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# Adsorption isotherms of phenols from water onto macroreticular resins

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## Abstract

The amounts of equilibrium adsorption of phenol and 4-chlorophenol from water on non-ionic macroreticular resins were measured in the temperature range 288–318 K. It was shown that the isotherm data could not be fit by any conventional two- or three-parameter equation including the Langmuir, Freundlich, BET, and Redlich–Peterson equations over the entire range of concentration (1–32 mol m<sup>-3</sup>). They were well fit by combined BET equation or its modified form with the Freundlich or Langmuir equation, depending on the types of solutes and the resins. Such different fitting results could be related to the solute–resin interactions owing to the relatively wide pore size distribution of the resins. The effect of temperature on adsorption equilibrium was also discussed. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Phenol; 4-Chlorophenol; Macroreticular resins; Adsorption; Isotherm analysis

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## 1. Introduction

Phenolic compounds including substituted phenols are versatile raw materials and/or solvents in the petroleum and other chemical processes. Almost all phenolic compounds are highly toxic at the concentration discharged into the receiving effluents. Increasing

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*Abbreviations:*  $C_e$ , Aqueous-phase solute concentration at equilibrium (mol m<sup>-3</sup>);  $C_s$ , Saturated solute concentration in the aqueous phase (mol m<sup>-3</sup>);  $C_0$ , Initial solute concentration in the aqueous phase (mol m<sup>-3</sup>);  $D_p$ , Pore size of the adsorbent (m);  $D_s$ , Diameter of solute molecule (m);  $\Delta H$ , Apparent enthalpy of adsorption (kJ mol<sup>-1</sup>);  $K$ , Equilibrium constants defined in Eqs. (2)–(6);  $m$ , Parameter in the Freundlich equation;  $n$ , Number of layers defined in Eq. (3);  $R$ , Universal gas constant (J mol<sup>-1</sup> K<sup>-1</sup>);  $q_e$ , Amount of phenols adsorbed at equilibrium (mol kg<sup>-1</sup>);  $V$ , Volume of the solution (m<sup>3</sup>);  $V_p$ , Pore volume of the adsorbent (m<sup>3</sup>);  $W$ , Weight of the dry resins (kg)

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concern for public health and environmental quality has led to the establishment of rigid limits on the acceptable environmental levels of specific pollutants. Thus, the removal or destruction of phenols from process or waste streams becomes a major environmental problem [1].

Liquid-phase adsorption is shown to be effective for collection of suspended solids, odors, organic matter, and oils. Powdered or granular activated carbon is the most widely used adsorbent for this purpose. In recent years, non-ionic macroreticular polymeric resins have been increasingly viewed as an alternative to activated carbon for the removal of organic pollutants from waste streams. Previous studies indicated that the macroreticular resins have a lower adsorption capacity for most organics than the activated carbon on a mass basis [2]; however, they can selectively remove low-molecular-weight organics [3]. The wide variations in functionality, surface area, and porosity available for the resins present the possibility for selective removal of specific organics [4,5]. Furthermore, the regeneration of the resins can easily be accomplished with a solvent [6], while a high temperature and/or steam is needed for regeneration of the activated carbon [7].

A large amount of batch equilibrium studies have been made for the adsorption of phenols on commercial or synthetic non-ionic polymeric resins [8–17]. In this work, we focused on analysis of adsorption isotherms of phenol and 4-chlorophenol on Amberlite XAD macroreticular resins at different temperatures over a relatively wider range of concentration ( $< 32 \text{ mol m}^{-3}$ ) using either theoretical or empirical equations. This would be important because the isotherm describes how solutes interact with adsorbents and so is critical in optimizing the use of adsorbents.

## 2. Experimental

### 2.1. Resins, reagents and solutions

Two non-ionic macroreticular resins Amberlite XAD-4 and XAD-7 were offered from Rohm and Haas. Their physical properties are listed in Table 1. Prior to use, they were washed with deionized water (Millipore Milli-Q) several times to remove inorganic

Table 1  
Properties of non-ionic macroreticular resins provided from the manufacturer

Property	Amberlite XAD-4	Amberlite XAD-7
Structure	aromatic, styrene-divinylbenzene	aliphatic, methyl methacrylate
Hydrophobicity	hydrophobic	moderately polar
BET surface area ( $\text{m}^2 \text{g}^{-1}$ ) <sup>a</sup>	730	310
Mean pore diameter (nm) <sup>a</sup>	4.6	5.8
Pore volume ( $\text{cm}^3 \text{g}^{-1}$ ) <sup>a</sup>	0.841	0.448
Porosity ( $\text{g cm}^{-3}$ ) <sup>a</sup>	0.590	0.584
Particle size (wet mesh)	20–50	20–50
Swelling ratio <sup>b</sup>		
in water	1.02	1.14
in phenol (88 wt.%)	1.18	1.20

<sup>a</sup>Measured by sorptometer in this work.

<sup>b</sup>Taken from Ref. [12].

