

Synthesis of anion exchange adsorbent particles by surface functionalization of polystyrene-divinylbenzene based spherical porous matrices

A. Tongta^a, A.I. Liapis^{*a}, S. Hagen^b

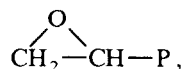
^aDepartment of Chemical Engineering and Biochemical Processing Institute, University of Missouri-Rolla, Rolla, Missouri 65401-0249, USA

^bPharmacia Biotech AS, P.O. Box 213, N-2001 Lillestrom, Norway

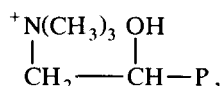
Received 26 October 1995; accepted 11 December 1995

Abstract

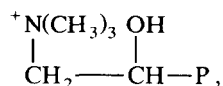
The replacement of Br[−] by trimethylamine for the synthesis of anion exchange adsorbent particles by surface functionalization of polystyrene-divinylbenzene based spherical porous particles was studied experimentally and theoretically. The calculated values of the kinetic parameters indicate that the net rate of the replacement of Br[−] by trimethylamine is dominated by the kinetic mechanism involving the formation and opening of an epoxide,



where P represents the polymeric backbone. The theoretical results obtained from the solution of the equations of the mathematical model that describes the dynamic behavior of the kinetic mechanisms, clearly indicate that the highest concentration of the desired product,



on the surface of the pores of the particles, is obtained when the initial concentration of trimethylamine is highest. The equilibrium adsorption of bovine serum albumin (BSA) into the anion exchange adsorbent particles produced in this work was also studied, and the results indicate that the maximum value of the concentration of BSA in the adsorbed phase is a weak function of the concentration of the desired product,



on the surface of the pores of the particles.

Keywords: Anion exchange; Porous adsorbent particles; Surface functionalization

1. Introduction

Ion exchange chromatography separates molecules based on their ionic charge. The separation occurs by

differential ionic interaction of the sample molecules with the charged functional groups of the support matrix. Due to their stability throughout a wide range of pH values of the mobile phase (Walton, 1980; FPLC Ion Exchange and Chromatofocusing, Principles and Methods, 1985; Small, 1991), polystyrene-divinylbenzene (PS-DVB) supports are commonly used

* Corresponding author.

for manufacturing polymer-based ion exchangers. High-performance liquid chromatography (HPLC) with PS-DVB based anion exchange supports has been widely used for the separation of both organic and inorganic species (Pohl and Johnson, 1980; Wood, et al., 1980; Pietrzyk et al., 1991). Several methods have been reported to produce surface-functionalized PS-DVB anion exchangers (Farral and Frechet, 1976; Lee, 1984; Round and Regnier, 1988; Warth et al., 1989; Ludwig, 1992; Corradini et al., 1994). In this work, PS-DVB based strong anion exchange adsorbent particles were produced by introduction of a charged group (quaternary ammonium ion) to the hydrophilized PS-DVB porous matrices (Ellingsen, 1990). Experiments on the replacement of bromide on the surface of the pores of brominated PS-DVB spherical porous particles by trimethylamine for the production of strong anion exchange adsorbent particles were performed at different temperatures, pH values, and initial concentrations of trimethylamine (Tongta, 1995). Two chemical reaction mechanisms for the reaction of trimethylamine (the replacement of bromide by trimethylamine) on the surface of the pores of PS-DVB spherical porous particles were proposed and a mathematical model that could describe the replacement of Br^- by trimethylamine on the surface of the pores of PS-DVB spherical porous particles was constructed. The experimental data and the mathematical model are used to estimate the parameters that characterize the mechanisms of the reaction. Furthermore, the strong anion exchange adsorbent particles produced were used for the adsorption of bovine serum albumin (BSA) and the equilibrium adsorption data are reported.

2. Experimental methods and procedures

2.1. Experimental methods for the replacement of bromide by trimethylamine

2.1.1 Materials and equipment

Brominated PS-DVB based spherical porous particles (particle diameter = 30 μm) with bromide on the surface of the pores were provided by Pharmacia Biotech, Lillstrom, Norway. Trimethylamine hydrochloride was from Sigma, St. Louis, Missouri, USA, while the sodium hydroxide solution (2.0 N) was from Fisher Scientific, St. Louis, Missouri, USA.

The column (1 cm length \times 1 cm inside diameter) and packing funnel were from Upchurch Scientific, Oak Harbor, Washington, USA, while the HPLC pump was from Beckman, Fullerton, California, USA. A three neck flask (25 ml) was from Kontes, Vineland, New Jersey, USA, while the syringes (50 μl) were from Fisher Scientific, St. Louis, Missouri, USA.

2.1.2 Experimental procedures

The brominated PS-DVB based spherical porous

particles with Br on the surface of the pores and having a particle diameter of 30 μm , were washed with distilled water and centrifuged in order to remove the Br^- in the solution in which the particles were stored. The remaining water, after the centrifugation, was removed by freeze-drying at a temperature below -20°C .

The dried spherical porous particles were packed in a pre-weighed empty column (the inside diameter of the column was 1 cm and its length was also 1 cm) by a packing funnel and the column was shaken as it was being packed. The packed column was weighed again in order to determine the weight of the particles in the column. A trimethylamine hydrochloride solution of 0.01 M was prepared, and the pH was adjusted to a value of 10.5 by adding a solution 2.0 N sodium hydroxide. The experimental system was set up as shown in Fig. 1. The outlet tube of the three neck flask (inlet tube to the pump) was first connected to the trimethylamine hydrochloride solution reservoir. The solution was drawn through the pump to valve B which opened to the waste reservoir in order to fill the tube and the pump head with the solution. The packed column was connected to the system and was submerged in a constant-temperature water bath for 10 min in order to allow the column to reach thermal equilibrium. The temperature of the water in the bath was kept constant at 40°C . A volume of 20 ml of trimethylamine hydrochloride solution was pipetted into a 25 ml three neck flask, a stirring bar was placed in the flask and a magnetic stirrer was used to stir the solution in the flask, the inlet and outlet tubes were connected to the opening of the flask, and the remaining (third) opening was closed by a cap with a septa.

Before the start of the experiment, a sample of 20 μl of trimethylamine hydrochloride solution was taken from the reservoir where the solution was kept, by using a 50 μl syringe. The initial concentrations of Cl^- and trimethylamine in the sample were measured using the procedures described in section 3.2 of this work. At a noted time, the experiment was started by feeding the trimethylamine hydrochloride solution

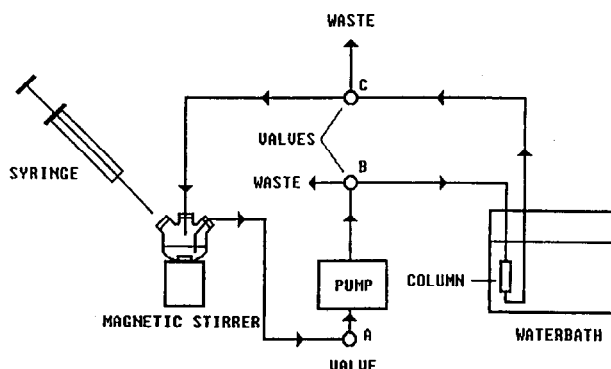


Fig. 1. Experimental system for the replacement of Br^- by trimethylamine.

from the flask to the packed column, and the solution exiting from the column was returned to the flask. The flow-rate was kept constant at 2 ml/min. Samples of 20 μ l were taken from the flask at various times and the concentrations of the Br^- , Cl^- and trimethylamine in the samples were measured. The total time for the experiment was 12 h. After the experiment had been completed, the particles were washed by pumping distilled water through the column for 10 min.

