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Theory of Adsorption by Activated Carbon. III. Effects of Equalization Tanks on Time-Dependent Feeds

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Abstract

Operation of a flow equalization tank and activated carbon column in series was simulated by computer. The flow equalization tank smooths out concentration and flow rate variations in strongly time-dependent feeds; this results in the reduction or elimination of breakthrough of solute in the column effluent due to shock loadings. The effects of various concentration and flow rate pulses on column performance were examined with flow equalization tanks of various sizes. Use of a flow equalization tank is compared with increasing the length of the carbon column.

INTRODUCTION

The uniqueness of activated carbon as an adsorbent for trace organics is well established (*1*). Absorption columns of activated carbon are operated in a continuous flow mode, where an unsteady state prevails unless the column is operated in a countercurrent fashion. In this mode of operation the system is best described by the time-dependent continuity and mass balance equations. Several attempts have been made to model these columns (*2–12*). Recently Wilson and Clarke have examined a realistic model for diffusion of solute from a large pool of liquid into a pore, followed by reversible chemisorption on the walls of the pore (*13*). The computational results of this model were compared with the results of a much simpler lumped parameter model; the results from the two models were almost identical. They then applied the lumped parameter model

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to the operation of continuous flow columns (*14*). The lumped parameter model is the basis of this study.

In the present study an equalization tank is incorporated to feed the column. The purpose of the equalization tank is to smooth out any shock loading to the column. Such a shock may be a concentration pulse, a flow rate pulse, or both; the pulses may occur at the same time or at different times. By smoothing out the shock the column can be operated without transient breakthroughs resulting from such shocks, resulting in improved effluent quality from a column of given size.

ANALYSIS

In the lumped parameter model the column is partitioned into a number of finite elements (slabs), and uniform concentrations of solute in the liquid and solid phases in each slab are assumed. The mass flow between slabs is assumed continuous in the liquid phase, and no mass flow takes place in the solid phase between slabs.

Mass balance in each slab gives:

Change in mass flow with time = flow in − flow out + axial dispersion + diffusion into the activated carbon

In mathematical notation:

$$V_l \frac{\partial C_l}{\partial t} = -Q\left(\frac{\partial C_l}{\partial x}\right) + D_l \frac{\partial^2 C_l}{\partial x^2} + D_p(C_p - C_l) \tag{1}$$

where V_l = volume of free liquid per unit length of column (cm^2)
V_p = volume of liquid in pores per unit length of column (cm^2)
$C_l(x, t)$ = concentration of solute in the free liquid at x, t (moles/mL)
t = time (sec)
Q = volumetric flow rate through the column (mL/sec)
x = distance from the top of the column (cm)
D_l = effective axial dispersion constant (cm^4/sec)
D_p = effective pore diffusion constant (cm^2/sec)
C_p = concentration of solute in the pore liquid (moles/mL)

Equation (1) describes the change of the concentration in the fluid passing through the column. For the change of the concentration in the pore liquid, the material balance gives:

Change in mass flow with time = diffusion into the pores − adsorption in the pores

$$V_p \frac{\partial C_p}{\partial t} = D_p(C_l - C_p) - S_p \frac{\partial \Gamma}{\partial t} \tag{2}$$

where S_p = surface area of the pores in one slab
Γ = surface concentration of solute in the pores of one slab

The above differential equations are second-order and nonlinear, and cannot be solved analytically. They are soluble numerically, and we make the following approximation concerning the kinetics of adsorption. We assume that (a) adsorption is instantaneous compared to pore diffusion and (b) a Langmuir isotherm is adequate to describe the adsorption.

$$\Gamma_{\text{eq}} = \frac{\Gamma_{\max} b C_p}{1 + bC_p}$$

Thus $\Gamma = \Gamma_{\text{eq}}$ at all times.

This leads to:

$$\frac{\partial \Gamma}{\partial t} = \left[\frac{\Gamma_{\max} b}{(1 + bC_p)^2}\right] \frac{\partial C_p}{\partial t}$$

where b = concentration of solute at which the equilibrium surface concentration of solute is $\Gamma_{\max}/2$. Substituting the expression for $\partial\Gamma/\partial t$ in Eq. (2) gives

$$V_p \frac{\partial C_p}{\partial t} = D_p(C_l - C_p) - \frac{S_p \Gamma_{\max} b}{(1 + bC_p)^2} \frac{\partial C_p}{\partial t} \tag{3}$$

Equations (1) and (3) can now be approximated by means of a finite difference mesh system as follows:

$$V_l \frac{\partial C_{l(j,t)}}{\partial t} = Q[C_l(j-1) - C_l(j)] + D_l[C_l(j-1) - 2C_l(j) + C_l(j+1)] + D_p[C_p(j) - C_l(j)] \tag{4}$$

$$\frac{\partial C_{p(j,t)}}{\partial t} = \frac{D_p[C_{l(j)} - C_{p(j)}]}{V_p + \dfrac{S_p \Gamma_{\max} b}{[1 + bC_p(j)]^2}} \tag{5}$$

where j refers to the jth slab into which the column is partitioned. The above equations can readily be integrated numerically using the predictor-corrector method described by Kelly (*15*). In our earlier solution of Eqs. (4) and (5) the column was run continuously with constant feed rate and constant concentration in the feed (*14*). In the present work the feed rate and its concentration vary as functions of time. The changes in flow rate and concentration are in the form of triangular or square pulses which last for a certain period of time; then the feed goes back to its initial constant flow rate and concentration.

