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Cycling Zone Adsorption: Variable-Feed Mode of Operation

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Abstract

Relatively large separations are possible using a single cycling zone adsorption column when operated with product recycle. Such a recycle may cause a large cyclic step-change in feed concentration, resulting in significant differences in alternating product stream concentrations. It is concluded that such a "variable-feed mode of operation" may allow the separation of compounds whose solid–fluid equilibrium distribution coefficients are only slightly affected by changes in a thermodynamic potential, or compounds which are difficult to separate by classical techniques such as distillation or extraction. It will also be apparent that the "variable-feed mode of operation" of a single zone (column) produces separations that could only be previously developed by a number of constant feed concentration zones operating in a series. Theoretical and experimental studies show that longitudinal diffusion is the primary cause of effluent concentration profile distortion, limiting the duration of peak product concentration flow.

INTRODUCTION

Cycling zone adsorption is a wave propagational adsorption separation process that produces alternating high and low concentration effluent streams by cyclic variation of a thermodynamic potential, usually temperature. The process was invented by Pigford et al. for binary systems (*1*), while Wankat et al. (*2, 3*) have extended the investigation to multicomponent systems. Details of the application of the equilibrium theory (with the use of the method of characteristics) as applied to parametric pumping have been discussed by Pigford et al. (*4*) and by Rice (*5*). The use of these equations to

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model cycling zone adsorption is discussed by Baker (*6*). A detailed review of cycling zone adsorption separations for the unfamiliar reader has been developed by Wankat et al. (*7*). Briefly, the separation process may function as follows: Figure 1 depicts the generalized equilibrium isotherms for a single component of a binary fluid adsorbing upon a given substrate at two different temperatures, T_{hot} and T_{cold}. If such a binary system (equally applicable, however, for multicomponent systems) of concentration X_F is continuously fed into a packed adsorber of a given solid substrate and if the temperature of the column is cycled as a periodic step change, then a continuous effluent stream is produced which is alternately high and low in the component concentration. The thermally cyclic operation of a single zone is shown in Fig. 2. The idealized effluent profile is illustrated in Fig. 3.

The aspects of longitudinal diffusion, which may distort the idealized effluent profile, as shown in Fig. 3, have been previously considered by Nelson et al. (*8*). The reader may wish to compare the experimental data of this paper and that of Rieke (*10*) with the analysis of Nelson et al. (*8*). The effects of product recycle about a cycling zone adsorption column have been suggested by Frey (*9*). Details of product recycle and zone cascades appear

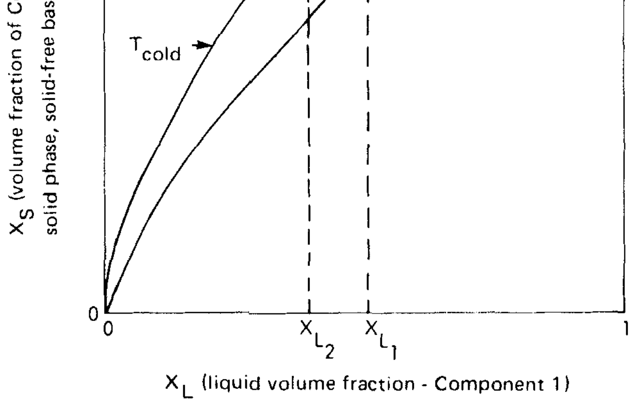

FIG. 1. Idealized equilibrium isotherms.

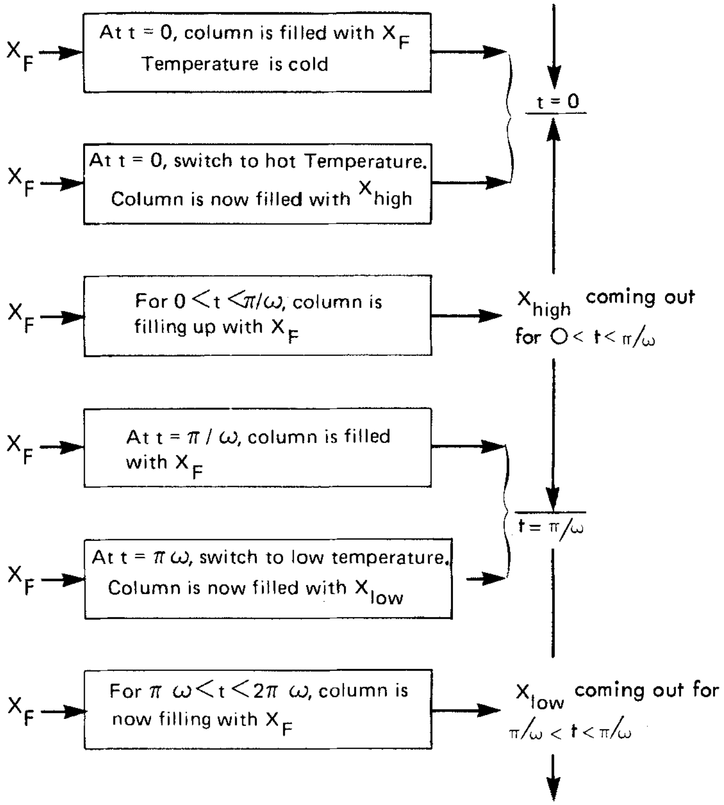

FIG. 2. Plan for cyclic operation of a single zone.

in Rieke (*10*). It is the purpose of this paper to theoretically explore the distortional effects of longitudinal diffusion upon the effluent profile of a cycling zone adsorption column, with experimental comparisons, and to propose a product recycle stream operation, termed "variable-feed mode of operation," which amplifies separations produced by a single cycling zone adsorption column.

