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Adsorption Properties and Breakthrough Model of 1,1-Dichloro-1-fluoroethane on Granular Activated Carbon and Activated Carbon Fiber

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ABSTRACT

1,1-Dichloro-1-fluoroethane (HCFC-141b) is current recognized as an excellent substitute for chlorofluorocarbons (e.g., CFC-11 and CFC-113). In the present work fixed-bed adsorption studies were performed on the use of granular activated carbon (GAC) and activated carbon fiber (ACF) for the recovery of HCFC-141b vapor from air. Adsorption equilibria were obtained at 283, 293, 303, and 313 K. Three classic models (Langmuir, Freundlich, and Dubinin–Radushkevich) were applied and their parameter constants were determined by regression analysis. It was found that these isotherms were fitted well by the measured adsorption data, and the determined parameters of isotherm equations were consistent with the physical properties (e.g., specific surface areas and pore volumes) of these carbon adsorbents. It is clear that the performance of adsorbent ACF is significantly better than that of adsorbent GAC in terms of the adsorption capacity and the adsorption rate. A simple two-parameter model, originally introduced by Yoon and Nelson, was adopted to describe the entire breakthrough curves regarding the adsorption of HCFC-141b vapor through carbon columns at 283 K. The results indicate that the calculated breakthrough curves agree well with the corresponding experimental data.

Key Words. HCFC-141b; Granular activated carbon; Activated carbon fiber; Adsorption

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INTRODUCTION

Hydrochlorofluorocarbons (HCFCs) are being used as replacements for ozone-depleting chlorofluorocarbons (CFCs) (1). 1,1-Dichloro-1-fluoroethane (HCFC-141b), one of the most common HCFCs, is currently used as a popular substitute for CFC-113, which was the cleaning solvent employed in the electronic and precision-machining industries, and as an excellent replacement for CFC-11, which was the foam-blowing agent in the polyurethane (PU) industry (2). The HCFCs, although less dangerous to stratospheric ozone than the CFCs, still pose a threat to the environment due to their expectedly large use in industries and their relatively high global warming potentials (GWPs) as greenhouse gases (1). Under strict guidelines of the Montreal Protocol Amendments, the reduction timetables for the production and consumption of HCFCs have scheduled the phase out of HCFCs by the year 2030 or earlier (3). As a result, it is expected that the recovery and recycle of HCFCs will become extremely important in forthcoming years (4).

Adsorption, absorption, and condensation are three common technologies for the recovery of volatile organic compounds (VOCs) from gas streams generated by industrial sources (5). One of the most effective ways to achieve the reduction of organic solvents or VOCs is adsorption process by the use of granular activated carbon (6–8). However, the applications of activated carbons present some disadvantages. These include possible corrosion caused by such corrosive solvents as 1,1,1-trichloroethane (9) and HCFC-141b (used as the target adsorbate in the present study) (10), which may proceed together with the elimination or hydrolysis reactions with the carbon itself or with the steam normally used for the regeneration of spent adsorbent. Therefore, there is a demand for more suitable types of carbon adsorbents to complement the activated carbon. Recently, activated carbon fiber (ACF) has been considered as one of the proper adsorbents for VOCs adsorption (9, 11–14). Although relatively more expensive when compared to GAC, ACF has many unique advantages. First of all, ACF contains only one-tenth to one-half of the metals content of GAC, so that catalysis or hydrolysis is inhibited during the steam regeneration of ACF. Second, its thin-fiber shape clearly assures fast intraparticle adsorption kinetics compared with GAC, resulting in a considerable decrease in the size of the adsorption system (12).

A few discussions appear in the literature about the adsorption behavior of HCFC-141b on carbon adsorbents (4, 15–18). These studies were only isotherm investigations carried out under specific conditions and scarcely present discussions referring to the breakthrough behaviors of highly different carbon adsorbents (i.e., GAC vs ACF). In this paper the adsorption equilibrium data of HCFC-141b on adsorbents GAC and ACF in the 350–2000 ppmv concentration range at various temperatures (283–313 K) are presented. These experimental conditions are typical for the design of a recovery system of

VOCs (6). The applicability of three common isotherms for predicting the adsorption equilibrium relationships of the HCFC-141b and GAC/ACF is also reported by regression analysis of the experimental data. In addition, theoretical breakthrough curves at an adsorption temperature of 283 K and at five different concentrations (from 350 to 2000 ppmv) are generated and studied to compare the corresponding experimental data by using a simple model introduced by Yoon and Nelson (19) which gives an two-parameter equation predicting the entire breakthrough curve. The results will be useful for the design of fixed-bed adsorption columns for HCFC's adsorption on GAC and ACF.

