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Prediction of Adsorption from Multicomponent Solutions by Activated Carbon Using Single-Solute Parameters. Part II - Proposed Equation

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ABSTRACT

Prediction of multicomponent adsorption is still one of the most challenging problems in the adsorption field. Many models have been proposed and employed to obtain multicomponent isotherms from single-component equilibrium data. However, most of these models were based on either unrealistic assumptions or on empirical equations with no apparent definition. The purpose of this investigation was to develop a multicomponent adsorption model based on a thermodynamically consistent equation, and to validate that model using experimental data. Three barbiturates — phenobarbital, mephobarbital, and primidone — were combined to form a ternary system. The adsorption of these barbiturates from simulated intestinal fluid (without pancreatin) by activated carbon was studied using the rotating bottle method. The concentrations, both before and after the attainment of equilibrium, were determined with a high-performance liquid chromatography system employing a reversed-phase column. The proposed equation and the competitive Langmuir-like equation were both fit to the data. A very good correlation was obtained between the experimental data and the calculated data using the proposed equation. The results obtained from the original competitive Langmuir-like model were less satisfactory. These results suggest that the proposed equation can successfully predict the trisolute isotherms of the barbituric acid derivatives employed in this study.

KEYWORDS: adsorption, activated carbon, proposed equation, multicomponent, trisolute, barbiturate.

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INTRODUCTION

Prediction of multicomponent adsorption is one of the most challenging problems in the field of adsorption. In drug formulations, and also in acute overdoses, adsorption rarely involves 1 component. Therefore, the ability to predict multicomponent adsorption from single-component isotherm parameters would be extremely useful. Many models have been proposed and employed for that purpose [1-7]. However, most of these models were based on either unrealistic assumptions or empirical equations with no apparent definition. Alkhamis [8] and Wurster et al [9] presented the various methods used to predict multicomponent equilibrium adsorption and applied these methods to bisolute systems. The authors compared the different models and concluded that the modified competitive Langmuir-like model was the best for predicting the adsorption of barbituric acid derivatives from bisolute systems. The latter model's main disadvantage was that it was applicable only to bisolute systems.

This investigation extended the modified competitive Langmuir-like model to trisolute systems and validated the proposed equation by applying it to a trisolute system of barbituric acid derivatives.

Determination of the proper terminology to be employed in this paper is difficult. The original Langmuir equation was derived for a 2-component, vapor-solid system and employed a kinetic argument [10]. The Langmuir equation has also been applied to 3-component, solute-solvent-solid systems, but the 2-component kinetic derivation is not directly applicable to this latter system. Therefore, the application of the original Langmuir equation to such systems has been ad hoc.

For the adsorption from solution case, the following equilibrium is physically realistic:

Absorbed Solvent + Solute in Solution ↔ Absorbed Solute + Solvent in Solution (1)

An equation to describe adsorption in the system described by Equation 1 can be derived via a thermodynamic argument. The result of such a derivation is identical in form to the original Langmuir equation. While several of the necessary assumptions are the same between the two derivations, they are not all identical. Therefore subtle differences exist in the definitions of the capacity and affinity constants. Therefore, when the Langmuir equation is derived using a thermodynamic argument, it is customary, in the physical chemistry literature, to refer to it as the Langmuir-like equation. This terminology is less common in the pharmacy and engineering literature. It is not clear who first derived the Langmuir-like relationship, but Kipling [11] attributes it to Everett [12].

Early work in the area of competitive adsorption involved 2 component vapors, so the original Langmuir relationship was used with various modifications. Early investigators in the area of competitive adsorption from solution also invoked the original Langmuir equation as a starting point. Presentation of a thermodynamic derivation of the Langmuir-like equation clarified the situation for 1 solute adsorption but did little to clarify the modeling of 2 solute competitive adsorption. In the derivation of competitive adsorption models, the Langmuir equation was frequently taken to be a given. Since the Langmuir and Langmuir-like equations appear to be identical, the source of the Langmuir equation was rarely identified. Thus it is impossible to use the terms Langmuir and Langmuir-like in a completely accurate manner in this paper.