A stirred tank is to be used to smooth out the flow rate and solute concentration of the feed to the activated carbon column. The concentration

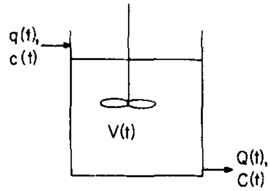

FIG. 1. A stirred equalization tank.

of solute in the overflow is equal to that in the tank. In Fig. 1, $q(t)$ is the input flow rate of the tank and $c(t)$ is the input solute concentration. $q(t)$ and $c(t)$ are known functions of time (t). $V(t)$ is the volume of liquid in the tank at time (t); $Q(t)$ and $C(t)$ are the tank output flow rate and concentration, respectively. The output flow rate is also a known function of the volume of liquid in the tank; so $Q(t) = Q[V(t)]$. The change of V with time is then given by

$$\frac{dV}{dt} = q(t) - Q[V] \tag{6}$$

The equation of continuity gives

$$\frac{d}{dt}(CV) = q(t)c(t) - Q[V]C \tag{7}$$

$$V\frac{dc}{dt} + C\frac{dV}{dt} = qc - QC \tag{8}$$

Substituting for dV/dt from Eq. (6) yields

$$V\frac{dC}{dt} + Cq - CQ = qc - QC$$

Rearranging gives

$$\frac{dC}{dt} = \frac{q}{V}(c - C) \tag{9}$$

Equations (6) and (9) are nonlinear and must be solved numerically.

The output is a transform of the input, which may be arbitrary in form. Two forms of input are explored in this study; the first is a triangular wave and the second is the square wave as shown in Fig. 2. Although the tank could be of any shape, only the most common shapes (cylindrical and square cross-sectional) are considered as examples. The outflow from the tank was assumed to be due to the hydraulic head in the tank. Application of Bernoulli's energy equation gave the outflow as a function of the volume of fluid in the tank as

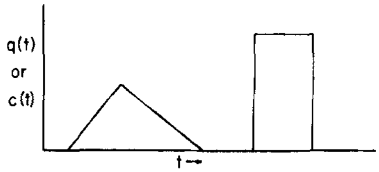

FIG. 2. The hydraulic and concentration pulses used.

$$Q = D\sqrt{V} \tag{10}$$

where D is a constant for a given tank and outflow pipe.

$$D = \sqrt{2g/A_t}\,A_p$$

where g = acceleration due to gravity, A_t = cross-sectional area of the tank, A_p = cross-sectional area of the tank effluent pipe.

The two forms of variation (square and triangular pulses) which have been used for the influent flow rate were also used for the influent solute concentration. The predictor-corrector method was used to solve Eqs. (6) and (9) as follows.

Initial predictor:

$$C^*(\Delta t) = C(0) + \Delta t\,\frac{q(0)}{V(0)}[c(0) - C(0)] \equiv C(0) + \Delta t\,\frac{dC(0)}{dt}$$

$$V^*(\Delta t) = V(0) + \Delta t[q(0) - Q((V(0))] \equiv V(0) + \Delta t\,\frac{dV(0)}{dt}$$

Initial corrector:

$$C(\Delta t) = C(0) + \frac{\Delta t}{2}\left\{\frac{dC(0)}{dt} + \frac{dC^*(\Delta t)}{dt}\right\}$$

$$V(\Delta t) = V(0) + \frac{\Delta t}{2}\left\{\frac{dV(0)}{dt} + \frac{dV^*(\Delta t)}{dt}\right\}$$

General predictor:

$$C^*(t + \Delta t) = C(t - \Delta t) + 2\Delta t\,\frac{dC(t)}{dt}$$

$$V^*(t + \Delta t) = V(t - \Delta t) + 2\Delta t\,\frac{dC(t)}{dt}$$

General corrector:

$$C(t + \Delta t) = C(t) + \frac{\Delta t}{2}\left\{\frac{dC(t)}{dt} + \frac{dC^*(t + \Delta t)}{dt}\right\}$$

$$V(t + \Delta t) = V(t) + \frac{\Delta t}{2}\left\{\frac{dV(t)}{dt} + \frac{dV^*(t + \Delta t)}{dt}\right\}$$

A computer program was written to integrate the equations using the above algorithm and then incorporated as a subroutine to the carbon column simulator program.

