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Chemical Engineering Journal 98 (2004) 237–243

Chemical Engineering Journal

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Apparent desorption kinetics of phenol in organic solvents from spent activated carbon saturated with phenol

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Accepted 13 October 2003

Abstract

This paper presents the result of an experimental work designed to develop a desorption kinetic model of phenol from activated carbon (AC) by acetone, *N*,*N*-dimethylformamide (DMF), and methanol. The kinetic model assumed that a driving force for desorption might be accounted for by the difference between the equilibrium concentration of phenol in solvents corresponding to its adsorbed amount on AC and the bulk phenol concentration in solvents at a time. The equilibrium concentration of phenol in solvents was estimated from a non-linear relationship with its adsorbed amount on AC at a time. Apparent desorption rate constants were described as a function of temperature by Arrhenius relationship. Desorption rate of phenol increased with desorption temperature of solvents. The desorption rates attained by acetone and DMF were close each other but greater than those by methanol. Theoretical kinetic results duplicated experimental data quite well, supporting the practicality of the proposed kinetic model. Acetone and DMF were found to be more efficient for desorbing phenol from AC than methanol.

Keywords: Spent activated carbon; Phenol; Acetone; DMF; Methanol; Desorption kinetic model

1. Introduction

Activated carbon (AC) has been widely used in various fields due to its outstanding adsorption capacity of organic compounds. AC can remove harmful organic compounds from industrial wastewaters. Recently, the demand for AC is growing rapidly in Korea as the emission standards of treated wastewater become more stringent. However, a disadvantage of using AC is its high cost in both operation and disposal of spent ones, which makes the regeneration of the spent activated carbon (SAC) economically feasible. Thermal regeneration has been a broadly applied method among various techniques, but, upon the regeneration, it suffers from production of air pollutants, a high energy input, decrease in hardness of AC, and enlargement of pore size.

As an alternative to the thermal regeneration, chemical regeneration of SAC using organic solvents might be a choice due to its high regeneration rates as well as recovery of the original integrity of SAC. Chemical regeneration becomes more economical than thermal regeneration as the amount of adsorbate increases [1]. In general, the chemical regeneration is considered economically infeasible insofar as expensive organic solvents are used as regenerants. Therefore, the chemical regeneration process should be optimized with respect to its economics and a study on desorption kinetics of organic solvents from SAC would be an essential part of it.

Most previous studies viewed the desorption of adsorbate in aqueous solution as the reverse process of adsorption [2–6]. Adsorption of contaminants on AC mainly occurred in aqueous solutions, whereas desorption of contaminants was commonly accomplished in organic solvents for effective regeneration. Therefore, application of the previously developed desorption models to the chemical desorption using organic solvents was not appropriate and the kinetic model that represents the chemical desorption process should be developed.

A few studies have been reported for desorption kinetics of adsorbates from AC by organic solvents. Sutikno and Himmelstein [7] used acetone to regenerate AC saturated with phenol and developed a desorption kinetic model assuming that a driving force for desorption might be the difference between the equilibrium concentration of phenol in acetone with the adsorbed amount on AC and bulk concentration in acetone. They assumed that the equilibrium concentration

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doi:10.1016/j.cej.2003.10.006

Nomenclature

A	pre-exponential factor (min^{-1})
C	concentration in solvent (mg/l)
C^*	equilibrium concentration of phenol in solvent with adsorbed amount on activated carbon (mg/l)
E	activation energy (J/mol)
k	reaction rate constant (min^{-1})
k_e	Freundlich parameter ($(\mathrm{mg/g})(\mathrm{mg/l})^{-n}$)
k_0	constant in Eq. (3) ($(\mathrm{mg/g})(\mathrm{mg/l})^{-n}$)
M_a	mass of activated carbon (mg)
n	reaction order
q	adsorbed amount of adsorbate on activated carbon (mg/g)
q_0	initial amount of adsorbate adsorbed on activated carbon (mg/g)
R	gas constant (8.314 J/mol K)
t	time (min)
T	absolute temperature (K)
T_c	celsius temperature (°C)
V	volume (ml)

