

MICROPORE STRUCTURE AND INTRAPORE DIFFUSION OF OXYGEN AND NITROGEN IN A MOLECULAR SIEVING CARBON

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Key Words: Molecular Sieving Carbon, Coconut Char, Hydrocarbon, Diffusivity, Adsorption, Kinetics, Adsorption Separation, Nitrogen, Oxygen

Both micropore size and volume in molecular sieving carbon (MSC) were controlled by heat treating of a hydrocarbon-impregnated MSC precursor, consisting of coconut-husk charcoal having various pore size distributions, in nitrogen at 1023, 1123 and 1223 K after heating at 10 K/min. The hydrocarbon mixtures used were guaiacol-naphthalene, diphenyl-naphthalene, fluorene-naphthalene and coal tar. The micropore size in the heat-treated MSC could be controlled to 0.28–0.4 nm through the proper combination of hydrocarbons, their concentrations and heat-treatment conditions, to give a high selectivity of separation of oxygen and nitrogen. The separation performance of the heat-treated MSC was evaluated in terms of the micropore volume W_0^* with pore size of 0.28–0.4 nm and the diffusivity ratio of oxygen and nitrogen D_{O_2}/D_{N_2} to obtain the following correlation:

$$D_{O_2}/D_{N_2} = 29(W_0^*/W_T)^{5.7}$$

It was found that the selectivity, D_{O_2}/D_{N_2} increases with increasing micropore volume W_0^* (pore size: 0.28–0.4 nm) for the limiting volume of adsorption space with pore size larger than 0.28 nm, W_T .

Introduction

Molecular sieving carbon (MSC) has micropores whose diameters are comparable with the molecular diameter of adsorbates. Air separation by pressure swing adsorption (PSA) using such a molecular sieving carbon pellet has been developed in recent years. The selectivity in this system depends on the differences in diffusion rates of oxygen and nitrogen in the micropores of MSC. Therefore, adjustment of the micropore structure is the key to accomplishing high

selectivity in this separation process. Two ways of controlling the size of the micropores have been proposed: (i) deposition of carbon produced by pyrolyzing a gaseous hydrocarbon onto the micropore^{1,2,6)}, and (ii) adding a resin and, e.g., pitch granulator to a carbide or activated carbon, heating and coating the pore walls with pyrolytic carbon^{6–8,10,12)}. Some success has been achieved in controlling the size of the micropores. However, it has not yet been reported how the volume as well as the size of the micropore effect both the diffusivities of gases and the selectivity of separation.

The objective of the present investigation is to

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Table 1. Properties of Precursors

		Precursor			
		A	B	C	D
Particle density	$[\text{kg} \cdot \text{m}^{-3}]$	980	980	910	950
True density	$[\text{kg} \cdot \text{m}^{-3}]$	1800	1770	1830	1770
Macropore volume, $v_{\text{ma}} \times 10^4$	$[\text{m}^3 \cdot \text{kg}^{-1}]$	3.20	2.68	4.00	3.29
Micropore volume, $v_{\text{mi}} \times 10^4$	$[\text{m}^3 \cdot \text{kg}^{-1}]$	1.42	1.87	1.52	1.59
Total pore volume, $v_t \times 10^4$	$[\text{m}^3 \cdot \text{kg}^{-1}]$	4.60	4.55	5.52	4.88
Micropore size, a	$[\text{nm}]$	0.28–0.4	0.28–0.4	0.28–0.4	0.28–0.4
	(%)	(8%)	(33%)	(3%)	(33%)
		0.4 – 0.5	0.4 – 0.5	0.4 – 0.5	0.4 – 0.5
	(%)	(89%)	(53%)	(17%)	(47%)
		0.5 –	0.5 –	0.5 –	0.5 –
	(%)	(3%)	(14%)	(80%)	(20%)

provide information on micropore structure such as pore size, pore volume and intrapore diffusivities suitable for the separation of oxygen and nitrogen. Four kinds of MSC precursors having different micropore size distributions were chosen as samples. The micropore size and volume in MSC were controlled by heat treating of the hydrocarbon-impregnated MSC precursors. The separation performance of the heat-treated MSC for oxygen and nitrogen was evaluated in terms of the micropore structure and the intrapore diffusivities of those gases obtained from analysis of adsorption rate based on two models.