The various parameters used for the tank subroutine are defined as follows:

C_B = base line concentration in the feed to the tank (moles/mL)
C_{max} = maximum value of concentration in the pulse in the feed (moles/mL)
C_0 = initial concentration in the tank (moles/mL)
V_0 = initial volume of liquid in the tank (mL)
Q_0 = base line influent flow rate (mL/sec)
Q_{max} = maximum value of influent flow rate (mL/sec)
D = tank constant ($cm^{3/2}$/sec)
T_1, T_2, T_3 = times when flow rate pulse starts, reaches maximum, and ends, respectively, for a triangular pulse
T_4, T_5, T_6 = times when concentration pulse starts, reaches maximum, and ends, respectively, for a triangular pulse
DTT = time increment for the numerical integration (sec)

Other parameters used by the carbon column program in addition to those defined in conjunction with the equations above are:

DT = time increment for carbon column integrations (sec)
NX = number of slabs into which the column is partitioned

RESULTS

In this study we explore the column performance as we vary the following variables: (a) time increment, (b) pulse height, (c) pulse width, (d) shape of pulse, (e) tank size, and (f) column length. One or more of these variables was varied to see the effect on the column separately or in combination. In our recent study (*14*) with constant influent flow rate and concentration we used the indicated values of the following parameters; we employ these values in the present work: $D_l = 0.00$, $D_p = 1.00$, $\Gamma_{max} = 3.0 \times 10^{-10}$, $b = 1.0 \times 10^{-8}$, $S_p = 4.0 \times 10^5$, $V_p = 1.0$, $V_l = 1.00$.

Time Increment

The program gave stable results up to a iime increment (ΔT) of 0.2 sec for the column with no tank. Triangular wave pulses of flow rate and concentration were used, with the following values of the various parameters: $C_B = 5.0 \times 10^{-7}$ mole/mL; $C_{max} = 2.5 \times 10^{-6}$ (mole/mL); $Q_{max} =$ 2.00 (mL/sec); $Q_0 = 100$ (mL/sec); T_1, T_2, T_3, T_4, T_5, T_6 = 20, 25, 30 35, 38, 41 sec, respectively; $NX = 20$. When a tank is incorporated, the above values of parameters are used in addition to the following parameter values which pertain to the tank: $C_0 = 1.0 \times 10^{-7}$, $V_0 = 1.00$. The maximum possible values of DT and DTT were found to be dependent on the size of the tank; the maximum time increment is very sensitive to flow rate (Q), and Q is dependent on the volume of liquid in the tank through $Q = D\sqrt{V}$. For a tank of $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec, the program gave stable results up to $DT = 0.4$ and $DTT = 0.1$ sec, whereas for a tank of $D = 0.53$ cm$^{3/2}$/sec, the upper limits for DT and DTT were found to be 0.1 and 0.05 sec, respectively. The time increments depend also on the duration of the influent flow rate pulse; the larger the duration time, the smaller the values of DT and DTT which are needed to have stable runs. This kind of instability is a mathematical artifact (*14*) which is overcome by reducing the time increments when the size of the tank is reduced or the flow rate pulse duration is increased.

Pulse Duration

The pulse durations were chosen so that there are substantial system changes in moderately short times in order to have short computation times and at the same time allow comparisons between different pulse durations. The flow rate pulse may or may not occur at the same time as the concentration pulse. Four pulse durations for the same pulse heights of triangular waves are compared in Fig. 3, where the concentration in the column influent and effluent are plotted versus time with a tank of $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec. The plot shows how the tank smooths out the pulses and gives a feed to the column in which the pulse heights are reduced considerably, and the pulses are spread out for longer periods of time than the original pulse; the reduction in maximum concentration due to the tank assists the column in effective removal of solute from the influent.

In Fig. 4 the same pulse durations as in Fig. 3 are compared for the column operated without the tank. More extensive breakthrough occurs than in the case where the tank was employed. The decreased time to breakthrough is caused in part by the decreased volume of the entire system.