Greek letters

α	constant in Eq. (6), q_0/k_e
β	constant in Eq. (6), $1/\rho_c k_e(1-\varepsilon)(V_s/V_a)$
γ	constant in Eq. (3) (K)
ε	porosity of activated carbon
η	maximum desorption rate (%)
ρ	true density of activated carbon (mg/ml)
τ	operational reaction time (h)

Subscripts

d	desorption
e	equilibrium
exp	experimental
i	ith point
max	maximum
p	phenol
s	solvent
theo	theoretical

of phenol in the acetone was correlated linearly with the adsorbed amounts on the AC [7]. However, other researchers reported that a non-linear relation might be more appropriate to describe the equilibrium concentrations of phenol with its adsorbed amount on AC [8,9].

Since the desorption of adsorbates is a temperature dependent process [5,8–11], determination of the optimal desorption temperature should be a crucial factor in designing an energy efficient process. Little effort has been made, however, to quantify the effect of temperature on the desorption kinetics of adsorbates by organic solvents.

Phenol is a representative of the organic contaminants found in industrial wastewaters. This paper presents the results of the experimental work for the development of a desorption kinetic model of phenol from AC using organic solvents as regenerants. In this study, phenol was chosen as an adsorbate, while acetone, *N*,*N*-dimethylformamide (DMF), and methanol were used as organic solvents. Temperature dependency of the model was investigated as well. Apparent desorption rate constants were estimated for practical application of the model.

2. Desorption kinetic model

Desorption of phenol from AC was described by the mass transfer from AC to organic solvents. The desorption kinetic model based on mass transfer and kinetic equation was expressed by

$$\frac{\mathrm{d}C_p}{\mathrm{d}t} = k_d(C_p^* - C_p) \tag{1}$$

The assumptions of the kinetic equation were as follows:

1. Driving force of desorption might be the difference between the equilibrium concentration in a solvent with the adsorbed amount of phenol on AC at a time and the bulk concentration of phenol in organic solvents.
2. At equilibrium, the relationship between the concentration of phenol in organic solvent (C_p^*) and the adsorbed amount on the AC (q_p) might be expressed like the Freundlich isotherm equation:

$$q_p = k_e(C_p^*)^n \tag{2}$$

k_e was expressed as an exponential function to temperature [8,9,12–14]:

$$k_e(T) = k_0 \exp\left(\frac{\gamma}{T}\right) \tag{3}$$

On the other hand, q_p was estimated by

$$q_p = q_0 - \frac{C_p V_s}{\rho_a(1-\varepsilon)V_a} \tag{4}$$

By letting Eqs. (2) and (4) be equal, C_p^* could be computed as follows:

$$C_p^* = \left\{\frac{q_0}{k_e} - \frac{1}{\rho k_e(1-\varepsilon)}\left(\frac{V_s}{V_a}\right)C_p\right\}^{1/n} \tag{5}$$

Substituting Eq. (5) into Eq. (1) yielded the following kinetic equation in the liquid phase:

$$\frac{\mathrm{d}C_p}{\mathrm{d}t} = k_d\left\{(\alpha - \beta C_p)^{1/n} - C_p\right\} \tag{6}$$

The fourth order Runge–Kutta method was applied to solve Eq. (6) with an initial condition of C_p being zero ($C_p(0) = 0$). The k_d was chosen to allow the best fit to the experimental kinetic data of C_p. The best fit was determined based on a minimum reduced root-mean-square (RMS) deviation that is described by

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(C_{\mathrm{exp},\,i} - C_{\mathrm{theo},i})^2}{C_{\mathrm{exp},\,i}^2}} \quad (7)$$

In order to account for the time dependency of the desorption rate constant, k_d, Arrhenius equation was introduced as follows [11]:

$$k_\mathrm{d} = A_\mathrm{d} \exp\left(-\frac{E_\mathrm{d}}{RT}\right) \quad (8)$$

It was necessary to verify the desorption kinetic model which was based on film transfer model. One of the reliable ways to verify the desorption model would check the validity of key parameters related to the assumptions of the model. In this study, the k_d would be regarded as a key parameter. Reasonable way to check the validity of k_d would be to compare experimental desorption kinetic results at certain temperatures with predicted ones. The model verification was carried out in Section 4.