Table 2  
Physical properties of the solutes at 298 K

Solute	Surface area (m <sup>2</sup> /molecule) <sup>a</sup>	Cross-sectional distance (nm) <sup>b</sup>	Density (g cm <sup>-3</sup> )	Saturated concentration in water, C <sub>s</sub> (mol m <sup>-3</sup> )	pK <sub>a</sub> <sup>b</sup>
Phenol	3.05 × 10 <sup>-19</sup>	0.43	1.034	925	9.89
4-Chlorophenol	3.26 × 10 <sup>-19</sup>	0.50	1.265	202	9.41

<sup>a</sup>Taken from Ref. [12].

<sup>b</sup>Taken from Ref. [21].

impurities like Na<sub>2</sub>CO<sub>3</sub> and NaCl, followed by acetone and *n*-hexane to remove organic impurities, and then dried at 323 K in a vacuum for 2 h. The pore size distributions were determined from N<sub>2</sub> adsorption isotherms at 77 K with a sorptiometer (Porous Materials, Model BET-202A). Prior to use in the adsorption experiments, the resins were wet with methanol and then the methanol was thoroughly replaced with deionized water. They were stored in a desiccator containing deionized water in order to maintain constant moisture content.

The aqueous phase was prepared by dissolving analytical-reagent grade phenol or 4-chlorophenol (Merck) in deionized water without pH adjustment. During adsorption the pH varied slightly within 6.77–6.80 for phenol and 6.68–6.77 for 4-chlorophenol under the concentration range studied. Because they were much less than each pK<sub>a</sub> (Table 2), the dissociated forms of phenols were assumed to be absent in the aqueous phase.

## 2.2. Adsorption equilibrium experiments

A fixed amount of the resins (0.1 g) and 0.1 dm<sup>3</sup> of an aqueous phase were placed in a 0.25-dm<sup>3</sup> glass-stoppered flask and shaken at 130 rpm for 5 days using a thermostatted shaker bath (Firstek Model B603, Taiwan). Preliminary runs showed that the adsorption studied was nearly complete after 4 days. After adsorption equilibrium, the aqueous pH was measured (Horiba pH meter, Model F-23) and the concentrations of phenols were analyzed using a Jasco UV/visible spectrophotometer (Model U-551) at each appropriate wavelengths. Each experiments was duplicated at least under identical conditions. The resin-phase concentration of phenols, *q<sub>e</sub>* (mol kg<sup>-1</sup>), was calculated according to

$$q_e = V(C_0 - C_e) / W \quad (1)$$

where *C*<sub>0</sub> and *C*<sub>e</sub> are the initial and equilibrium liquid-phase concentrations (mol m<sup>-3</sup>), respectively, *V* is the volume of solution (m<sup>3</sup>), and *W* is the weight of dry resins (kg).

## 3. Results and discussion

### 3.1. Equilibrium adsorption

Figs. 1–4 show the amount of equilibrium adsorption of phenol and 4-chlorophenol on Amberlite XAD-4 and XAD-7 resins at different temperatures. For all systems

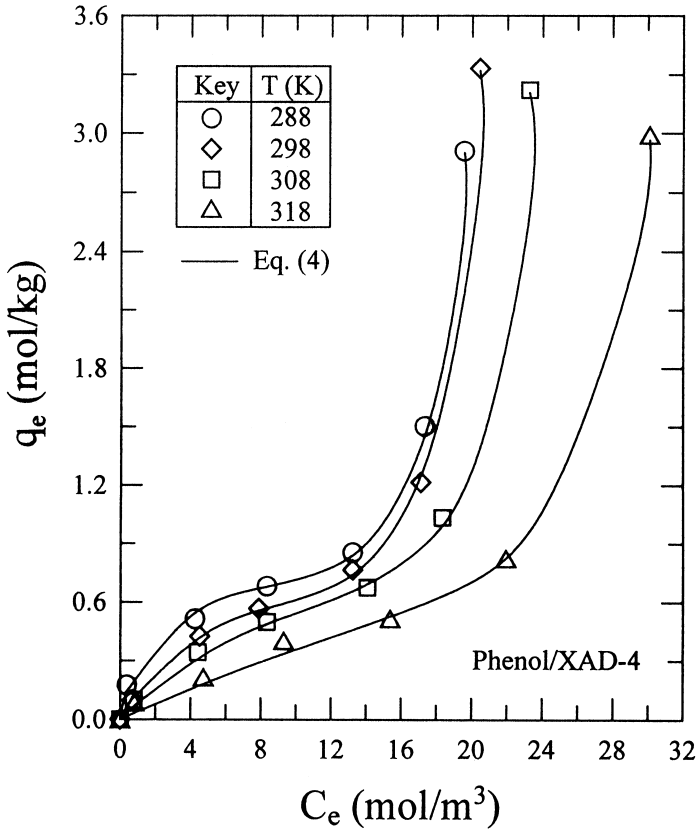


Fig. 1. Measured and modeled isotherms of phenol adsorption on XAD-4 at different temperatures. The solid lines are calculated from Eq. (4).

studied the adsorption ability decreases with raising temperature, indicating exothermic nature of adsorption process. For a given resin, 4-chlorophenol has a higher affinity at low  $C_e$ , but phenol has a higher affinity at high  $C_e$  (Figs. 1 and 2). As expected, the affinity for the more hydrophobic solute 4-chlorophenol is stronger with hydrophobic resins, although XAD-7 is moderately polar. Satisfactory explanation for the reverse of  $q_e$  at high  $C_e$  cannot be given at this stage, but similar phenomena were observed earlier [12].