IDEAL VARIABLE-FEED MODE OF OPERATION (no diffusion present)

A binary mixture of *n*-heptane and toluene is being separated in a packed bed of silica gel. All concentrations shall refer to toluene. When the

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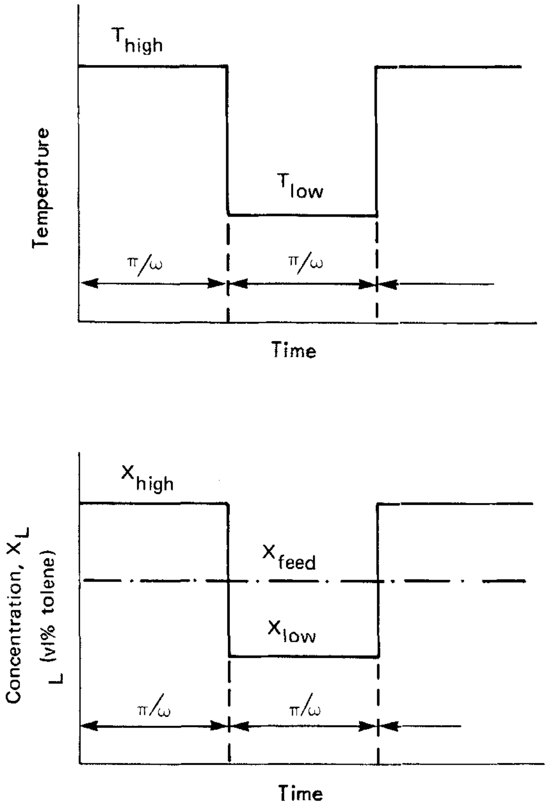

Fig. 3. Idealized temperature and effluent profiles.

temperature of such a system is changed from a high value to a low value, toluene is preferentially adsorbed by the silica gel (in accordance with equilibrium isotherm data, Fig. 1 (idealized)). When the temperature is changed from the low value to the high value, toluene is preferentially desorbed by the silica gel.

Consider the flow diagram of Fig. 4 and the accompanying feed and effluent concentration profile of Fig. 5. A periodic square-wave temperature change is now imposed upon the packed bed (usually referred to as the direct mode of operation), also with a square-wave feed concentration input to the zone. The zone is filled with low concentration feed, $X_{F,\text{low}}$, while the zone is at some high temperature, T_{high}. The zone temperature is now changed to some low value, T_{cold}. Because of the solids' preference for toluene at the low temperature, the interstitial fluid loses toluene to the silica gel and now has a concentration of $X_{\text{low}} < X_{F,\text{low}}$. The low-concentration interstitial fluid in the zone is now displaced by a high-concentration feed, $X_{F,\text{high}} > X_{F,\text{low}}$. After the displacement of the low-concentration interstitial fluid, the zone is filled with the high-concentration feed and the temperature is switched from hot to cold. At the high temperature the solid particles desorb toluene into the interstitial fluid. At this point the bed becomes filled with high-concentration interstitial fluid, $X_{\text{high}} > X_{F,\text{high}}$. The high-concentration fluid is now displaced by low-concentration feed, $X_{F,\text{low}}$, and the process repeats itself.

As indicated by Fig. 4, portions of the product streams of composition X_{low} and X_{high} are recycled back to the initial feed stream of constant composition, $X_{F\text{av}}$, in order to maintain the two intermediate feed streams of composition $X_{F,\text{low}}$ and $X_{F,\text{high}}$. The nonrecycled portions of the effluent stream may be removed as product or further processed by successive zones in an appropriately designed staged cascade, as done by Rieke (*10*). Figure 5 shows an idealized effluent stream concentration profile, neglecting any diffusional distortion effects (concentration wave velocity differences), for the operation of such a single zone. The apparent advantage of such an operation over that of a constant-concentration feed input (Fig. 3) is the increased separation due to the square-wave feed input. Neglect of longitudinal diffusion effects implies that any feed amplitude to the zone may be used, with an increase in the effluent product stream amplitude due to the

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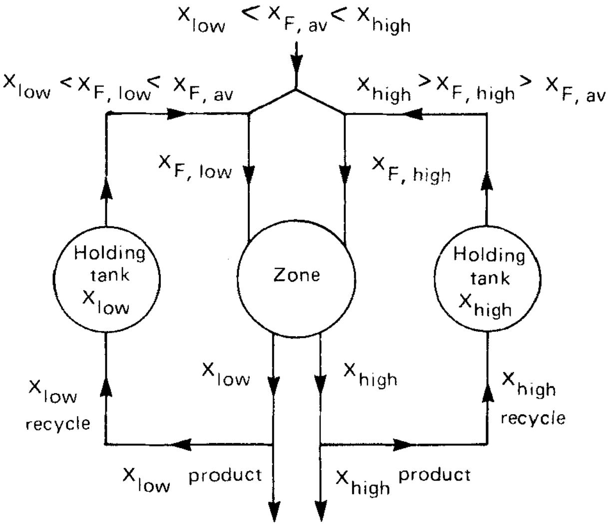

FIG. 4. Variable-feed mode of operation.