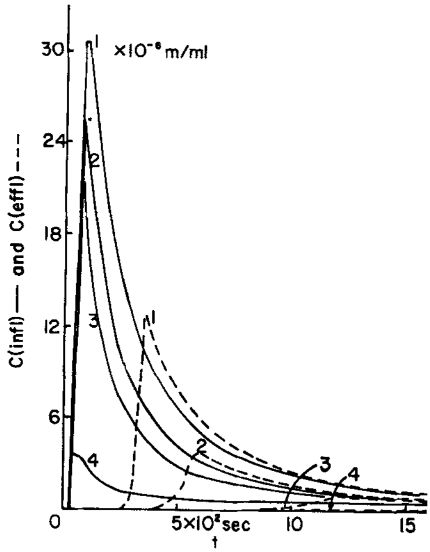

FIG. 3. Plot of C_{in} [C(infl)] and C_{out} [C(effl)] of column versus time (t). Comparsion of various pulse durations for a column with a tank. $D_l = 0.00$ cm^3/sec, $D_p = 1.00$ cm^2/sec, $\Gamma_{max} = 3.0 \times 10^{-10}$ mole/cm^2, $b = 1.0 \times 10^{-8}$ mole/mL, $S_p = 4.0 \times 10^5$ cm^2, $V_p = 1.0$ cm^2, $V_l = 1.00$ cm^2, $DT = 0.2$ sec, $NX = 20$, $C_B = 5.0 \times 10^{-7}$ mole/mL, $C_{max} = 5.0 \times 10^{-5}$ mole/mL, $C_0 = 1.0 \times 10^{-7}$ mole/mL, $Q_0 = 1.00$ mL/sec, $Q_{max} = 2.00$ mL/sec, $V_0 = 1.00$ mL, $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec, $DTT = 0.1$ sec, T_1, T_2, T_3, T_4, T_5, T_6, respectively, (1) 20, 70, 120, 20, 70, 120; (2) 40, 70, 100, 40, 70, 100; (3) 40, 60, 80, 40, 60, 80; and (4) 25, 25, 30, 25, 40, 45 sec. Triangular pulses for influent flow rate and concentration.

Pulse Height

Concentration pulse heights of 2.5×10^{-6}, 5.0×10^{-6}, 1.0×10^{-5}, 2.5×10^{-5}, 5.0×10^{-5}, and 1.0×10^{-4} (mole/mL) were used. No immediate breakthrough occurred for the pulses 2.5×10^{-6} and 5.0×10^{-6} whether or not a tank was used. No tank breakthrough occurred in the case of a pulse of 1.0×10^{-5}, whereas with a tank having $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec the column was not saturated for up to a time of 2000 sec

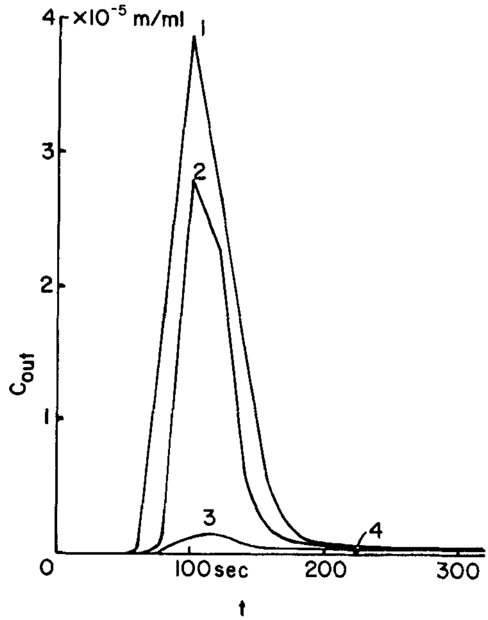

FIG. 4. Plot of C_{out} of column versus t. Comparison of pulse duration for column without tank. The values for the parameters are as in Fig. 3, with parameters pertaining to tank not used, and $DT = 0.1$ sec.

using triangular pulse durations of 20, 70, 120, 20, 70, 120 sec for T_1 to T_6, respectively. Figure 5 shows a plot of C_{in} and C_{out} of column vs volume for concentration pulse heights 1.0×10^{-4}, 5.0×10^{-5}, and 2.5×10^{-5} (mole/mL). The higher the concentration pulse, the more difficult it is for the tank to smooth it out adequately. For a pulse height of 1.0×10^{-4} even with the tank used, the breakthrough in the column occurs quickly (due to column saturation) whereas for the 2.5×10^{-5} pulse, breakthrough takes a much longer time to occur. With no tank, breakthrough takes place very quickly with all three pulse heights (almost at the same time as the pulses in the feed) and the outflow concentration is almost identical with that in the feed. This shows that the column without tank becomes quite inefficient with such pulses.