It is evident that XAD-4 and XAD-7 give comparable  $q_e$  for both phenols. In fact, the adsorption capacity per unit area of XAD-7 is comparatively high because the specific surface area of XAD-7 ( $310 \text{ m}^2 \text{ g}^{-1}$ ) is much smaller than XAD-4 ( $730 \text{ m}^2 \text{ g}^{-1}$ ) (Table 1). Such results agree with those reported earlier [15]. Gusler et al. [12] indicated that the uptake of organic solutes on specific polymeric resins may be not only due to surface adsorption but also solute absorption (i.e. penetration into the resin

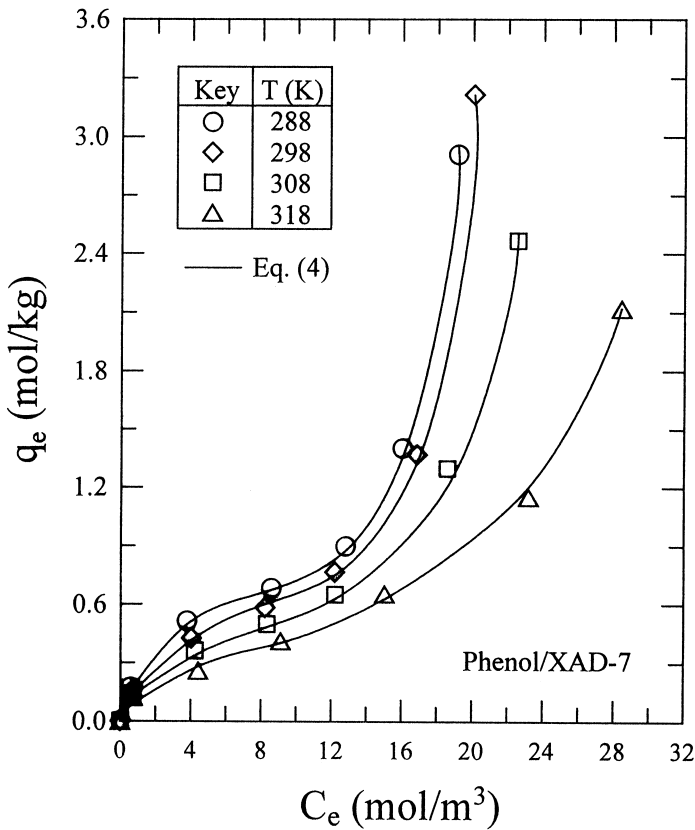


Fig. 2. Measured and modeled isotherms of phenol adsorption on XAD-7 at different temperatures. The solid lines are calculated from Eq. (4).

matrix). To check the possibility of solute absorption, the fraction of the pore volume filled is calculated in this work [12]. Under the conditions studied, the amount of adsorption does not exceed the total pore volume, indicating that the contribution of absorption to solute uptake is small. However, the ester linkages of XAD-7 for hydrogen-bonding may also explain the higher affinity of phenol relative to XAD-4 [16,17].

The sharp increase in  $q_e$  at high  $C_e$  can be explained by the pore-blockage mechanism [18]. The distribution of solute adsorbed in the resin may be determined by intraparticle diffusion rate of the solute into the matrix, which is in turn by the concentration gradient of solute and the resin porosity. At low  $C_0$ , the initial solute flux through the matrix is low and so the solutes adsorb on the sites near the outer surface of the resin. Eventually, the adsorbed solute clusters clog the pores near the outer surface so the solute no longer diffuses to active sites deep within the interior surface. In this case the solute is mostly loaded in a shell near the outer surface of the resin. In contrast,

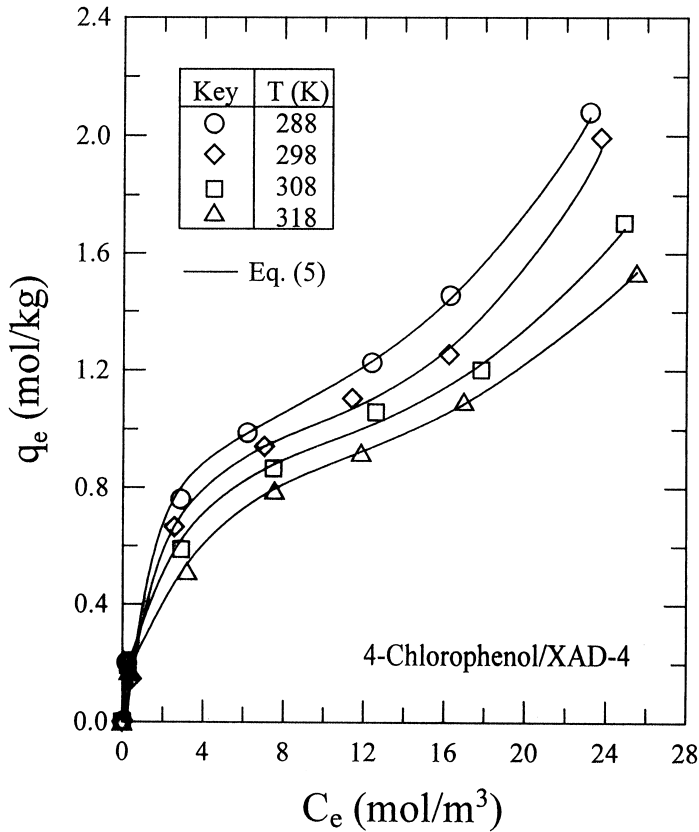


Fig. 3. Measured and modeled isotherms of 4-chlorophenol adsorption on XAD-4 at different temperatures. The solid lines are calculated from Eq. (5).

at high  $C_0$  the initial flux is high and so the solute shoots deep into the interior matrix until the pores are clogged. The solute more uniformly loads into the resin and thus  $q_e$  is unusually higher.