The experimental procedures described above were repeated for five different initial concentrations of trimethylamine hydrochloride solution (Tongta, 1995); those five initial concentrations were 0.01 M, 0.02 M, 0.04 M, 0.06 M, and 0.09 M. The experiments were also performed at 30°C and 50°C for all five different initial concentrations (Tongta, 1995). Furthermore, the following additional experiments, for comparison purposes, were performed: (i) at $T = 40^\circ\text{C}$ and $\text{pH} = 11.5$, the experimental procedures were repeated for all five different initial concentrations of trimethylamine hydrochloride solution (Tongta, 1995); and (ii) at $T = 40^\circ\text{C}$ and $\text{pH} = 9.5$, the experimental procedures were repeated for the following two different initial concentrations of trimethylamine hydrochloride solution: 0.013 M and 0.067 M (Tongta, 1995).

3. Experimental methods for determining the concentrations of Cl^- , Br^- , and trimethylamine in the samples

3.1. Materials and equipment

Methane sulphonic acid was from Sigma, St. Louis, Missouri, USA. The sodium hydroxide solution (0.1 N) was from Fisher Scientific, St. Louis, Missouri, USA, while the SAX Analytical HPLC column (Strong anion exchange-quaternary amine) was from Isco, Inc. Lincoln, Nebraska, USA. The aminex HPX-72-O column (ion moderated partition column in hydroxide form (HPLC column, Method and Application, 1993)) was from BIO-RAD, Hercules, California, USA. Model 2350 HPLC Pumps, V4 Variable UV-Vis Detector, Valco Injection Valves with 5 μ l sample loops and 0.45 μ l filters were from Isco, Inc., Lincoln, Nebraska, USA, while the Dynamax Absorbance Detector Model UV-DII was purchased from Rainin, Emeryville, California, USA.

3.2. Experimental procedures

Two ion chromatographic systems were used in order to analyze the concentrations of the components in the samples. One ion chromatographic system was used to analyze the concentrations of Cl^- and Br^- in the samples, while the second ion chro-

matographic system was used to analyze the concentration of trimethylamine in the samples.

3.2.1. The analysis of the concentrations of Cl^- and Br^-

The ion chromatographic system consisted of Isco's Model 2350 programmable HPLC pump, Valco injector valve with 5 μ l sample loop, SAX (strong anion exchange-quaternary amine) column, and Dynamax absorbance detector Model UV-DII. The system was controlled and the chromatographic data were analyzed by using an IBM compatible PC with ChemResearch software.

The eluent was methane sulphonic acid, which is relatively UV-transparent (Ivery, 1983; Ayers and Gillett, 1984). The eluent's concentration was 0.02 M and it was filtered through a 0.45 μ l filter. The wavelength of the UV detector was set at 190 nm, and the flow-rate of the eluent was kept constant at 1.5 ml/min. A solution containing 100 ppm Cl^- and 100 ppm Br^- was prepared and used as a standard solution. The sample taken from the flask of the experimental procedures described in section 2.1.2 and which contained Cl^- , Br^- and trimethylamine, was injected into the ion chromatographic system. Cl^- and Br^- were separated from each other and from trimethylamine. The concentrations of Cl^- and Br^- were measured by comparing the peak areas of the sample with the peak areas of the standard solution.

3.2.2. Analysis of the concentration of trimethylamine

The ion chromatographic system used in the measurement of the concentrations of trimethylamine in the samples, was the same as the system used in section 3.2.1 except that the column was an aminex HPX-72-O column, and the UV detector was Isco's V4 variable UV-Vis detector. The eluent used was 0.1 N sodium hydroxide solution, and the eluent was filtered through a 0.45 μ m filter before being pumped to the system. The wavelength used was 214 nm, the flow-rate of the eluent was kept constant at 0.5 ml/min, and a 0.05 M trimethylamine hydrochloride solution was used as the standard solution.

The sample taken from the flask of the experimental procedures described in section 2.1.2 and which contained Cl^- , Br^- , and trimethylamine, was injected into the system. The trimethylamine was separated from the anions in the sample, and the concentration was measured by comparing the peak area of the sample with the peak area of the standard solution.

4. Experimental methods for the adsorption of bovine serum albumin in the strong anion exchange adsorbent particles

4.1. Materials and equipment

Bovine serum albumin (BSA) and Bis-Tris propane

were from Sigma, St. Louis, Missouri, USA, while sodium chloride was from Fisher Scientific, St. Louis, Missouri, USA. The column (1 cm length \times 2 mm inside diameter) and a packing funnel were from Upchurch Scientific, Oak Harbor, Washington, USA, while the HPLC pump was purchased from Beckman, Fullerton, California, USA, and the UA-5 Absorbance Detector was purchased from Isco, Inc., Lincoln, Nebraska, USA.

4.2. Experimental procedures

The adsorbent particles produced from the experimental procedures described in section 2.1.2, were freeze-dried at a temperature below -20°C . The dried adsorbent particles were packed in the pre-weighed empty column by using a packing funnel and the column was being shaken as it was being packed. The packed column was weighed again in order to determine the weight of the adsorbent particles in the column.

4.2.1. Adsorption experiments

The experimental system is shown in Fig. 2. The adsorption experiments were carried out at room temperature (23°C). The volumetric flow-rate of the bovine serum albumin solution was kept constant at 2.0 ml/min in all adsorption experiments. The following experimental steps were employed: (a) the packed column was equilibrated with a 20 mM Bis-Tris propane buffer solution (pH = 7.0) until the baseline was stable; (b) at a noted time, the protein solution (BSA in 20 mM Bis-Tris Propane buffer solution; pH = 7.0) of known concentration was introduced to the column until the outlet concentration determined by the UV detector was constant. The wavelength of the UV detector used was 280 nm; and (c) buffer solution was introduced to the column until the baseline was constant.

The anion exchange adsorbent particles that were produced from the experimental procedures described in section 2.1.2 were used in the column, and the above described experimental procedures were employed for five different inlet concentrations of BSA (Tongta, 1995); the five different concentrations of BSA were 0.1 mg/ml, 0.2 mg/ml, 0.5 mg/ml, 0.7 mg/ml, and 1.0 mg/ml (Tongta, 1995).

4.2.2. Desorption experiments

The desorption experiments were also carried out at room temperature (23°C). The eluent was 1.0 M NaCl solution, and the flow-rate was kept constant at 2.0 ml/min. The system used for the desorption experiments is shown in Fig. 2.

After step (c) of the adsorption experiment described above, the eluent was introduced to the column and the outlet concentration of BSA in the

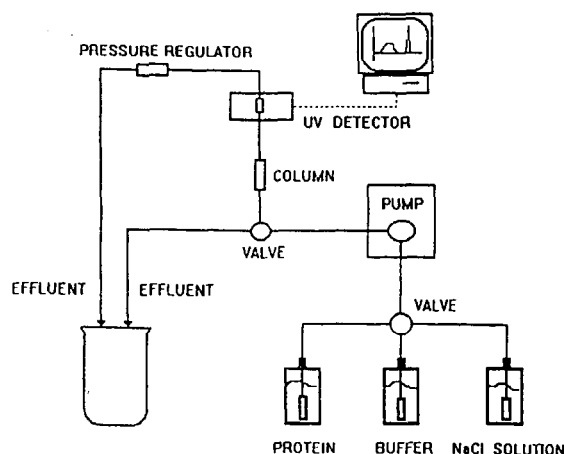


Fig. 2. Experimental system used for the adsorption of bovine serum albumin in the adsorbent particles, and for the desorption of bovine serum albumin from the adsorbent particles.

eluent solution was determined by the UV detector with the wavelength set at 280 nm. The desorption experiment was terminated when the baseline became constant.

