 10 W for 180 s

9 for the grafted PDMS membranes. For all the membranes, the TCE concentration in the permeate increased with increasing feed concentration, and for the grafted PDMS membranes, the tendency was significant. The relationship between the feed concentration and the permeate concentration was observed to be linear. The pervaporation through the grafted PDMS could be used for easy quantitative analysis. The feed concentration can be known by the measurement of the permeate concentration. The grafted PDMS membrane had a high selectivity for VOCs. It is important to concentrate the VOC solutions for quantitative analysis.

The separation factor, α_{pv} , as a function of the TCE concentration in the feed solution is shown in Figure 10 for the grafted PDMS membranes. α_{pv} was significantly increased with increasing feed concentration for the grafted membranes. In the grafted PDMS membrane, the best separation performance was due to introducing the hydrophobic polymer, poly(HDFNMA). The pervaporation results of dilute TCE, PCE, benzene, and toluene solutions through the grafted PDMS membranes are shown in Table II. The permselectivity for VOCs through the grafted PDMS membrane at 10 W for 180 s were high when compared with the PDMS membrane.

Sorption of Grafted PDMS Membrane

The degrees of sorption of the VOC–water mixtures for the grafted PDMS membranes are shown in Table III. The solubility of VOCs for the grafted PDMS membrane at 10 W for 180 s was high when compared with the PDMS membrane. The grafted PDMS membrane that had the high VOC concentrations in the sorbed solution showed the best separation performance.

CONCLUSIONS

The PDMS membrane was improved by graft polymerization with HDFNMA by plasma, which



Figure 10 Separation factor (α_{pv}) as a function of feed concentration in pervaporation through PDMS and grafted PDMS membranes: (\bigcirc) membrane irradiated at 10 W for 180 s and grafted; (\triangle) membrane irradiated at 10 W for 300 s and grafted; (\Diamond) membrane irradiated at 10 W for 180 s and exposed in the air; (\Box) PDMS.

VOC	Membrane	VOC in Feed (wt %)	Degree of Swelling (wt %)	TCE in Membrane (wt %)	Separation Factor α_s
TCE	Grafted membrane PDMS	0.017 0.018	51	20 12	$\begin{array}{c} 1500 \\ 720 \end{array}$
PCE	Grafted membrane PDMS	$0.010 \\ 0.0085$	3 2	$\frac{68}{25}$	$\begin{array}{c} 20300\\ 4000 \end{array}$
Benzene	Grafted membrane PDMS	$\begin{array}{c} 0.013\\ 0.014\end{array}$	4 4	$\frac{34}{8.0}$	$\begin{array}{c} 4000\\ 630\end{array}$
Toluene	Grafted membrane PDMS	$0.017 \\ 0.016$	8 1	33 27	$\begin{array}{c} 2900\\ 2400 \end{array}$

Table IIISorption Data for Various VOCs in PDMS Membrane and Plasma-graftedPDMS Membrane at 10 W for 180 s

had the effect of increasing the selectivity for VOCs. When the pervaporation is used as an analytical method, it is expected that the relationship between the feed concentration and the permeate concentration will be linear as well as that for PDMS. The use for easy quantitative analysis of the pervaporation through plasma-grafted PDMS membranes was investigated.

The degree of grafting was around 7.5 wt %. The degree of sorption for the PDMS with HDFNMA was 13 wt %. Only a part of the HDFNMA sorbed into the PDMS membrane was grafted onto the PDMS membrane.

The radicals on the surface were significantly increased with increasing plasma power. Hence, the degree of grafting increased with increasing plasma power and oxidation was also increased. The radical on the surface was gradually increased with increasing plasma irradiation time. Hence, the degree of grafting and hydrophobicity increased with increasing plasma irradiation. After the irradiation, the degassed HDFNMA was introduced into the reactor and the PDMS membranes were soaked in HDFNMA and then grafted. The graft polymerization was promoted in the PDMS membrane. The degree of grafting on the inside and reverse side of the PDMS membranes was lower than on the surface.

The flux of the grafted PDMS membrane increased with increasing plasma power. The radical produced on the surface significantly increased with increasing plasma power. The degree of grafting and oxidation simultaneously increased. The flux of the grafted PDMS membrane was constant regardless of the plasma irradiation time. The degree of grafting increased with increasing plasma irradiation. The hydrophobicity of the grafted PDMS membranes was effectively increased due to introducing the hydrophobic polymer, poly(HDFNMA).

The solubility of VOCs represented by TCE, PCE, benzene, and toluene for the grafted PDMS membrane at 10 W for 180 s was significant when compared with the PDMS membrane. The grafted PDMS membrane that had high VOC concentrations in the sorbed solution showed the best separation performance.

The permselectivity for VOCs of the membrane was enhanced by the introduction of the hydrophobic polymer, poly(HDFNMA). The relationship between the feed concentration and the permeate concentration was observed to be linear. The feed concentration is able to be introduced from the permeate concentration. The pervaporation through the grafted PDMS membrane could to be used for easy quantitative analysis.

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