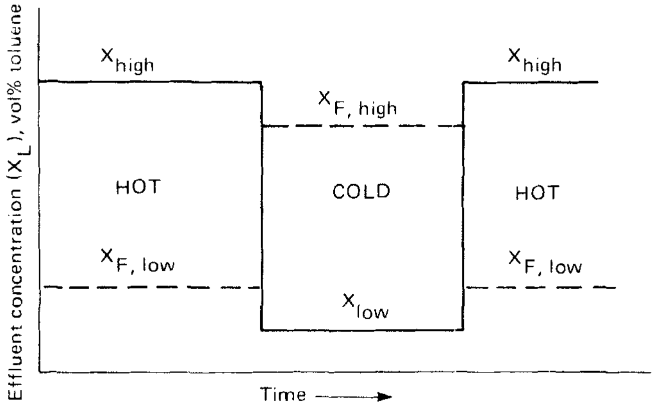

FIG. 5. Idealized effluent concentration profile.

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square-wave cycling of the zone temperature. As will be shown later, this is not always possible in practice.

It is also apparent that the variable-feed, recycle operation of a single zone produces separations that could only be previously developed by a number of constant-feed concentration zones operating in a series (*6*, *10*). However, the introduction of a large step-change in feed concentration at the input to the zone will be an added cause of longitudinal diffusion, which will greatly distort the desired square-wave effluent concentration profile. The distortional aspect of longitudinal diffusion shall be further discussed.

MATHEMATICAL MODEL

In previous articles (*1*, *3*, *5*, *7*, *12*), simplified equations describing cycling zone adsorption have been developed. In the analysis of Baker and Pigford (*6*, *12*), the first-order equations and the graphical method of characteristics were applied to the governing nonlinear equation and the results were found to be valid for any concentration amplitude, only if diffusion were zero. The mathematical analysis of this article will present a solution of the linearized problem. The results will be valid for sufficiently small values of the concentration changes. However, improvement over the nonlinear analysis is gained by allowing for longitudinal diffusion.

Consider a single zone experiencing a square-wave temperature change and a square-wave feed concentration input as previously described. The solute balance on the fluid and solid phases may be written as:

$$\alpha \frac{\partial X_L}{\partial t} + (1-\alpha)\varepsilon \frac{\partial X_s}{\partial t} + \alpha V \frac{\partial X_L}{\partial z} = \alpha \mathcal{D} \frac{\partial^2 X_L}{\partial z^2} \tag{1}$$

with boundary conditions:

$$X_{LF} = X_L(0,t) - \frac{\mathcal{D}}{V} \frac{\partial X_L}{\partial t}(0,t)$$

$$0 = \frac{\partial X_L}{\partial z}(Z,t)$$

$$X_{LF} = X_L(z,0)$$

At equilibrium between the phases the equilibrium isotherm relationship may be stated as

$$X_s = F(X_L, T) \tag{2}$$

Differentiation of Eq. (2) gives

$$\frac{\partial X_s}{\partial t} = \left.\frac{\partial X_s}{\partial X_L}\right|_T \frac{\partial X_L}{\partial t} + \left.\frac{\partial X_s}{\partial T}\right|_{X_L} \frac{\partial T}{\partial t} \tag{3}$$

Now let:

$$\left.\frac{\partial X_s}{\partial X_L}\right|_T = m \frac{\alpha}{(1-\alpha)\varepsilon}, \qquad \left.\frac{\partial X_s}{\partial T}\right|_{X_L} = m_T \frac{\alpha}{(1-\alpha)\varepsilon}$$

Through linearization of the isotherms, constant values of these partials are used in the analysis over concentration and temperature ranges of interest. Here the values of m and m_T are determined at the average operating temperature and the average feed concentration. Let $V_C = V/(1+m)$ and $\mathcal{D}_C = \mathcal{D}/(1+m)$. Equation (1) can now be rearranged into

$$\frac{\partial X_L}{\partial t} + V_c \frac{\partial X_L}{\partial z} - \mathcal{D}_c \frac{\partial^2 X_L}{\partial z^2} = -\left(\frac{m_T}{1+m}\right) \frac{\partial T}{\partial t} \tag{4}$$

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A Fourier series may be used to express the square-wave variation of the temperature and feed input to the zone:

$$T(t) = T_0 + \frac{\Delta T}{\pi} \sum_{n=1}^{\infty} \frac{1 - (-1)^n}{n} \sin \left(n\pi \frac{t}{\Delta t} \right) \tag{5}$$

$$X_{LF} = X_{F,\mathrm{av}} + \left(\frac{\Delta F}{\pi} \right) \sum_{n=1}^{\infty} \frac{[1 - (-1)^n]}{n} \sin \left(\frac{n\pi t}{\Delta t} - F\pi \right) \tag{6}$$

Note that Eq. (6) contains a phase shift factor F. This factor allows a switching time lag to be employed between the step-change in the temperature and the step-change in the feed concentration. As described in the "ideal variable-feed mode of operation," the temperature and feed concentration step-changes occur 180° out-of-phase. The solution of Eq. (1) will allow the determination of the optimum phase relationship between the two step-changes.