5. Mathematical model

In this work, the batch (finite bath) model with recycle is considered instead of the distributed (fixed bed) model with recycle. The lumped (batch) model is considered to be appropriate for this system because the experimental data and the calculated time constants of the various mass transfer (intraparticle fluid flow; macropore diffusion; micropore diffusion) and chemical reaction mechanisms indicated (Tongta, 1995) that the rates of the chemical reactions are the rate limiting steps in the process of interest (Tongta, 1995), and furthermore, the flow rate of the solution being recycled in the system is such that the rates of the chemical reactions in the packed column are negligibly affected (Tongta, 1995).

The values of the calculated time constants are presented in the work of Tongta, 1995 and indicate that the concentrations of trimethylamine in the pore fluid, in the flowing fluid stream in the column, and in the fluid in the finite bath, are in effect almost equal at a given time during the time period of the experiment. Thus, in the mathematical model that is presented in the following section, the concentrations of trimethylamine in the pore fluid, in the flowing fluid stream in the column, and in the fluid in the finite bath, are taken to be equal to each other. Isothermal conditions are considered to be present throughout the system since the heat capacity of the liquid in the system is relatively high and a constant temperature bath was employed to control the temperature of the column where the reaction occurred.

The differential mass balances of trimethylamine and hydroxyl ion in the system (the system is defined to be the column and the finite bath) are as follows:

$$\frac{dC_{Tr}}{dt} = \frac{(1 - \epsilon)}{\epsilon} r_{Tr} \quad (1)$$

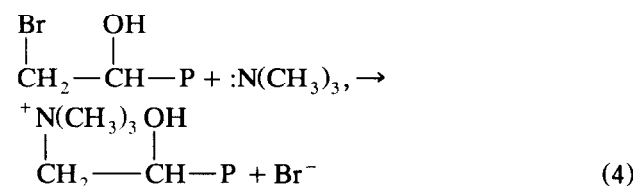
$$\frac{dC_{OH}}{dt} = \frac{(1 - \epsilon)}{\epsilon} r_{OH} \quad (2)$$

The value of ϵ in Eqs. (1) and (2) is the void fraction which is obtained from expression (3)

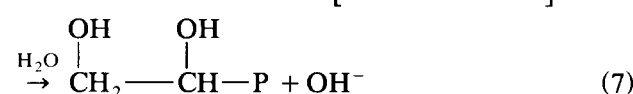
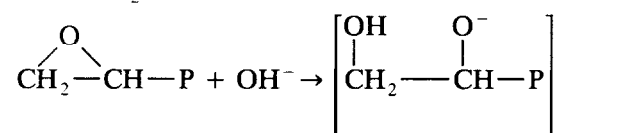
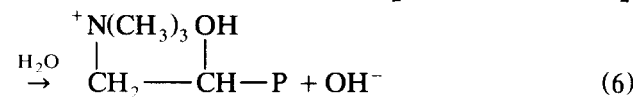
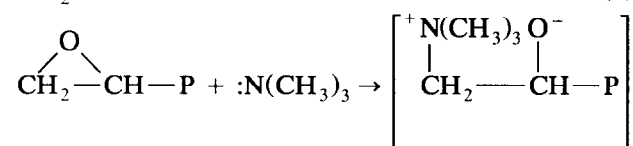
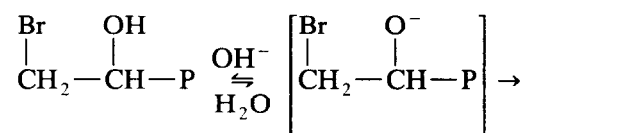
$$\epsilon = \frac{V_b}{V_b + V_s} \quad (3)$$

where V_b represents the value of the volume of trimethylamine hydrochloride solution used in each experiment and V_s represents the volume of the solid phase of adsorbent particles used in each experiment; the value of ϵ for each experiment was 0.990 (Tongta, 1995).

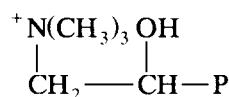
The reaction of trimethylamine (the replacement of Br^- by trimethylamine) on the surface of the pores of the porous adsorbent particles could take place by the following two chemical reaction mechanisms (the symbol P in the chemical formulas denotes the polymeric backbone) Mechanism 1:



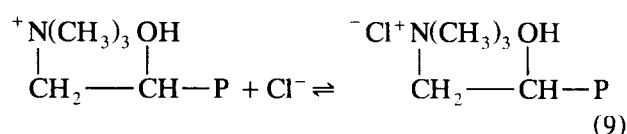
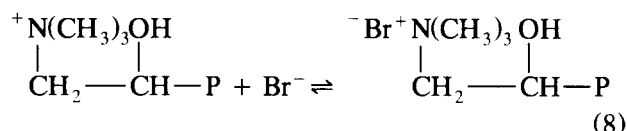
Mechanism 2:



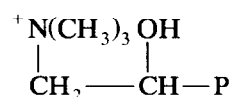
The component



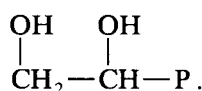
represents the active site on the surface of the pores of the adsorbent particles, and this component could interact with Br^- and Cl^- (from trimethylamine hydrochloride) as follows:



In the above mechanisms, the desired product is



and the undesired product is

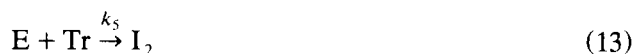


For convenience in the discussions that follow, the chemical compounds in Eqs. (4–9) are defined by appropriately abbreviated symbols (please see the section of nomenclature of this work), as follows:

Mechanism 1:



Mechanism 2:



The interactions of P^+ with Br^- and Cl^- are as follows:



The net rate expressions for A, Tr, OH^- , and E are given by expressions (19–22)

$$-r_A = k_1 C_A C_{Tr} + k_2 C_A C_{OH} - k_3 C_{I_1} C_{H_2O} \quad (19)$$

$$-r_{Tr} = k_1 C_A C_{Tr} + k_5 C_E C_{Tr} \quad (20)$$

$$r_{OH} = k_3 C_{I_1} C_{H_2O} - k_2 C_{OH} C_A + k_6 C_{I_2} C_{H_2O} + k_8 C_{I_3} C_{H_2O} - k_7 C_E C_{OH} \quad (21)$$

$$r_E = k_4 C_{I_1} - k_5 C_E C_{Tr} - k_7 C_E C_{OH} \quad (22)$$

The concentrations C_{I_1} , C_{I_2} , and C_{I_3} can be obtained from the rate expressions (23–25)

$$r_{I_1} = k_2 C_A C_{OH} - k_3 C_{I_1} C_{H_2O} - k_4 C_{I_1} \quad (23)$$

$$r_{I_2} = k_5 C_E C_{Tr} - k_6 C_{I_2} C_{H_2O} \quad (24)$$

$$r_{I_3} = k_7 C_E C_{OH} - k_8 C_{I_3} C_{H_2O} \quad (25)$$

by setting r_{I_1} , r_{I_2} , and r_{I_3} equal to zero (pseudo steady-state assumption). The resulting expressions for C_{I_1} , C_{I_2} , and C_{I_3} are as follows:

$$C_{I_1} = \frac{k_2 C_A C_{OH}}{k_3 C_{H_2O} + k_4} \quad (26)$$

$$C_{I_2} = \frac{k_5 C_E C_{Tr}}{k_6 C_{H_2O}} \quad (27)$$

$$C_{I_3} = \frac{k_7 C_E C_{OH}}{k_8 C_{H_2O}} \quad (28)$$

The total rate, $r_{Br,t}$, of the production of bromide in both Br^- and PBr forms, is given by

$$r_{Br,t} = r_{Br} + r_{PBr} \quad (29)$$

where

$$r_{Br} = k_1 C_A C_{Tr} + k_4 C_{I_1} - r_{PBr} \quad (30)$$

By combining Eqs. (29) and (30) the following expression for $r_{Br,t}$ is obtained:

$$r_{Br,t} = k_1 C_A C_{Tr} + k_4 C_{I_1} \quad (31)$$

By substituting C_{I_1} from expression (26) into Eq. (31), the expression for $r_{Br,t}$ becomes as follows:

$$r_{Br,t} = (k_1 C_{Tr} + \xi C_{OH}) C_A \quad (32)$$

where

$$\xi = \frac{k_4 k_2}{k_3 C_{H_2O} + k_4} \quad (33)$$

By letting $C_{Br,t}$ be the concentration of bromide in the form of Br^- and PBr with units of mol/l, Eq. (32) can then be expressed as

$$r_{Br,t} = \frac{d\left(\frac{\epsilon}{1-\epsilon}\right) C_{Br,t}}{dt} = (k_1 C_{Tr} + \xi C_{OH}) C_A \quad (34)$$

The void fraction, ϵ , is taken to be constant, and thus, Eq. (34) takes the form given by expression (35)

$$\frac{dC_{Br,t}}{dt} = \frac{1-\epsilon}{\epsilon} (k_1 C_{Tr} + \xi C_{OH}) C_A \quad (35)$$

By substituting the expressions for C_{I_1} , C_{I_2} , and C_{I_3} into Eqs. (12) and (13) and by inserting the resulting expressions into Eqs. (1) and (2), respectively, the following expressions are obtained:

$$\frac{dC_A}{dt} = -(k_1 C_{Tr} + \xi C_{OH}) C_A \quad (36)$$

$$\frac{dC_{Tr}}{dt} = -\frac{1-\epsilon}{\epsilon} (k_1 C_A + k_5 C_E) C_{Tr} \quad (37)$$

$$\frac{dC_{OH}}{dt} = \frac{1-\epsilon}{\epsilon} (k_5 C_E C_{Tr} - \xi C_A C_{OH}) \quad (38)$$

$$\frac{dC_E}{dt} = \xi C_A C_{OH} - k_5 C_E C_{Tr} - k_7 C_E C_{OH} \quad (39)$$

The initial conditions for Eqs. (35–39) are

$$C_{Br,t} = 0 \quad t = 0 \quad (40)$$

$$C_A = C_{A0} \quad \text{at } t = 0 \quad (41)$$

$$C_{Tr} = C_{Tr0} \quad \text{at } t = 0 \quad (42)$$

$$C_{OH} = C_{OH0} \quad \text{at } t = 0 \quad (43)$$

$$C_E = 0 \quad \text{at } t = 0 \quad (44)$$

The values of the parameters k_1 , k_5 , ξ , k_7 , and C_{A0} could be estimated by matching the experimental data of C_{Tr} and $C_{Br,t}$ with the theoretical results of C_{Tr} and $C_{Br,t}$ obtained from the solution of Eqs. (35–44).

6. Computational methods

Equations (35–44) represent a system of non-linear ordinary differential equations. The equations were solved numerically by Gear's Method which is in the routine LSODE of the ordinary differential equations solver package titled ODEPACK (Wicks, 1988). The

values of the unknown parameters k_1 , k_5 , ξ , k_7 and C_{A0} were estimated by using the orthogonal distance regression method routine DODRC from the package ODRPACK (Boggs et al., 1992).

7. Results and discussion

7.1. Evaluation of the parameters k_1 , k_5 , ξ , k_7 , and C_{A0} of the mathematical model

The values of the parameters k_1 , k_5 , ξ , k_7 , and C_{A0} were estimated by matching the experimental data of C_{Tr} and $C_{Br,t}$ with the predictions of the mathematical model Eqs. (35–44). The experimental values of $C_{Br,t}$ in Eq. (35) were calculated from the overall material balance for the system, as follows:

$$C_{Br,t} = C_{Br}^+ (C_{Tr0} - C_{Tr}) - (C_{Cl0} - C_{Cl}) \quad (45)$$

The values of C_{Br} , C_{Tr0} , C_{Tr} , C_{Cl0} , and C_{Cl} used in Eq. (45) were determined experimentally.

In Figs. 3–6, the experimental data and the results from the mathematical model for C_{Tr} and $C_{Br,t}$ are presented for pH = 10.5 and $T = 40^\circ\text{C}$. The initial concentrations of trimethylamine, C_{Tr0} , are presented in the captions of Figs. 3–6. In Table 1, the values of the parameters k_1 , k_5 , ξ , k_7 , and C_{A0} that provide the best fit between the experimental data and the results from the mathematical model shown in Figs. 3–6, are presented. Experimental data and theoretical results for other experimental values of pH, temperature, and C_{Tr0} are reported in Tongta, 1995. For all

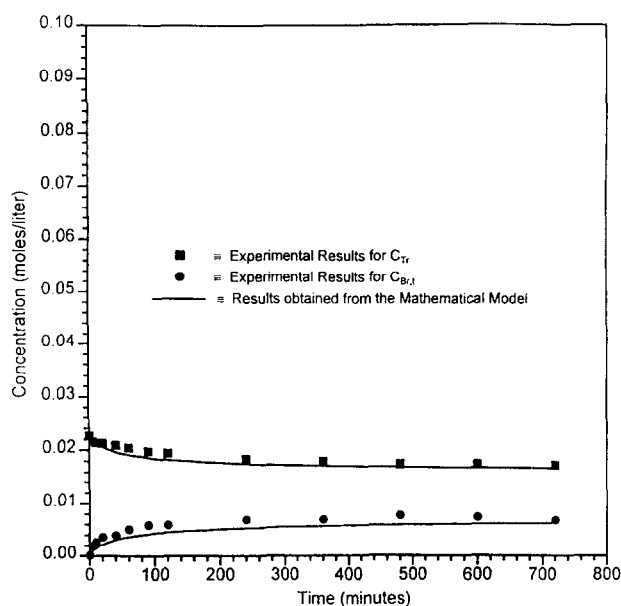


Fig. 3. Experimental and theoretical results for C_{Tr} and $C_{Br,t}$ obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.02252$ M.

