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Separation of Valuable Bicyclic Aromatic Components from Light Cycle Oil by an Emulsion Liquid Membrane

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ABSTRACT

Emulsion liquid membrane permeation was used to separate bicyclic aromatic components [the naphthalene (NA) group components with carbon number 10–12] from light cycle oil (LCO). A batch-stirred tank was used as a permeation unit. An aqueous solution of dimethylsulfoxide (DMSO) and saponin and *n*-hexane were used as the liquid membrane and the outer oil phase, respectively. The smaller the carbon number of the NA group component, the higher were the permeation rate and selectivity in reference to a paraffin component [*n*-nonane (NO)]. The larger the differences of carbon number among the NA group components with a

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different carbon number, the easier was the separation. The selectivity of aromatic components with the same carbon number was 1, so the separation between isomer components was difficult. Increasing the concentration of the permeation promoter (DMSO) into the liquid membrane and the stirring speed enhanced the permeability of the NA group components, yet reduced the selectivity. As the volume ratio of the solvent/(O/W) emulsion was increased, the permeability and selectivity of the NA group components were increased.

Key Words: Dimethylnaphthalene; Light cycle oil; Bicyclic aromatic component; O/W emulsion; Permeation rate.

INTRODUCTION

Recently, it has been stressed that petroleum should be used as a raw material rather than for energy in view of efficient resource utilization. However, light cycle oil (LCO) mixed with heavy oil has been used as fuel. The 2,6-dimethylnaphthalene (2,6-DMNA) in LCO has received attention as an elementary raw material for an engineering plastic (PEN plastic) and a liquid polymer, etc. Therefore, it is significant to separate and to recover valuable aromatic hydrocarbons, such as 2,6-DMNA by dearomatization of LCO. Also, dearomatized LCO might be used instead of diesel oil due to the enhanced cetane number of the raffinate oil.

Solvent extraction has been broadly used to separate aromatic compounds from hydrocarbon mixtures. In previous work,[1,2] we have investigated the separation efficiency of valuable bicyclic aromatic hydrocarbons in LCO by extraction, using a solvent such as dimethylsulfoxide (DMSO), *N*,*N*-dimethylforamide, and sulfolane.

A new separation technique for LCO might be extensively studied and developed for widespread use as an alternative to the conventional separation processes such as extraction. Currently, the liquid membrane separation method, which was developed by Li,[3–5] is considered to be a promising separation technique because it separates hydrocarbon mixtures with relatively high selectivity and because it might be a less energy-consuming operation. Although several studies of liquid membrane separation of hydrocarbon mixture have been published since Li, most of them have involved the separation of aromatic–nonaromatic model hydrocarbons (carbon numbers 6–8)[3–19] or petroleum-refining intermediates such as naphtha and kerosene.[13,20–24] Only a few studies used liquid membranes to separate heavy hydrocarbons, such as LCO.

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In this work, valuable bicyclic aromatic components [naphthalene (NA) group components with carbon number 10–12] from LCO were separated by a liquid membrane method in which the membrane phase was an aqueous solution of DMSO and saponin. It was observed that experimental factors and conditions affected the separation performance (yield and selectivity) of NA components.

EXPERIMENT

Apparatus and Method

Emulsification[4]

An aliquot of LCO as a raw material (an inner oil phase) and an aqueous membrane solution were added to a batch-stirred tank (20 cm i.d. and 20 cm height) and emulsified at 10 sec^{-1} of stirring speed for 10 min. Resultant O/W emulsion was circulated with the pump equipped, and simultaneously, emulsified by the high-speed homogenizer (stirring speed: 333 sec^{-1}) and the stirrer for 10 min to make O/W emulsion further particulate.

Permeation

A batch-stirred tank (8 cm i.d. and 8 cm height) made of a glass material was used as a contactor for O/W emulsion and a solvent (an outer oil phase).[5] A six-flatblade turbine type, impeller was located at the center of the liquid. Four baffle plates were equipped with the tank to prevent free interfaces from forming.