Lin and Ma [19] studied the mass transfer in liquid chromatographic columns packed with microporous (silicalite crystal, pore size 0.6 nm) and macroporous (activated alumina, pore size 8 nm) adsorbents. They found that the pore diffusion model is appropriate for microporous adsorbents, and the pore diffusion and adsorption model is suited for macroporous adsorbents. Furthermore, if the pore size of the adsorbent ( $D_p$ ) is similar to that of the solute molecule ( $D_s$ ), e.g.,  $D_p/D_s = 1-2$ , no solute molecules accumulate in the pores of the adsorbent, and at the same time, the solute molecules diffuse through the pores. On the other hand, if  $D_p/D_s = 10-20$  the solute molecules may either diffuse in the pore center or be adsorbed on the pore surface. In the present work, the value of  $D_p/D_s$  is about 10 for XAD-4 and 20 for XAD-7 (Tables 1 and 2). However, it remains uncertain whether the more apparent effect of pore blockage for

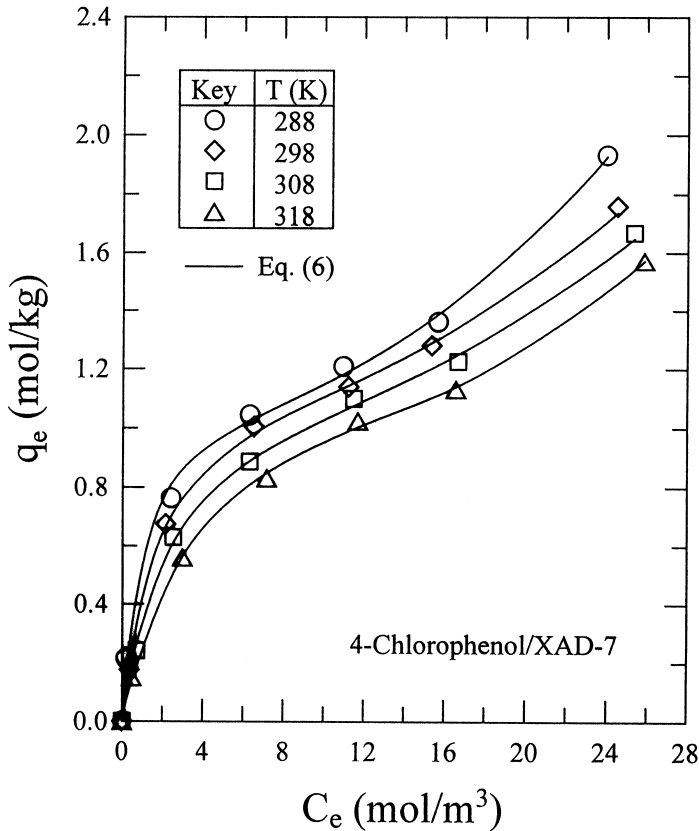


Fig. 4. Measured and modeled isotherms of 4-chlorophenol adsorption on XAD-7 at different temperatures. The solid lines are calculated from Eq. (6).

phenol adsorption (Figs. 1–4) is due to its larger  $D_p/D_s$  or not, compared to 4-chlorophenol. Another possible explanation for this behavior is a change in the adsorbed configuration of the phenol molecules as surface coverage increases [12].

### 3.2. Isotherm analysis

Basically, the isotherm data are often quantified via theoretical or empirical equations, because they describe how solutes interact with adsorbents and so is critical in optimizing the use of adsorbents. It is evident that the sharp rise of  $q_e$  at high  $C_e$  in all cases studied is a result of multilayer adsorption. Hence, the widely-used two-parameter Langmuir and Freundlich equations are inapplicable for the present cases (not shown), as also indicated previously for similar solute–adsorbent systems [12,15].

It was reported that the three-parameter Redlich–Peterson equation gives a good fit for phenol adsorption from aqueous solutions on XAD-8 [11] and on XAD-4 and