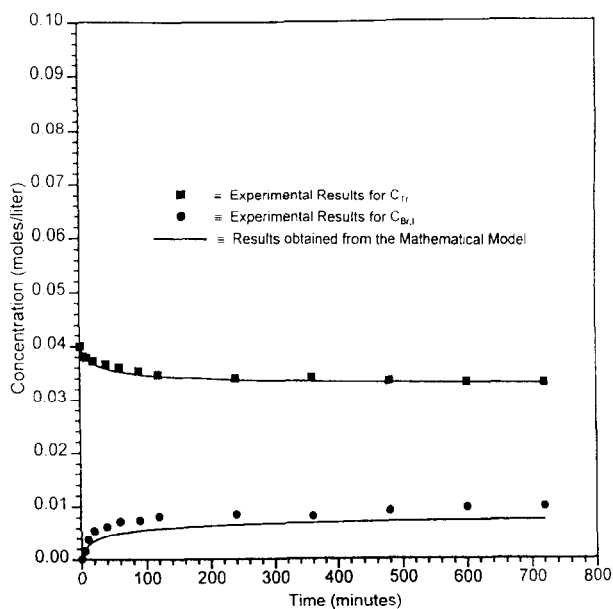
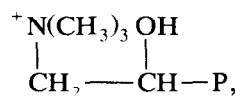
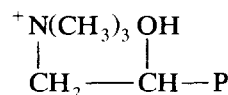


Fig. 4. Experimental and theoretical results for C_{Tr} and $C_{Br,t}$ obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.03985$ M.

experiments performed in this work, the values of k_1 presented in Table 1, are significantly smaller than the values of k_5 and ξ . This result indicates that the replacement of Br^- by trimethylamine is dominated by chemical reaction mechanism 2. Furthermore, the calculated values of the concentrations of the desired product,



produced from chemical reaction mechanism 2 are found to be much larger than the concentrations of the desired product,



produced from chemical reaction mechanism 1 (Tongta, 1995). The value of C_{A0} presented in Table 1, increases as the initial concentration of trimethylamine, C_{Tr0} , increases. This suggests that the value of C_{A0} that becomes observable in a given experiment, depends on the initial value of the concentration of trimethylamine, C_{Tr0} , which appears to have a significant effect on the whole sequence of the chemical reaction rates of kinetic mechanisms 1 and 2. It was found (Tongta, 1995) that the effects of the variation of the values of pH and temperature on the calculated value of C_{A0} , do not suggest an apparent trend.

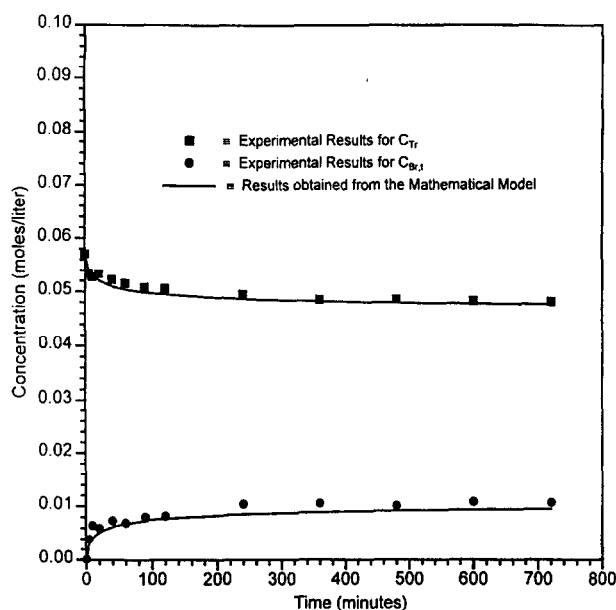
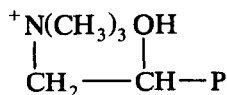


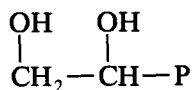
Fig. 5. Experimental and theoretical results for C_{Tr} and $C_{Br,i}$ obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.05697$ M.

7.2. Concentrations of desired, C_P , and undesired, C_U , products calculated from the theoretical model

The calculated values of C_P ($P \equiv$



is the desired product) and C_U ($U \equiv$



is the undesired product) were obtained by considering the chemical reaction mechanisms 1 and 2 given in Eqs. (10-18). The rate expression for P^+ is given by

$$r_{P^+} = k_1 C_A C_{Tr} + k_6 C_{I_2} C_{H_2O} - r_{PBr} - r_{PCl} \quad (46)$$

where the terms r_{PBr} and r_{PCl} represent the net rates of production of PBr and PCl on the surface of the

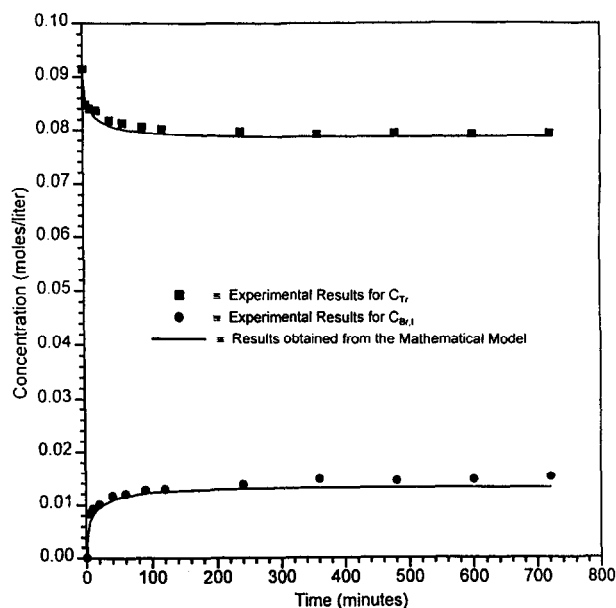


Fig. 6. Experimental and theoretical results for C_{Tr} and $C_{Br,i}$ obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.09141$ M.

pores of the adsorbent particles. The rate of interaction between OH^- with P^+ is not included in equation (46), although OH^- is also present in the solution, because the hydroxyl ion is the weakest replacing ion on a strong-base exchanger when compared to bromide and chloride (Berg, 1963). Generally, the rate of interaction of P^+ with Br^- or Cl^- is considered to be fast, and P^+ has to be coupled with either Br^- or Cl^- . Therefore, the net rate for r_{P^+} could be considered to be approximately equal to zero.

By substituting the expression of C_{I_2} into Eq. (46) and letting r_P be the net rate of production of the product in both PBr and PCl forms, the following expression is obtained for dC_P/dt :

$$r_P = r_{PBr} + r_{PCl} = \frac{dC_P}{dt} = k_1 C_A C_{Tr} + k_5 C_E C_{Tr} \quad (47)$$

The values of C_U were calculated from the solution of Eq. (48)

$$r_U = \frac{dC_U}{dt} = k_7 C_E C_{OH} \quad (48)$$

Table 1

Values of the parameters C_{A0} , k_1 , k_5 , ξ , and k_7 for pH = 10.5, $T = 40^\circ\text{C}$, and different experimental initial values of trimethylamine

C_{Tr0} (mol/l)	C_{A0} (moles/l of solid phase of adsorbent particles)	k_1 (l/mol·s)	k_5 (l/mol·s)	ξ (dimensionless)	k_7 (l/mol·s)
0.02252	0.7451	3.0249E-07	0.4182	20.7200	61.007
0.03985	0.8846	3.9328E-07	0.6561	16.6840	66.097
0.05697	1.0724	1.3331E-07	1.7871	11.7990	83.130
0.09141	1.3217	1.2956E-07	3.2793	24.5405	125.72