An aliquot of solvent was charged to the batch-stirred tank and heated to the experiment temperature (30°C). An aliquot of O/W emulsion that was kept at the experiment temperature was added and stirred in. After the permeation time elapsed, stirring stopped, the solution was allowed to settle, and the volumes of the raffinate phase (an emulsion phase) and the extract phase (a solvent phase) were measured. The extract phase was analyzed, and its composition was determined. The raffinate phase was demulsified by adding acetone. At this time, the composition of the oil phase recovered by the demulsification operation of the raffinate phase was different from that of the oil phase in the raffinate phase because of some hydrocarbons of the oil phase in the raffinate phase moving to the aqueous phase. Therefore, the ratio of the oil phase to an aqueous phase was sufficiently increased by adding hydrocarbons (benzene, etc.) that were not in the material system (feed, solvent) of this work, so that content of the hydrocarbons in the aqueous phase might be ignored. The oil phase was separated and washed with water to

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remove the acetone. The oil phase was analyzed to determine its composition. To confirm the reliability of the rest, the experiment was repeated by using standard (known composition) emulsions. The oil phase and extract phase were analyzed by gas chromatograph (Hewlett Packard Co., HP 6890: capillary column, HP-1) equipped with a flame ionization detector.

Material System and Conditions

The material system and the experiment conditions are summarized in Table 1. It was difficult to quantify the paraffin components (carbon number 11–25) included in LCO because of the peak of the paraffin group components that overlapped with that of the aromatic components in the gas chromatogram. Therefore, the separation between the NA group components and the paraffin group components [*n*-heptane (HP), *n*-octane (OT), *n*-nonane (NO)] was investigated by using LCO A, that a small quantity of NO was added into LCO and LCO B, and a small quantity of HP, OT, and NO was added into LCO, as raw materials. These results allow us to estimate the separation between the NA group components and the paraffin group components in LCO.

Even though water with high polarity was a main component in the liquid membrane, a polar substance could be added into a liquid membrane to control the permeability and the selectivity of a liquid membrane. Namely, a polar solvent used in an extraction method was added into a liquid membrane to enhance the solubility, and a subsequently higher permeation rate could be obtained. This method is possible for the separation of the heavy hydrocarbons, such as LCO, which have a lower solubility in water.

Table 1. Material system and experimental conditions.

System	
Feed	LCO A (LCO + *n*-nonane)
	LCO B (LCO + *n*-heptane + *n*-octane + *n*-nonane)
Membrane	Water + DMSO + saponin
Solvent	*n*-hexane
Experimental conditions	
$C_{sap,0}$ (—)	0.002
$C_{DMSO,0}$ (—)	0.1–0.4
$(E/R)_0$ (—)	2–11
N (s^{-1})	7.5–15
$(R_{IO}/R)_0$ (—)	0.5
T (°C)	30
t (sec)	0–300

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In this work, an aqueous solution with saponin and DMSO was used as a liquid membrane. *n*-Hexane was used as an outer oil phase (solvent). The initial mass fraction ($C_{sap,0}$) of the saponin, which was added to the liquid membrane, the initial volume fraction $(R_{IO}/R)_0$ of an inner oil phase (raw material) within an emulsion, and the operation temperature (T) were all fixed in this study. The permeation time (t), the initial mass fraction ($C_{DMSO,0}$) of DMSO within the liquid membrane, the stirring speed (N), and the initial volume ratio $(E/R)_0$ of a solvent/emulsion were varied.

RESULTS AND DISCUSSION

Gas Chromatogram of Light Cycle Oil

Light cycle oil hydrocarbons. Approximately 80 wt% are aromatic components, and the rest are paraffin components with carbon number 10–25. The aromatic components comprise monocyclic, bicyclic, and tricyclic aromatic components; monocyclic aromatic components were an alkylbenzene group and an indane group; bicyclic aromatic components were a NA group, a biphenyl group, and a fluorene group; and tricyclic components were an anthracene group.

