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Meenakshi Goyal[a]; Rashmi Dhawan[a]; Mamta Bhagat[a]
[a] Department of Chemical Engineering & Technology, Panjab University, Chandigarh, India

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Adsorption of Gallic Acid from Aqueous Solution Using Fixed Bed Activated Carbon Columns

Meenakshi Goyal, Rashmi Dhawan, and Mamta Bhagat
Department of Chemical Engineering & Technology, Panjab University, Chandigarh, India

Naturally occuring matter (NOM), a heterogeneous mixture of complex organic compounds, is invariably present in all surface and ground waters. These materials act as substrate for the growth of bacteria in the distribution system. The disinfection of such water by chlorination produces disinfection by products consisting of several halogenated compounds which are toxic and carcinogenic. As gallic acid is the building block of most NOM, its adsorptive removal from water has been studied using activated carbon columns. The operating variables studied are the hydraulic loading rate (HLR), bed depth (Z), and the feed concentration (C_o). The breakthrough curves are S-shaped and the breakthrough time increases with increasing Z and decreases with increasing HLR and C_o. The adsorption increases with increasing HLR and is maximum around HLR = 8 $m^3/hr/m^2$. The column design parameters such as the critical bed depth and the depth of the mass transfer zone (MTZ) as calculated using the bed depth service time (BDST) approach are found to agree fairly closely with the experimental values. MTZ is smaller for the carbon cloth indicating its better adsorption characteristics. The adsorption column parameters such as the treated volume and the mass of the carbon required for a desired effluent concentration have been determined from the column data.

Keywords adsorption; BDST equation; breakthrough curves; critical bed depth; fixed bed column; mass transfer zone

INTRODUCTION

Naturally occurring matter (NOM), a heterogeneous mixture of complex organic compounds which include humic acid, gallic acid, fulvic acid, and tannic acid is invariably present in all surface and ground waters. These compounds are derived from the vegetable matter in contact with soil or water in rivers, streams, and lakes. These materials act as substrate for the growth of bacteria in the distribution system. Consequently, water before domestic supply is given a disinfectant treatment. The most common disinfectant treatment is the chlorination. The chlorination of water containing these compounds, however, results in the formation of several halogenated organic compounds, the more important being the trihalomethanes and halo acids. Yousseffi and Faust (1) found that when water containing 10 ppm of these compounds was kept in contact with 10 ppm of chlorine, a considerable amount, varying between 10–35 ppm of chloroform was formed in just 30 minutes and the amount increased with increase in the time of contact up to 2 hrs.These halogenated products are toxic, carcinogenic, and mutagenic to humans. Besides, the presence of naturally occurring matter and their decomposition imparts color to water which is undesirable. Thus the adsorption of NOM has been studied by several workers using different activated carbons. Karanfil et al. (2), Lee et al. (3), Newcomb (4) and Kilduff et al. (5,6) observed that the adsorption was determined by the porous structure as well as by the acidic nature of the carbon surface. Utrera-Hidalgo et al. (7) studied the static and dynamic adsorption of gallic acid on activated carbons prepared from agricultural waste and found that while the static adsorption obeyed the Langmuir adsorption equation and increased with the degree of activation of the carbon, the dynamic adsorption was very well related to the pore volume accessible to water molecules.

As gallic acid is the building block of these naturally occurring materials, it was thought of interest to study its removal from aqueous solutions using activated carbon adsorption columns and to apply a suitable model to determine the column design parameters. These studies may also help to promote the use of activated carbon cloth, a fibrous carbon material, as a more convenient fixed bed carbon adsorbent because it will produce a low hydrodynamic resistance to flow and shall take up the shape of the adsorption system more easily.

EXPERIMENTAL

Materials

Two samples of activated carbons namely a granulated activated carbon (GAC) I-60 and an activated carbon cloth were used as adsorbents. I-60 is a wood based carbon obtained from Industrial Carbons Private

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Address correspondence to Meenakshi Goyal, Department of Chemical Engineering & Technology, Panjab University, Chandigarh, India. Tel.: (0172) 2534910; Fax: 91(172) 2779173. E-mail: meenakshi_chem@yahoo.co.in

TABLE 1
Surface characteristics of activated carbons

Activated carbon	BET surface area (m^2/g)	Pore volume (cm^3/g)	Average pore diameter (nm)	Surface acidic groups (milli.eq./g)
Activated carbon cloth	792	0.248	0.80	1.25
I-60	705	0.195	0.60	1.57

Limited, Ankleshwar, India. The activated carbon cloth is a viscose rayon based material and obtained from HEG, Bhopal, India. The surface characteristics of these two activated carbon samples are given in Table 1. The BET surface area has been determined using a micromeritic surface area analyzer while the pore volume and average pore diameter were determined by adsorption of benzene vapours at 25°C. The amount of acidic carbon-oxygen surface group was determined by neutralization with 0.1 N sodium hydroxide solution. These acidic carbon-oxygen surface groups have been identified as carboxyls and lactones using several physical, chemical, and physico-chemical techniques, which include neutralization of alkalies, desorption, IR, and X-ray photoelectron spectroscopy (8–11). These groups on ionization in water render the carbon surface negatively charged and thus considerably influence the adsorption properties of activated carbons (12).