1. Materials and Experimental Procedure

Powdered coconut-husk charcoal, pelletized by adding coal tar or coal tar pitch as a granulator, was pyrolyzed at 1023–1173 K, treated with dilute mineral acid to remove alkali and alkaline-earth metals, and then washed with water to give four kinds of precursors (called precursors A, B, C and D). These precursors consisted of cylindrical pellets, $3\text{--}4 \times 10^{-3}$ m long and 2×10^{-3} m in diameter. The properties of the precursors are given in **Table 1**. They were impregnated with guaiacol (carbolic oil), naphthalene, diphenyl (heavy oil), fluorene (anthracene oil), and coal tar.

Each precursor (0.005–0.01 kg) was soaked in solutions of the above hydrocarbons (solution temperature 473 K) and stirred thoroughly to impregnate the precursor with the liquid. The impregnated sample was then suspended in a platinum-wire basket in a heat-treatment apparatus as described in the previous paper⁸⁾. The apparatus consisted of a reaction tube, electric furnace, PID controller, and nitrogen gas lines. The reaction tube was a mullite tube, 1.5 m long, with an inside diameter of 4.2×10^{-2} m and an outside diameter of 5.0×10^{-2} m, which was surrounded by a siliconite heater. The bottom of the reaction tube was packed with stainless-steel netting, surmounted with alumina balls,

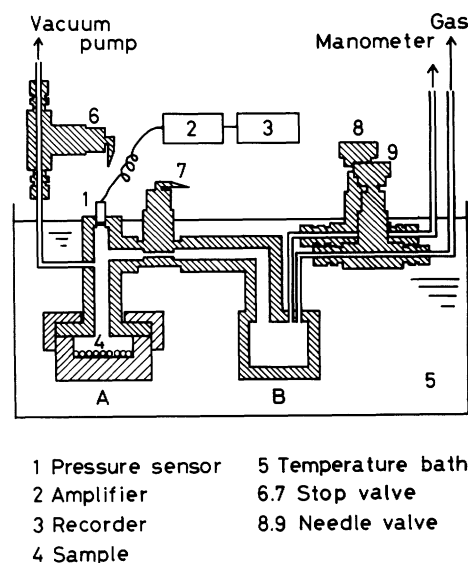


Fig. 1. Outline of batch adsorption apparatus for measurement of gaseous adsorption rate

to promote heat transfer. The temperature of the reactor was measured using a Pt–Pt/Rh thermocouple. Temperature control was by means of a PID controller. The reaction temperature of the sample was measured by a Pt–Pt/Rh thermocouple positioned 5×10^{-2} m below the sample. After the impregnated sample (5×10^{-3} kg) had been set in place in this way, nitrogen was admitted at a rate of 1.0×10^{-3} m³ (STP)/min and the temperature was raised to a preset level (1023–1223 K) at a rate of 10 K/min. The heat treatment was continued at the desired temperature for 0.5 hour.

The rate of adsorption of the gas and the equilibrium amount adsorbed were determined using a batch adsorption apparatus, shown in **Fig. 1**. The precisely weighed sample was packed into chamber A and then the entire system was evacuated. A known amount of the adsorbed gas was then introduced into chamber B and valves 8 and 9 were closed. Valve 7 was then

opened quickly and adsorption commenced. The initial pressure was varied in the range of 0–100 kPa. The change in gas pressure during adsorption was measured by a semiconductor pressure sensor until adsorption equilibrium was reached. The amount of gas adsorbed was calculated from the decrease in pressure. The whole apparatus was set in a constant-temperature bath at 298 K.