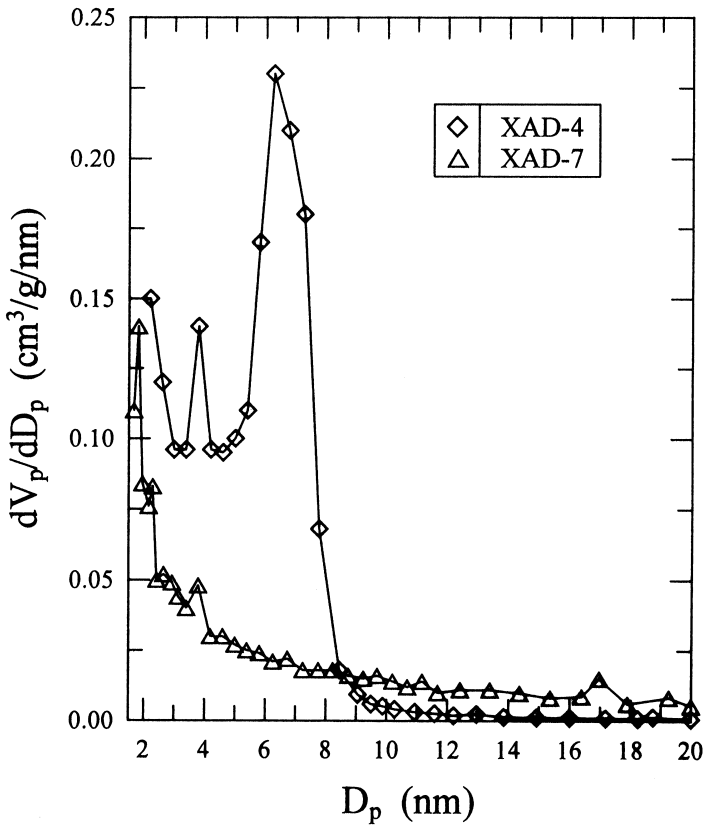


Fig. 5. Pore size distributions of the XAD-4 and XAD-7 resins.

XAD-7 [14]. This is not the case here because this equation is a type of the Langmuir equation in nature. Thus, the conventional BET equation with multilayer adsorption is tried [20].

$$q_e = \frac{q_m K_{BET} X}{(1 - X)[1 + (K_{BET} - 1) X]} \tag{2}$$

where  $q_m$  is the amount of adsorption which takes place in a complete monolayer,  $K_{BET}$  is the equilibrium constant and  $X = C_e/C_s$  ( $C_s$  is the saturated solubility of solutes in

Table 3  
The fitting parameters of Eq. (4) for phenol adsorption on XAD-4

$T$ (K)	$q_m$ (mol kg <sup>-1</sup> )	$K_{BET}$	$1/m$	$K_F$ (mol kg <sup>-1</sup> )(m <sup>3</sup> mol <sup>-1</sup> ) <sup><math>m</math></sup>
288	0.71	1.01	0.12	$1.55 \times 10^{-11}$
298	0.75	1.01	0.11	$9.76 \times 10^{-13}$
308	0.92	1.01	0.10	$1.15 \times 10^{-14}$
318	1.22	1.01	0.11	$5.87 \times 10^{-14}$



Table 4

The fitting parameters of Eq. (4) for phenol adsorption on XAD-7

$T$ (K)	$q_m$ (mol kg <sup>-1</sup> )	$K_{\text{BET}}$	$1/m$	$K_F$ (mol kg <sup>-1</sup> )(m <sup>3</sup> mol <sup>-1</sup> ) <sup><math>m</math></sup>
288	0.60	1.01	0.17	$6.67 \times 10^{-8}$
298	0.62	1.01	0.15	$2.82 \times 10^{-9}$
308	0.64	1.01	0.19	$9.38 \times 10^{-8}$
318	0.84	1.01	0.17	$2.55 \times 10^{-9}$

water, which is temperature dependent [21]). If the fit is well,  $K_{\text{BET}}$  and  $q_m$  can be obtained from the linearized plot of  $1/q_e(1-X)$  vs.  $(1-X)/X$ . This attempt fails again (not shown).

On the other hand, a modified BET equation which describes adsorption with a finite number of layers has been applied for adsorption of dyes on cross-linked chitosan fibers [22,23] and of water vapor on hydrophilic polymers [24]. It is given by:

$$q_e = \frac{q_m K_{\text{MBET}} X [1 - (n+1)X^n + nX^{n+1}]}{(1-X)[1 + (K_{\text{MBET}} - 1)X - K_{\text{MBET}} X^{n+1}]} \quad (3)$$

where  $n$  is the number of layers. When  $n \rightarrow \infty$ , Eq. (3) is reduced to Eq. (2). In addition, Eq. (3) becomes a type of the Langmuir equation when  $n = 1$ .

It was claimed that the parameters  $K_{\text{MBET}}$  and  $q_m$  in Eq. (3) can be first obtained from the conventional linearized BET plot when  $X < 0.3$  [22,23], however, it is inapplicable to the present systems. The three parameters in Eq. (3),  $K_{\text{MBET}}$ ,  $q_m$ , and  $n$ , are evaluated using a powerful computer program “KaleidaGraph” (Synergy Software, USA), which can smoothly fit the data to an assigned non-linear equation without entering any initial values of the parameters. This program also provides correlation coefficient to judge validity of the regression. The fit of Eq. (3) to isotherm data obtained in this work is good only at a restricted range of concentrations. Therefore, a piecewise fitting is required if Eq. (3) is applied.

Basically, the structure of the adsorbents contains pores classified into three groups, micropores (pore size  $< 2$  nm), mesopores (2–50 nm), and macropores ( $> 50$  nm) [25]. Fig. 5 shows the pore size distributions of the resins. It is found that both resins have predominantly large contribution in the mesopore range. An attempt was made to fit the isotherm data considering liquid-phase capillary condensation because it was indicated that this factor may play an important role at a sufficiently high solute concentration (e.g.,  $C_e/C_s > 0.2$ ) for such macroreticular adsorbents with mesopores [26]. However, this is not the case here likely due to the relatively low solute concentration; i.e.  $C_e/C_s < 0.03$  for phenol and  $C_e/C_s < 0.13$  for 4-chlorophenol (Figs. 1–4 and Table 2).