EXPERIMENTAL SECTION

Materials

Two different types of commercial activated carbons were chosen as adsorbents in the present study. The first type was granular activated carbon (GAC), supplied by Taipei Chemical Co. (Taipei, Taiwan) and made of coconut shell (symbolized TPE-G). It was highly irregular in both shape and size. The second type of carbon adsorbent was activated carbon fiber (ACF) in felt form, obtained from Toyobo Co. (Osaka, Japan) and designated KF-1500. It was made of cellulose fiber (viscose rayon). The surface areas and pore volumes of the carbon samples were obtained by an automatic volumetric sorption analyzer (model ASAP 2000, Micromerites Instrument Co., Norcross, GA, USA) using nitrogen adsorption at 77 K. The main characteristics of the adsorbent materials used in the present investigation are presented in Table 1.

TABLE 1
Main Characteristics of Activated Carbons
(Taipei Chemical Co., Taipei, Taiwan, for GAC; Toyobo Co., Osaka, Japan, for ACF)

Characteristics	GAC	ACF
Grain size (mm)[a] or fibrous diameter (μm)[b]	0.718	17–18
Precursor	Coconut	Rayon
Specific surface area[c] (m^2/g)	994	1659
Micropore surface area[c] (m^2/g)	862	1229
Total pore volume[c] (cm^3/g)	0.508	0.627
Micropore volume[c] (cm^3/g)	0.401	0.552
Average micropore diameter[d] (Å)	18.6	18.0

[a] GAC sample was sieved to mesh no. 20/30 (ASTM).
[b] From manufacturers's report.
[c] From BET experiment by ASAP-2000
[d] Estimated from data of the area of micropores and the micropore volume (29).

The adsorbate HCFC-141b investigated was obtain from Allied Signal Inc. (New Jersey, USA) and has a purity of over 99.5%. The vapor pressures, liquid densities, and refractive indices of liquid HCFC-141b over a range of temperatures can be expressed by the appropriate correlations (20, 21) that will be applied to evaluate the isotherms for the experimental data.

Apparatus and Procedures

A laboratory fixed-bed unit and experimental procedures were set up for the continuous flow study to obtain the equilibrium data of adsorption, as described previously (22, 23). The GAC was sieved to a mesh number range of 20 × 30 (average particle diameter of 0.718 mm). The ACF, however, was cut to round shape, which is slightly smaller than the inside diameter (i.e., 1.5 cm) of the adsorption column. In order to reduce the influence of wall effects in experimental columns, it is suggested that the ratio of tube diameter to particle diameter must be at least 20 from the nearest wall (24). In the present study this ratio was approximately 21 and thus complies with the above consideration. The concentration of HCFC-141b vapors at the inlet of the adsorption column was set at a certain value ranging from 350 to 2000 ppmv. The adsorption temperatures, 283, 293, 303, and 313 K, were maintained by a refrigerated circulating water bath (±0.1 K accuracy). The inlet feed, which consisted of a 2895 cm^3/min gas stream with HCFC-141b, was controlled and measured in relative humidity (RH) ranges of less than 3% for all experimental runs. The linear (superficial) velocity of 0.27 m/s thus obtained is in the practical range of 0.25–0.50 m/s (25).

The reproducibility analysis of HCFC-141b vapor concentration was made at an influent concentration of approximately 1950 ppmv. A value of 1950 ± 33.8 ppmv (i.e., mean ± standard deviation) was obtained for 12 samples. The reproducibility analysis of adsorption capacity (equilibrium) was determined by a microbalance (Model R200D, Sartorius Co., Germany; sensitivity of 0.1 mg) at an influent concentration of 1,210 ppmv and an adsorption temperature of 293 K. A value of 0.2835 ± 0.0002 g HCFC-141b/g adsorbent was obtained for five experimental runs.

RESULTS AND DISCUSSION

Adsorption Equilibrium

Adsorption equilibrium data of HCFC-141b vapors on GAC and ACF were obtained at temperatures of 283, 293, 303, and 313 K. It is important to establish the most appropriate correlations for the adsorption equilibrium in designing an adsorption system. In this work, three common isotherm equations widely used for describing organic vapor adsorption were tested, viz., Langmuir, Freundlich, and Dubinin–Radushkevich (D-R) equations (26, 27).