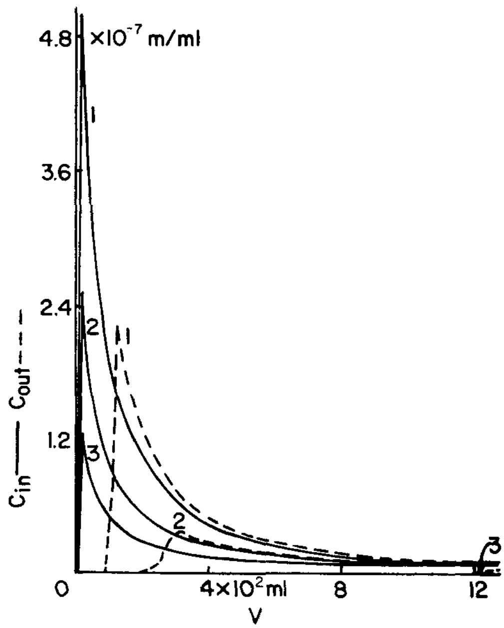

FIG. 5. Plot of C_{in} and C_{out} of column versus V ($V = \int_0^t Q(t')\,dt'$). Comparison of concentration pulse heights for column with tank. D_l, D_p, Γ_{max}, b, S_p, V_l, V_p, DT, NX, C_B, C_0, Q_0, Q_{max}, V_0, D, and DTT have the same values used for Fig. 3. Triangular pulses for flow rate and concentration pulse duration: T_1, T_2, T_3, T_4, T_5, T_6 = 40, 70, 100, 40, 70, 100 sec, respectively. Pulse height (C_{max}): (1) 1.0×10^{-4}, (2) 5.0×10^{-4}, and (3) 2.5×10^{-5} mole/mL.

In Fig. 6 the column effluent is compared for the column with and without a tank for triangular concentration pulses of 2.5×10^{-5} mole/mL. A sharp breakthrough occurred after 60 sec for the column without the tank, whereas for the column with the tank it took more than 1400 sec for breakthrough to take place.

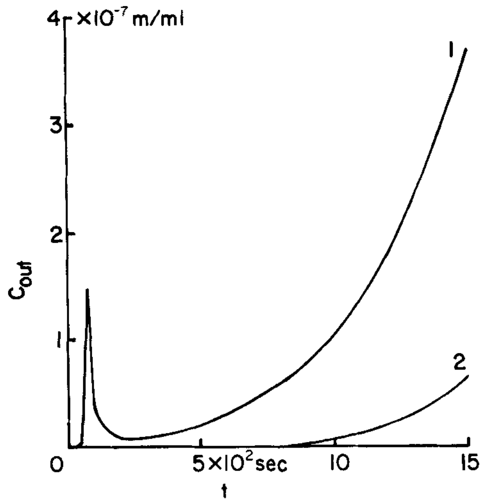

FIG. 6. Plot of C_{out} versus t. Breakthrough curves: (1) no tank, (2) with tank of $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec. Concentration pulse height 2.5×10^{-5}, triangular wave pulses of width 40, 70, 100, 40, 70, 100 for T_1–T_6, respectively. Other parameters have the same values as in Fig. 3.

Tank Size

Breakthrough occurs when the pulse is high enough even when a tank is incorporated; this suggests increasing the tank size for a specified pulse

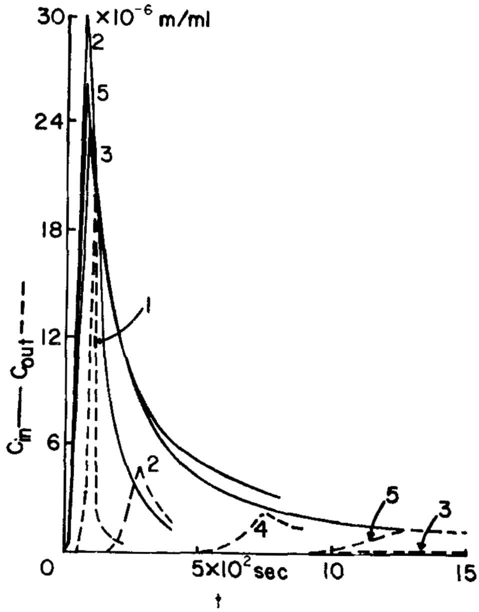

FIG. 7. Plot of C_{in} and C_{out} versus t. Comparison of column performance: (1) without tank, (2) tank of $D = 0.139$, (3) tank of $D = 1.39 \times 10^{-2}$, (4) tank of $D = 5.3 \times 10^{-2}$, and (5) tank of $D = 3.4 \times 10^{-2}$ cm$^{3/2}$/sec. Concentration pulse height 5.0×10^{-5}, triangular feed pulse with duration 25, 50, 75, 25, 50, 75 for T_1–T_6, respectively. Other parameters have the same values as in Fig. 3.

height if breakthrough occurs. In Figs. 7–9 the performances of columns with tanks of various sizes are compared with each other and with the performance of a column without a tank. Table 1 gives an idea as to the size of the various tanks. If the pipe dimensions are as shown in the table,