The gas chromatogram of LCO and the component names of hydrocarbons identified are shown in Fig. 1.[1,2] Peaks 1 and 5, respectively, present NA and phenanthrene (PNTR). This indicated that LCO contained a significant amount of monocyclic and bicyclic aromatic components. Though DMNA with 10 structural isomers presented five peaks, they were summed and regarded as one component (DMNAs). Table 2 shows the composition of the hydrocarbons quantified.[1,2] The LCO contained about 1.5 wt% of NA, 3 wt% 2-methylnaphthalene (2-MNA), 1.8 wt% 1-MNA, 9 wt% DMNA, 2.3 wt% a mixture of 2,6- and 2,7-DMNA isomers, and 0.5 wt% PNTR.

Definition Equation

Yield and Permeation Rate

The yield (Y_i) of component i was defined as Eq. (1)

$$Y_i = \frac{(Ey_i)}{(R_0 x_{i,0})} \tag{1}$$

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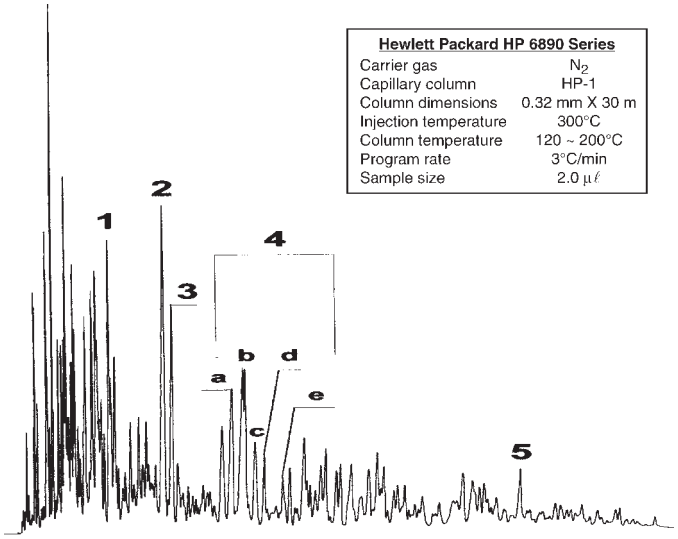

Figure 1. Gas chromatogram of LCO.[1,2]

where E and R_0 denote the mass of the outer oil phase at the permeation time t and the initial mass of the raw material (LCO A or LCO B), respectively, $x_{i,0}$ and y_i denote the initial mass fraction of component i in the raw material and the mass fraction of component i in the outer phase at the permeation time t. From Eq. (1), the permeation rate (dEy_i/dt) of component

Table 2. Composition of LCO.[1,2]

Component	Composition (mass fraction)
Naphthalene	0.015
2-Methylnaphthalene	0.030
1-Methylnaphthalene	0.018
DMNA mixture with 10 structural isomers (DMNAs)	0.091
a: 2,6- and 2,7-DMNA mixture	0.023
b: 1,7-, 1,3-, and 1,6-DMNA mixture	0.040
c: 1,4-, 2,3-, and 1,5-DMNA mixture	0.013
d: 1,2-DMNA	0.008
e: 1,8-DMNA	0.007
Phenanthrene	0.005

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i was correlated with the slope of the time course curve of the yield (dY_i/dt) as follows:

$$\frac{d(Ey_i)}{dt} = \frac{R_0 x_{i,0} dY_i}{dt} \tag{2}$$

where t denotes the permeation time.

Selectivity

To investigate the separation between the hydrocarbons, the selectivity, $\beta_{i,j}$, was defined as the following Eq. (3)

$$\beta_{i,j} = \frac{(y_i/x_i)}{(y_j/x_j)} \tag{3}$$

where i and j denote any hydrocarbon component and a reference component, x_i and x_j denote the mass fraction of the random component i and the reference component j in the inner oil phase at the permeation time t, y_i, and y_j denote the mass fraction of the random component i and the reference component j in the outer phase at the permeation time t.