Langmuir Model

The best known monolayer adsorption isotherm for modeling adsorption equilibrium data is the Langmuir equation, written as

$$\frac{q}{q_\mathrm{m}} = \frac{K_\mathrm{L}C}{1 + K_\mathrm{L}C} \tag{1}$$

where q is the equilibrium adsorption capacity, C is the HCFC-141b concentration at equilibrium, and q_m and K_L are functions of temperature and are constant parameters to be determined from a linear regression of $1/q$ versus $1/C$ for each set of experimental data. The Langmuir constants q_m and K_L were determined and are listed in Table 2. As shown in Table 2, the isotherm data may be reasonably expressed by the Langmuir equation with correlation coefficients (R^2) in the 0.95–0.99 range. Table 2 also indicates that the parameters q_m and K_L for both carbon adsorbents decrease with increasing equilibrium adsorption temperature, as expected. Carbon adsorption is generally exothermic, and adsorption affinity would be reduced at higher temperatures. It was also found that the q_m values of adsorbent ACF are approximately 1.15 times greater than those of adsorbent GAC. This supports the view that the total pore volume of adsorbent ACF (i.e., 0.627 cm^3/g) is larger than that of adsorbent GAC (i.e., 0.508 cm^3/g) since the parameter q_m denotes the amount adsorbed

TABLE 2
Parameters of Langmuir Isotherm for Adsorption of HCFC-141b Vapors on Adsorbents GAC and ACF at Various Temperatures

Adsorbent	Adsorption temperature (K)	Concentration range[a] (ppmv)	Langmuir parameters q_m (mol/kg)	Langmuir parameters K_L (m^3/mol)	R^2
GAC	283	398–1954	2.94	180.0	0.9844
	293	399–1955	2.75	131.8	0.9844
	303	396–1954	2.49	106.1	0.9721
	313	401–1952	2.20	90.76	0.9688
ACF	283	428–1716	3.96	58.56	0.9570
	293	429–1715	3.52	47.65	0.9877
	303	435–1739	2.80	46.11	0.9788
	313	422–1729	2.77	25.75	0.9963

[a] Five data at each specified temperature.

at monolayer saturation (27). The temperature effects on parameters (i.e., q_m and K_L) listed in Table 2 can be correlated as well, as shown in Fig. 1, by the following equations (28):

For GAC:

$$q_m = 0.1442 \exp(858.5/T)$$

$$K_L = 0.1141 \exp(2080/T)$$

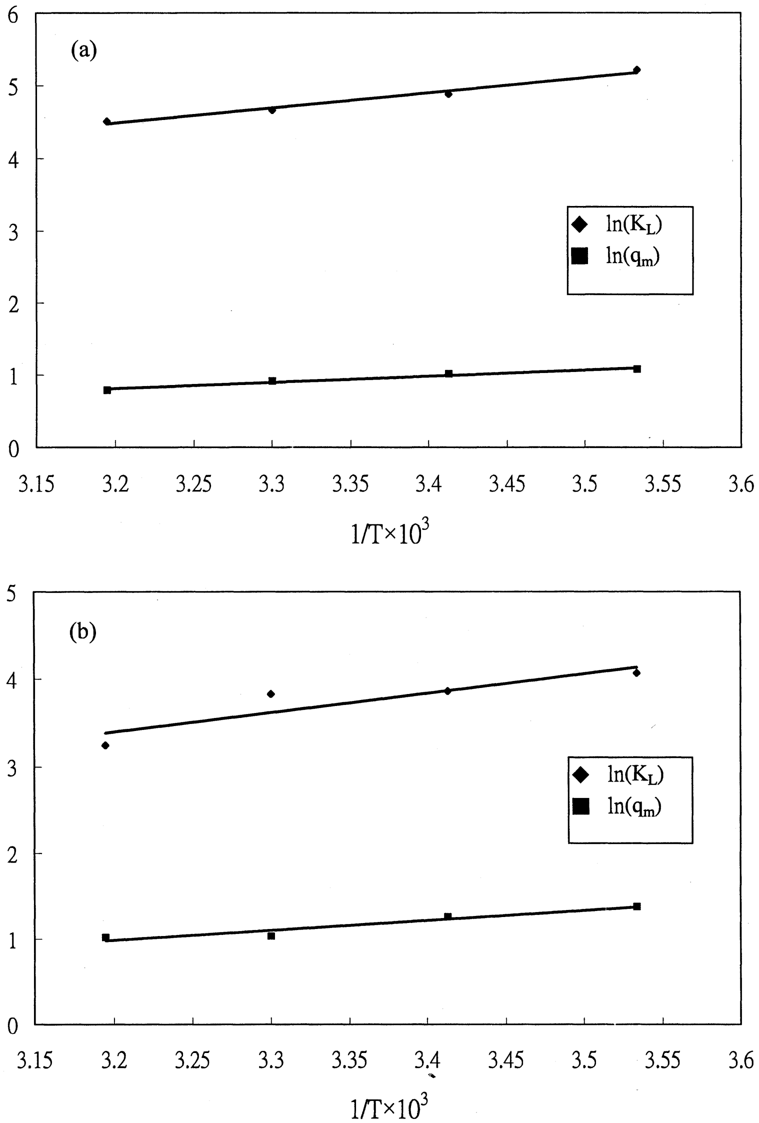

FIG. 1 Temperature effects on equilibrium constants (i.e., q_m and K_L) in Eq. (1) for HCFC-141b adsorption on activated carbons. (a) GAC ($R^2 = 0.9732$ and 0.9804, respectively); (b) ACF ($R^2 = 0.9220$ and 0.8180, respectively).

For ACF:

$$q_m = 0.0653 \exp(1160.4/T)$$
$$K_L = 0.0273 \exp(2189/T)$$

Freundlich Model

The Freundlich equation is an empirical relationship based on the assumption of a logarithmic decrease in adsorption heat with adsorption surface coverage (29). The Freundlich equation is commonly used in the form

$$q = K_F C^{1/n} \tag{2}$$

where q and C are defined as for Eq. (1), and K_F and n are empirical constants which also depend on the temperature. Using the equilibrium experimental data (q and C), the isotherm parameters (K_F and n) in Eq. (2) can be determined by plotting $\ln(q)$ against $\ln(C)$. Generally, the parameter n has a value greater than unity (29), and the value of $1/n$ represents a measure of the adsorption intensity (30). The magnitude of K_F indicates a measure of the adsorbent capacity.

The isotherm parameters for the Freundlich equation are given in Table 3. It is obvious from the listings that there are very good correlations between the Freundlich model predications and the experimental data. It seems that in the present study the Freundlich isotherm fits the experimental data more faithfully than the Langmuir isotherm. It may be noted that the Langmuir isotherm is based on monolayer adsorption on homogeneous surfaces. However, the ad-

TABLE 3
Freundlich Parameters for Adsorption of HCFC-141b Vapor on Adsorbents GAC and ACF at Various Temperatures

			Freundlich parameters		
Adsorbent	Adsorption temperature (K)	Concentration range[a] (ppmv)	K_F ($\mathrm{mol}^{1-1/n}\cdot\mathrm{m}^{3/n}\cdot\mathrm{kg}^{-1}$)	$1/n$	R^2
GAC	283	398–1954	3.95	0.14	0.9859
	293	399–1955	4.12	0.19	0.9906
	303	396–1954	4.16	0.23	0.9981
	313	401–1952	3.98	0.27	0.9993
ACF	283	428–1716	8.28	0.35	0.9930
	293	429–1715	7.87	0.39	0.9976
	303	435–1739	6.55	0.41	0.9977
	313	422–1729	6.54	0.48	0.9869

[a] Five data at each specified temperature.

sorbent carbon surface is a nonuniform property. Therefore, its adsorption isotherm would be suitably described and fitted to an empirical equation; that is, the Freundlich isotherm would provide a better fit to the data than the Langmuir model. This is consistent with the results of Tables 2 and 3. The $1/n$ values of adsorbent ACF are obviously higher than those of adsorbent GAC, and the $1/n$ values of both adsorbents increase with increasing temperature. Also, the K_F values of adsorbent ACF are larger than those of adsorbent GAC at the same temperature. This is consistent with the results based on the Langmuir analysis, namely, adsorbent ACF has a higher capacity for the adsorption of HCFC-141b vapor than does adsorbent GAC because of the larger BET surface areas and pore volumes in adsorbent ACF.

Dubinin–Radushkevich (D-R) Model

The Dubinin–Radushkevich (D-R) equation is usually used to describe the physical adsorption of organic vapors on microporous adsorbents. It is based on the micropore volume-filling theory and the Polanyi concept of adsorption potential (27). The D-R equation can be expressed as

$$W = W_0 \exp[-(\kappa/\beta^2)\{RT \ln(P_{sat}/P)\}^2] \tag{3}$$

where W is the equilibrium adsorption capacity, W_0 is the total volume of the micropores accessible to the given adsorbate, κ is a characteristic constant related to the pore structure of the adsorbent, β is an affinity coefficient, P_{sat} is the saturated pressure of liquid adsorbate at adsorption temperature T, and P is the partial pressure of adsorbate vapor in equilibrium. The affinity coefficient, β, in Eq. (3) has been correlated with several physical properties of the adsorbate such as liquid molar volume, molecular parachors, and electronic polarization (31). In this study it is reasonably assumed that β can be calculated by the ratio of the electronic polarization of the adsorbate, P_e, to that of the nopolar reference adsorbate (e.g., benzene) (32) because HCFC-141b is a polar adsorbate (33). The electronic polarization, P_e (m^3/mol), is defined as

$$P_e = \left(\frac{n_r^2 - 1}{n_r^2 + 2}\right)\frac{M}{\rho} \tag{4}$$

where n_r is the refractive index of the liquid adsorbate, M is the molecular weight of the adsorbate, and ρ is the liquid density of the adsorbate. The physical parameters (P_{sat}, ρ, and n_r) over the range from 283 to 313 K can be obtained from *Handbook of Chemistry and Physics* (34) and other references (20, 21).