Fixed Bed Adsorption Studies

The experimental set up for the adsorption studies consisted of a glass column of 25 mm diameter and 600 mm length. The activated carbon under this study was saturated with water to remove the entrapped air and was packed in the glass column supported on perforated plates. Gallic acid solution of known concentration was prepared and pumped into an overhead tank with overflow for maintaining a constant head. This ensures a constant influent flow rate throughout the experiment because the solution from the overhead tank to the column is gravity fed. A control valve to regulate the flow and a rotameter to monitor the flow rate are installed in the feed tank. The effluent from the column is collected at regular intervals and analyzed with the help of UV-Visible spectrophotometer at a wavelength of 258.8 nm. The details of the experimental set up are published elsewhere (13).

During the passage through the bed, the solution continuously meets a fresh part of the adsorbent and tends to establish new equilibrium. However, as the time of contact with a given part of the adsorbent is limited, a true equilibrium is never attained. The operating variables in these investigations are the hydraulic loading rate (HLR), which is the volume flow rate of influent per unit cross sectional area of the adsorbent bed, bed depth (Z), the feed concentration (C_o) and the bed diameter. The values of these variables are given below:

Hydraulic loading rate (HLR)	3–6 $m^3/hr/m^2$
Bed depth (Z)	80–150 mm
Feed concentration (C_o)	50–150 mg/L
Bed diameter	25 mm

The bed diameter has been kept constant in these investigations.

RESULTS AND DISCUSSIONS

The breakthrough curves for gallic acid showing the effluent concentration at different time intervals for the two activated carbons i.e., granulated activated carbon I-60 and activated carbon cloth, at HLR 4.3 $m^3/hr/m^2$ with a carbon bed depth of 100 mm and an influent concentration of 50 mg/L are shown in Fig. 1. The effluent concentration rises very slowly in the beginning but increases at a considerable rate after this slow period. The period of slow rise in the effluent concentration and the breakthrough time 't_b' are slightly longer (152 min for carbon

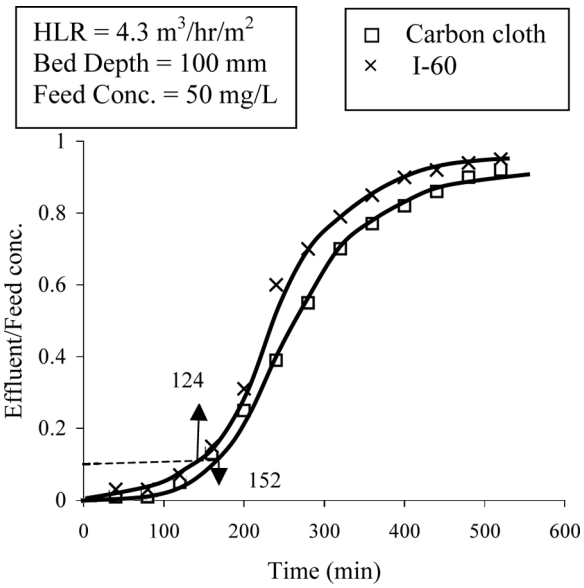

FIG. 1. Breakthrough curves for gallic acid on different activated carbons.

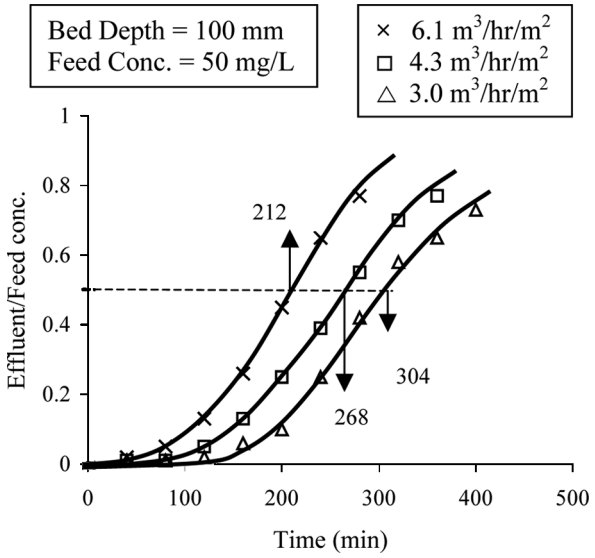

FIG. 2. Effect of hydraulic loading rate on the breakthrough curves for gallic acid on activated carbon cloth.

cloth and 124 min for granulated carbon) for the carbon cloth than that for the granulated carbon.