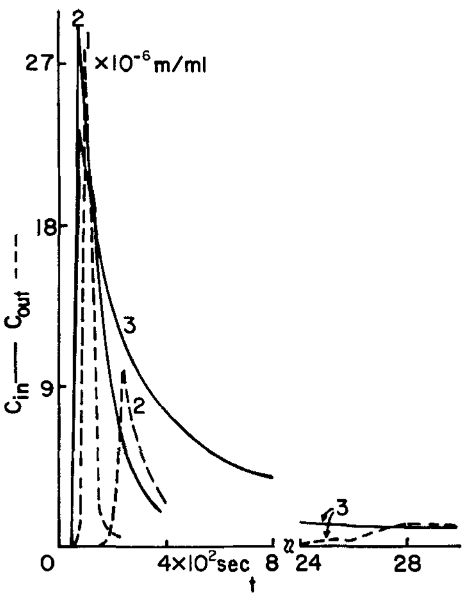

FIG. 8. Plot of C_{in} and C_{out} vs t. Comparison of column performance: (1) no tank, (2) tank of $D = 0.139$, and (3) tank of $D = 1.39 \times 10^{-2}$ cm$^{3/2}$/sec. Concentration pulse height 5.0×10^{-5}, triangular feed pulse with duration 40, 70, 100, 40, 70, 100 for T_1–T_6, respectively. Other parameters have the same values as in Fig. 3.

the corresponding cross-sectional areas of the tanks are shown for each value of D.

As Fig. 7 shows, when a breakthrough of the column with no tank occurs after 60 sec and gives a sharp pulse, breakthrough occurs after 180

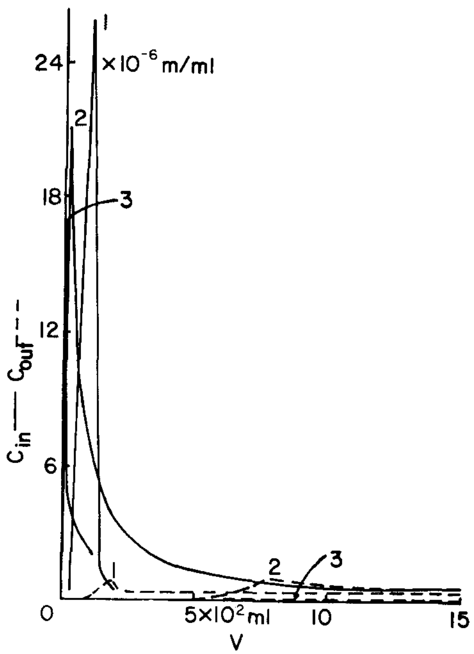

FIG. 9. Plot of C_{in} and C_{out} versus V. Comparison of column performance with tanks of (1) $D = 0.53$, (2) $D = 5.3 \times 10^{-2}$, and (3) $D = 5.3 \times 10^{-3}$ cm$^{3/2}$/sec. Triangular pulses, $C_{max} = 5.0 \times 10^{-5}$, with 40, 60, 80, 40, 60, 80 for T_1–T_6, respectively. Other parameters have the same values as in Fig. 3.

sec with a tank having $D = 0.138$, after 900 sec for a tank having $D = 3.4 \times 10^{-2}$, and does not occur for a tank having $D = 1.39 \times 10^{-2}$ during the course of the run time ($T = 1500$ sec). Similar trends are shown in Figs. 8 and 9.

TABLE 1[a]

D (cm$^{3/2}$/sec)	r_p (cm)	A_p (cm^2)	A_t (cm^2)	L (cm)	R_t (cm)
0.53	0.5	0.7854	4.306×10^3	65.626	37.0255
	0.25	0.1963	2.690×10^2	16.4023	9.2540
	0.10	0.0314	6.8908	2.625	1.4810
0.139	0.5	0.7854	6.261×10^4	250.228	141.1764
	0.25	0.1963	3.911×10^3	62.541	35.285
	0.10	0.0314	1.000×10^2	10.004	5.644
5.3×10^{-2}	0.5	0.7854	4.3068×10^5	656.26	370.255
	0.25	0.1963	2.6903×10^4	164.0232	92.540
	0.10	0.0314	6.884×10^2	26.237	14.803
3.4×10^{-2}	0.5	0.7854	1.0465×10^6	1022.994	577.162
	0.25	0.1963	6.5373×10^4	255.68	144.254
	0.10	0.0314	1.6727×10^3	40.899	23.075
1.39×10^{-2}	0.5	0.7854	6.2614×10^6	2502.286	1441.76
	0.25	0.1963	3.9114×10^5	625.412	352.85
	0.10	0.0314	1.0008×10^4	100.04	56.442
5.3×10^{-3}	0.5	0.7854	4.30677×10^7	6562.60	3702.55
	0.25	0.1963	2.69036×10^6	1640.232	925.40
	0.10	0.0314	6.8838×10^4	262.37	148.026

[a] r_p = radius of pipe (cm), A_p = cross-sectional area of pipe (cm^2), A_t = cross-sectional area of tank, L = side length for a square tank (cm), and R_t = radius of cylindrical tank (cm).