3. Experimental

3.1. Preparation of activated carbons saturated with phenol

Granular activated carbons (Calgon F-300, 8 × 30 mesh) were repeatedly rinsed with Milli-Q water to remove the fines, dried overnight at 110 °C, and stored under vacuum in a desiccator. About 1 g of AC prepared by the above procedures was put into a glass bottle with Teflon-lined caps containing 150 ml of 2000 mg/l phenol solutions. The bottles were placed in a shaker and mixed at 300 rpm for period of up to 2 weeks at 25 ± 1 °C. Then the AC was separated from the solution via vacuum filtration through a 0.45 μm membrane filter. The adsorbed amount of phenol on the AC was estimated to be 184.7 mg/g by calculating the difference of phenol concentration between initial and final aqueous solution. Phenol in the aqueous solution was analyzed by calorimetric method using UV-Vis Spectrophotometer (SMART PLUS 2700) at a wavelength of 500 nm [15].

3.2. Equilibrium experiments of phenol

Organic solvents used here were acetone (99.8% purity, Carlo Erba Reagenti Co.), DMF (99.9% purity, Mallinckrodt Co.), and methanol (99.8% purity, AnalaR Co.). Five different quantities (0.1, 0.3, 0.5, 0.7, and 0.8 g) of pulverized SACs were separately put into the 150 ml bottles with Teflon-lined caps. Three sets of bottles were prepared for the equilibrium tests for each of the three solvents. To avoid any solvent evaporation, no headspace was allowed in the bottles. The bottles were placed in a shaking incubator (SI-600R, JEIO TECH Co.) followed by mixing at 300 rpm for 2 weeks at four different temperatures of 25 ± 1, 35 ± 1, 45 ± 1, and 55 ± 1 °C. Two blanks were included for each solvent.

3.3. Desorption kinetic experiments of phenol

For desorption kinetic tests, the changes in phenol concentration of the solvents with time (total desorption time = 550 min) were recorded. Bottles with Teflon-lined caps were prepared to load identical doses of pulverized SAC (184.7 mg/g) in fresh solvents of 150 ml and the bottles were shaken in a shaking incubator at 300 rpm at the four different temperatures that were kept constant (25 ± 1, 35 ± 1, 45 ± 1, and 55 ± 1 °C). No headspace was allowed in the test bottles and two blanks were prepared. At each sampling time, a bottle was sacrificed and two 1 ml solutions were collected from the bottle by a pipette immediately to minimize solvent evaporation. The solutions were then filtered through a 0.45 μm membrane filter. UV-Vis Spectrophotometer (SMART PLUS 2700) was used to measure the phenol concentrations in the filtrates at a wavelength of 270 nm.

4. Results and discussion

4.1. Estimation of equilibrium constant (k_e)

If the SAC would be put into a batch reactor filled with fresh solvents, the concentration of phenol in the solvents might increase with time, whereas the amount of phenol on the AC might decrease. The equilibrium state at which the concentration of phenol in the solvents remained constant with time was achieved in 1–2 days under the desorption conditions used in this study.

After taking natural logarithm of Eq. (2), the equilibrium constant (k_e) was obtained from the intercept of the plot of $\ln C_\mathrm{e}$ versus $\ln q_\mathrm{e}$ and the Freundlich constant (n) from the slope of the plot. As shown in Table 1, the squares of correlation coefficient (R^2) for the plots of $\ln C_\mathrm{e}$ versus $\ln q_\mathrm{e}$ are close to unity for all occasions, suggesting the appropriateness of Eq. (2) describing the equilibrium state. The values of k_e and n were close for the three solvents. In particular, the proximity of the values for acetone and DMF implied that both solvents exhibited nearly identical desorption patterns for phenol.