2. Control of Micropore Structure by Impregnation of Hydrocarbons and Heat Treatment

2.1 Evaluation of micropore structure

Both the diameter and the volume of the micropores in the heat-treated MSCs as well as the precursors were evaluated by the molecular probe method. They are normally estimated by observing whether or not a gas with molecules of a certain size can pass through the micropores. The molecular diameters of the gases used here are: O₂ 0.28 nm, C₂H₆ 0.40 nm, iso-C₄H₁₀ 0.50 nm. The adsorption isotherms of the gases O₂, C₂H₆ and iso-C₄H₁₀ on those samples were expressed in terms of the Dubinin-Astakhov formula:

$$W/W_0 = \exp[-(A/E)^n] \quad (1)$$

where

$$A = R \cdot T \cdot \ln(P_0/P) \quad (2)$$

$$W = q \cdot M/\rho \quad (3)$$

The saturated vapor pressure of the gas and the density of the adsorbent phase were estimated by the Frost-Karwarf-Thodos formula⁹⁾ and the Rackett formula as modified by Yamada and Gunn (when the temperature of adsorption was below the standard boiling point)⁹⁾ or the Nikolaev formula (when the temperature of adsorption was above the standard boiling point)⁹⁾. The plot of $\log W$ vs A^n was linear, the intercept giving the limiting volume W_0 of the micropores. All the data for the samples could be fitted to Eq. (1) if $n=2$ was given.

2.2 Micropore structure of precursors A, B, C and D.

Figure 2 shows the limiting volume W_0 of the micropores in the precursors, A, B, C and D. The micropores in precursor A had a narrow distribution of 0.40 to 0.50 nm diameter while most of the micropores in precursor C had a pore distribution greater than 0.5 nm diameter. The distribution of pore size in precursors B and D were much wider than that in precursor A. The particle density of B was $980 \text{ kg} \cdot \text{m}^{-3}$, which was larger than the $950 \text{ kg} \cdot \text{m}^{-3}$ of D. The properties of all the precursors are summarized in Table 1.

2.3 Control of micropore structure of the precursors

Figure 3 shows the adsorption rate curves of O₂ and N₂ on precursor A and the heated MSCs prepared by impregnating hydrocarbons such as guaia-

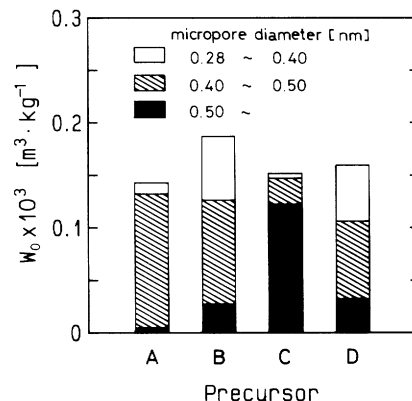


Fig. 2. Limiting volume of adsorption space for four kinds of precursors

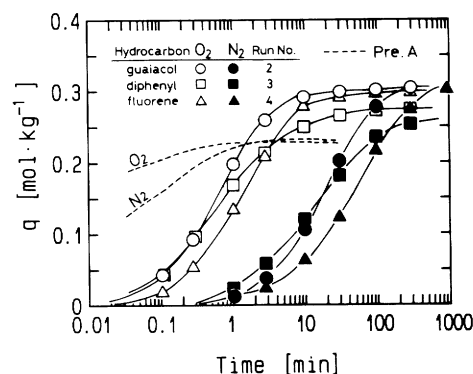


Fig. 3. Adsorption rates of O₂ and N₂ for precursor A and heat-treated MSCs

col-naphthalene, diphenyl-naphthalene and fluorene-naphthalene under the conditions shown in Tables 2 and 3. MSCs impregnated with naphthalene solution alone had similar adsorption characteristics with respect to oxygen and nitrogen to those of the precursors. Therefore, naphthalene was used as a solvent in this study. The broken and solid lines represent precursor A and heat-treated MSCs respectively. With precursor A, the equilibrium amounts of O₂ and N₂ adsorbed were small, and there was very little difference in their rates of adsorption. With the heat-treated MSCs, on the other hand, the equilibrium amounts adsorbed were much larger than that of the precursor and there was also a big difference in their rates of adsorption. Most micropores in precursor A were easily controlled at low concentration for all hydrocarbons to give a smaller pore size distribution (0.28 to 0.40 nm) than that of precursor A, as shown in Fig. 4.