Effect of HLR

The effect of HLR on the breakthrough curve for the two carbons is presented in Fig. 2 for the activated carbon cloth and in Fig. 3 for the activated carbon I-60. The curves are S-shaped in all the cases. It is apparent from these curves that the breakthrough time decreases considerably on increasing the HLR. The breakthrough time or the adsorption time at 50% effluent concentration decreases from 304 min to 212 min for the carbon cloth (cf Fig. 2) and from 276 min to 184 min for the granulated carbon (cf Fig. 3) as the HLR is enhanced from 3 to 6.1 $m^3/hr/m^2$.

Effect of Bed Depth and Feed Concentration

The influence of bed depth (Z) on the breakthrough curves or the adsorption process at HLR 4.3 $m^3/hr/m^2$ is shown in Figs. 4 and 5 for the two carbons. In this case the breakthrough time for any effluent concentration increases with increase in the bed depth. The shape and the gradient of the breakthrough curve are also slightly different as the bed depth changes. The breakthrough curve for the largest bed depth tends to be gradual meaning thereby that the column takes more time to be exhausted. At 50% effluent concentration, the breakthrough time increases from 220 to 420 min for carbon cloth (cf Fig. 4) and from 170 to 370 min in the case of the granulated carbon (cf Fig. 5) as the bed depth increases from 80 to 150 mm. Similar breakthrough curves at different feed concentrations showed that the breakthrough time for any effluent concentration decreased with increase in the concentration of the feed solution.

Variation in Effluent Concentration

The variation in effluent concentration with bed depth for the two carbons is shown in Fig. 6. The effluent concentration decreases with increasing bed depth. At a bed depth of 80 mm, the effluent concentration is 1.0 mg/L for carbon cloth and 1.5 mg/L for the granulated carbon. This shows that the adsorption zone height which is also called the

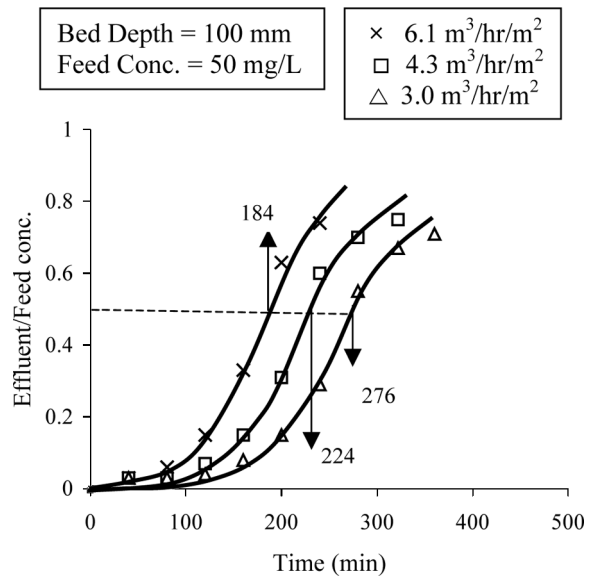

FIG. 3. Effect of hydraulic loading rate on the breakthrough curves for gallic acid on activated carbon I-60.

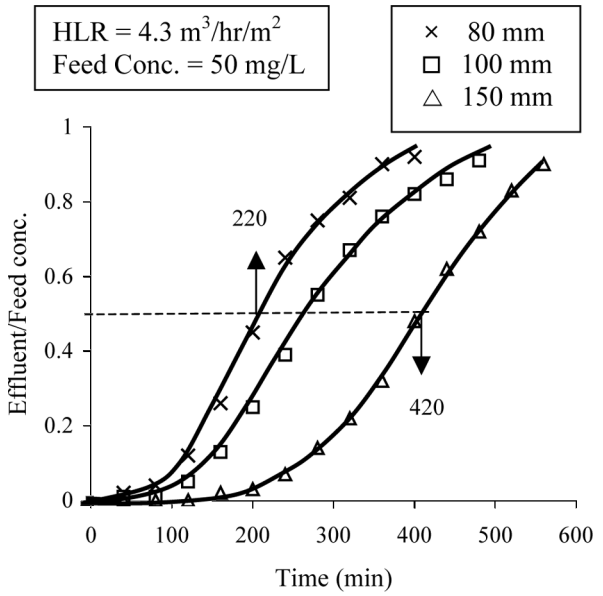

FIG. 4. Effect of bed depth on the breakthrough curves for gallic acid on activated carbon cloth.

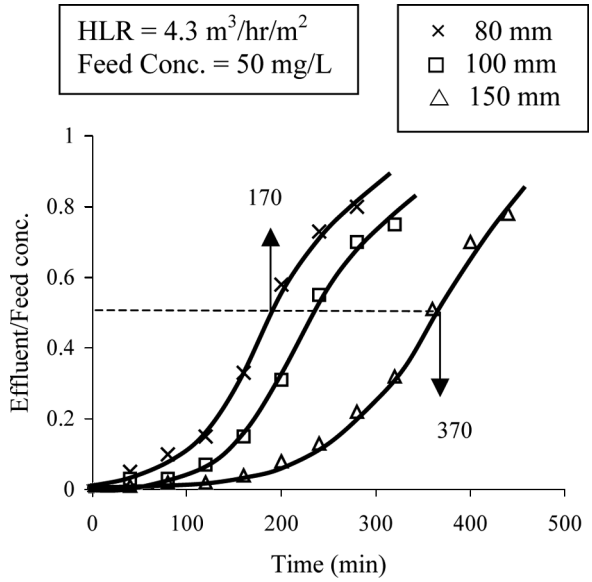

FIG. 5. Effect of bed depth on the breakthrough curves for gallic acid on activated carbon I-60.