The new boundary conditions may now be written as:

$$X_{F,\mathrm{av}} + \left(\frac{\Delta F}{\pi} \right) \sum_{n=1}^{\infty} \frac{[1 - (-1)^n]}{n} \sin \left(\frac{n\pi t}{\Delta t} - F\pi \right)$$

$$= X_L(0,t) - \frac{\mathcal{D}_c}{V_c} \frac{\partial X_L}{\partial z} (0,t)$$

$$0 = \frac{\partial X_L}{\partial z} (Z,t)$$

By substitution of Eq. (5) into Eq. (4), the following partial differential equation may be written:

$$\frac{\partial X_L}{\partial t} + V_c \frac{\partial X_L}{\partial z} - \mathcal{D}_c \frac{\partial^2 X_L}{\partial z^2}$$

$$= -\frac{m_T \Delta T}{(1 + m)\Delta t} \sum_{n=1}^{\infty} [1 - (-1)^n] \cos \left(n\pi \frac{t}{\Delta t} \right) \tag{7}$$

Introduction of the LaPlace transform,

$$\bar{X}_L(z,p) = \{X_L(z,t)\} = p \int_0^{\infty} e^{-pt} X_L(z,t) dt$$

allows Eq. (7) to be written as

$$p(\bar{X}_L - X_{LF}) + V_c\frac{d\bar{X}_L}{dz} - \mathcal{D}_c\frac{d^2\bar{X}_L}{dz^2} = -\frac{m_T}{1+m}\frac{\Delta T}{\Delta t}\sum_{n=1}^{\infty}\frac{[1-(-1)^n]p^2}{\left(\dfrac{n\pi}{\Delta t}\right)^2 + p^2} \tag{8}$$

The boundary conditions now become

$$\bar{X}_L(0,p) - \frac{\mathcal{D}_c}{V_c}\frac{d\bar{X}_L}{dz}(0,p) = X_{F,\mathrm{av}}$$

$$+\frac{\Delta F}{\pi}\sum_{n=1}^{\infty}\frac{[1-(-1)^n]}{n}\left\{\frac{\left(\dfrac{n\pi}{\Delta t}\right)p}{\left(\dfrac{n\pi}{\Delta t}\right)^2 + p^2}\left[\cos F\pi - \frac{\Delta t}{n\pi}p\sin F\pi\right]\right\}$$

$$0 = \frac{d\bar{X}_L}{dz}(Z,p)$$

The solution of Eq. (8) takes the form

$$\bar{X}_L(Z,p) = X_{F,\mathrm{av}} - \left(\frac{m_T}{1+m}\right)\left(\frac{\Delta T}{\pi}\right)\sum_{n=1}^{\infty}\frac{[1-(-1)^n]}{n}$$

$$\times\frac{\left(\dfrac{n\pi}{\Delta t}\right)p}{\left(\dfrac{n\pi}{\Delta t}\right)^2 + p^2}$$

$$\times\left\{1 - \frac{e^{\xi}\sqrt{1+4\mathcal{D}_c/V_c^2}}{\left(1+2\dfrac{\mathcal{D}_c p}{V_c^2}\right)\sin h + \sqrt{1+4\dfrac{\mathcal{D}_c p}{V_c^2}}}\right.$$

$$\left.\times\left[1+\left(\frac{1+m}{m_T}\right)\frac{\Delta F}{\Delta T}\left(\cos F - \frac{\Delta t}{n\pi}p\sin F\pi\right)\right]\right\} \tag{9}$$

where the argument of hyperbolic functions is

$$\sqrt{1+4\frac{\mathcal{D}_c p}{V_c^2}}\left(\frac{V_c Z}{2\mathcal{D}_c}\right)$$

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Inversion of Eq. (9) gives the final form of the effluent concentration profile for a single cycling zone adsorber experiencing a square-wave temperature change and a square-wave feed concentration input:

$$
\begin{aligned}
X_L(Z,t) = X_{F,\mathrm{av}} - \left(\frac{m_T}{1+m}\right)\frac{\Delta T}{\pi}\sum_{n=1}^{\infty}\frac{[1-(-1)^n]}{n}\Bigg\{&\sin\left(\frac{n\pi}{\Delta t}t\right) \\
&- e^{\xi}\left(\frac{\alpha R+\beta S}{R^2+S^2}\right)\sin\left(\frac{n\pi}{\Delta t}t\right) \\
&+ e^{\xi}\left(\frac{\alpha S-\beta R}{R^2+S^2}\right)\cos\left(\frac{n\pi}{\Delta t}t\right) + e^{\xi}\left(\frac{1+m}{m_T}\right)\left(\frac{\Delta F}{\Delta T}\right) \\
&\times\left[\left(\frac{\alpha R+\beta S}{R^2+S^2}\right)\cos\left(\frac{n\pi}{\Delta t}t\right)\right. \\
&\left.+\left(\frac{\alpha S-\beta R}{R^2+S^2}\right)\sin\left(\frac{n\pi}{\Delta t}t\right)\right]\sin(F\pi) \\
&- e^{\xi}\left(\frac{1+m}{m_T}\right)\left(\frac{\Delta F}{\Delta T}\right)\left[\left(\frac{\alpha R+\beta S}{R^2+S^2}\right)\sin\left(\frac{n\pi}{\Delta t}t\right)\right. \\
&\left.-\left(\frac{\alpha S-\beta R}{R^2+S^2}\right)\cos\left(\frac{n\pi}{\Delta t}t\right)\right]\cos(F\pi)\Bigg\} \qquad (10)
\end{aligned}
$$