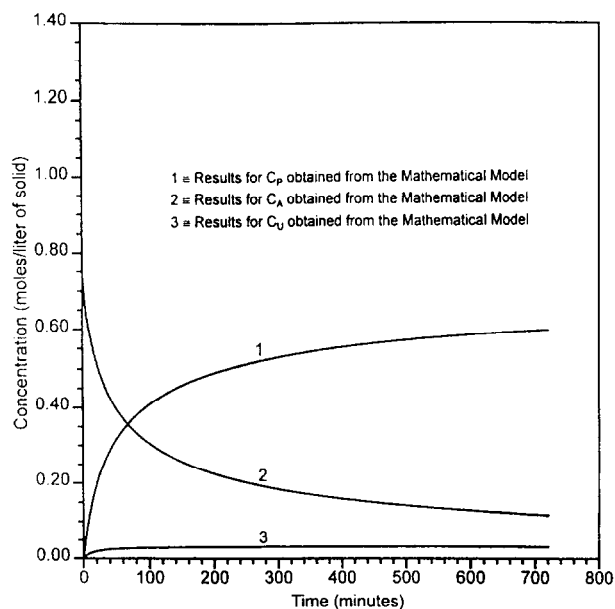


Fig. 7. Theoretical results for C_P , C_A , and C_U obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.02252$ M.

The initial conditions of Eqs. (47) and (48) are

$$C_P = 0 \quad \text{at } t = 0 \quad (49)$$

$$C_U = 0 \quad \text{at } t = 0 \quad (50)$$

The numerical solution of Eqs. (47–50) along with Eqs. (35–44) provides the dynamic (unsteady-state) behavior of C_P and C_U .

In Figs. 7–10, the calculated results of C_A , C_P , and C_U are presented for pH = 10.5 and $T = 40^\circ\text{C}$. The initial concentration of trimethylamine, C_{Tr0} , is pre-

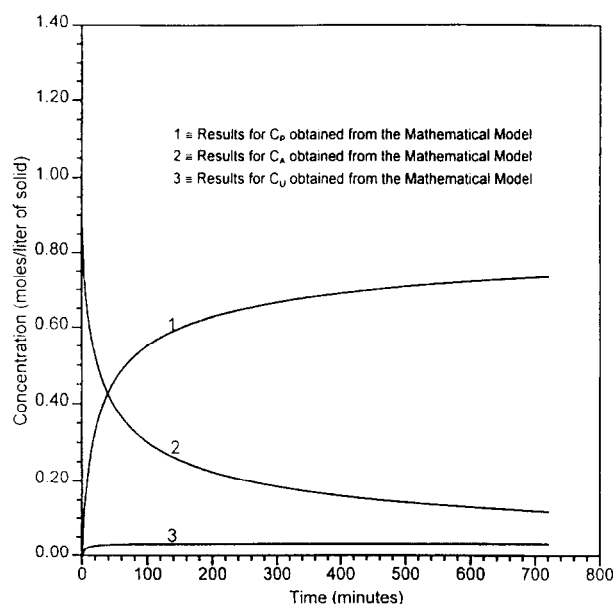


Fig. 8. Theoretical results for C_P , C_A , and C_U obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.03985$ M.

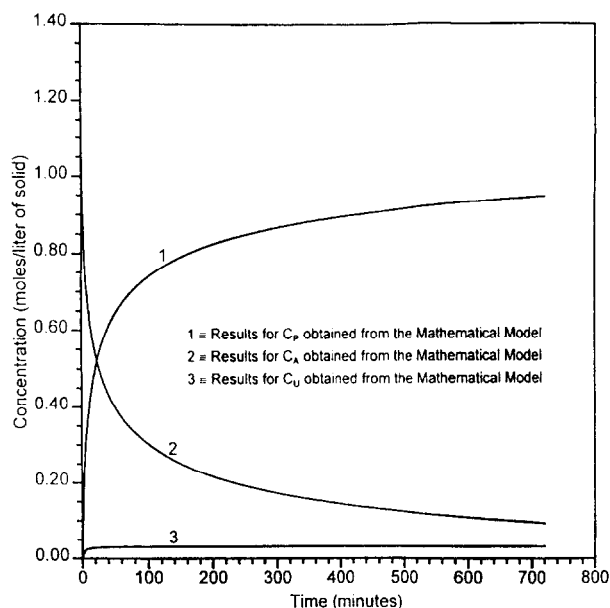


Fig. 9. Theoretical results for C_P , C_A , and C_U obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.05697$ M.

sented in the captions of Figs. 7–10. The values of the parameters k_1 , k_5 , ξ , k_7 , and C_{A0} used for the calculation of C_A , C_P , and C_U are presented in Table 1. In Table 2, the calculated values of C_P , C_U , and C_P/C_U at $t = 720$ min after the start of each experiment, along with the values of C_{Tr0} and C_{A0} are presented. The results in Table 2 indicate that the values of C_P and C_P/C_U significantly increase as C_{Tr0} increases, while the changes in the value of C_U are not significant when the value of C_{Tr0} increases. The calculated values of C_A , C_P , and C_U for other experimental values of pH, temperature, and C_{Tr0} are reported in the work of Tongta, 1995.

7.3. Adsorption results

The experimental equilibrium concentrations of BSA in the liquid solution, C_d , and in the adsorbed phase, C_s , are obtained from the experimental procedures described in section 4 of this work. The Langmuir equilibrium adsorption model

$$C_s = \frac{C_T K_a C_d}{1 + K_a C_d} \quad (51)$$

was found to represent the experimental equilibrium data satisfactorily. In Fig. 11, the equilibrium experimental and theoretical results of the adsorption of BSA onto the anion exchange particles produced at pH = 10.5, $T = 40^\circ\text{C}$, and $C_{Tr0} = 0.09141$ M, are presented. In Table 3, the adsorption parameters C_T and K_a that provide the best fit between the equilibrium experimental and theoretical results, are pre-

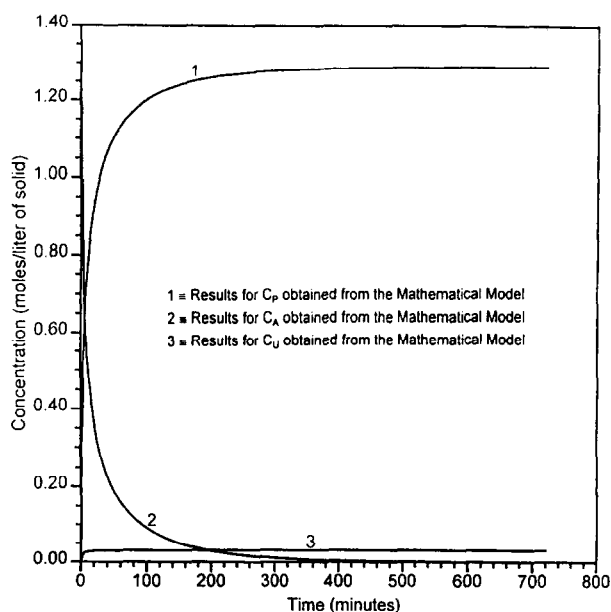


Fig. 10. Theoretical results for C_P , C_A , and C_U obtained for pH = 10.5, $T = 40^\circ\text{C}$, and $C_{\text{Tr}0} = 0.09141 \text{ M}$.

sented along with the conditions (pH, temperature, and $C_{\text{Tr}0}$) that were used to produce the anion exchange adsorbent particles. The equilibrium experimental and theoretical results of the adsorption of BSA onto the anion exchange adsorbent particles produced at other experimental values of pH, temperature, and $C_{\text{Tr}0}$ are presented in Tongta, 1995.