In an attempt to bring some order to this situation, the terminology in this paper will be based on the physical system being discussed. A model will be identified as a competitive, or modified competitive, Langmuir model when the system involves adsorption from the vapor phase. When adsorption occurs from solution, the model will be identified as a competitive, or modified competitive, Langmuir-like model. These authors are not trying to change the interpretations of the original manuscripts in any way; the fundamental problem is the lack of specificity in the original papers. The terminology employed herein will simply assign a correct physical model to the adsorption system being described, thereby allowing equation naming to be done in a systematic manner.

THEORETICAL SECTION

Competitive Langmuir-Like Model

Early applications of the Langmuir model [10] to competitive adsorption phenomena were published by Butler and Ockrent [1], Schwab [13], and Markham and Benton [14]. A similar approach was later taken by Moriguchi and Kaneniwa [15]. The equations proposed by Markham and Benton [14] have frequently been employed to analyze competitive adsorption from solutions, even though these equations were originally derived for the vapor-phase adsorption case. Therefore, in this work, these equations will hereafter be referred to as Langmuir-like, since it is clear that a solution-phase equilibrium best describes the adsorption system employed.

The fraction of the surface covered, θ, is given by

$$\theta_1 = \frac{AC_{eq_1}}{1 + AC_{eq_1} + BC_{eq_2}} \quad (2)$$

$$\theta_2 = \frac{BC_{eq_2}}{1 + BC_{eq_2} + AC_{eq_1}} \quad (3)$$

where, θ is the fraction of the surface covered by an adsorbed component, C_{eq} is the concentration of a component in solution at equilibrium, and A and B are the affinity constants of components 1 and 2, respectively. This model can also be extended to more than 2 components [16]. The competitive Langmuir-like model can successfully predict multicomponent adsorption under the following conditions. First, the competing components must obey the assumptions of the Langmuir-like equation for single solutes. Second, the capacity of the surface for each component must be the same. Third, the adsorbates must be competing for the same binding sites.

The competitive Langmuir-like model is thermodynamically consistent only when the condition 2 in the previous paragraph is met [17]. Slight differences in molecular sizes or in orientations on the surface could result in the surface not being equally available to all of the competing adsorbates. If adsorption occurs on sites that are not equally accessible to all of the competing adsorbates, the Langmuir-like model for competitive adsorption is not expected to yield accurate results.

Modified Competitive Langmuir-Like Model

The original competitive Langmuir-like model was improved by Jain and Snoeyink [18], whose modification

was based on the hypothesis that adsorption without competition occurs on some sites when the capacities are not all equal. Further, it was assumed that the number of sites for noncompetitive adsorption would be proportional to the difference between the maximum loadings of the species; ie, ($X_{m,1}$ - $X_{m,2}$), where $X_{m,1} > X_{m,2}$. On this basis, the following equations were described:

$$X_1 = \frac{(X_{m,1} - X_{m,2})AC_{eq1}}{1 + AC_{eq1}} + \frac{X_{m,2}AC_{eq1}}{1 + AC_{eq1} + BC_{eq2}} \quad (4)$$

$$X_2 = \frac{X_{m,2}BC_{eq_2}}{1 + AC_{eq_1} + BC_{eq_2}} \quad (5)$$

where, X_1 and X_2 are the amounts of solutes 1 and 2 adsorbed per unit weight, or per unit surface area, of adsorbent at equilibrium concentrations C_{eq1} and C_{eq2}, respectively; and A and B are the affinity constants of components 1 and 2, respectively, that are derived from single-solute adsorption isotherms. The first term on the right side of Equation 4 is the Langmuir-like expression for the amount of species 1 that adsorbs without competition. The second term represents the amount of species 1 adsorbed on the surface in competition with species 2 and is based on the Langmuir-like model for competitive adsorption.

The modified competitive Langmuir-like model does not assume equal adsorption capacities for different components. This model can successfully predict multicomponent adsorption using single-solute parameters, even if the difference in the adsorption capacities is quite large. This is true as long as the difference is based on steric factors and/or size factors and not based on totally different binding sites. The main disadvantage of this model is that it is applicable only to bisolute systems.