The k_e values were evaluated at several temperatures and the k_e decreased with increasing desorption temperature (Table 1). As shown in Eq. (9), k_e was expressed in its logarithmic form as a function of reciprocal of temperature. The slope and intercept in Fig. 1, respectively, correspond to γ and $\ln k_0$ in Eq. (9):

$$\ln k_\mathrm{e} = \ln k_0 + \gamma\left(\frac{1}{T}\right) \quad (9)$$

The γ values for acetone, DMF, and methanol were 270.02, 285.23, and 64.87 K, respectively, while the k_0 values are

Table 1
Equilibrium constants and reaction order for isothermal desorption of phenol from activated carbon in acetone, DMF, and methanol at operating temperatures of 25, 35, 45, and 55 °C ($q_0 = 184.7$ mg/g)

Temperature (°C)	Acetone			DMF			Methanol		
	k_e ((mg/g) (mg/l)$^{-n}$)	n	R^2 [a]	k_e ((mg/g) (mg/l)$^{-n}$)	n	R^2 [a]	k_e ((mg/g) (mg/l)$^{-n}$)	n	R^2 [a]
25	1.0688	0.3046	0.9984	1.0749	0.3021	0.9984	1.1352	0.3210	0.9967
35	1.0384	0.3083	0.9972	1.0449	0.3038	0.9973	1.1273	0.3240	0.9958
45	1.0053	0.3121	0.9978	1.0079	0.3052	0.9976	1.1207	0.3351	0.9962
55	0.9855	0.3187	0.9930	0.9872	0.3074	0.9938	1.1125	0.3467	0.9935
Average		0.3109			0.3046			0.3317	

[a] Square of linear correlation factor of $\ln C_e$ vs. $\ln q_e$.

0.432, 0.413, and 0.913 (mg/g) (mg/l)$^{-n}$, respectively. Little difference was noticed for the values of γ and k_0 between acetone and DMF, which coincided with the proximity of the k_e values between the two solvents (Table 1). Methanol demonstrated lower γ but higher k_0 than both acetone or DMF.

As shown in Table 1, the average values of n for acetone, DMF, and methanol over the entire temperature range tested, respectively, were 0.3109 ± 0.0096, 0.3046 ± 0.0036, and 0.3317 ± 0.0186 within a confidence interval of 95%. Because relative standard deviations of the n values fell within 4%, the n value demonstrated reasonably similar values with respect to temperature.

The desorption of phenol from AC should occur maximally at the equilibrium, and at this time, the maximum desorption rate of phenol in a batch reactor is denoted by

$$\eta_{\max}\,(\%) = \frac{q_0 - q_e}{q_0} \times 100 = \frac{C_e}{q_0}\left(\frac{V_s}{M_a}\right) \times 100 \tag{10}$$

Eq. (10) was plotted in Fig. 2, in which the C_e was estimated from Eq. (11) by trial-and-error method. A tolerance of 10^{-5} was introduced in numerical evaluation of the C_e.

$$C_e = \frac{M_a}{V_s}\left(q_0 - k_e C_e^{1/n}\right) \tag{11}$$

Experimental data fitted reasonably well to the theoretical $\eta_{\max}$ values (Fig. 2), suggesting that Eq. (10) could be used to predict a maximum desorption rate for specific loading conditions (V_s, M_a, and q_0).

As shown in Fig. 2, $\eta_{\max}$ increased rapidly when V_s/M_a was lower than 25 l/kg. However, the increasing rate of $\eta_{\max}$ slowed and it became insensitive to the applied volume of the solvents when V_s/M_a was over 50 l/kg.

4.2. Determination of apparent desorption rate constant

In order to determine how fast a target desorption rate would be achieved, apparent desorption rate constant (k_d) was estimated. As already mentioned in the theoretical section, the k_d that allowed the best fit to experimental kinetic data of phenol concentration in solvents (C_p) was chosen. Fig. 3 shows excellent data fits over the entire temperature conditions. From the best fit, apparent desorption rate constants for the three organic solvents were determined and those for acetone and DMF were close each other (Table 2),