mass transfer zone (MTZ), is smaller for the carbon cloth than that for the I-60 carbon. As the bed depth is enhanced there is a steep fall in the effluent concentration. Extrapolation of the two curves (cf Fig. 6) indicates that the adsorption zone is about 135 mm in length for carbon cloth and about 155 mm for the carbon I-60 since the effluent concentration tends to become more or less zero for bed depths beyond this length.

Effect of HLR on Adsorption

The amount of gallic acid adsorbed by a carbon at different values of HLR has been calculated from the breakthrough time t_b at 50% breakthrough concentration C_b using the relationship

$$\text{Adsorption Capacity (mg/g)} = \frac{t_b Q(C_o - C_b)}{m}$$

where Q is the liquid flow rate in litres per hr, C_o is the feed concentration, C_b is the effluent concentration in mg/L, and m is the mass of the carbon in the bed in grams. The amount adsorbed has been plotted against the hydraulic loading rate in Fig. 7. The adsorption increases with increase in HLR but the rate of increase becomes slower at higher loading rates. The adsorption tends to attain a maximum value around HLR = 8 $m^3/hr/m^2$. Extrapolation of curve shows that maximum adsorption capacity for I-60 is about 17 mg/g corresponding to HLR of 8 $m^3/hr/m^2$ while that for the carbon cloth is around 60 mg/g. In general, the adsorption capacity of the carbon cloth is more than three times the adsorption capacity for carbon I-60.

The difference in breakthrough curves of the two carbons indicates that the activated carbon cloth has better adsorption characteristics than granulated carbon I-60 for gallic acid. This can be attributed to the differences in the surface area and the chemical structure of the carbon surfaces. As the two activated carbons have been prepared using different source raw materials and using different preparation procedures, they are expected to have different surface structures. The benzene vapor adsorption isotherms on these two carbons have shown that the carbon

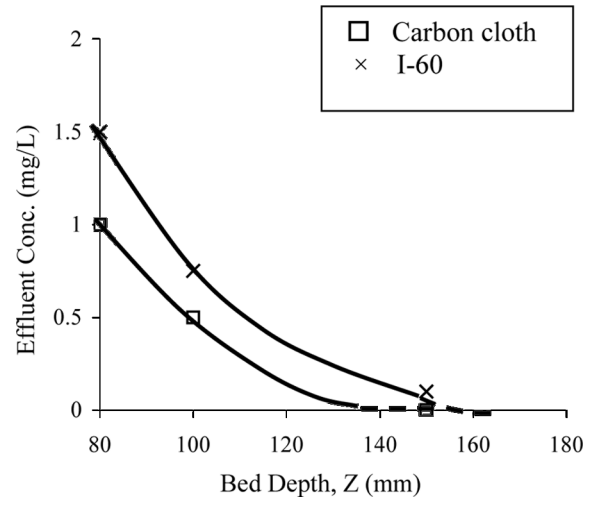

FIG. 6. Variation in effluent concentration with bed depth for the two activated carbons.

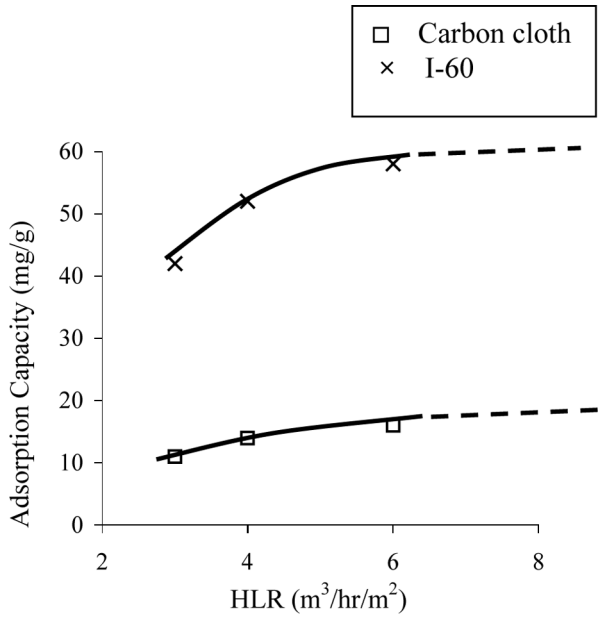

FIG. 7. Effect of hydraulic loading rate on adsorption capacity of activated carbons for gallic acid.

cloth has a larger pore volume, average pore diameter and surface area than the granulated carbon (cf Table 1). The carbon cloth surface is also associated with smaller amounts of the acidic carbon-oxygen surface groups (1.25 milliequiv./g as against 1.57 milliequiv./g for the GAC). These acidic surface groups which have been identified as carboxyls or lactones on ionization produce negatively charged COO^- sites on the carbon surface (12,13). This results in smaller electrostatic repulsive interactions between the carbon cloth surface and the gallic acid anions than in the case of the GAC. All these factors enhance the adsorption of gallic acid anions on the carbon cloth. The relatively lower value of minimum effluent concentration in the case of carbon cloth compared to the granulated carbon (cf Fig. 6) is also due to its better adsorption characteristics due to which a large portion of the gallic acid gets adsorbed at any point of time leading to its smaller concentration in the effluent.