From Eq. (10), the relationships for the temperature switching contribution and the feed switching contribution may be developed. These are given by Eqs. (11) and (12), respectively:

$$
\begin{aligned}
X_L(Z,t) = X_{LF} - \left(\frac{m_T\Delta T}{1+m}\right)\left(\frac{1}{\pi}\right)\sum_{n=1}\frac{[1-(-1)^n]}{n}\Bigg[&\sin\left(\frac{n\pi}{\Delta t}t\right) \\
&- e^{\xi}\left(\frac{\alpha R+\beta S}{R^2+S^2}\right)\sin\left(\frac{n\pi}{\Delta t}t\right) \\
&+ e^{\xi}\left(\frac{\alpha S-\beta R}{R^2+S^2}\right)\cos\left(\frac{n\pi}{\Delta t}t\right)\Bigg] \qquad (11)
\end{aligned}
$$

$$
\begin{aligned}
X_L(Z,t) = X_{F,\mathrm{av}} - e^{\xi}\frac{\Delta F}{\pi}\sum_{n=1}^{\infty}\frac{[1-(-1)^n]}{n}\Bigg\{&\sin\left(\frac{n\pi}{\Delta t}t\right) \\
&\times\left[\left(\frac{\alpha S-\beta R}{R^2+S^2}\right)\sin(F\pi) - \left(\frac{\alpha R+\beta S}{R^2+S^2}\right)\cos(F\pi)\right]
\end{aligned}
$$

$$+\cos\left(\frac{n\pi}{\Delta t}t\right)\left[\left(\frac{\alpha R+\beta S}{R^2+S^2}\right)\sin(F\pi)\right.$$

$$\left.\left.+\left(\frac{\alpha S-\beta R}{R^2+S^2}\right)\cos(F\pi)\right]\right\} \tag{12}$$

It is seen that Eq. (10) is therefore composed of a function, Eq. (11), that accounts for the effect of the square-wave temperature change of the zone, and a function, Eq. (12), that accounts for the effect of a square-wave feed input into the zone.

EXPERIMENTAL

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The variable-feed mode of operation and the mathematical model presented are based upon the ability of a column or zone to operate under a perfect square-wave temperature change and a perfect square-wave feed concentration input. However, the experimental production of such conditions is difficult. In order to approach these conditions, an intermittent-flow, variable-feed mode of operation, has been used experimentally by Rieke (*10*) (ideal variable-feed mode of operation). Consider the previously described mode of operation. However, let the flow stop temporarily at the instant of the temperature change and at the instant of the step-change in feed concentration input. During this interruption, the zone is allowed to come to thermal equilibrium. Flow is then resumed. In this manner the temperature profile of the column as a function of the time of the actual flow is a square-wave, satisfying the boundary condition. It is not possible to produce a perfect square-wave in the feed concentration input since diffusion occurs during the interrupted flow period of operation. Figure 6 is a brief description of the experimental cycling zone adsorption column used by Rieke (*10*), incorporating in-bed heat exchangers as used later by Sweed and Rigaudeau (*14*) and Stokes and Chen (*13*).

Figure 7 is a plot of the experimental effluent concentration profile obtained under the operation just described (Table 1 lists the operating conditions). Figure 8 is a plot of the experimental equilibrium isotherm for the system *n*-heptane, toluene, silica gel (*10*). The feed amplitude, ΔF, is 4.1 vol% toluene, $X_{F,\mathrm{high}} = 34.8$ vol% toluene, and $X_{F,\mathrm{low}} = 30.7$ vol% toluene. The operating temperature change is 57°C, the high and low temperatures being 59 and 2°C, respectively. The final low and high product amplitude is 9.6 vol% toluene. In this particular case the temperature swing (as determined from the experimental equilibrium isotherms) contributes a

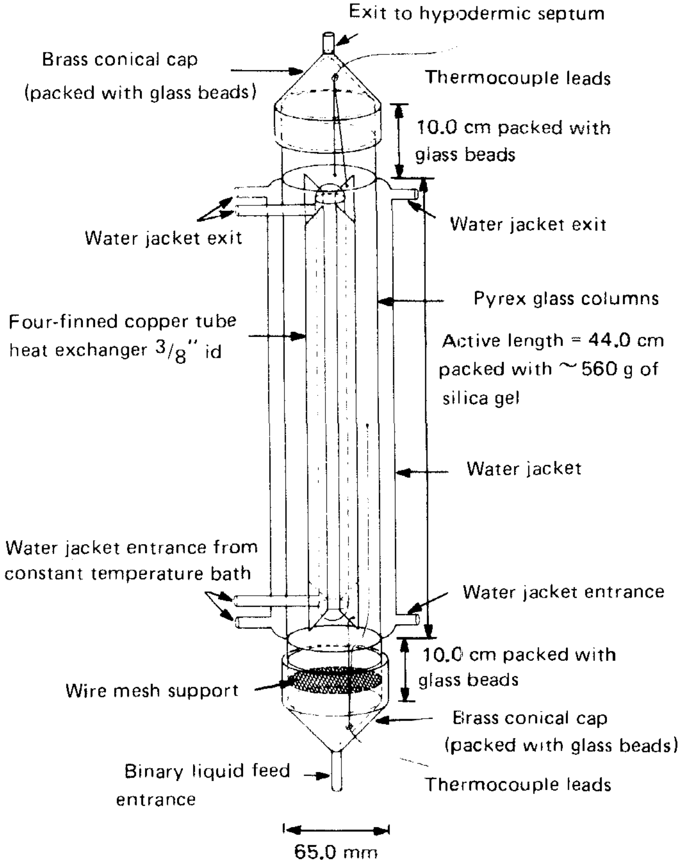

FIG. 6. Experimental equipment.