To search for the best fit covering the whole range of concentration examined, the combined forms of any two equations of the Langmuir, Freundlich, and Eqs. (2) and (3) are tried. For phenol adsorption on XAD-4 and XAD-7, the most preferred one is the combined Freundlich and BET equation (Eq. (4)).

$$q_e = K_F C_e^{1/m} + \frac{q_m K_{\text{BET}} C_s C_e}{(C_s - C_e)[C_s + (K_{\text{BET}} - 1)C_e]} \quad (4)$$

Table 5

The fitting parameters of Eq. (5) for 4-chlorophenol adsorption on XAD-4

$T$ (K)	$q_m$ (mol kg <sup>-1</sup> )	$K_{\text{BET}}$	$K_L$ (m <sup>3</sup> mol <sup>-1</sup> )
288	1.12	0.481	0.84
298	1.22	0.262	0.46
308	1.24	0.092	0.30
318	1.47	0.034	0.15

In the case of 4-chlorophenol adsorption on XAD-4, it becomes the combined Langmuir and BET equations (Eq. (5)).

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} + \frac{q_m K_{\text{BET}} C_s C_e}{(C_s - C_e)[C_s + (K_{\text{BET}} - 1)C_e]} \quad (5)$$

Finally, it is the combined Langmuir and BET equation with a finite number of layers (Eq. (6)) for 4-chlorophenol adsorption on XAD-7.

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} + \frac{q_m K_{\text{MBET}} X [1 - (n + 1)X^n + nX^{n+1}]}{(1 - X)[1 + (K_{\text{MBET}} - 1)X - K_{\text{MBET}} X^{n+1}]} \quad (6)$$

The parameters in Eqs. (4)–(6) are also determined using KaleidaGraph program and are listed in Tables 3–6. It is noted that Eqs. (4)–(6) are selected merely from the correlation coefficients of non-linear fitting, which are all beyond 0.992 in this work.

In practice, Itaya et al. [14] found that the isotherm data of phenol adsorption from water on XAD-4 and XAD-7 can be well represented by the Redlich–Peterson equation, although it has no theoretical basis. However, this fitting is valid in a concentration range of 0.01–10 mol m<sup>-3</sup> at 273–323 K. Compared to the present results (Figs. 1 and 2), this conclusion appears to be convincible at  $C_e < 10$  mol m<sup>-3</sup>.

The different fitting results can be explained from the solute–resin interactions. Such types of isotherms as Figs. 1–4 are often observed in adsorbents in which there is a wide range of pore sizes [25], as exactly the case shown in Fig. 5. In such systems, there is a continuous progression with increasing loading from monolayer to multilayer adsorption, and finally to capillary condensation if the loading is high enough [27]. The combined term of the Langmuir equation, rather than the Freundlich equation, in Eqs. (5) and (6) for 4-chlorophenol adsorption indicates the chemical nature of the more hydrophobic 4-chlorophenol compared to phenol [27]. This reflects a comparatively large extent of the chemical factor for the adsorption of 4-chlorophenol on the resins, as discussed from temperature dependence in Section 3.3.

Table 6

The fitting parameters of Eq. (6) for 4-chlorophenol adsorption on XAD-7

$T$ (K)	$q_m$ (mol kg <sup>-1</sup> )	$K_{\text{MBET}}$	$n$	$K_L$ (m <sup>3</sup> mol <sup>-1</sup> )
288	1.12	0.091	4	1.03
298	1.19	0.059	4	0.58
308	1.21	0.043	4	0.40
318	1.31	0.031	5	0.25

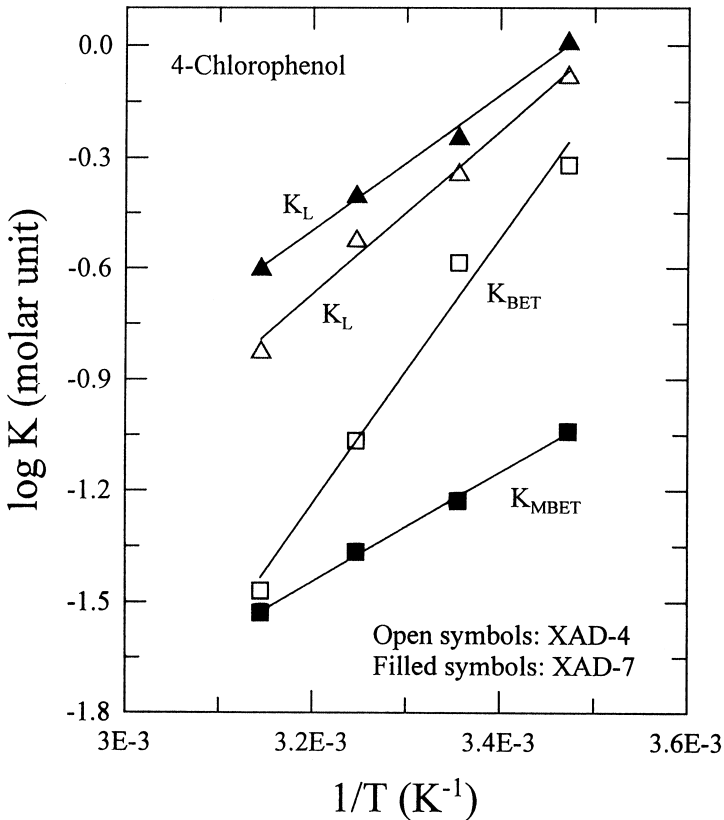


Fig. 6. Determination of the apparent enthalpy of adsorption.