Figures 5 and 6 show, respectively, the effects of the hydrocarbon concentration on pore size distribution and volume for precursors B and D. As an example, the mixture of diphenyl-naphthalene is chosen as the hydrocarbon. When the concentration of diphenyl increased, the volume of micropores having a pore

Table 2. Conditions of adsorption rate measurement in Figure 3

Hydrocarbon	Keys		$W_s \times 10^3$ [kg]		P_i [kPa]		P_e [kPa]	
	O ₂	N ₂	O ₂	N ₂	O ₂	N ₂	O ₂	N ₂
Precursor			1.999	1.999	94.52	94.52	80.76	80.46
Guaiacol	○	●	2.005	2.005	93.29	93.36	76.31	76.14
Diphenyl	□	■	2.000	2.000	93.84	94.34	77.30	78.89
Fluorene	△	▲	2.000	2.000	93.46	95.01	75.34	76.59

W_s : weight of precursor; P_i : initial pressure; P_e : pressure in equilibrium.

Table 3. Properties of micropore structure in heat-treated MSCs produced under various conditions

Pre.	Impregnation		Heat treatment		$W_{0.28-0.40} \times 10^3$	$W_{0.40-0.50} \times 10^3$	$W_{0.50-0.70} \times 10^3$	$W_T \times 10^3$	Run No.
	Hydrocarbon	Conc. [wt%]	Temp. [K]	Time [h]	[m ³ ·kg ⁻¹]	[m ³ ·kg ⁻¹]	[m ³ ·kg ⁻¹]	[m ³ ·kg ⁻¹]	
A	—	—	—	—	0.011	0.128	0.005	0.144	1
A	Guaiacol	10	1173	0.5	0.193	0	0	0.193	2
A	Diphenyl	15	1223	0.5	0.182	0.020	0	0.202	3
A	Fluorene	5	1223	0.5	0.138	0.003	0	0.141	4
B	—	—	—	—	0.061	0.099	0.027	0.187	5
B	Diphenyl	15	1223	0.5	0.135	0.024	0.018	0.177	6
B	Diphenyl	100	1023	0.5	0.101	0.056	0.020	0.177	7
B	Diphenyl	100	1123	0.5	0.145	0.017	0.019	0.181	8
B	Diphenyl	100	1223	0.5	0.168	0.012	0	0.180	9
B	Fluorene	10	1223	0.5	0.181	0.008	0	0.189	10
B	Fluorene	30	1123	0.5	0.149	0.001	0.022	0.172	11
C	—	—	—	—	0.005	0.025	0.122	0.152	12
C	Guaiacol	10	1173	0.5	0.035	0.080	0.043	0.158	13
C	Diphenyl	10	1223	0.5	0.083	0.071	0.028	0.182	14
C	Diphenyl	100	1223	0.5	0.130	0.018	0.017	0.165	15
D	—	—	—	—	0.053	0.074	0.032	0.159	16
D	Diphenyl	10	1223	0.5	0.124	0.035	0.017	0.176	17
D	Diphenyl	50	1223	0.5	0.121	0.041	0.021	0.183	18
D	Diphenyl	75	1223	0.5	0.128	0.035	0.015	0.178	19
D	Diphenyl	100	1023	0.5	0.075	0.085	0.009	0.169	20
D	Diphenyl	100	1123	0.5	0.147	0.023	0.011	0.181	21
D	Diphenyl	100	1223	0.5	0.159	0.004	0	0.163	22
D	Fluorene	10	1223	0.5	0.139	0.018	0.009	0.166	23
D	Fluorene	30	1223	0.5	0.130	0.013	0.015	0.143	24
D	Fluorene	50	1223	0.5	0.154	0.014	0	0.168	25
D	Coal tar	10	1223	0.5	0.161	0.001	0	0.162	26

Pre.: Precursor; Conc.: concentration of guaiacol, diphenyl, fluorene or coal tar in naphthalene solution.

size larger than 0.4 nm diameter decreased gradually to create a smaller volume in the 0.28 to 0.4 nm range. It was found that the biggest difference between the adsorption rates of oxygen and nitrogen occurred when most of the micropores were controlled to a diameter of 0.28 to 0.4 nm.