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product concentration change of 6 vol%, while the remainder of the product amplitude is due to the step-change in the feed concentration input. It is of interest to note that the operation of a zone in this manner (because of the sharpness of the effluent profiles) allows very large step-changes in feed concentration to be used.

DISCUSSION

Important operational factors are revealed by the theoretical development for the effluent concentration profiles from a single zone operating under

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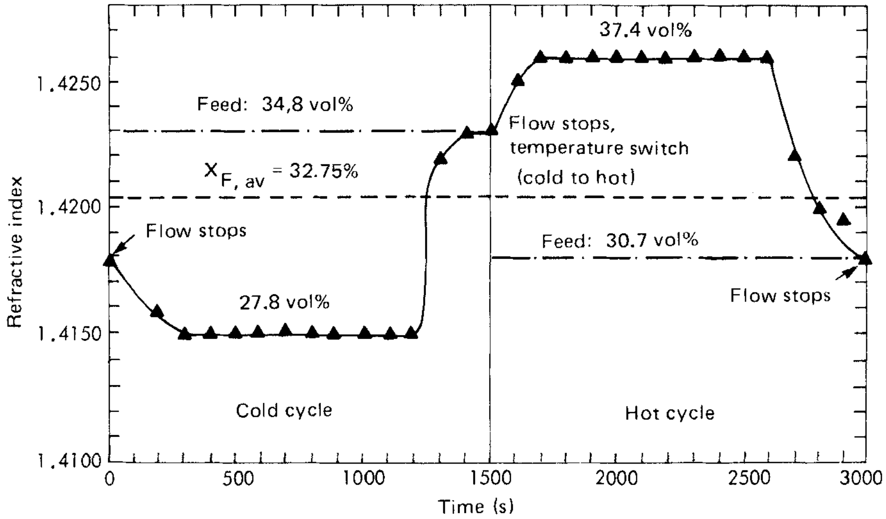

FIG. 7. Intermittent-flow, variable-feed mode of operation.

variable-feed conditions. Table 2 lists the operating conditions and values of constants found in Eq. (10). Figure 9 is a plot of Eq. (10) for a variation in the phase shift factor, F, between the step-change in the temperature and the step-change in the feed concentration input to the zone (for a half cycle of operation). Figures 10 (half cycle) and 11 (full cycle) are plots of the temperature switching contribution and the feed switching contribution to the

TABLE 1

Operating Conditions for Experimental Variable-Feed Mode of Operation (Fig. 7)

Interstitial fluid velocity: 0.0466 cm/s
High-feed concentration: 34.8 vol% toluene
Low-feed concentration: 30.7 vol% toluene
$X_{F,\mathrm{av}} = 32.75\%$ toluene
Period: 3000 s
Temperature switching frequency (Δt): every 1500 s
Temperatures: 2 and 59°C
High-concentration product: 37.4 vol% toluene
Low-concentration product: 27.8 vol% toluene
Feed amplitude: 4.1 vol% toluene
Product amplitude: 9.6 vol% toluene

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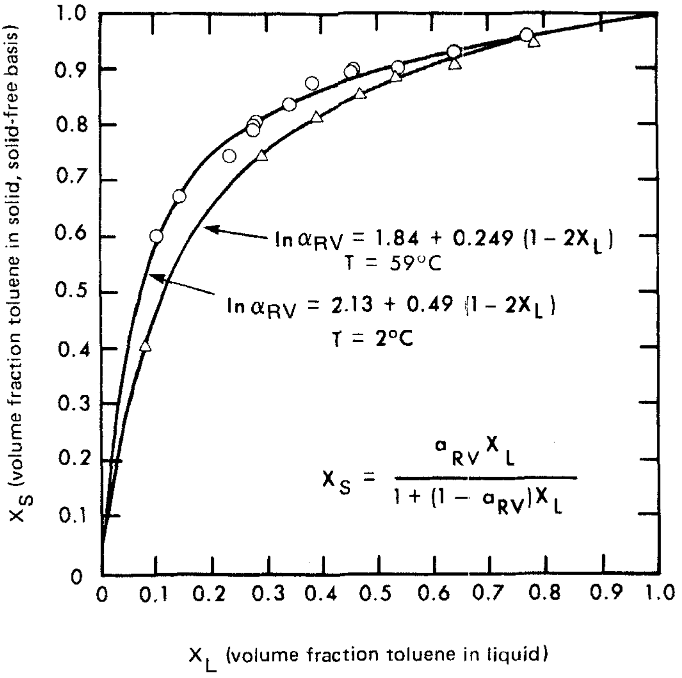

FIG. 8. Experimental equilibrium isotherm. Solid: silica gel. Liquid: *n*-heptane/toluene.