Permeation Rate

In a liquid membrane, the component i moved between an inner oil phase and an outer oil phase through membrane permeation, membrane breakage, and mechanical entrainment. However, Kawasaki et al.[19] reported that the overall mass transfer rate by membrane permeation, membrane breakage, and mechanical entrainment were almost equal to that of membrane permeation alone under the experimental conditions of this work. Therefore, it was assumed that the mass transfer of the component i occurred only by membrane permeation, and Eq. (4) was derived.

$$\frac{d(Ey_i)}{dt} = P_i a(x_i - y_i)V \tag{4}$$

where a, V, and P_i denote the specific surface area between a raffinate (an emulsion phase) and an extract phase (a solvent phase), the total volume of a raffinate phase and an extract phase, and the overall permeation coefficient of the component i at the permeation time t, respectively.

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Mass Balance

To confirm that the values observed by the experiment were reasonable, we examined the mass balance of the component i at the random time (t) by the following Eq. (5)

$$Rx_i = R_0 x_{i,0} + E_0 y_{i,0} - E y_i \tag{5}$$

where R is the mass of an inner oil phase at the permeation time t, and E_0 is the initial mass of an outer oil phase, $y_{i,0}$ denotes the initial mass fraction of component i in an outer oil phase. The mass of component i in an inner oil phase at the permeation time t, Rx_i, found from analyzing an outer oil phase was compared with Rx_i, which resulted from analyzing an inner oil phase after the demulsification. Both were found to be comparable within $\pm 30\%$, and the measured values of this work were thought to be reasonable. Also, the experiments were replicated two or three times at the same condition to confirm the reproducibility of the measured value. The range of mass variation of each component in an inner or an outer oil phase was within $\pm 10\%$.

Time Course Curves

Figure 2(a) shows the yield of each hydrocarbon, which is derived from Eq. (1) to investigate the permeation rate through liquid membranes for the hydrocarbon components included in the raw material (LCO A), according to the permeation time (t). The yield of each aromatic component increased with the permeation time elapsing. At $t = 10$ sec, the yields of NA, 2-MNA, 1-MNA, and DMNAs were 0.11, 0.05, 0.07, and 0.03, respectively. At $t = 300$ sec, the yields of NA, 2-MNA, 1-MNA, and DMNAs were 0.68, 0.53, 0.58, and 0.36, respectively. The permeation rate of hydrocarbon through a liquid membrane depends on the diffusivity and, in particular, on the solubility of a hydrocarbon in liquid membranes.[21] Thus, in each aromatic hydrocarbon, the hydrocarbon with a smaller carbon number due to its higher solubility in membrane solution showed a larger permeation rate than that with a larger carbon number. Also, the yield of bicyclic aromatic hydrocarbon was much higher than that of the paraffin component (NO). The permeation rate of DMNAs, which was derived from Eq. (2) substituted for the slope of the time course curve of each component, was 10 times faster than that of NO. Therefore, it indicated that the permeation rate of the paraffin group components with a carbon number above 11 in LCO might be very slow. The selectivity, $\beta_{i,\mathrm{NO}}$, of the random NA group component i calculated from Eq. (3) based on NO as the reference component ($j = \mathrm{NO}$) according to the