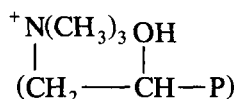
The results in Tables 2 and 3 indicate that the maximum value of the concentration of BSA in the adsorbed phase (the value of C_T) is a weak function of C_P . This suggests that the value of C_T depends weakly on the concentration of active sites on the surface of the pores of these adsorbent particles. It should be noted that the dependence of C_T on C_P could be different if the adsorbate was not BSA (Liapis, 1991; McCoy and Liapis, 1991).

8. Conclusions and remarks

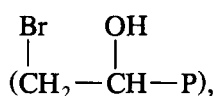
The replacement of Br^- by trimethylamine for the production of anion exchange adsorbent particles was studied experimentally and theoretically for different

values of pH, temperature, and initial concentrations of trimethylamine (Tongta, 1995).

The calculated values of the kinetic parameters k_1 , k_5 , ξ , and k_7 clearly indicate that the net rate of the chemical reaction (the replacement of Br^- by trimethylamine) is dominated by chemical reaction mechanism 2, and most of the product of interest

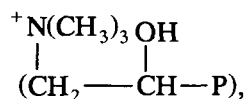


is produced through the reaction steps of kinetic mechanism 2. It was found that the calculated value of the initial concentration of component A



C_{A0} , for all experiments performed at the same pH and temperature, increases as the initial concentration of trimethylamine, $C_{\text{Tr}0}$, increases. This suggests that the value of C_{A0} that becomes observable in a given experiment, depends on the initial value of the concentration of trimethylamine, $C_{\text{Tr}0}$, which appears to have a significant effect on the whole sequence of the chemical reaction rates of mechanisms 1 and 2.

The results of this work clearly indicate that the highest value of the concentration of the desired product



C_P , is obtained (for the experimental conditions of pH = 10.5 and $T = 40^\circ\text{C}$) when the initial concentration of trimethylamine is highest. Also, the results of the adsorption of BSA into the anion exchange adsorbent particles produced at pH = 10.5 and $T =$

Table 2

Values of C_{A0} , C_P , C_U , and C_P/C_U for pH = 10.5, $T = 40^\circ\text{C}$, and different experimental initial values of trimethylamine; the values of C_P and C_U were calculated at $t = 12 \text{ h}$

$C_{\text{Tr}0}$ (mol/l)	C_{A0} (mol/l of solid phase of adsorbent particles)	C_P (mol/l of solid phase of adsorbent particles)	C_U (mol/l of solid phase of adsorbent particles)	$\frac{C_P}{C_U}$
0.02252	0.7451	0.59702	0.03168	18.845
0.03985	0.8846	0.73413	0.03271	22.444
0.05697	1.0724	0.94627	0.03215	29.433
0.09141	1.3217	1.29029	0.03121	41.342

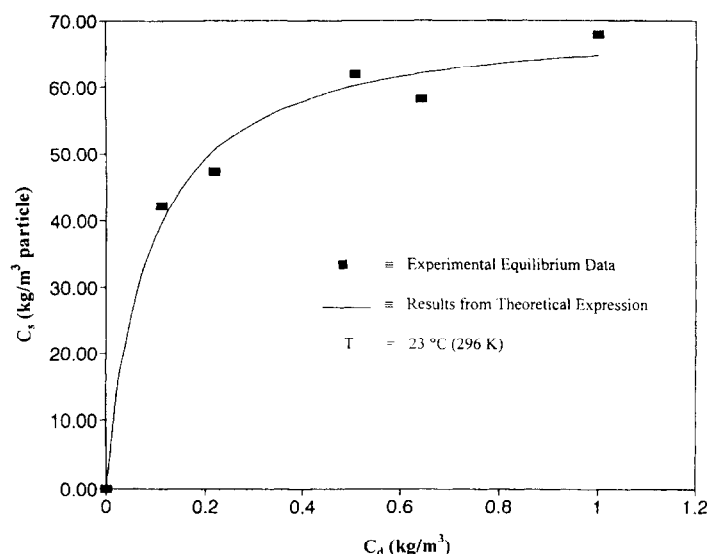
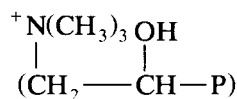


Fig. 11. Experimental and theoretical equilibrium results of the adsorption of BSA into the anion exchange adsorbent particles produced at pH = 10.5, $T = 40^{\circ}\text{C}$, and $C_{T(0)} = 0.09141\text{ M}$; the correlation coefficient is equal to 0.9929.

40°C , indicate that the maximum value of the concentration of BSA in the adsorbed phase (the value of C_T) is a weak function of the concentration of the desired product



C_p , on the surface of the pores of the anion exchange adsorbent particles. It is worth stating here that the dependence of C_T on C_p could be different if the adsorbate was not BSA (Liapis, 1991; McCoy and Liapis, 1991).

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Royal Thai Government and Pharmacia Biotech AS, Norway.

Table 3

Values of the parameters C_T and K_a of the adsorption of BSA into the adsorbent particles produced for different values of initial concentrations of trimethylamine, $C_{T(0)}$, and at pH = 10.5 and $T = 40^{\circ}\text{C}$. The equilibrium adsorption experiments were performed at $T = 23^{\circ}\text{C}$ and five different inlet concentrations of BSA were used as discussed in section 4.2.1.

$C_{T(0)}$ (mol/l)	C_T (kg/m ³ of adsorbent particles)	K_a (m ³ /kg)
0.02252	68.265	12.232
0.03985	66.524	11.549
0.05697	64.675	15.174
0.09141	70.349	11.648

Nomenclature

C_A	≡	concentration of A in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
$C_{A(0)}$	≡	initial concentration of A in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
C_{Br}	≡	concentration of Br^- in the fluid phase, mol/l
$C_{Br,t}$	≡	concentration of total bromide in the system (in both Br^- and PBr forms), mol/l
C_{Cl}	≡	concentration of Cl^- in the fluid phase, mol/l
$C_{Cl(0)}$	≡	initial concentration of Cl^- , mol/l
C_d	≡	equilibrium concentration of adsorbate in the liquid solution, kg/m ³
C_E	≡	concentration of E in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
$C_{\text{H}_2\text{O}}$	≡	concentration of H_2O , mol/l
C_{I_1}	≡	concentration of I_1 in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
C_{I_2}	≡	concentration of I_2 in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
C_{I_3}	≡	concentration of I_3 in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
C_{OH}	≡	concentration of OH^- , mol/l
$C_{\text{OH}(0)}$	≡	initial concentration of OH^- , mol/l
C_P	≡	concentration of P (desired product) in the solid phase of adsorbent particles,