Extension of the Modified Competitive Langmuir-Like Model to Trisolute Systems

$$X_1 = \frac{(X_{m,1} - X_{m,2})AC_{eq1}}{1 + AC_{eq1}} + \frac{(X_{m,2} - X_{m,3})AC_{eq1}}{1 + AC_{eq1} + BC_{eq2}} + \frac{X_{m,3}AC_{eq1}}{1 + AC_{eq1} + BC_{eq2} + CC_{eq3}} \quad (6)$$

$$X_2 = \frac{(X_{m,2} - X_{m,3})BC_{eq_2}}{1 + AC_{eq_1} + BC_{eq_2}} + \frac{X_{m,3}BC_{eq_2}}{1 + AC_{eq_1} + BC_{eq_2} + CC_{eq_3}} \quad (7)$$

$$X_3 = \frac{X_{m,3}CC_{eq_3}}{1 + AC_{eq_1} + BC_{eq_2} + CC_{eq_3}} \quad (8)$$

The first term on the right side of Equation 6 is the Langmuir-like expression for the amount of species 1 that adsorbs without any competition. The second term of Equation 6 represents the amount of species 1 adsorbed on the surface in competition with species 2 and is based on the Langmuir-like model for competitive adsorption. The third term of Equation 6 represents the amount of species 1 adsorbed on the surface in competition with species 2 and species 3 and is based on the Langmuir-like model for competitive adsorption. The first term on the right side of Equation 7 represents the amount of species 2 adsorbed on the surface in competition with species 1 and is based on the Langmuir-like model for competitive adsorption. The second term represents the amount of species 2 adsorbed on the surface in competition with species 1 and species 3.

MATERIALS AND METHODS

Preparation of the Activated Carbon

A small amount of activated carbon, SuperChar (lot G812R, Gulf Bio-Systems, Inc, Dallas, TX) was spread evenly in a petri dish and placed in a vacuum oven. The vacuum setup consisted of a NAPCO vacuum oven (Model 5831, Precision Scientific, Chicago, IL), a Metroline vacuum pump (Metroline Industries, Inc, Corona, CA), and a Labconco Mcleod vacuum gauge (Model 75850, Labconco Corporation, Kansas City, MO). The activated carbon was dried at 100°C and 25 μmHg for 24 hours prior to use. Upon removal from the vacuum oven, the sample was placed in a vacuum desiccator and allowed to reach room temperature. The sample was then immediately used for the experiment.

Adsorption from Solution by the Rotating Bottle Method

Simulated Intestinal Fluid (SIF), without pancreatin, was prepared according to USP 23-NF 18. SIF consisted of 6.8 g of potassium phosphate monobasic (enzyme grade, lot numbers 955698 and 962007, Fisher Scientific, Fair Lawn, NJ), ~190 mL of 0.2N NaOH (lot 946154, Fisher

Scientific), and sufficient water to make 1000 mL (pH adjusted to 7.5 ± 0.1 with 0.2N NaOH).

The stock solution was prepared by dissolving mephobarbital, lot 97F-0466; phenobarbital, lot 76H0293; and primidone, lot 48F0043 (all from Sigma Chemical Company, St Louis, Mo) in 500 mL of SIF. Aliquots were then removed from this stock solution and diluted to 100 mL using the same batch of SIF that was used to prepare the stock solution. Five-mL aliquots were removed from each of these latter dilutions and used as standards for further analysis. Nine samples of the activated carbon (approximately 5 mg each) were individually weighed in glass weighing funnels. Each sample, including the glass weighing funnel, was placed in an individual screw-top bottle, and the appropriate solution was added. Two layers of Teflon tape were placed over the top of the bottle to prevent leakage and to avoid direct contact of the suspension with the cap. The screw cap was then put on the bottle. The filled bottles were rotated with a Vanderkamp Sustained Release Apparatus (Model W-115 water bath, Model 103906 motor, Van-Kel Industries, Inc, Edison, NJ) equipped with a heating circulator (Model 1120, VWR Scientific, St Paul, MN). Samples were rotated at 25 rpm for 45 minutes at 37.0°C. At 45 minutes, bottle rotation was stopped with the bottles in an upright position in the water bath. The activated carbon was allowed to settle to the bottom of the bottles (2 hours at 37.0°C). An aliquot of the supernatant was removed from each bottle for subsequent analysis. These adsorption studies were performed in triplicate.