Figures 7 and 8 show, respectively, the effects of the heat treatment temperature on pore size distribution and volume when precursors B and D were impregnated with diphenyl. With both precursors B and D the volume of micropores having a pore size of 0.4 to 0.5 nm decreased while the volume of

micropores larger than 0.5 nm in diameter remained unchanged at 1023 and 1123 K. At the still higher temperature of 1223 K, the micropore size of precursors B and D was almost completely in the range of 0.28 to 0.4 nm. With precursor C, in which most of the pores were greater than 0.5 nm in diameter, it was very difficult to control the size of the micropores, their volume and the rates of adsorption of O₂ and N₂ by impregnating a hydrocarbon on the precursor followed by heat treatment. The treatment conditions and the properties of micropore structure in the heat-treated MSCs are summarized in Table 3. It was

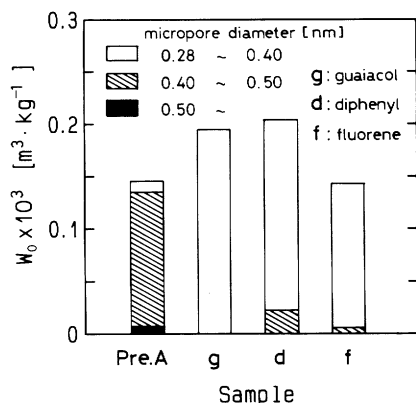


Fig. 4. Limiting volume of adsorption space for MSCs produced by heat treating hydrocarbon-impregnated precursor A

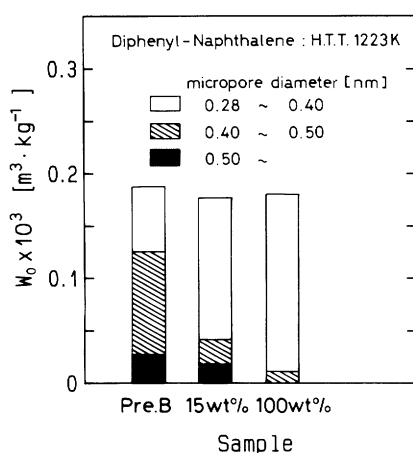


Fig. 5. Effects of concentration of diphenyl on the limiting volume of adsorption space for heat-treated MSCs (Basis: precursor B)

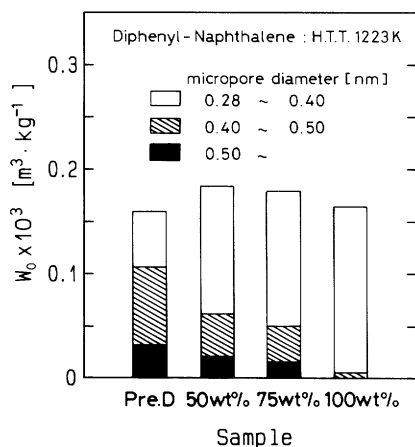


Fig. 6. Effects of concentration of diphenyl on the limiting volume of adsorption space for heat-treated MSCs (Basis: precursor D)

found that guaiacol (carbolic oil) and diphenyl (heavy oil) are effective for fine control of pore size, while fluorene (anthracene oil) is more effective in altering

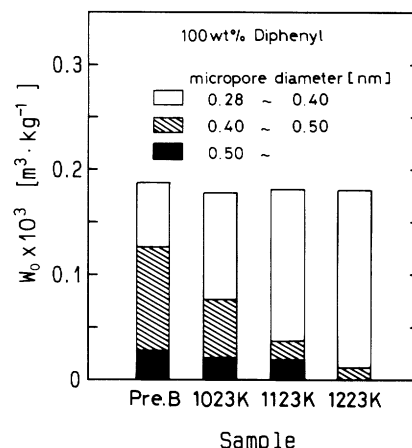


Fig. 7. Effects of heat temperature on the limiting volume of adsorption space for heat-treated MSCs (Basis: precursor B)