TABLE 2

Operating Conditions Used in Evaluation by Eqs. (10), (11), and (12)

$V = 0.046$ cm/s
$\Delta t = 1800$ s
$\Delta T = 59°$C
$T_{av} = 29.5°$C
$Z = 38$ cm
$m = 0.82$
$m_T = 0.001$
$X_{F,av} = 0.13$ volume fraction toluene
$\Delta F = 0.05$ volume fraction toluene
$d_p = 0.05$ cm (20–60 mesh size packing)
$\mathcal{D}_c = 4.0 \times 10^{-2}$ cm^2/s (experimentally determined)

final effluent concentration profile of Fig. 9. As seen from Fig. 9, the maximum separation occurs when the temperature switch and the feed concentration switch are 180° out-of-phase. That is, when the temperature is switched to the high value, the feed concentration is changed to the low value, and when the temperature is switched to the low value, the feed concentration is changed to its high value. Note also that the diffusional

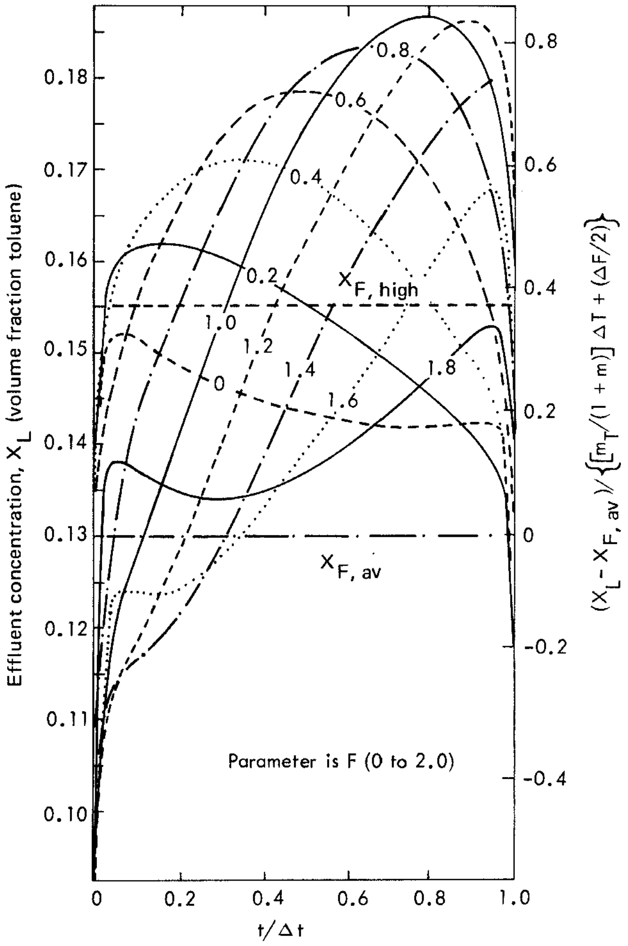

FIG. 9. Equation (10) for variation of switching phase lag factor F (high temperature, half cycle).

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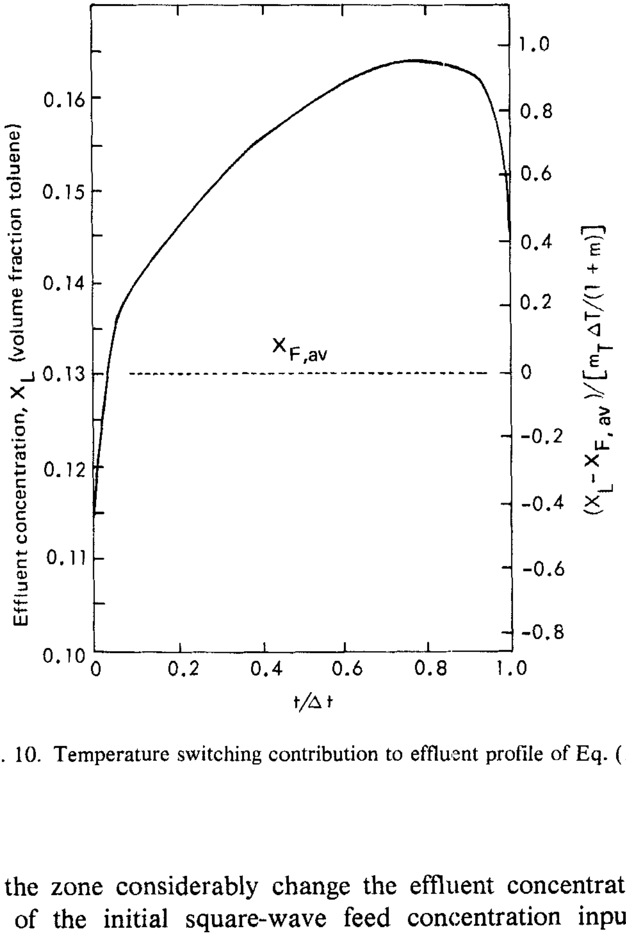

FIG. 10. Temperature switching contribution to effluent profile of Eq. (11).

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effects in the zone considerably change the effluent concentration profile from that of the initial square-wave feed concentration input. This is emphasized further by the effluent profiles of Fig. 12 for five values of the Peclet number. As shown by Fig. 11, the calculated effluent concentration profile is rounded off and becomes more like a sine wave rather than the input square wave. If an enriched or depleted stream is to be produced by cycling zone adsorption, the effect of the temperature swing, as shown by Fig. 10, must overcome the losses due to diffusion as shown by Figs. 11 and 12. It is obvious that longitudinal diffusion limits the amplitude of the input concentration square-wave obtained by product stream recycle. Enrichment or depletion due to temperature changes then compete with amplitude reduction due to diffusion. It may therefore be concluded that in the separation of liquid systems via cycling zone adsorption, longitudinal diffusion is a prime limiting factor.