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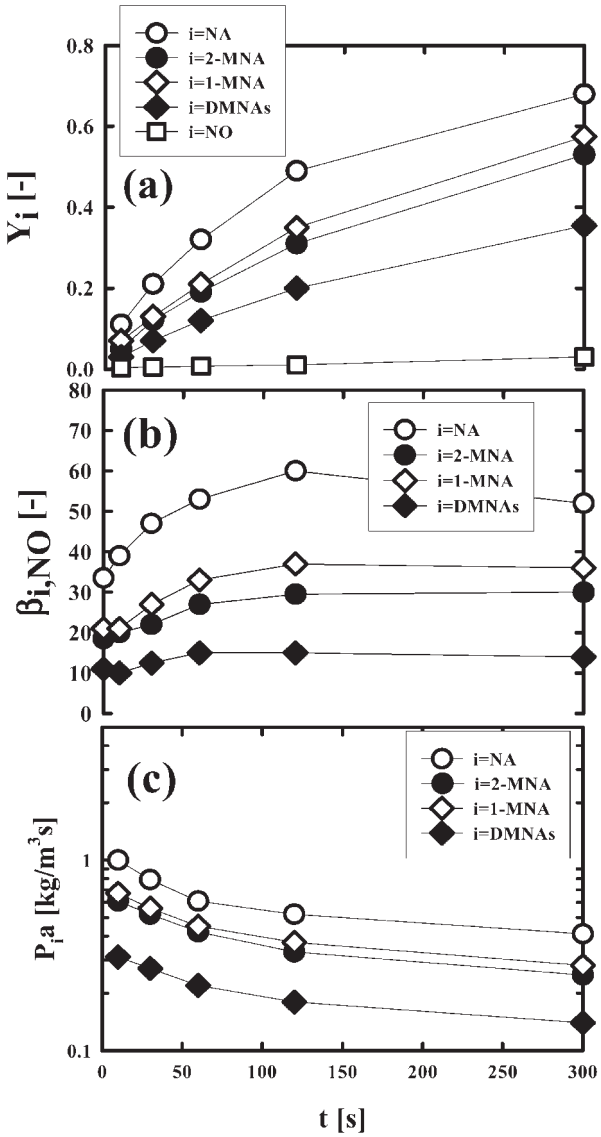

Figure 2. Time course of (a) the yield for hydrocarbon component *i*, (b) the selectivity for the bicyclic aromatic component *i* based on NO, and (c) overall capacity coefficient of permeation for the bicyclic aromatic component *i*. Feed: LCO A; Experimental conditions: $C_{DMSO,0} = 0.2$, $(E/R)_0 = 4$, $N = 10\ \text{sec}^{-1}$, $T = 30°\text{C}$. Abbreviations: NA: naphthalene, 2-MNA: 2-methylnaphthalene, 1-MNA: 1-methylnaphthalene, DMNAs: dimethylnaphthalene mixture with 10 structural isomers, NO: *n*-nonane.

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permeation time to study the separation between the hydrocarbon components is shown in Fig. 2(b). Since the ratio of the slope of the yield curve for the NA group component i to that for NO at the starting point of the permeation ($t = 0$ sec) was equal to $\beta_{i,NO}$ at $t = 0$ sec[21] the selectivity at $t = 0$ sec, $(\beta_{i,NO})_{t=0}$, resulted from Fig. 2(a) was represented simultaneously in Fig. 2(b). Generally, the selectivity represented in the separation method of the rate difference through the batch operation like this work went through maximum value due to the difference of the permeation rate of each component and then approached unity after the permeation time sufficiently passed. There was the maximum selectivity in only the NA, which showed the highest permeation rate, among NA group components in the range of the permeation time of this work. The selectivity of the other components increased as the permeation time elapsed. At $t = 0$ sec, $(\beta_{i,NO})_{t=0}$ of NA, 2-MNA, 1-MNA, and DMNAs, respectively, were 33, 19, 21, and 10. At $t = 300$ sec, $\beta_{i,NO}$ of NA, 2-MNA, 1-MNA, and DMNAs, respectively, were 52, 30, 36, and 14. Therefore, it was found that the smaller the carbon number among NA group components, the larger the selectivity. Figure 2(c) shows the overall capacity coefficient of permeation ($P_i a$) derived from Eq. (4) substituted for the permeation rates of NA group components according to the permeation time. The value of $P_i a$ decreased as the permeation time elapsed. This decreasing tendency could not be explicitly explained, but it seemed to be attributed to the increase of mechanical entrainment etc., as the permeation time elapsed. $P_i a$ increased with decreasing of the carbon number in NA group components, because the decrease of the carbon number in NA group components resulted from increasing the permeation rate.