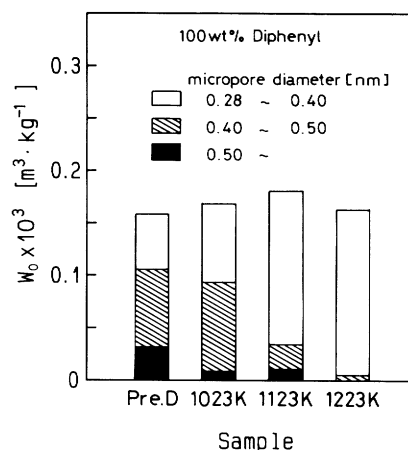


Fig. 8. Effects of heat temperature on the limiting volume of adsorption space for heat-treated MSCs (Basis: precursor D)

the pore size over a wide range. These results imply that the strong depressant effect of the impregnated fluorene on the rate of adsorption was connected with the increased resistance to diffusion due to the presence of the carbide deposited in the micropores.

3. Discussion

The micropore diffusivities of oxygen and nitrogen in the heat-treated MSCs were evaluated by analyzing the adsorption rate curves, which were obtained by using the constant-volume adsorption apparatus, based on two methods.

According to one method developed by Huang and Chihara^{1,3)}, the expression for the change in gas pressure during adsorption is given by the following equations.

Table 4. Diffusivity ratio D_{O_2} and D_{N_2} in heat-treated MSCs produced under various conditions

Run No.	$D_{O_2}/a^2 \times 10^3$ [s ⁻¹]	$D_{N_2}/a^2 \times 10^3$ [s ⁻¹]	D_{O_2}/D_{N_2} (Huang) [—]	D_{O_2}/D_{N_2} (Ruthven) [—]	$W_o^* \times 10^3$ [m ³ ·kg ⁻¹]	W_o^*/W_T [—]
1	4.59	2.82	—	1.63	0.0110	0.0764
2	1.60	0.0600	26.7	—	0.193	1.00
3	1.45	0.0700	20.7	—	0.182	0.901
4	0.910	0.0180	50.6	—	0.138	0.979
5	3.51	1.18	—	2.97	0.0610	0.326
6	4.63	0.938	—	4.94	0.135	0.763
7	2.81	1.79	—	1.57	0.101	0.571
8	2.98	0.467	—	6.38	0.145	0.801
9	2.50	0.110	22.7	18.0	0.168	0.933
10	1.42	0.0440	32.3	—	0.181	0.958
11	2.78	0.358	—	7.77	0.149	0.866
12	4.21	1.80	—	2.34	0.00500	0.0329
13	4.02	2.32	—	1.73	0.0350	0.222
14	3.82	2.70	—	1.42	0.0830	0.456
15	2.04	0.292	—	6.99	0.130	0.788
16	3.28	3.34	—	0.982	—	0.333
17	4.93	0.933	—	5.28	0.0530	0.705
18	3.70	0.964	—	3.84	0.124	0.661
19	2.82	0.616	—	4.58	0.121	0.719
20	3.25	2.97	—	1.09	0.128	0.444
21	3.45	0.366	—	9.43	0.0750	0.812
22	0.395	0.0170	23.2	—	0.147	0.975
23	2.47	0.369	—	6.69	0.159	0.837
24	4.80	0.300	16.0	13.3	0.139	0.909
25	0.836	0.0540	—	15.4	0.130	0.923
26	1.70	0.0750	22.7	—	0.154	0.994
					0.161	

$a(=4.1 \times 10^{-6} \text{ m})$: mean radius of microparticles.