Square Pulses

When square waves were used to feed the column with no tank, breakthrough occurred faster and more severely than when a triangular wave of the same height and same duration was used. Since the amounts of liquid and solute supplied by square waves are twice those of corresponding triangular waves, this is not surprising. Figures 10 and 11 compare

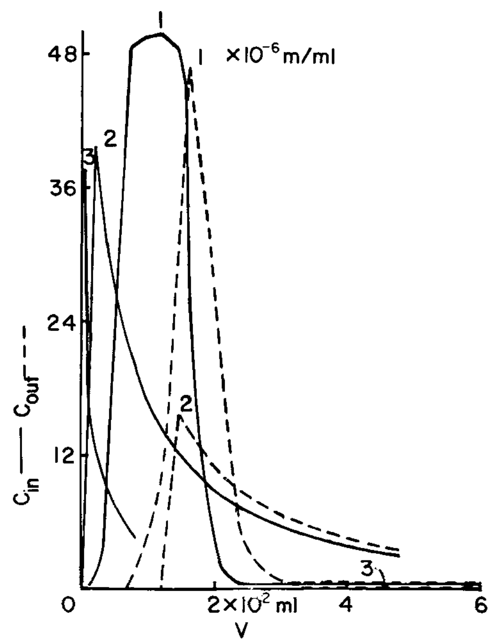

FIG. 10. Plot of C_{in} and C_{out} of column versus V. Square-wave pulse feed to tank of (1) $D = 0.53$, (2) $D = 5.3 \times 10^{-2}$, and (3) $D = 5.3 \times 10^{-3}$ cm$^{3/2}$/sec. $C_{max} = 5.0 \times 10^{-5}$, width 40–80 and 40–80 for T_1–T_3 and T_4–T_6, respectively. Other parameters have the same valnes as in Fig. 3.

the performance of three tanks. With a small tank ($D = 0.53$) the outflow from the tank was a rather square pulse, whereas the tank having $D = 5.3 \times 10^{-3}$ (a very large tank) protected the column from shock overload and breakthrough did not occur during the run time. A tank of moderate size ($D = 5.3 \times 10^{-2}$) smoothed the pulse considerably and reduced the height of the concentration breakthrough from the column to a marked extent.

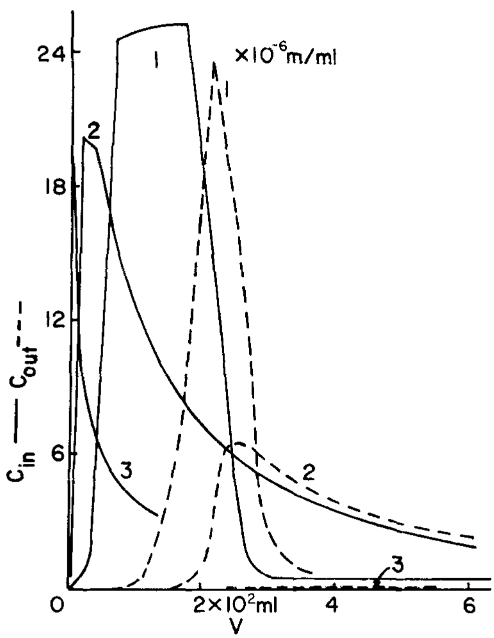

FIG. 11. Plot of C_{in} and C_{out} of column versus V. Square-wave pulse feed to tank having (1) $D = 0.53$, (2) $D = 5.3 \times 10^{-2}$, and (3) $D = 5.3 \times 10^{-3}$ cm$^{3/2}$/sec. $C_{max} = 2.5 \times 10^{-5}$, width 40–100 and 40–100 for T_1–T_3 and T_4–T_6, respectively. Other parameters have the same values as in Fig. 3.

Column Length

The length of the column was changed by changing the number of slabs (NX) into which the column was partitioned while holding the slab thickness constant. A slab thickness of unity makes NX equal to the length of the column.

Square pulses of $C_{max} = 5.0 \times 10^{-5}$ and 2.5×10^{-5} mole/mL were used to illustrate the effect of increasing the column length. Figure 12 compares the cases of (1) no tank, (2) a tank of $D = 0.53$, and (3) a tank of $D = 5.3 \times 10^{-2}$ for a concentration pulse of $C_{max} = 5.0 \times 10^{-5}$

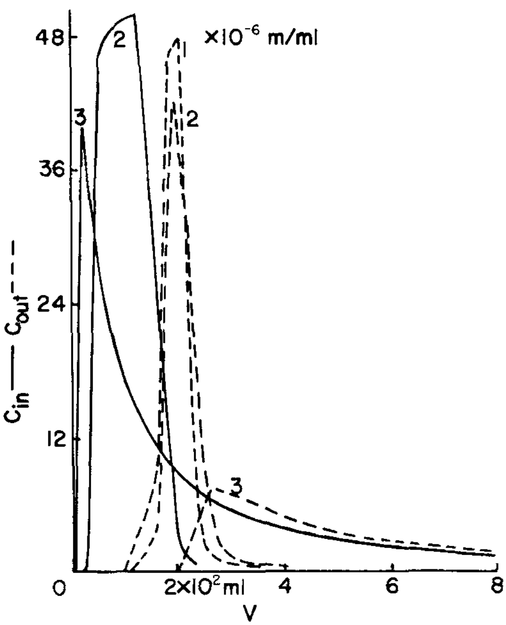

FIG. 12. Plot of C_{in} and C_{out} of column versus V. Column length $NX = 30$, square-wave feed pulse, $C_{max} = 5.0 \times 10^{-5}$, width 40–80 and 40–80 for T_1–T_3 and T_4–T_6, respectively. (1) No tank, (2) tank of $D = 0.53$, and (3) tank of $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec. Other parameters have the same values as in Fig. 3.