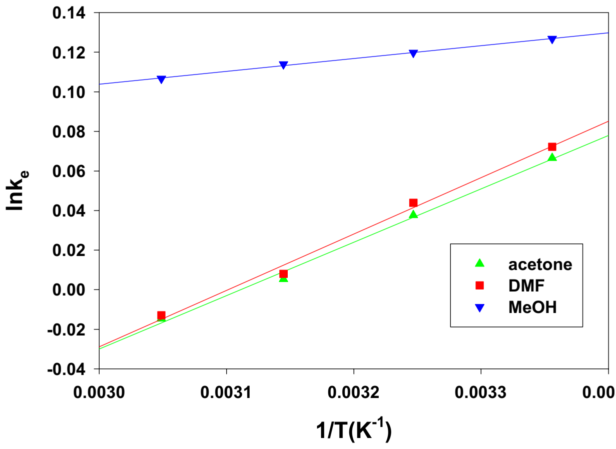

Fig. 1. Natural logarithm of equilibrium constant (k_e) of phenol in acetone, DMF, and methanol with its adsorbed amount on activated carbon with respect to the reciprocal of absolute temperature ($q_0 = 184.7$ mg/g).

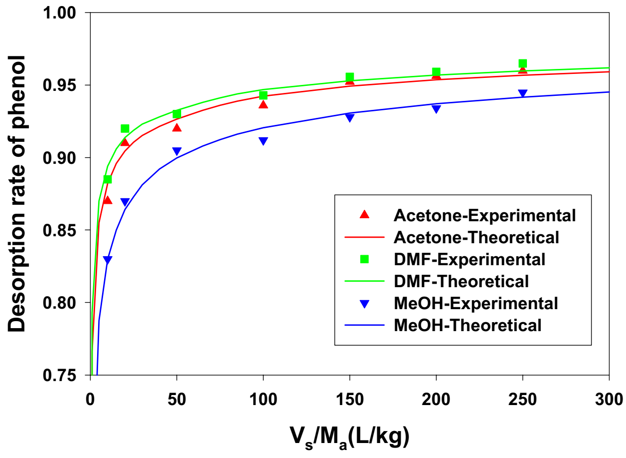

Fig. 2. Desorption rate of phenol as a function of applied volume of acetone, DMF, and methanol per unit mass of spent activated carbon ($q_0 = 184.7$ mg/g, reaction temperature: 55 °C).