High-Performance Liquid Chromatography Analysis of Mephobarbital-Phenobarbital-Primidone Solutions

The mephobarbital, phenobarbital, and primidone concentrations, both before the addition of activated carbon and after the attainment of adsorption equilibrium, were determined with a high-performance liquid chromatography (HPLC) system. The HPLC system included the following equipment: liquid pump Model LC-10AS, integrator Model CR501, variable wavelength UV-VIS detector Model SPD-10A, auto-injector Model SIL-10A, and system controller Model SCL-10A (all from Shimadzu Scientific Instruments, Columbia, MD). The HPLC assay conditions are given below.

Wavelength	250 nm	
Mobile phase	0.05M mol/L phosphate buffer (pH 3.0)	50%
	Methanol	50%
Flow rate	1.0 mL/min	
Column	µBondapak C18 (Waters Corp., Milford, MA)	
	3.9 x 300 mm	
	10 µm particle size	
Inj vol	20 to 50 µl	

The wavelength of analysis (250 nm) was chosen so that mephobarbital, phenobarbital, and primidone could be analyzed simultaneously in 1 chromatographic run. A new standard curve was constructed for each experiment, and quantitation was performed by peak area integration.

RESULTS AND DISCUSSION

The Langmuir-like model for competitive adsorption and the proposed equations both require the use of the Langmuir-like parameters for single-solute systems. Accordingly, it was necessary to determine single-solute adsorption isotherms for the adsorbates used in this study (mephobarbital, phenobarbital, and primidone).

The Langmuir-like model was proven to be appropriate for fitting single-solute adsorption data (solution phase) by previous investigators [19,20]. The nonlinear equilibrium adsorption isotherms are presented in **Figures 1 to 3**. The capacity and affinity constants of the Langmuir-like equation, for each adsorbate, are presented in **Table 1**. The capacity (952 mg/g) and affinity (17mL/mg) constants obtained for phenobarbital adsorption by SuperChar agree very well with the values obtained by Burke et al [21,22]. Those investigators, using the same lot number of SuperChar, obtained a capacity of 980 mg/g and an affinity of 16.4 mL/mg. The differences in the capacity and affinity constants among the different barbituric acid derivatives employed in this work, as well as their statistical analyses, were discussed previously by Wurster et al [9].

The experimental data for the adsorption studies of the single-solute and the trisolute (mephobarbital-phenobarbital-primidone) systems are presented in **Figures 4 to 6**. The results clearly show that the addition of competing components systematically decreases the extent of adsorption.

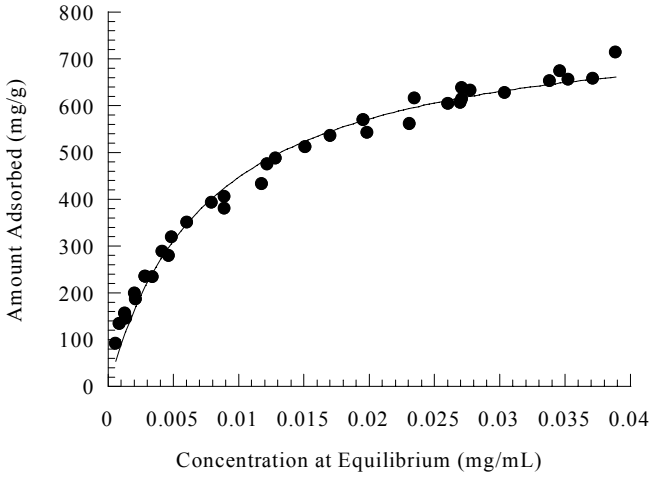

Figure 1. Nonlinear Langmuir-like plot for mephobarbital adsorption by SuperChar.