The increase in the amount adsorbed with increase in HLR may be attributed to the dynamics of the carbon column adsorption process. The variation in HLR affects the overall resistance to mass transfer which is a non-linear summation of the pore particle interphase and fluid resistances. At low values of HLR, laminar flow conditions prevail so that the mass transfer has to take place across a nearly stationary film of the liquid covering the adsorbent particles. This high resistance leads to low mass transfer rates and therefore, results in smaller adsorption. When the HLR is increased, the interphase resistance decreases and this results in an increase in the rate of mass transfer and hence in an increase in the amount of adsorption. Beyond a certain HLR, the rate of increase in adsorption tends to decrease due to the decreased residence time of the solution within the carbon bed and lower time available for mass transfer. The optimum HLR from the present studies has been found to be between 7 to 8 $m^3/hr/m^2$.

Theoretical Model

Several mathematical models have been developed to define relationship between the bed depth Z and the breakthrough time t_b for a given concentration of the effluent. However, the one proposed by Bohart and Adams discussed in (14,15) and later modified by Hutchins (15,16) has been used in these investigations. According to Bohart and Adams, the service time t of a column is related to the process conditions and operating parameters as

$$\ln\left(\frac{C_o}{C_b}-1\right)=\ln\left(Exp\frac{kN_oZ}{V}-1\right)-kC_ot \qquad (1)$$

Since the exponential term is always much larger than unity (14,15), the unity term in the parentheses on the right hand side is often neglected so that a rearrangement gives a linear relationship between t and Z.

$$t=\frac{N_oZ}{C_oV}-\frac{1}{kC_o}\ln\left(\frac{C_o}{C_b}-1\right) \qquad (2)$$

where C_o is the feed concentration (mg/L), C_b is the desired breakthrough concentration of the effluent (mg/L), Z is the bed depth (cm), k is the adsorption rate constant ($L\,mg^{-1}\,hr^{-1}$), N_o is the adsorption capacity (mg/cm^3), V is the linear flow velocity of the feed to the bed (cm/hr), and t is the service time of the column.

The above Bohart – Adam equation (2) can be used to determine the service time t of an adsorption column of bed depth Z knowing the values of N_o, C_o, and k which can be determined from column experiments carried out over a range of linear velocity values. However, this will require data from atleast nine different column experiments to determine these parameters. Hutchins (15,16) suggested a modification of the Bohart – Adam equation which requires only three fixed bed column experiments. In this approach called the bed depth service time (BDST) approach, the Bohart – Adam equation can be expressed in the linear form as

$$t=aZ+b \qquad (3)$$

According to this Eq. (3) the breakthrough data for each bed depth can be used to make BDST plot for service time t which is the operating time to obtain a certain removal of the adsorbate at each bed depth. Such linear BDST plots for three different flow rates for the two carbons are shown in Figs. 8 and 9. The slopes and intercepts of these linear plots are given by

$$\text{Slope}=\frac{N_o}{C_oV}$$

$$\text{Intercept}=-\frac{1}{kC_o}\ln\left(\frac{C_o}{C_b}-1\right)$$

The values of N_o and k calculated from these slopes and intercepts at different flow rates are recorded in Table 2.

At time $t=0$, the Eq. (2) can be solved for bed depth Z as

$$Z_o=\frac{V}{kN_o}\ln\left(\frac{C_o}{C_b}-1\right) \qquad (4)$$

where Z_o is the minimum bed depth of the adsorbent sufficient to produce an effluent concentration of C_b. This quantity is also called the critical bed depth. The values of critical bed depth Z_o for carbon cloth at different flow rates, calculated using the above Eq. (4), are recorded in Table 2.

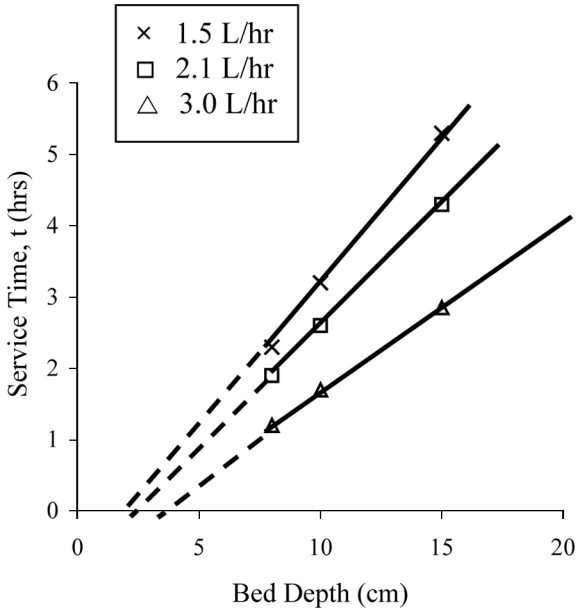

FIG. 8. BDST plot for the activated carbon cloth at different flow rates for 10% breakthrough concentration.