As clearly shown in Tables 3–6, an increase in temperature leads to an increase in  $q_m$ . For a given solute, a higher  $q_m$  is obtained on XAD-4 compared to XAD-7 as has been stated above. Furthermore, the more hydrophobic solute 4-chlorophenol shows a higher  $q_m$  than phenol. In the case of phenol adsorption (Tables 3 and 4), the extremely low  $K_F$  and  $1/m$  value indicates that the Freundlich equation mainly contributes  $q_e$  at sufficiently high  $C_e$ . If  $q_m$  is divided by the specific surface area of the resins, it appears that the total surface area of the resins is not completely covered. Some particular interaction between phenols and the polymeric matrix such as the ester linkages via hydrogen-bonding within XAD-7 likely plays an important role.

### 3.3. Effect of temperature on adsorption

In the case of 4-chlorophenol adsorption (Tables 5 and 6), the two constants decreases by increasing temperature. In a broad sense, the apparent enthalpy of “adsorption”  $\Delta H$  can be determined as follows:

$$d(\log K)/d(1/T) = \Delta H/2.303R \quad (7)$$

Fig. 6 shows the results. These plots give well linear relations (correlation coefficient  $> 0.990$ ). The values of  $\Delta H$  derived from  $K_L$  and  $K_{BET}$  with XAD-4 are  $-42.2$  and  $-68.7$   $\text{kJ mol}^{-1}$ , respectively. Furthermore, they are  $-34.9$  and  $-28.1$   $\text{kJ mol}^{-1}$  with XAD-7 derived from  $K_L$  and  $K_{MBET}$ , respectively.

Unlike the  $\Delta H$  derived from  $K_{BET}$  with XAD-4, the other three enthalpies evolved are less than  $45$   $\text{kJ mol}^{-1}$ , which are comparable to those reported for adsorption of phenols on other non-ionic polymeric resins [11,15]. However, they are lower than those obtained for adsorption of organic solutes on activated carbons [28]. In a word, the present results on temperature effect show the uptake of both phenols on non-ionic polymeric resins to be a type of transition between physical and chemical adsorption [20].

#### 4. Conclusions

The isotherms for liquid-phase adsorption of phenol and 4-chlorophenol on Amberlite XAD-4 and XAD-7 macroreticular polymeric resins have been analyzed. The following results are obtained.

1. The adsorption capacity for more hydrophobic 4-chlorophenol is higher. In contrast to XAD-4, the amount of adsorption of phenols on per unit area of XAD-7 is high due to the ester linkages of the sites for hydrogen-bonding provided by XAD-7. The sharp rise in  $q_e$  at high  $C_e$  can be explained by the pore-blockage effect. In addition to the hydrophobicity of the resins, the number of active sites plays an important role in the mechanism of phenols adsorption.

2. The isotherm data cannot be fit by the conventional Langmuir, Freundlich, BET, and Redlich–Peterson equations over the whole concentration range ( $< 32$   $\text{mol m}^{-3}$ ). They are well fit by combined the BET equation or its modified form with the Freundlich or Langmuir equation (Eqs. (4)–(6)), depending on the types of solutes and the resins. Owing to rather wide pore size distributions of the resins, the different fitting results can be explained from the solute–resin interactions.

3. Based on the apparent enthalpy changes of “adsorption” ( $< 45$   $\text{kJ mol}^{-1}$ ), the uptake of phenols on non-ionic macroreticular resins is a type of transition between physical and chemical adsorption.

#### Acknowledgements

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#### References

- [1] C.C. Lee, Y. Ku, Removal of chlorophenols from aqueous solutions by anionic ion exchange, *Sep. Sci. Technol.* 31 (1996) 2551–2577.
- [2] I.H. Suffet, L. Brenner, J.T. Coyle, P.R. Cairo, Evaluation of capacity of granular activated carbon and XAD-2 resin to remove trace organics from treated drinking water, *Environ. Sci. Technol.* 12 (1978) 1315–1322.