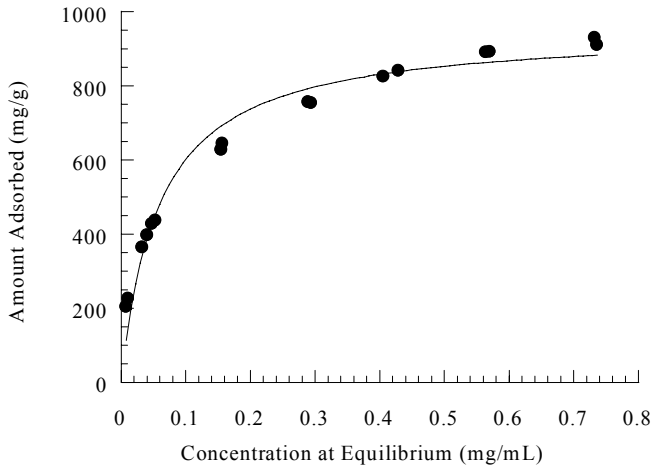

Figure 2. Nonlinear Langmuir-like plot for phenobarbital adsorption by SuperChar.

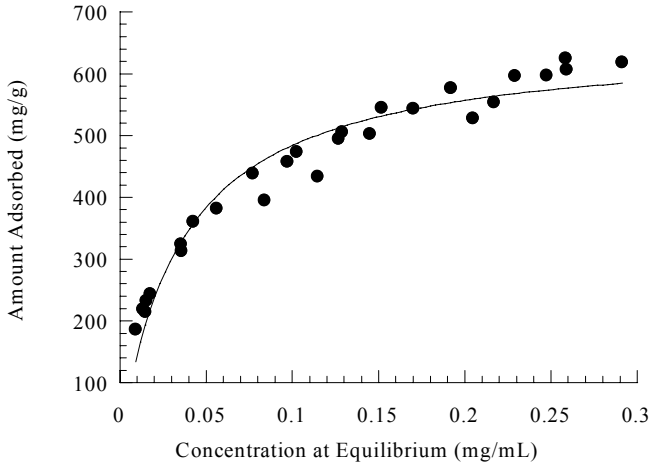

Figure 3. Nonlinear Langmuir-like plot for primidone adsorption by SuperChar.

Table 1. Adsorption Parameters Obtained from Curve-Fitting of the Nonlinear Langmuir-like Equation to Mephobarbital, Phenobarbital, and Primidone Data (Single Component)

	Mephobarbital	Phenobarbital	Primidone
Capacity Constant			
(μmol/gm)	3220	4100	3010
95% CL*	(3090-3350)	(3870-4340)	(2840-3170)
(mg/g)	792	952	656
95% CL	(760-824)	(898-1010)	(619-691)
Affinity Constant			
(mL/mg)	129	17	28
95% CL	(113-145)	(13-21)	(22-34)
r^2 (Coef. of Det.)	0.984	0.970	0.950

*CL indicates confidence limit.

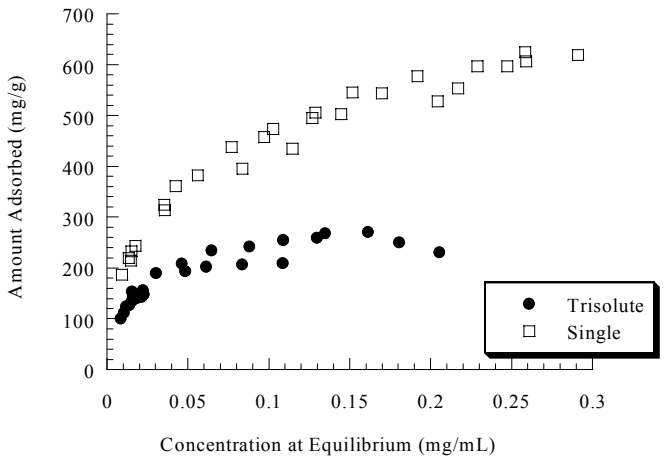

Figure 4. Adsorption of primidone by SuperChar in the presence and absence of phenobarbital and mephobarbital.