From plots of $\ln(W)$ versus $[RT \ln(P_{sat}/P)]^2$, the parameters κ and W_0 in the D-R equation were determined by the slope, $-\kappa/\beta^2$, and the intercept, $\ln(W_0)$, of the linear lines (with the correlation coefficients of 0.9918 and 0.9956 for the adsorbents GAC and ACF, respectively) in Fig. 2. The values of D-R parameters W_0 and κ for the two carbon adsorbents are summarized in Table 4.

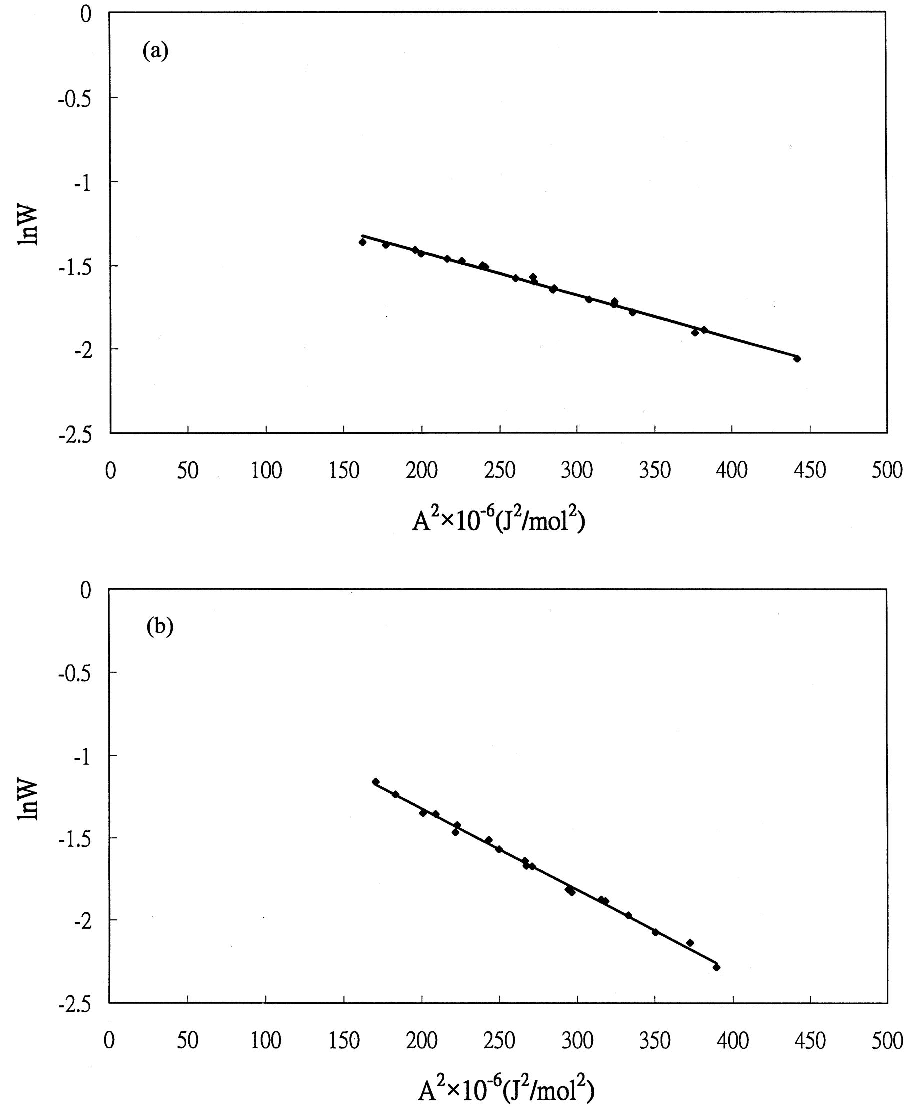

FIG. 2 Correlations of Dubinin–Radushkevich (D-R) equation for HCFC-141b adsorption on activated carbons. (a) GAC ($R^2 = 0.9918$); (b) ACF ($R^2 = 0.9956$). Symbols: experimental data; full lines: calculated from Eq. (3).