- [3] G.A. Junk, Synthetic polymers for accumulating organic compounds from water, in: I.H. Suffet, M. Malaiyandi (Eds.), *Organic Pollutants in Water. Sampling, Analysis, and Toxicity Testing*, Advances in Chemistry Series 214, ACS, 1987, pp. 201–246.
- [4] P. Cornel, H. Sontheimer, Sorption of dissolved organics from aqueous solution by polystyrene resins: I. Resin characterization and sorption equilibrium, *Chem. Eng. Sci.* 41 (1986) 1791–1800.
- [5] R. Kunin, Polymeric adsorbents for treatment of waste effluents, *Polym. Eng. Sci.* 17 (1977) 58–62.
- [6] T.M. Grant, C.J. King, Mechanism of irreversible adsorption of phenolic compounds by activated carbon, *Ind. Eng. Chem. Res.* 29 (1990) 264–271.
- [7] P.R. Cairo, J.T. Coyle, J.T. Davis, H.M. Neukrug, I.H. Suffet, A. Wickland, Evaluating regeneration of activated carbon through laboratory and pilot-column studies, *J. Am. Water Works Assoc.* 74 (1982) 94–102.
- [8] M. Chanda, K.F. O'Driscoll, G.L. Rempel, Sorption of phenolics onto cross-linked poly(4-vinylpyridine), *React. Polym.* 1 (1983) 39–48.
- [9] M. Chanda, K.F. O'Driscoll, G.L. Rempel, Sorption of phenolics and carboxylic acids on polybenzimidazole, *React. Polym.* 4 (1985) 39–48.
- [10] E.H. Crook, R.P. McDonnell, J.T. McNulty, Removal and recovery of phenols from industrial waste effluents with Amberlite XAD polymeric adsorbents, *Ind. Eng. Chem. Prod. Res. Dev.* 14 (1975) 113–118.
- [11] D.S. Farrier, A.L. Hines, S.E. Wang, Adsorption of phenol and benzoic acid from dilute aqueous solution onto a macroreticular resin, *J. Colloid Interface Sci.* 69 (1979) 233–240.
- [12] G.M. Gusler, T.E. Browne, Y. Cohen, Sorption of organics from aqueous solution onto polymeric resins, *Ind. Eng. Chem. Res.* 32 (1993) 2727–2735.
- [13] R.L. Gustafson, R.L. Albright, J. Heisler, J.A. Lirio, O.T. Reid Jr., Adsorption of organic species by high surface area styrene–divinylbenzene copolymers, *Ind. Eng. Chem. Process Des. Dev.* 7 (1968) 107–115.
- [14] A. Itaya, N. Kato, J. Yamamoto, Liquid phase adsorption equilibrium of phenol and its derivatives on macroreticular adsorbents, *J. Chem. Eng. Jpn.* 17 (1984) 389–395.
- [15] J. Paleos, Adsorption from aqueous and non-aqueous solutions on hydrophobic and hydrophilic high surface-area copolymers, *J. Colloid Interface Sci.* 31 (1969) 7–18.
- [16] N. Maity, G.F. Payne, J.L. Chipchoosky, Adsorptive separations based on the differences in solute–sorbent hydrogen bonding strengths, *Ind. Eng. Chem. Res.* 30 (1991) 2456–2463.
- [17] G.F. Payne, Y. Ninomiya, Selective adsorption of solutes based on hydrogen bonding, *Sep. Sci. Technol.* 25 (1990) 1117–1129.
- [18] G.L. Rorrer, T.Y. Hsien, J.D. Way, Synthesis of porous-magnetic chitosan beads for removal of cadmium ions from waste water, *Ind. Eng. Chem. Res.* 32 (1993) 2170–2178.
- [19] Y.S. Lin, Y.H. Ma, A comparative chromatographic study of liquid adsorption and diffusion in microporous and macroporous adsorbents, *Ind. Eng. Chem. Res.* 28 (1989) 622–630.
- [20] P.W. Atkins, *Physical Chemistry*, 6th edn., Oxford Univ. Press, Oxford, 1998, pp. 857–858.
- [21] H.T. Shu, D.Y. Li, A.A. Scala, Y.H. Ma, Adsorption of small organic pollutants from aqueous streams by aluminosilicate-based microporous materials, *Sep. Purif. Technol.* 11 (1997) 27–36.
- [22] H. Yoshida, S. Fukuda, A. Okamoto, T. Kataoka, Recovery of direct dye and acid dye by adsorption on chitosan fiber — Equilibria, *Water Sci. Technol.* 23 (1991) 1667–1676.
- [23] H. Yoshida, A. Okamoto, T. Kataoka, Adsorption of acid dye on cross-linked chitosan fibers: equilibria, *Chem. Eng. Sci.* 48 (1993) 2267–2272.
- [24] H. Gocho, A. Tanioka, T. Nakajima, Sorption isotherm analysis of water by hydrophilic polymer composed of different adsorption sites using modified BET equation, *J. Colloid Interface Sci.* 200 (1998) 155–160.
- [25] K.S.W. Sing, D.H. Everett, R.A.W. Haul, L. Moscou, R.A. Pierotti, J. Rouquerol, T. Siemieniowska, Reporting physisorption data for gas/solid systems, *Pure Appl. Chem.* 57 (1985) 603–619.
- [26] M. Miyahara, M. Kato, M. Okazaki, Liquid-phase capillary condensation and adsorption isotherm, *AIChE J.* 40 (1994) 1549–1557.
- [27] D.M. Ruthven, *Principles of Adsorption and Adsorption Processes*, Wiley, New York, 1984, pp. 55–58.
- [28] E. Costa, G. Calleja, L. Marijuan, Comparative adsorption of phenol, *p*-nitrophenol and *p*-hydroxybenzoic acid on activated carbon, *Adsorpt. Sci. Technol.* 5 (1988) 213–228.