Relation Between Carbon Number of Hydrocarbon and Selectivity

The selectivity of the separation method of the rate difference through batch operation like this study varied with the permeation time. In this study, $(\beta_{i,j})_{t=0}$ was used as an index for the selectivity of a liquid membrane separation. By using $(\beta_{i,j})_{t=0}$, and the separation of the aromatic–paraffin groups and the aromatic–aromatic groups in LCO were studied.

The relationship between $(\beta_{i,j})_{t=0}$ and the carbon number of hydrocarbons is shown in Fig. 3. The selectivity of aromatic components based on a paraffin component (NO) was much higher than that of the paraffin components. Also, it was found that the higher the carbon number, the easier the separation between an aromatic group and a paraffin group. It was anticipated that the carbon number of the paraffin components included in LCO was 2–16 times bigger than that of NO, even though any paraffin

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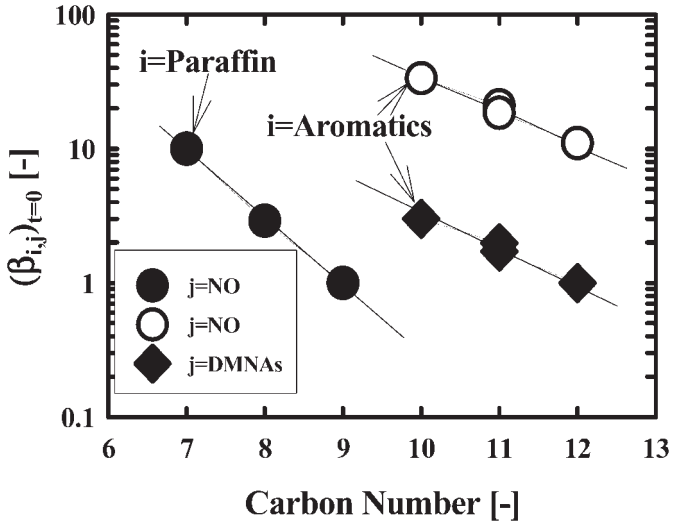

Figure 3. Relationship between $(\beta_{i,NO})_{t=0}$ and the carbon number of hydrocarbons. Feed: LCO B. Experimental conditions: $C_{DMSO,0} = 0.2$, $(E/R)_0 = 4$, $N = 10\,\text{sec}^{-1}$, $T = 30^{\circ}\text{C}$.

components in LCO were used as a reference component, the selectivity was thought to be higher than that based on NO of this study. Therefore, as the selectivity of the total aromatic mixture included in LCO based on total paraffin mixture included in LCO was anticipated to be higher, a liquid membrane separation method that DMSO was added into a liquid membrane was expected to be a promising method in the dearomatization of LCO. As the paraffin mixture in a raffinate phase was concentrated by the dearomatization of LCO, the cetane number of the raffinate phase was expected to be increased. This result indicated that it could be used as diesel oil. Also, it was found that the bigger the differences of the carbon number among aromatic group components with a different carbon number, the easier the separation. However, the selectivity among aromatic group components with the same carbon number was found to be unity, and, subsequently, it was difficult to separate between isomer components.

Effects of Experimental Factors and Conditions

Table 3 shows the effect of an initial mass fraction ($C_{DMSO,0}$) of DMSO used as a permeation promoter in a liquid membrane on the yield of the NA

Table 3. Effect of an initial mass fraction of DMSO in a liquid membrane ($C_{DMSO,0}$) on the yield of the bicyclic aromatic component i and the selectivity based on NO.