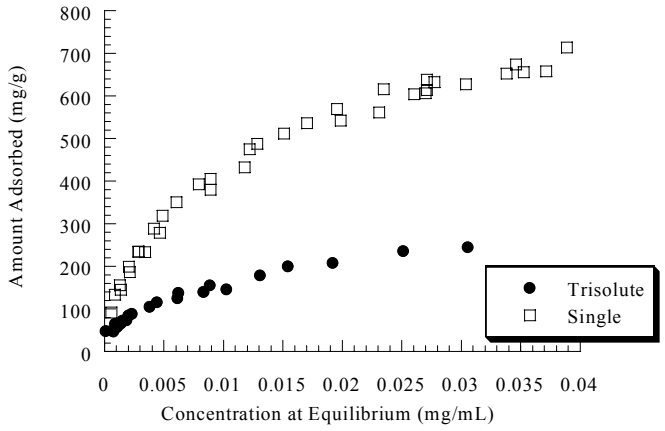

Figure 5. Adsorption of mephobarbital by SuperChar in the presence and absence of phenobarbital and primidone.

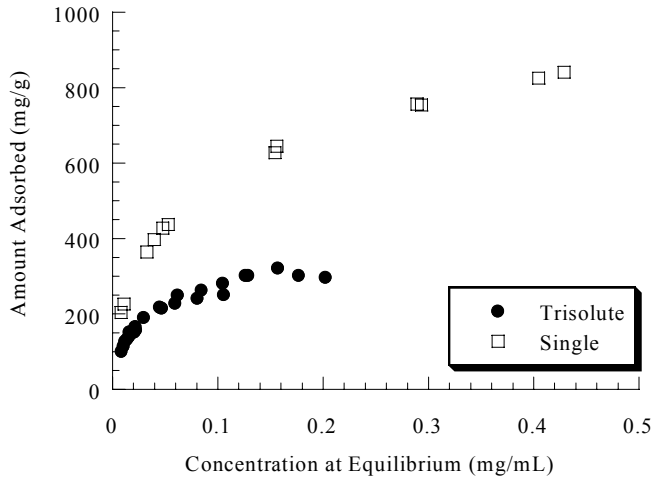

Figure 6. Adsorption of phenobarbital by SuperChar in the presence and absence of mephobarbital and primidone.

The competitive Langmuir-like model and the proposed equations were both applied to the trisolute systems. Correlations between the experimental and the calculated amounts of mephobarbital, phenobarbital, and primidone adsorbed by the activated carbon are presented in **Figures 7 to 9**. The Langmuir-like parameters for the single-solute systems were used in these calculations. Good correlations were obtained between the experimental and the calculated data when the proposed equations were used. The intercepts were close to zero, while the slopes were close to 1. Thus, the proposed equations can successfully predict the extent of adsorption for each of the 3 barbituric acid derivatives employed in this study.

The results obtained from the original competitive Langmuir-like model were less satisfactory. This result is not surprising and has already been reported by other investigators [23]. The competitive Langmuir-like model is thermodynamically consistent only in the special case in which the capacities of the adsorbates are all equal. This assumption is unrealistic, since each molecule occupies an area on the activated carbon surface that is dependent on its exact size, substitution pattern, three-dimensional conformation, and other steric factors.

CONCLUSION

This work presented a system of equations to extend the modified competitive Langmuir-like model to trisolute systems and thereby overcome its main disadvantage. This extension is based on the same assumptions as the original modified competitive Langmuir-like model. The ability of the proposed equations to predict adsorption in trisolute systems was demonstrated by conducting trisolute adsorption experiments with 3 barbiturates (phenobarbital, mephobarbital, and primidone). Correlations between the experimental and the predicted data were made and the following conclusions were reached. First, very good correlation was observed between the experimental and the calculated data when the proposed equations were used. This correlation suggests that the proposed equations can successfully predict the trisolute isotherms of other adsorbates as well. Second, the results obtained from the original competitive Langmuir-like model were less satisfactory. This is not surprising, since the competitive Langmuir-like model assumes that the capacities of all 3 adsorbates are equal. The proposed equations take into account the differences in the capacities of the adsorbates. Finally, the results demonstrate that the adsorbates used in this study are competing for the same binding sites. This was expected, given their structural similarities, and this expectation was 1 of the reasons that these 3 drugs were selected.