$$\frac{P}{P_i} = 1 - \left(\frac{1}{1 + \alpha} \right) \left[1 - \sum_{n=1}^{\infty} \frac{6\alpha(\alpha + 1) \cdot \exp(-q_n^2 \cdot \tau)}{(9 + 9\alpha + q_n^2 \cdot \alpha^2) - (6 + \alpha)\alpha \cdot q_n^2 / \text{Bi} + \alpha^2 q_n^4 / \text{Bi}^2} \right] \quad (4)$$

where q_n is the n -th root of

$$\frac{q_n}{\tan q_n} = 1 - \frac{q_n^2}{q_n^2 / \text{Bi} - 3/\alpha} \quad (5)$$

$$\alpha = \frac{1}{1 - c_{\infty}/c_0} - 1 \quad (6)$$

$$\tau = D \cdot t / a^2 \quad (7)$$

$$\text{Bi} = k_f \cdot a / D \quad (8)$$

The micropore diffusivity D in the above equation can be obtained by curve-fitting of the theoretical curve (Eq. (4)). $a(=4.1 \times 10^{-6} \text{ m})$ is the mean radius of the microparticles which make up the MSCs.

This method is usable for evaluating the diffusional time constants smaller than $D_{O_2}/a^2 = 5 \times 10^{-3} \text{ s}^{-1}$ and

$D_{N_2}/a^2 = 6 \times 10^{-4} \text{ s}^{-1}$ for oxygen and nitrogen, respectively. The diffusivity ratios of oxygen and nitrogen in the heat-treated MSCs produced by the method of impregnating the precursors (A, B, C, D) with various hydrocarbons are tabulated in **Table 4**.

The other method was reported by Ruckenstein *et al.*⁽¹¹⁾, Lee⁽⁵⁾ and Ruthven⁽¹⁰⁾. The expression for the initial stage of adsorption is presented as follows.

$$\frac{q}{q_e} = \frac{3\beta/\gamma}{1 + 3\beta/\gamma} + \frac{1}{1 + 3\beta/\gamma} \frac{6}{a} \sqrt{\frac{D \cdot t}{\pi}} \quad (9)$$

where $\beta[(=D/a^2)/(D_p/R_p^2)]$ is the ratio of diffusional time constants, D/a^2 in micropore to D_p/R_p^2 in macropore and $\gamma = 3\beta(1 - \varepsilon)q_e/\varepsilon C_e$. A plot of q/q_e vs $t^{1/2}$ for a heat-treated MSC gives essentially a straight line for each gas at the initial stage of adsorption. The diffusional time constant D/a^2 in micropore could be calculated from the initial slope of the $t^{1/2}$ plots. This method is applicable to the estimation of diffusional time constants larger than $D_{O_2}/a^2 = 2 \times 10^{-3} \text{ s}^{-1}$ and $D_{N_2}/a^2 = 1 \times 10^{-4} \text{ s}^{-1}$ for oxygen and nitrogen, respectively. The diffusivity ratio, D_{O_2}/D_{N_2} , obtained

by this method is also tabulated in Table 4.

To elucidate the relationship between the selectivity for separation and the micropore structure in the heat-treated MSCs, the diffusivity ratios D_{O_2}/D_{N_2} corresponding to the selectivity were plotted against the ratio W_0^*/W_T of the micropore volume with the specified pore size of 0.28–0.4 nm, W_0^* , to the limiting volume of adsorption space with pore size larger than 0.28 nm, W_T as shown in Fig. 9, where keys (○ and □) indicate the computations based on Ruthven¹⁰⁾ and Chihara¹⁾, respectively. When W_0^*/W_T was smaller than about 0.6, the diffusivity ratio was very small, so that the selectivity for separation of oxygen and nitrogen gases was extremely low. As the value of W_0^*/W_T increased beyond 0.6, however, the diffusivity ratio increased rapidly to reach the maximum value, $D_{O_2}/D_{N_2}=29$, in the MSCs produced in this study. The diffusivity ratios D_{O_2}/D_{N_2} were well correlated with W_0^*/W_T , giving the following equation.

$$D_{O_2}/D_{N_2}=29(W_0^*/W_T)^{5.7} \quad (10)$$

This implies that the micropore volume with the specified pore size of 0.28 to 0.4 nm plays an important role in separation of oxygen and nitrogen. This correlation provides useful information for designing a MSC of high selectivity for the separation of oxygen and nitrogen.