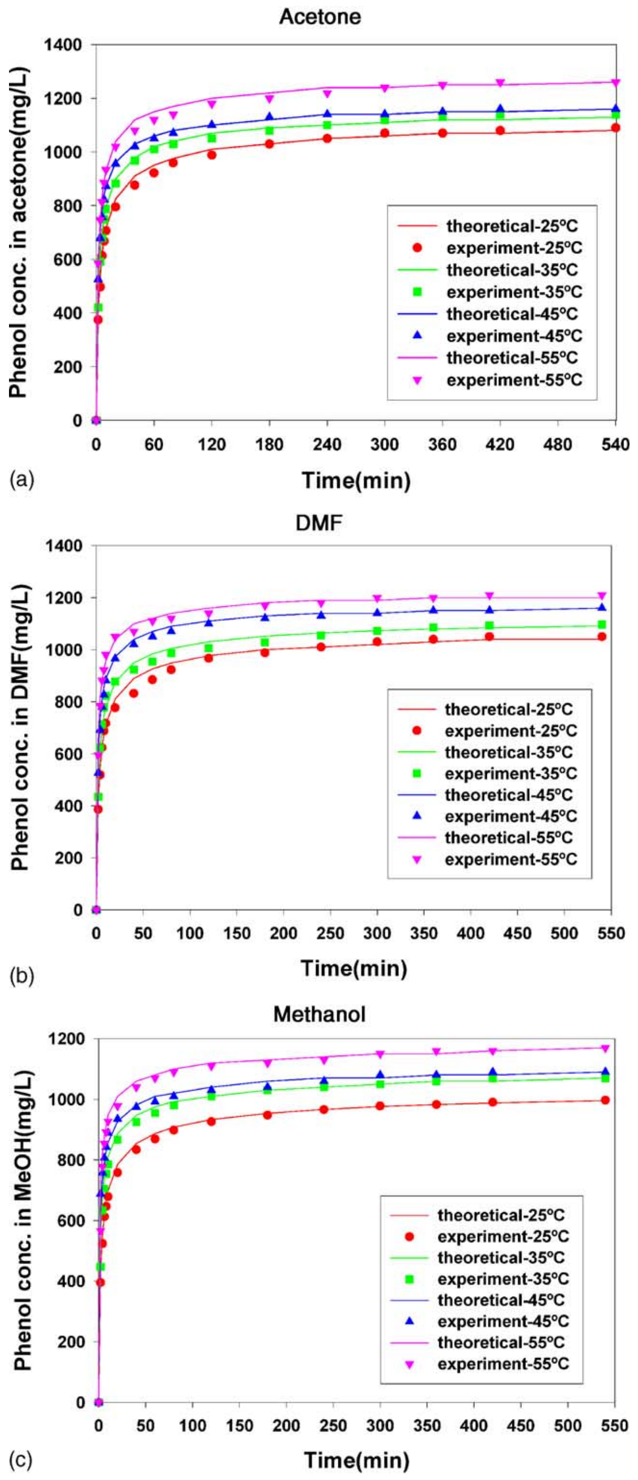

Fig. 3. Comparison of theoretical desorption kinetic results of phenol by acetone, DMF, and methanol with experimental ones at reaction temperatures of 25, 35, 45, and 55 °C ($q_0 = 184.7$ mg/g, $V_s/M_a = 150$ ml/g).

whereas those for methanol were lower at the desorption temperatures used here.

Temperature dependency of k_d was proposed as shown by Eq. (8). The properness of Eq. (8) would be checked by the linearity of the plot of $1/T$ versus $\ln k_d$. The squares of linear correlation coefficient (R^2) for acetone, DMF, and methanol were estimated to be 0.9984, 0.9974, and 0.9988, respectively. Therefore, the Arrhenius relationship could be justifiable for representing the temperature dependency expression of k_d. Furthermore, the excellent temperature dependency expression of k_d might indirectly supporting the properness of k_d values as well as that of the desorption kinetic model introduced in this study.

Table 2
Desorption reaction constants (k_d) of phenol from activated carbon by acetone, DMF, and methanol at operating temperatures of 25, 35, 45, and 55 °C ($q_0 = 184.7$ mg/g)

Temperature (°C)	k_d (min^{-1})		
	Acetone	DMF	Methanol
25	1.7111E−05	1.6368E−05	1.1328E−05
35	2.2506E−05	2.1810E−05	1.5348E−05
45	2.7732E−05	2.7330E−05	2.1150E−05
55	3.4530E−05	3.3528E−05	2.7090E−05

The activation energy of k_d was obtained from the slope ($-E_d/R$) of natural logarithm of Eq. (8), and frequency factor from the intercept ($\ln A_d$). The activation energy (k_d) was 18.83, 19.34, and 23.88 kJ/mol for acetone, DMF, and methanol, respectively, while the frequency factor was 0.0345, 0.0408, and 0.173 min^{-1}, respectively. When k_d value of phenol might be expressed as an exponential function of temperature, the equation for each solvent is as follows:

$$\text{acetone}: \quad k_d\ (\text{min}^{-1}) = 0.0345 \exp\left(-\frac{2264.60}{T}\right) \tag{12}$$

$$\text{DMF}: \quad k_d\ (\text{min}^{-1}) = 0.0408 \exp\left(-\frac{2326.22}{T}\right) \tag{13}$$

$$\text{methanol}: \quad k_d\ (\text{min}^{-1}) = 0.173 \exp\left(-\frac{2871.86}{T}\right) \tag{14}$$

As a result of using Eqs. (12)–(14), the desorption kinetics of phenol from SAC in the three organic solvents would be predicted at certain desorption temperatures.

4.3. *Determination of desorption time*

A desorption time was defined as the time it took to reach an equilibrium state of phenol at a temperature between solid phase (AC) and liquid phase (solvent). The time when C_p reached the 99% of C_e was defined as an operational desorption time. In the case of batch operation, the operational desorption time was estimated by solving Eq. (5) numerically to find out the time required for C_p to reach C_e.