TABLE 4
Dubinin–Radushkevich (D-R) parameters for Adsorption of HCFC-141b Vapor on Adsorbents GAC and ACF at Various Temperatures[a]

	D-R parameters		
Adsorbent	W_0 (cm^3/g)	κ	R^2
GAC	0.408	1.75×10^{-9}	0.9918
ACF	0.717	3.36×10^{-9}	0.9956

[a] β value of HCFC-141b is 0.82.

Several noteworthy features may be obtained from the results shown in Table 4 and comparisons with the data of Table 1. The value of W_0 of adsorbent ACF (i.e., 0.717 cm^3/g) is larger than that of adsorbent GAC (0.408 cm^3/g), supporting the fact that the adsorbent ACF contains more micropore volume.

It is noted that the results obtained in the present study only apply for specific adsorbate–adsorbent systems with a nonhumid stream. Because carbon's adsorption capacity drops greatly at 50–60% relative humidity (35), a humidity control (i.e., dehumidification) located upstream is often required in practical cases. It has been pointed out that the adsorption capacity is appreciably affected at relative humidities above 50% (7). The type of activated carbon and adsorbate may also affect the extent of impact of relative humidity on gas adsorption at the same adsorption temperature (36). Tsai and Chang (36) reported the effect of moisture on the ability of a GAC (made of coconut) to adsorb about 430 ppmv of 1,1,1-trichloroethane (chemically similar to HCFC-141b) vapor at 303 K for three different relative humidities, i.e., dry ($<3\%$), 60%, and 80%. The adsorption capacities thus obtained were 0.331, 0.313, and 0.267 g/g, respectively. Thus it may be reasonable to speculate that Yoon and Nelson's model parameters (i.e., τ and k') will be unaffected by relative humidities ranging from 0 to 50%. This expectation has been ascertained by the experimental results of Yoon and Nelson on a respirator cartridge (packed with activated carbon) for 1,1,1-trichloroethane vapor adsorption (37).

Dynamic Behavior of Fixed-Bed Adsorption

Many theoretical or empirical equations have been proposed for modeling adsorption breakthrough curves (27). These equations were theoretically addressed to describe the adsorbate diffusion in the porous adsorbent (e.g. activated carbon). It has been reported that breakthrough times (i.e., time to reach defined effluent concentrations) and adsorption capacities (i.e., amounts held at breakthrough) of adsorbent beds for a given adsorbate vapor are functions of the concentration of that vapor in air (19). Yoon and Nelson have developed a relatively simple model addressing the adsorption and breakthrough of adsorbate vapor with respect to activated charcoal (19). This model was based on the assumption that the rate of decrease in the probability of adsorption for each adsorbate molecule is proportional to the probability of adsorbate adsorption and the probability of adsorbate breakthrough on the adsorbent. Yoon and Nelson equation is not only less complicated than other equations, but also requires no detailed data concerning the characteristics of adsorbate, the type of adsorbent and the physical properties of adsorption bed. Therefore, the Yoon and Nelson equation is tentatively applied in this study to describe the breakthrough curves for adsorption of HCFC-141b vapor on adsorbents GAC and PCB at temperature of 283 K.

An expression of the Yoon and Nelson model (19) may be written as

$$t = \tau + \frac{1}{k'} \ln \frac{C_\mathrm{b}}{C_\mathrm{i} - C_\mathrm{b}} = \tau + \frac{\tau}{k} \ln \frac{C_\mathrm{b}}{C_\mathrm{i} - C_\mathrm{b}} \tag{5}$$

where t is the breakthrough (sampling) time; C_b and C_i are the breakthrough (effluent) concentration and inlet concentration, respectively; τ is the time required for 50% adsorbate breakthrough; k' is the rate constant; and k is a proportionality constant. It has been found that, in general, k is a constant for a given adsorbate and specified type of adsorbent, and also independent of the adsorbate concentration and the flow rate (19). On the other hand, both k' and τ are dependent on the adsorbate concentration and the flow rate. According to Eq. (5), the values of k', k, and τ can be determined from the slope and intercept of linear plots of $\ln C_\mathrm{b}/(C_\mathrm{i} - C_\mathrm{b})$ vs t. It is noted that the agreement between the Yoon and Nelson model and the experimental data is highly fitted in the present study, as listed in Table 5.