The critical bed depth can also be obtained from the BDST linear plots as the intercept on the abscissa where $t = 0$. These graphic values of the critical bed depth (Z_o) obtained from extrapolating the linear plots in Figs. 8 and 9 are also included in Table 2. It is interesting to note that there is a very good agreement between the theoretical and the experimental values of the critical bed depth (within 3%) at all flow rates. This indicates an agreement between the validity of the Bohart – Adam equation and the Hutchins modification to the adsorption of gallic acid on activated carbons.

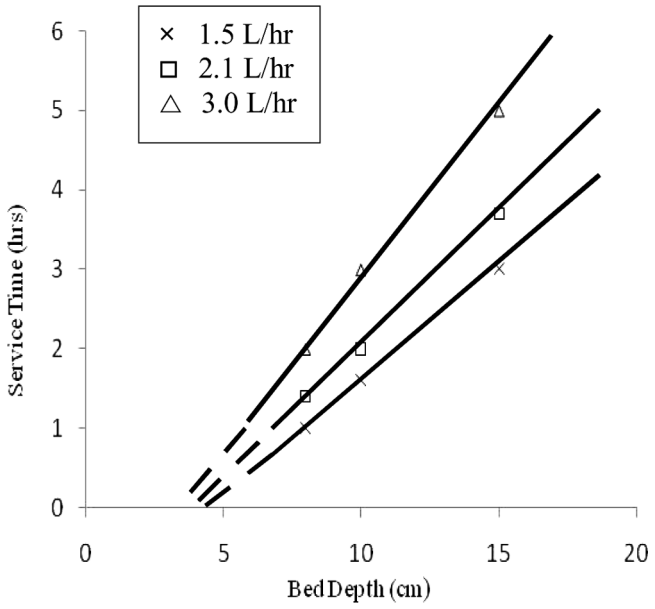

FIG. 9. BDST plot for the granulated activated carbon I-60 at different flow rates for 10% breakthrough concentration.

The BDST plots for two effluent concentrations i.e., 10% and 90% of the feed concentration at a flow rate of 2.1 L/hr and a feed concentration of 50 mg/L for the carbon cloth and the carbon I-60 are shown in Figs. 10 and 11. If the adsorption zone is arbitrarily defined as the adsorbent layer through which the effluent concentration varies from 10% to 90% of the feed concentration (14,17–19), then the depth of the adsorption zone is equal to the horizontal distance between these two lines in the BDST plots. This depth of the adsorption zone or the mass transfer zone is 122 mm for the carbon cloth and 148 mm for the carbon I-60. These values are roughly in agreement with the values of 135 mm and 155 mm obtained from curves between the effluent concentration and the bed depth (cf Fig. 6).

Design of Adsorption Columns for Different Flow Rates and Influent Concentrations

Hutchins (15,16) suggested that the design parameters obtained from one column experiment could be used to obtain design parameters for other flow rates and influent concentrations. According to BDST approach if a value of slope parameter 'a_1' is determined experimentally for one flow rate, the value 'a_2' at any other flow rate can be calculated by the relationship

$$a_2 = a_1 \frac{Q_1}{Q_2} \tag{5}$$

where Q_1/Q_2 is the ratio of the two flow rates. It was assumed that the value of the intercept parameter 'b' does not change significantly by change in flow rates.

Similarly the data collected at any influent concentration can be adjusted to design systems for other influent concentrations. If a column experiment is carried out at one influent concentration C_1, the BDST Eq. (3) can be expressed as

$$t_1 = a_1 Z + b_1$$

It is then possible to predict the equation for influent concentration C_2 as

$$a_2 = a_1 \frac{C_1}{C_2} \tag{6}$$

$$b_2 = b_1 \left(\frac{C_1}{C_2}\right) \frac{\ln\left(\frac{C_2}{C_F} - 1\right)}{\ln\left(\frac{C_1}{C_B} - 1\right)} \tag{7}$$

where a_1 and a_2 are the slopes, b_1 and b_2 are the intercepts and C_B and C_F are the effluent concentrations at influent

TABLE 2
Bohart-Adams equation parameters at different hydraulic loading rates, feed concentration = 50 mg/L