Experiment conditions	$C_{DMSO,0}$ (—)	Component i	Y_i (—)	$\beta_{i,NO}$ (—)
$(E/R)_0 = 4$,	0.1	NA	0.41	62
$N = 10\,sec^{-1}$,		2-MNA	0.26	33
$t = 120\,sec^{-1}$,		1-MNA	0.29	41
$T = 30^{\circ}C$		DMNAs	0.13	19
(feed: LCO A)				
	0.2	NA	0.49	60
		2-MNA	0.31	29
		1-MNA	0.35	37
		DMNAs	0.20	15
	0.3	NA	0.56	55
		2-MNA	0.38	24
		1-MNA	0.42	33
		DMNAs	0.27	12
	0.4	NA	0.61	53
		2-MNA	0.47	22
		1-MNA	0.50	31
		DMNAs	0.31	11

group components and the selectivity based on NO. The permeation of the NA group components was promoted because of the increase of $C_{DMSO,0}$, which resulted in an increase of the solubility of hydrocarbons. On the other hand, the selectivity of NA group components was decreased. As the increase of $C_{DMSO,0}$ resulted in promoting simultaneously the permeation of hydrocarbons and the demulsification by an unstable emulsion, it was expected that the selectivity of the NA group components decreased with increasing $C_{DMSO,0}$.

As mentioned, if $C_{DMSO,0}$ was higher, it was anticipated that at times, the emulsion operation could be impossible due to the demulsification with the unstable emulsion. The emulsion produced at more than $C_{DMSO,0} = 0.55$ was separated into an oil phase and an aqueous phase within a short time. However, it was believed that the increase of surfactant concentration in a liquid membrane could prevent the emulsion from being unstable due to an increase of $C_{DMSO,0}$ to a certain extent.

The emulsion produced at $C_{DMSO,0} = 0$ was used to carry out the permeation experiment, but because the concentration of the NA group components in an extract phase were lower, it was impossible to analyze them.

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The effect of the stirring speed (N) on the yield of the NA group components and the selectivity based on NO is shown in Table 4. The yield of the NA group components increased with increasing N. This result was ascribed to increase contact area between the emulsion and solvent, and a turbulent flow around the inner oil phase due to increasing N. However, because the breakage of a liquid membrane was increased with increasing N, the selectivity of NA group components decreased with increasing N.

Table 5 shows the effect of the initial volume ratio of a solvent/emulsion $(E/R)_0$ on the yield of the NA group components and the selectivity based on NO. The yield of naphthalene group components increased with increasing $(E/R)_0$. The increase of $(E/R)_0$ resulted in reducing a diameter of emulsion and a mechanical entrainment, and enhancing the driving force for the permeation, and, subsequently, it seemed that they had an effect on increasing the yield of NA group components. Also, the selectivity of NA group components increased with increasing $(E/R)_0$.

The permeation operation at less than $(E/R)_0 = 0.6$ was impossible because the emulsion of (O/W)/O type was transferred to that of O/W type due to the mechanical entrainment of an outer oil phase.

Table 4. Effect of the stirring speed (N) on the yield of the bicyclic aromatic component i and the selectivity based NO.

Experiment conditions	N (sec^{-1})	Component i	Y_i (—)	$\beta_{i,\text{NO}}$ (—)
$C_{\text{DMSO},0} = 0.2$,	7.5	NA	0.36	63
$(E/R)_0 = 4$,		2-MNA	0.20	31
$t = 120$ sec,		1-MNA	0.25	40
$T = 30°\text{C}$		DMNAs	0.11	16
(Feed: LCO A)				
	10	NA	0.49	60
		2-MNA	0.31	29
		1-MNA	0.35	37
		DMNAs	0.20	15
	12.5	NA	0.55	55
		2-MNA	0.37	24
		1-MNA	0.40	32
		DMNAs	0.26	11
	15	NA	0.64	49
		2-MNA	0.48	20
		1-MNA	0.52	26
		DMNAs	0.37	7

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Table 5. Effect of the initial volume ratio of a solvent/emulsion $(E/R)_0$ on the yield of the bicyclic aromatic component i and the selectivity based on NO.