As expected, the operational reaction times for acetone and DMF were almost identical and so were the maximum desorption rates, whereas those for methanol were lower than those for acetone and DMF (Table 3). Theoretical desorption times were similar to those obtained from experimental kinetic data within an average deviation of 5% (Table 3).

Table 3
Operational desorption reaction times and maximum desorption rates of phenol from spent activated carbon by acetone, DMF, and methanol at operating temperatures of 25, 35, 45, and 55 °C ($V_s/M_a = 150$ ml/g, $q_0 = 184.7$ mg/g)

Solvent	Temperature (°C)	Operational reaction time and deviation			Maximum desorption rate (%)
		Theoretical (h)	Experimental (h)	Deviation (%)	
Acetone	25	7.32	7.12	2.81	83.35
	35	6.47	6.22	4.02	87.71
	45	5.36	5.13	4.48	92.43
	55	4.64	4.78	2.93	95.83
DMF	25	7.28	7.08	2.83	83.28
	35	6.36	6.14	3.58	87.39
	45	5.28	5.46	3.30	92.26
	55	4.57	4.66	1.93	95.27
Methanol	25	7.03	6.82	3.08	78.25
	35	6.34	6.14	3.26	83.51
	45	5.37	5.12	4.88	86.82
	55	4.68	4.58	2.18	90.55

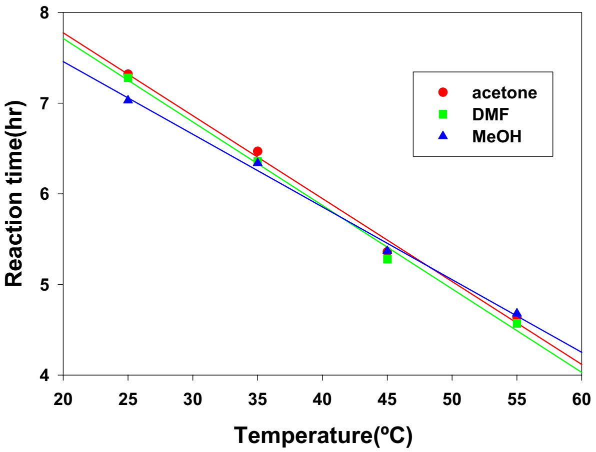

Fig. 4. Reaction time of spent activated carbon saturated with phenol by acetone, DMF, and methanol with respect to reaction temperature ($q_0 = 184.7$ mg/g, $V_s/M_a = 150$ ml/g).

The desorption time decreased linearly with increasing desorption temperature (Fig. 4). Based on the linear relationships, the operational desorption time with respect to temperature was empirically expressed in Table 4. In the case of $V_s/M_a = 150$ ml/g and $q_0 = 184.7$ mg/g, the operational desorption times for a batch operation ranged from ~7 h at 25 °C to ~4.5 h at 55 °C. As pointed out by Mollah and Robinson [16], a single batch operation seemed to be impractical in desorbing the phenol from the AC because it requires relatively long desorption time and large amount of solvents.

Although the empirical equations in Table 4 would be applicable only for the specific desorption conditions tested here, a practical method estimating the design parameters to remove organic pollutants from the SAC was demonstrated in this work.

4.4. *Verification of desorption kinetic model*

One of the most reliable ways to check the validity of the kinetic model would be the comparison of theoretical kinetic results with experimental ones at certain reaction temperatures. To this end, three kinetic results at reaction temperatures of 30, 40, and 50 °C were chosen, because they were different from those (25, 35, 45, and 55 °C) used to evaluate the kinetic parameters (activation energy and pre-exponential factor). The k_d values of three organic solvents at reaction temperatures of 30, 40, and 50 °C were estimated from substituting the kinetic parameter values into Eqs. (12)–(14). From the k_d values, the theoretical kinetic results of three organic solvents were constructed at desorption temperatures of 30, 40, and 50 °C. The theoretical results were compared with the experimental ones, as shown in Fig. 5. The predicted kinetic results were in good agreement with experimental ones within an average deviation of ~7% (acetone: 7.3%, DMF: 5.4%, methanol: 5.5%), supporting the properness of k_d values as well as the kinetic model at least within a temperature range of 25–55 °C.