The results of Table 5 demonstrate that the value of τ decreases with increasing adsorbate inlet concentration while that of k' increases. The values of k, on the other hand, seem to be independent of adsorbate inlet concentration and are 11.86 ± 1.53 and 23.12 ± 2.72 for the adsorbents GAC and ACF, respectively. Further, the modeling breakthrough curves can be obtained for a given set of experimental conditions by applying Eq. (5) and using the deter-

TABLE 5

Parameters of Yoon and Nelson Model for Adsorption of HCFC-141b Vapor on Adsorbents GAC and ACF at Various Inlet Concentrations and 283 K

Adsorbent	Inlet concentration (ppmv)	Yoon and Nelson parameters: τ (min)	k' (min^{-1})	k	R^2
GAC[a]	399	147.7	0.092	13.56	0.9932
	734	92.1	0.145	13.34	0.9883
	1139	59.8	0.193	11.56	0.9925
	1531	49.2	0.216	10.63	0.9904
	1954	39.9	0.256	10.22	0.9963
ACF[b]	427	66.8	0.393	26.24	0.9941
	786	48.7	0.439	21.38	0.9831
	1070	40.5	0.584	26.69	0.9975
	1404	32.4	0.601	19.45	0.9897
	1729	27.6	0.900	24.84	0.9973

[a] The weight used in this study was 2.52 ± 0.01 g.
[b] The weight used in this study was 1.22 ± 0.01 g.

mined values of k' and τ (Table 5), as shown in Fig. 3. It is clear that the agreement between the model and experimental results is very satisfactory in our experiments (Fig. 3). As shown in Fig. 3, very steep breakthrough curves were obtained for the adsorption of HCFC-141b onto the adsorbent ACF. This characteristic shape has already been mentioned in the review of Suzuki (12). However, the sharper shapes of the breakthrough curves observed in the ACF bed suggests smaller overall mass-transfer resistance compared with those obtained in the GAC bed in the present study.

Obviously, the use of Yoon and Nelson equation is good for the design of a fixed-bed adsorber because the information on the kinetic parameters (e.g., k' and τ) can be easily obtained in the adsorption breakthrough system. Nevertheless, another approach was developed to obtain the relevant kinetic parameters (i.e., intraparticle mass transfer coefficient) by using the effective diffu-

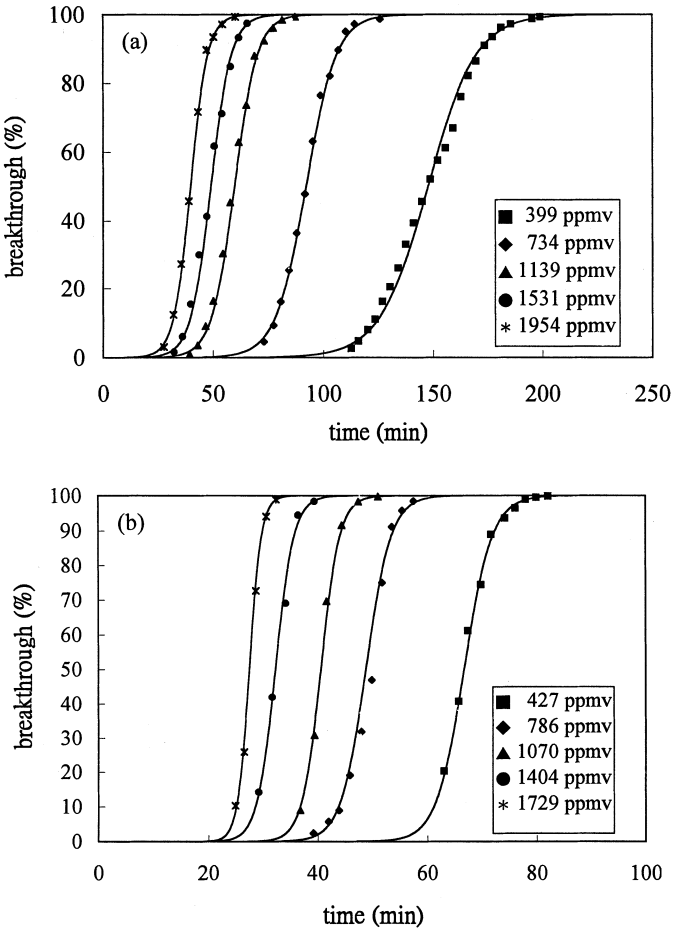

FIG. 3 Breakthrough curves of HCFC-141b adsorption on activated carbons at various concentrations. (a) GAC; (b) ACF. Symbols: experimental data; full lines: calculated from Eq. (5) and Table 5.