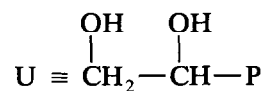
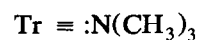
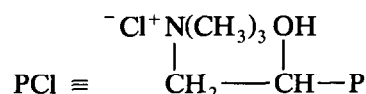
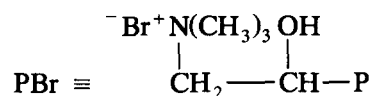
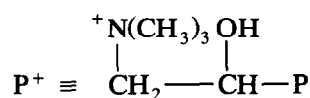
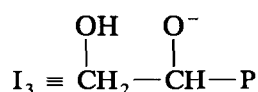
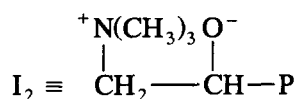
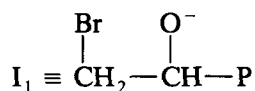
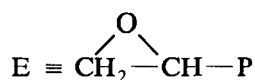
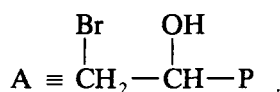
	mol/l of solid phase of adsorbent particles
C_s	\equiv equilibrium concentration of adsorbate in the adsorbed phase of adsorbent particles, kg/m ³ of adsorbent particles
C_T	\equiv maximum equilibrium concentration of adsorbate in the adsorbed phase, kg/m ³ of adsorbent particles
C_{Tr}	\equiv concentration of trimethylamine in bulk fluid, mol/l
C_{Tr0}	\equiv initial concentration of trimethylamine in bulk fluid, mol/l
C_U	\equiv concentration of U (undesired product) in the solid phase of adsorbent particles, mol/l of solid phase of adsorbent particles
k_1	\equiv rate constant in expression (15), 1/mol·s
k_2	\equiv rate constant in expression (16), 1/mol·s
k_3	\equiv rate constant in expression (16), 1/mol·s
k_4	\equiv rate constant in expression (17), 1/s
k_5	\equiv rate constant in expression (18), 1/mol·s
k_6	\equiv rate constant in expression (19), 1/mol·s
k_7	\equiv rate constant in expression (20), 1/mol·s
k_8	\equiv rate constant in expression (21), 1/mole·s
k_9	\equiv rate constant in expression (22), 1/mole·s
k_{10}	\equiv rate constant in expression (22), 1/s
k_{11}	\equiv rate constant in expression (23), 1/mol·s
k_{12}	\equiv rate constant in expression (23), 1/s
K_a	\equiv equilibrium adsorption constant of BSA, m ³ /kg
r_A	\equiv reaction rate of A, mol/(l of solid phase of adsorbent particles)·s
r_{Br}	\equiv reaction rate of Br ⁻ , mol/(l of solid phase of adsorbent particles)·s
$r_{Br, t}$	\equiv reaction rate of bromide (total bromide) in the system (in both Br ⁻ and PBr forms), mol/(l of solid phase of adsorbent particles)·s
r_{Cl}	\equiv reaction rate of Cl ⁻ , mol/(l of solid phase of adsorbent particles)·s
r_{OH}	\equiv reaction rate of OH ⁻ , mol/(l of solid phase of adsorbent particles)·s
r_P	\equiv reaction rate of product in both PBr and PCl forms, mol/(l of solid phase of adsorbent particles)·s
r_{P^+}	\equiv reaction rate of P ⁺ , mol/(l of solid phase of adsorbent particles)·s
r_{PBr}	\equiv reaction rate of PBr, mol/(l of solid phase of adsorbent particles)·s
r_{PCl}	\equiv reaction rate of PCl, mol/(l of solid phase of adsorbent particles)·s
r_{Tr}	\equiv reaction rate of trimethylamine, mol/(l of solid phase of adsorbent particles)·s
T	\equiv temperature, °C or K as indicated
t	\equiv time, s
V_b	\equiv volume of the solution used in the experiment, m ³

V_s \equiv volume of the solid phase of adsorbent particles, m³

Greek letters

ϵ \equiv void fraction in the finite bath
 ξ \equiv parameter defined in Eq. (33), l/mol·s

Symbols used to represent the chemical formulas in equations (10–18)



References

- Ayers, G.P. and Gillett, R.W. (1984) Sensitive detection of anion ion chromatography using UV detection at wavelength less than 200 nm. *J. Chromatogr.* 284, 510.
- Berg, E.W. (1963) *Physical and Chemical Methods of Separation*. McGraw-Hill Book Company, Inc., New York, USA.
- Boggs, P.T., Byrd, R.H., Donalson, J.R. and Schnabel, R.B. (1992) *User's Reference Guide for ODRPACK — Software for Weighted Orthogonal Distance Regression (ODRPACK Version 2.01)*. National Institute of Standards and Technology, Gaithersburg, Maryland, USA.

- Corradini, C., Corradini, D., Huber, C.G. and Bonn, G.K. (1994) Synthesis of polymeric-based stationary phase for carbohydrate separation by high-pH anion-exchange chromatography with pulsed amperometric detection. *J. Chromatogr. A* 658, 213.
- Ellingsen, T., Aune, O., Ugelstad, J. and Hagen, S. (1990) Mono-sized stationary phases for chromatography. *J. Chromatogr.* 535, 147.
- Farrall, M.J. and Frechet, J.M.J. (1976) Bromination and lithiation: Two important steps in the functionalization of polystyrene resins. *J. Org. Chem.* 41, 3877.
- FPLC Ion Exchange and Chromatofocusing, Principles & Methods (1985) Pharmacia Laboratory Separation Division, Uppsala, Sweden.
- HPLC Column, Method and Application (1993) Bio-Rad Laboratories, Hercules, California, USA.
- Ivey, J.P. (1983) Novel eluent for the UV and conductometric detection of anions in unsuppressed ion chromatography. *J. Chromatogr.* 267, 218.
- Lee, D.P. (1984) A new anion exchange phase for ion chromatography. *J. Chromatogr. Sci.* 22, 327.
- Liapis, A.I. (1991) Biospecific adsorption-mechanisms and processes of affinity chromatography, in *Fundamentals of Adsorption*. In: Mersmann, A.B., Scholl, S.E. (Eds), Engineering Foundation, New York, NY, USA, pp. 25–61.
- Ludwig, R.C. (1992) Application of a pellicular anion-exchange resin to the separation of inorganic and organic anion by single column anion exchange. *J. Chromatogr.* 592, 101.
- McCoy, M.A. and Liapis, A.I. (1991) Evaluation of kinetic models for biospecific adsorption and its implications for finite bath and column performance. *J. Chromatogr.* 548, 25.
- Pietrzyk, D.J., Senne, S.M. and Brown, D.M. (1991) Anion-cation separations on a mixed-bed ion-exchange column with indirect photometric detection. *J. Chromatogr.* 546, 101.
- Pohl, C.A. and Johnson, E.L., (1980) Ion chromatography-the state-of-the-art. *J. Chromatogr. Sci.* 18, 442.
- Round, M.A. and Regnier, F.E. (1988) Synthesis of a non-porous, polystyrene-based strong anion exchange packing material and its application to fast high-performance liquid chromatography of proteins. *J. Chromatogr.* 443, 73.
- Small, H. (1991) Twenty years of ion chromatography. *J. Chromatogr.* 546, 3.
- Tongta, A. (1995) Ph.D. Dissertation, Department of Chemical Engineering, University of Missouri-Rolla, Rolla, Missouri, USA.
- Walton, H.F. (1980) Ion exchange and liquid column chromatography. *Anal. Chem.* 52, 15R.
- Warth, L.M., Fritz, J.S. and Naples, J.O. (1989) Preparation and use of latex-coated resins for anion chromatography. *J. Chromatogr.* 462, 165.
- Wicks, T. (1988) User's Guide to ODEPACK, Scientific Computing and Analysis Library Report, SCA-LR-52. Boeing Computer Services, Seattle, Washington, USA.
- Wood, R., Cummings, L. and Jupille, T. (1980) Recent developments in ion-exchange chromatography. *J. Chromatogr. Sci.* 18, 551.