Carbon sample	Volume flow rate (L/hr)	Slope (hr/cm)	Intercept (hr)	k ($Lmg^{-1}hr^{-1}$)	N_o (mg/cm^3)	Critical bed fepth, Z_o (cm) Using eqn' (4)	Critical bed fepth, Z_o (cm) From graph (Figs. 8 & 9)
Carbon cloth	1.5	0.45	−1.0	0.043	6.70	2.28	2.30
	2.1	0.34	−0.9	0.048	7.14	2.68	2.60
	3.0	0.25	−0.7	0.058	7.50	2.98	2.90
Indcarb-60	1.5	0.40	−1.6	0.027	6.02	4.01	3.65
	2.1	0.32	−1.2	0.036	6.72	3.80	3.70
	3.0	0.25	−0.8	0.055	7.50	3.20	3.10

concentrations of C_1 and C_2. Thus Eq. (3) for t_2 can be written as

$$t_2 = a_2 Z + b_2$$

$$t_2 = a_1 \frac{C_1}{C_2} + b_1 \left(\frac{C_1}{C_2}\right) \frac{\ln\left(\frac{C_2}{C_F} - 1\right)}{\ln\left(\frac{C_1}{C_B} - 1\right)} \qquad (8)$$

In order to examine the applicability of the BDST approach to the adsorption column data obtained in these investigations, the values of a_2 and b_2 were calculated for influent concentration of 100 mg/L and 150 mg/L at a flow rate of 2.1 L/hr with bed depth of 100 mm from the a_1 and b_1 values obtained from experimental run at 50 mg/L influent concentration under similar conditions of flow rate and bed depth. The breakthrough time or service time (t_2) corresponding to an effluent concentration of 10% were calculated using equation (8) both for the ACC and the GAC and are given in Table 3. The values obtained from experimental runs at these two influent concentrations are also included in Table 3. It is seen that the calculated and experimental values are roughly comparable for both ACC and GAC. Similar values of breakthrough times were calculated using the relationship $a_2 = a_1 \frac{Q_1}{Q_2}$ at a flow rate of 3.0 L/hr using the experimental value of a_1 at flow rate of 2.1 L/hr. The calculated value of t_2 is 1.48 hr against the experimental value of 1.86 hr. The two values agree fairly.

It is thus apparent that the design parameters obtained from one column experiment when used to calculate design parameters for other flow rates and concentrations using

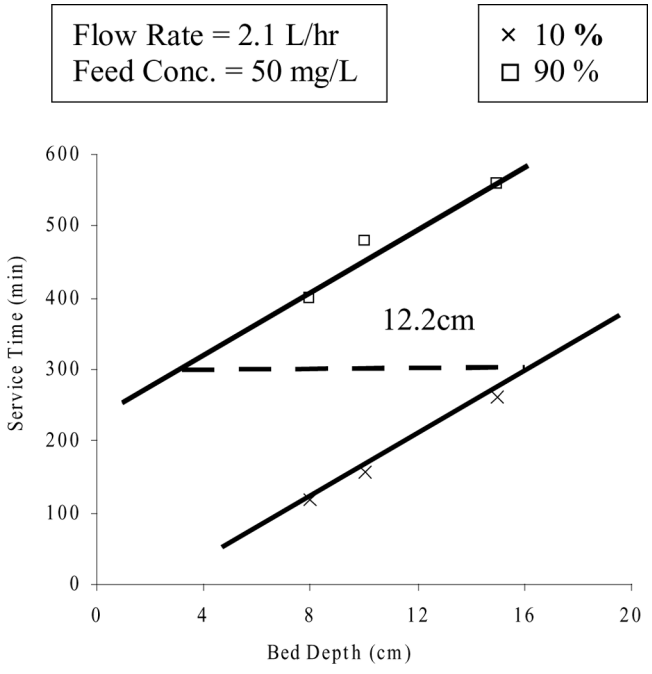

FIG. 10. BDST plots at two different effluent concentrations for the carbon cloth.

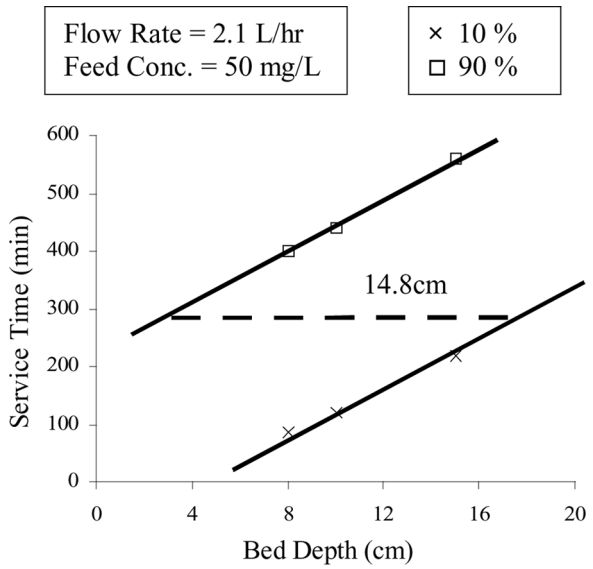

FIG. 11. BDST plots at two different effluent concentrations for I-60.