Conclusion

Molecular sieving carbon (MSC) suitable for the separation of oxygen and nitrogen was produced by heat-treating a precursor of MSC impregnated with a mixture of hydrocarbons (guaiacol, naphthalene, diphenyl and fluorene or coal tar). The separation performance of the heat-treated MSC was evaluated in terms of micropore size, pore volume and rates of diffusion of gases. The following results were obtained.

Impregnation with a hydrocarbon and heat treatment enabled the micropore diameter to be controlled to 0.28–0.4 nm, giving high selectivity for the separation of oxygen and nitrogen. In a precursor in which most of the micropores were 0.4–0.5 nm in diameter, the pore size was easily kept within the range 0.28–0.4 nm by any hydrocarbon of low concentration. In a precursor having micropores greater than 0.5 nm in diameter, the pore size was controlled by using fluorene (anthracene oil) of high concentration or coal tar.

The ratio of diffusivities, D_{O_2}/D_{N_2} , was well correlated with the ratio of micropore volume (pore size: 0.28–0.4 nm), W_0^* , to the limiting volume of adsorption space with pores more than 0.28 nm, W_T .

$$D_{O_2}/D_{N_2}=29(W_0^*/W_T)^{5.7}$$

It was found that the diffusivity ratio D_{O_2}/D_{N_2} , i.e.,

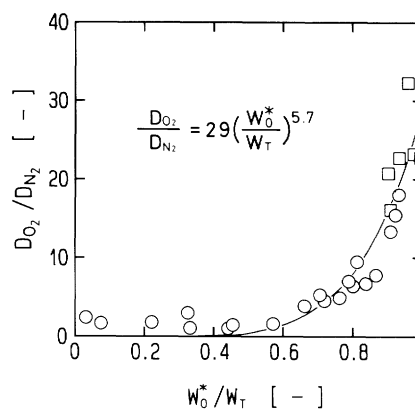


Fig. 9. Correlation between diffusivity ratio D_{O_2}/D_{N_2} and W_0^*/W_T

the selectivity, is greatly effected by the volume of micropores with pore size of 0.28–0.4 nm as well as by the adjustment of micropore size.

Nomenclature

A	= adsorption potential	$[J \cdot mol^{-1}]$
a	= microparticle radius	$[m]$
C_0	= initial concentration of adsorbate	$[mol \cdot m^{-3}]$
C_x	= final concentration of adsorbate	$[mol \cdot m^{-3}]$
D	= micropore diffusivity based on amount of adsorbate	$[m^2 \cdot s^{-1}]$
D_p	= macropore diffusivity based on amount of adsorbate	$[m^2 \cdot s^{-1}]$
E	= characteristic energy of adsorption	$[J \cdot mol^{-1}]$
k_f	= mass transfer coefficient through micropore mouth	$[m \cdot s^{-1}]$
M	= molecular weight	$[-]$
P	= pressure	$[kPa]$
P_i	= initial pressure	$[kPa]$
P_e	= pressure in equilibrium	$[kPa]$
P_0	= saturated vapor pressure	$[kPa]$
q	= amount adsorbed	$[mol \cdot kg^{-1}]$
q_e	= equilibrium amount adsorbed	$[mol \cdot kg^{-1}]$
R	= gas constant	$[J \cdot mol^{-1} \cdot K^{-1}]$
R_p	= radius of pellet	$[m]$
T	= temperature	$[K]$
t	= time	$[s, min, h]$
W_0	= limiting volume of adsorption space	$[m^3 \cdot kg^{-1}]$
W_0^*	= limiting volume of adsorption space with pore size of 0.28–0.4 nm	$[m^3 \cdot kg^{-1}]$
W_s	= weight of precursor	$[kg]$
W_T	= limiting volume of adsorption space with pore size larger than 0.28 nm	$[m^3 \cdot kg^{-1}]$
ρ	= density of adsorbate	$[kg \cdot m^{-3}]$
α	= defined by Eq. (6)	
ε	= porosity of pellet	$[-]$
τ	= dimensionless time defined by Eq. (7)	$[-]$

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