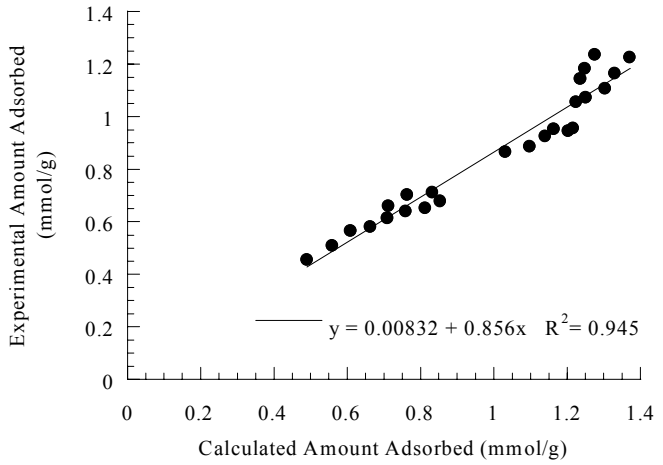

Figure 7. Correlation of experimental and calculated adsorption data for primidone (trisolute system) by SuperChar. Calculated data are from the competitive Langmuir-like model and the proposed equations. (Same equation for the lowest capacity component).

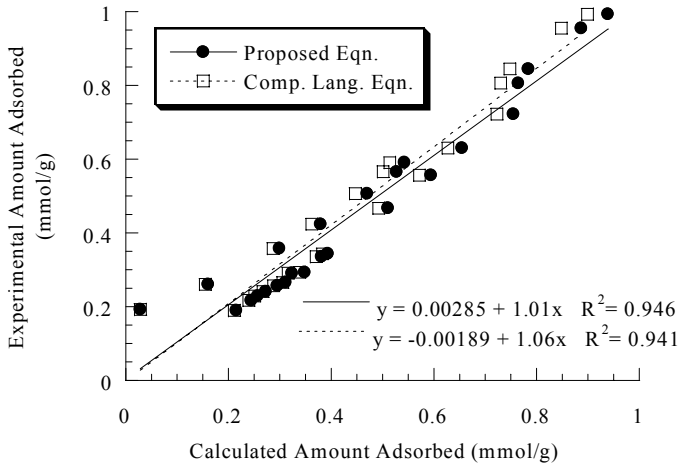

Figure 8. Correlation of experimental and calculated adsorption data for mephobarbital (trisolute system) by SuperChar. Calculated data are from the competitive Langmuir-like model and the proposed equations.

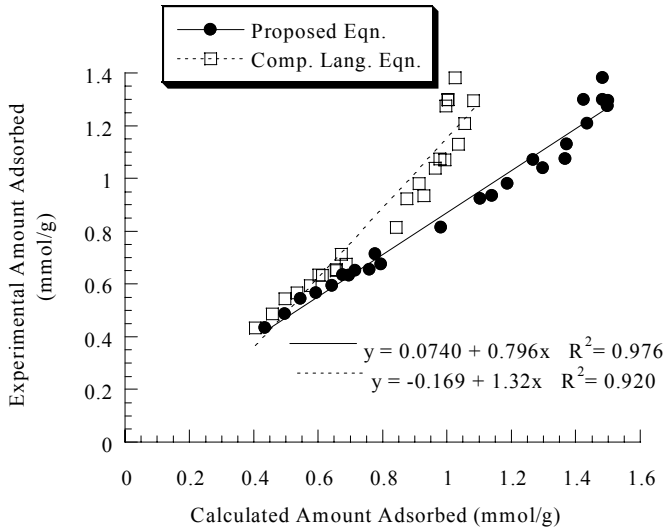

Figure 9. Correlation of experimental and calculated adsorption data for phenobarbital (trisolute system) by SuperChar. Calculated data are from the competitive Langmuir-like model and the proposed equations.

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