using a column having $NX = 30$. Figure 13 shows the same comparison for a column of $NX = 40$. If the effluent from the column is compared for the three column lengths ($NX = 20$, 30, and 40) using the same influent pulse height and duration and the same tank (for example, compare the outflow for a column having a tank of $D = 5.3 \times 10^{-2}$ in Figs. 10, 12, and 13), one sees that doubling the column length reduces the breakthrough pulse to one-fifth or less its height with the original column length, and makes breakthrough occur after a much longer time. One might ask whether a longer column or an equalization tank should be used to prevent breakthroughs of shock loadings. Some runs have been carried

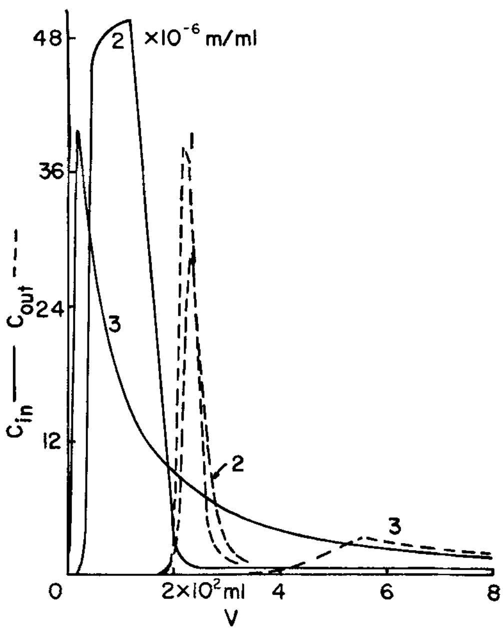

FIG. 13. Plot of C_{in} and C_{out} of column versus V. Column length $NX = 40$, square-wave feed pulse, $C_{max} = 5.0 \times 10^{-3}$, width 40–80 and 40–80 for T_1–T_3 and T_4–T_6, respectively. (1) No tank, (2) tank of $D = 0.53$, and (3) tank of $D = 0.53$, and (3) tank of $D = 5.3 \times 10^{-2}$ cm$^{3/2}$/sec. Other parameters have the same values as in Fig. 3.

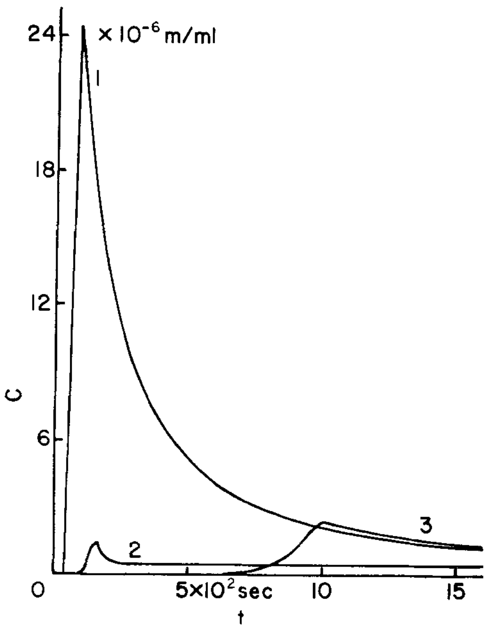

FIG. 14. Plot of C_{in} and C_{out} versus t. Comparison of a column with tank with a column of 1.5 length without tank. Triangular feed pulse, $C_{max} = 5.0 \times 10^{-5}$, duration 40, 70, 100, 40, 70, 100 for T_1 to T_6, respectively. (1) Inflow to column from tank of $D = 3.4 \times 10^{-2}$; (2) outflow from column without tank, $NX = 30$; and (3) outflow from column with tank, $NX = 20$. Other parameters have the same values as in Fig. 3.

out in which the same pulses of flow rate and concentration were fed to a column with a tank and to a longer column without a tank. Figure 14 gives an example of this; here a column of $NX = 20$ with a tank of $D = 3.4 \times 10^{-2}$ is compared to a column of $NX = 30$ without a tank. It is evidently better in this case to use the above equalization tank than to increase the length of column by 50%. On the other hand, if a column of twice the original length is used, removal of the pulse is more complete than using the above tank and column combination (data not shown).

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