Experiment conditions	$(E/R)_0$ (—)	Component i	Y_i (—)	$\beta_{i,NO}$ (—)
$C_{DMSO,0} = 0.2$,	2	NA	0.47	47
$N = 10\,sec^{-1}$,		2-MNA	0.30	24
$t = 120\,sec$,		1-MNA	0.33	31
$T = 30^{\circ}C$		DMNAs	0.19	13
(Feed: LCO A)				
	4	NA	0.49	60
		2-MNA	0.31	29
		1-MNA	0.35	37
		DMNAs	0.20	15
	7.5	NA	0.48	58
		2-MNA	0.33	30
		1-MNA	0.37	36
		DMNAs	0.22	16
	11	NA	0.57	62
		2-MNA	0.39	31
		1-MNA	0.45	39
		DMNAs	0.25	16

CONCLUSION

1. It was found that the smaller the carbon number of the NA group component, the faster the permeation rate and the higher the selectivity based on the paraffin component (NO). The larger the differences of the carbon number among the aromatic group components with a different carbon number, the easier the separation. It was difficult to separate the isomer components because the selectivity of the aromatic group components with the same carbon number was found to be unity.
2. The increase of a DMSO concentration in a liquid membrane resulted in promoting the permeation of the NA group components but decreasing the selectivity based on NO. The permeation operation was impossible at more than 0.55 of a DMSA concentration in a liquid membrane.
3. The permeation rate of the NO group component and the selectivity based on NO increased with increasing the initial volume ratio of a solvent/emulsion. At more than 0.6 of the initial volume ratio of a solvent/emulsion, the emulsion of (O/W)/O type was transferred to

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that of O/W type, and there was a limit in the initial volume ratio of a solvent/emulsion.

4. Increasing the stirring speed resulted in an increase in the permeation rate of NA group component but a decrease in the selectivity based on NO.

NOMENCLATURE

a	Specific surface area between raffinate phase (emulsion) and extract phase (solvent) (m^{-1})
$C_{DMSO,0}$	Initial mass fraction of DMSO in liquid membrane (—)
$C_{sap,0}$	initial mass fraction of saponin in liquid membrane (—)
E	Mass of extract phase (solvent) (kg)
E_0	Initial mass of extract phase (solvent) (kg)
N	stirring speed (sec^{-1})
P_i	Overall permeability of component i ($kg\,m^{-3}\,s^{-1}$)
R	Mass of raffinate phase (emulsion) (kg)
R_{IO}	Mass of inner oil in raffinate phase (emulsion) (kg)
R_0	initial mass of raffinate phase (emulsion) (kg)
T	Operation temperature (°C)
t	Permeation time (sec)
V	Volume of total liquid (m^3)
x_i or x_j	Mass fraction of component i or j in raffinate phase (emulsion) (—)
$x_{i,0}$	Initial mass fraction of component i in raffinate phase (emulsion) (—)
Y_i	Yield of component i defined by Eq. (1) (—)
y_i or y_j	Mass fraction of component i or j in extract phase (solvent) (—)
$y_{i,0}$	Initial mass fraction of component i in extract phase (solvent) (—)

Greek

$\beta_{i,j}$	Selectivity of component i based on component j defined by Eq. (3) (—)

Subscript

DMSO	Dimethylsulfoxide
DMNA	Dimethylnaphthalene
DMNAs	Mixture of dimethylnaphthalene with 10 structural isomers
i	Component i
IO	Inner oil in raffinate phase (emulsion)

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j	Component *j*
1-MNA	1-Methylnaphthalene
2-MNA	2-Methylnaphthalene
NA	Naphthalene
NO	*n*-Nonane
sap	Saponin
0	At initial ($t = 0$)

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