TABLE 3
Comparison of breakthrough times obtained from experimental graphs and from calculations. Bed depth = 100 mm; Flow rate = 2.1 L/hr

	Feed conc. = 100 mg/L		Feed conc. = 150 mg/L	
Carbon sample	Experimental breakthrough time (hrs)	Calculated breakthrough time (hrs)	Experimental breakthrough time (hrs)	Calculated breakthrough time (hrs)
Activated carbon cloth	1.25	1.66	0.83	1.01
Granulated activated carbon	1.00	1.66	0.76	1.06

Hutchins treatment give only approximate values for the adsorption of gallic acid.

Adsorption Column Parameters

The adsorption column parameters such as the treated volume, the weight of the carbon at a desired breakthrough concentration were calculated from column experiments carried out using different bed depths, flow rates, and at different feed concentrations. These results for 10% and 70% breakthrough concentrations for the carbon cloth are given in Tables 4–6. It is interesting to note (Table 4) that although the breakthrough time for a given concentration at a given flow rate of the effluent increases with bed depth, the amount of activated carbon required per litre of the feed solution is roughly of the same order. This indicates that the adsorption characteristics of the activated carbon determine the breakthrough time and the volume of the solution treated. This receives further support from the results of the column studies carried out at different flow rates keeping the bed depth and the feed concentration as constant. In this case (cf Table 5) the amount of the carbon per liter of the feed solution decreases with increase in the flow rate. This is due to an increase in the amount of adsorption with increasing HLR as discussed earlier in the paper. As expected the amount of carbon per liter of the feed solution also increases with increase

TABLE 4
Activated carbon cloth column parameters at different bed depths. Feed conc. = 50 mg/L; Flow rate = 2.1 L/hr

	Parameters for 10% breakthrough concentration			Parameters for 70% breakthrough concentration		
Bed depth (mm)	Breakthrough time, t_b (hrs)	Treated volume (litres)	Amount of carbon per litre treated water (g/L)	Breakthrough time, t_b (hrs)	Treated volume (litres)	Amount of carbon per litre treated water (g/L)
80	2.0	4.2	0.86	4.5	9.4	0.38
100	2.5	5.2	0.86	5.5	11.5	0.39
150	4.3	9.0	0.83	7.8	16.3	0.46

TABLE 5
Activated carbon cloth column parameters at different flow rates. Bed depth = 100 mm; Feed conc. = 50 mg/L

	Parameters for 10% breakthrough concentration			Parameters for 70% breakthrough concentration		
Flow rate (L/hr)	Breakthrough time, t_b (hrs)	Treated volume (litres)	Amount of carbon per litre treated water (g/L)	Breakthrough time, t_b (hrs)	Treated volume (litres)	Amount of carbon per litre treated water (g/L)
1.5	3.3	4.9	0.92	6.0	9.0	0.50
2.1	2.5	5.2	0.86	5.5	11.5	0.39
3.0	1.86	5.6	0.80	4.2	12.6	0.35

TABLE 6
Activated carbon cloth column parameters at different feed concentrations. Bed Depth = 100 mm; Flow Rate = 2.1 L/hr

	Parameters for 10% breakthrough concentration			Parameters for 70% breakthrough concentration		
Conc. (mg/L)	Breakthrough time, t_b (hrs)	Treated volume (litres)	Amount of carbon per litre treated water (g/L)	Breakthrough time, t_b (hrs)	Treated volume (litres)	Amount of carbon per litre treated water (g/L)
50	2.5	5.2	0.86	5.5	11.5	0.39
100	1.8	3.8	1.2	4.0	8.4	0.53
150	1.0	2.1	2.1	3.0	6.3	0.70

in the feed concentration keeping all other parameters the same (cf Table 6). It has been found that with a bed depth of 100 mm, flow rate of 2.1 L/hr and a feed concentration of 50 mg/L of gallic acid, the amount of the activated carbon cloth needed to get 10% and 70% effluent concentrations respectively are 86 g and 39 g for treating 100 liters of the solution. The amounts of carbon I-60 for similar influent and effluent concentrations are 350 g and 150 g per 100 liters of the gallic acid solution.

CONCLUSIONS

The breakthrough time of gallic acid on activated carbon cloth and granulated activated carbon increases with increase in the bed depth but decreases on increasing the hydraulic loading rate and the feed concentration. The effluent concentration decreases with increasing bed depth. At bed depth of 80 mm, the effluent concentration is 1.0 mg/L for carbon cloth and 1.5 mg/L for the granulated carbon. With increasing bed depth there is a steep fall in the effluent concentration. The extrapolation of these curves indicates that the depth of the adsorption zone is about 135 mm for the carbon cloth and 155 mm for the other activated carbon. The adsorption capacity of the carbon bed increases with hydraulic loading rate and is maximum at HLR around $8\,m^3/hr/m^2$. The critical bed depth and the depth of mass transfer zone obtained using the BDST theoretical approach agree closely with the experimental values. The design parameters obtained for one flow rate and feed concentration from one column experiment can be used to calculate design parameters for other feed concentrations and flow rates.

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