sion model (31). This model describes the intraparticle diffusion in terms of the effective intraparticle diffusion coefficient, D_e. Future work on the prediction of adsorption breakthrough behavior by solving a general material balance equation would be helpful. As a first approximation, D_e is generally given by

$$D_e = \varepsilon/\delta/[(1/D_m) + (1/D_K)] \tag{6}$$

where ε is particle porosity, δ is tortuosity factor, D_m is molecular diffusivity, and D_K is Knudsen diffusivity. The tortuosity factor δ generally fall within the 2–6 range (26, 27). Also, it is known that ACF possesses a uniformly narrow and straight pore structure. Assuming the particle porosity ε to be equal to 0.6 for GAC and 0.4 for ACF (38), and the tortuosity factor δ to be equal to 4.0 for GAC (27) and 2.0 for ACF, D_e was calculated from Eq. (6) to be approximately equal to 1.69×10^{-8} m^2/s for GAC and 1.96×10^{-8} m^2/s for ACF. It is significant that the value of D_e for ACF is slightly larger than that for GAC and thus would result in faster adsorption kinetics compared with GAC, which is consistent with the results shown in Table 5.

CONCLUSIONS

The adsorption characteristics of HCFC-141b, currently used as a major replacement for CFCs, on commercial carbon adsorbents (granular activated carbon, GAC; activated carbon fiber, ACF) were investigated in the fixed-bed adsorption system. From the experimental results and data regression analysis, adsorption equilibrium relationships (isotherms) were obtained in the 283–313 K temperature range and found to agree well with the Langmuir, Freundlich, and Dubinin–Radushkevich (D-R) equations. It was also found that the parameters q_m, K_F, W_0, and κ of these models thus obtained were higher for adsorbent ACF than for adsorbent GAC, probably due to ACF's higher specific surface area and the porous volume. Furthermore, the adsorption capacities of adsorbent ACF are higher than those of adsorbent GAC in the same conditions. The breakthrough curves obtained with adsorbent ACF at 283 K are steeper than those with adsorbent GAC. This is probably due to the small diameter of the fibers in adsorbent ACF, which results in the large external surface area exposed to the flowing gas. The simple two-parameter model of Yoon and Nelson was applicable for modeling the breakthrough curves of HCFC-141b vapor through a carbon adsorbent column. The parameters determined from the fitting of the experimental data with the model were introduced into the model to generate the entire breakthrough curves. The calculated empirical breakthrough curves were in good agreement with the corresponding experimental data in this study. Future work on a comparison of the results of batch experiments and column experiments will be helpful. It is also noted that the slight deviation shown by the presented data (i.e., equilibrium loading and Yoon and Nelson's parameter constants) when low humidity is present is both expected and inevitable.

NOMENCLATURE

A	adsorption potential defined as $RT \ln(P_{sat}/P)$ ($J \cdot mol^{-1}$)
C	adsorbate concentration ($mol \cdot m^{-3}$)
C_b	breakthrough concentration ($mol \cdot m^{-3}$)
C_i	inlet concentration ($mol \cdot m^{-3}$)
D_e	effective mass transfer coefficient ($m^2 \cdot s^{-1}$)
D_K	Knudsen diffusivity ($m^2 \cdot s^{-1}$)
D_m	molecular diffusivity ($m^2 \cdot s^{-1}$)
K_F	parameter of Freundlich adsorption isotherm ($mol^{1-1/n} \cdot m^{3/n} \cdot kg^{-1}$)
K_L	adsorption equilibrium constant of Langmuir isotherm ($m^3 \cdot mol^{-1}$)
k	proportionality constant (dimensionless)
k'	rate constant (min^{-1})
M	molecular weight of adsorbate ($kg \cdot mol^{-1}$)
n	adsorption intensity defined by Freundlich isotherm (dimensionless)
n_r	refractive index of adsorbate liquid (dimensionless)
P	equilibrium pressure of adsorbate vapor (Pa)
P_e	electronic polarization of adsorbate (dimensionless)
P_{sat}	saturated vapor pressure of adsorbate (Pa)
q	adsorption capacity ($mol \cdot kg^{-1}$)
q_m	adsorption capacity at equilibrium ($mol \cdot kg^{-1}$)
R	gas constant ($= 8.314\ J \cdot mol^{-1} \cdot K^{-1}$)
T	temperature (K)
t	breakthrough time (min)
W	adsorption capacity ($cm^3 \cdot g^{-1}$)
W_0	active pore volume ($cm^3 \cdot g^{-1}$)
β	affinity coefficient (dimensionless)
δ	tortuosity factor (dimensionless)
ε	particle porosity (dimensionless)
κ	structural constant (dimensionless)
ρ	adsorbate liquid density ($kg \cdot m^{-3}$)
τ	time required for 50% adsorbate breakthrough (min)

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