According to the comparison results between theoretical and experimental kinetic results, the assumption of film

Table 4
Empirical expressions for maximum desorption rate and operational desorption reaction time as a function of reaction temperature

Solvent	Maximum desorption rate (%) with respect to reaction temperature	Operational desorption reaction time (h) with respect to reaction temperature
Acetone	$\eta = 0.4216T_c + 72.9660$, $R^2 = 0.9958$	$\eta = 0.0915T_c + 34.857$, $R^2 = 0.9940$
DMF	$\eta = 0.4084T_c + 73.2140$, $R^2 = 0.9923$	$\eta = 0.0921T_c + 34.700$, $R^2 = 0.9941$
Methanol	$\eta = 0.4021T_c + 68.6985$, $R^2 = 0.9894$	$\eta = -0.0802T_c + 30.958$, $R^2 = 0.9951$

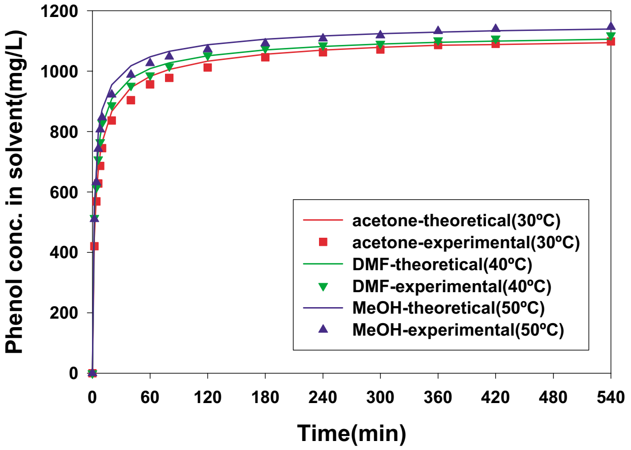

Fig. 5. Comparison of experimental desorption kinetic results of phenol with theoretical ones derived from the estimated k_d values from Eqs. (12)–(14) at reaction temperatures of 30, 40, and 50 °C for acetone, DMF, and methanol, respectively ($q_0 = 184.7$ mg/g, $V_s/M_a = 150$ ml/g).

transfer model used here seemed to be acceptable. In addition, the predicted desorption times resemble those of experimental ones (Table 3), also supporting the properness of the desorption kinetic model derived here. Therefore, the role of pore diffusion in the experimental conditions used here would not be so significant as it was firstly expected. One of the possible explanations would be accounted for by the use of pulverized activated carbon which might have minimized the role of pore diffusion. At least, this simple model developed here simulated the experimental kinetic results excellently. Hence, the desorption model introduced here offered an insight into designing the chemical desorption of SAC using the organic solvents for engineering application.

5. Conclusions

A desorption model was developed here based on mass transfer of phenol from solid phase (AC) to liquid phase (organic solvent). A driving force for desorption was assumed to be accounted for by the difference between the equilibrium concentration of phenol in solvents with adsorbed amount on AC and its bulk concentration in solvents. The model assumed that the amount of phenol adsorbed on AC at equilibrium might be correlated with phenol concentration in solvents with a non-linear relationship of *n*th order. Theoretical kinetic results of phenol concentration in solvents derived from the desorption model demonstrated good agreements with the experimental data, suggesting that the desorption model would be practically useful to design the chemical desorption process using organic solvents.

Apparent desorption rate constants of phenol for the three solvents were temperature dependent with the Arrhenius relationship. Arrhenius parameters, activation energy and pre-exponential factor, were estimated by a simple differential method. The reliability of kinetic parameters was verified by comparing predicted kinetic results with experimental ones at different temperatures from those which were used to evaluate the kinetic parameters. The apparent desorption rate increased with temperature. The desorption rates of acetone and DMF were in a close proximity, and they were higher than those of methanol. Both acetone and DMF were found out to be more efficient than methanol. Since DMF is a toxic substance, acetone may be a better candidate for practical application.

Acknowledgements

This work was supported by the Hallym Academy of Sciences, Hallym University, South Korea, 2000–2001.

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