Summary

As discussed by Baker and Pigford (*6*, *12*), separation amplification difficulties are evident in cycling zone adsorption. Because of the small shift in the equilibrium distribution coefficient for moderate temperature changes, numerous zones must be used to effect large separations. However, as is theoretically and experimentally shown by this article, large separations may be obtained by operating a single zone in the variable-feed mode of operation. Such an operation reduces the thermal requirements necessitated by a large number of zones in a cascade.

The effects of diffusion and possible intraparticle diffusion-controlled mass transfer may be minimized by the intermittent-flow, variable-feed mode of operation. During the stagnant period of time for which the thermal equilibrium may be obtained, any delay in the approach to solid–liquid

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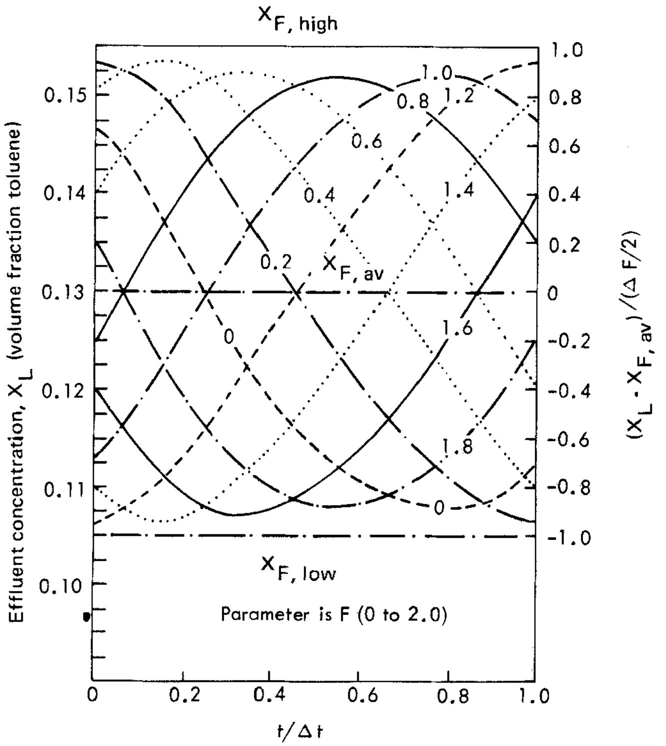

FIG. 11. Feed switching relationship (Eq. 12).

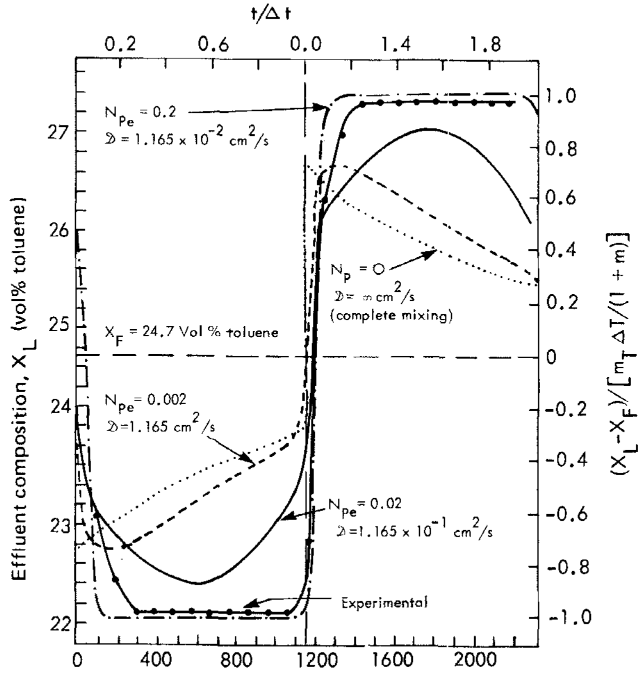

FIG. 12. Equation (11) for variation of diffusivity in N_{Pe} (temperature switch contribution only, full cycle).

equilibrium may be mitigated. After such a required period of interrupted operation, the volume of the column may be displaced by the feed concentration fluid at a very high velocity. Such an operation would then tend to preserve the initial input square-wave. It would therefore be possible to produce durations of high and low concentration product, each approaching a half cycle of operation.

As explored and revealed by Baker (*9*), cycling zone adsorption is an attractive process for the intermediate scale separation of materials which must now be treated chromatographically. However, the variable-feed mode of operation provides the means by which the separation technique may possibly attain some commercial status.

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SYMBOLS

A	$(1-\alpha)\varepsilon/\alpha$
$\mathscr{D}$	diffusion coefficient
$\mathscr{D}_c$	$\mathscr{D}/(1+m)$
F	phase lag factor between feed and temperature switch
ΔF	feed amplitude, vol% toluene
L	zone length
N_{Pe}	Peclet number
R	$\sinh \alpha\zeta \cos \beta\zeta - 2n\pi q \cosh \alpha\zeta \sin \beta\zeta + \alpha \cos \alpha\zeta \cos \beta\zeta - \beta \sinh a\zeta \sin \beta\xi$
S	$2\pi nq \sinh \zeta \cos \beta\zeta + \cosh \zeta \sin \beta\zeta + \alpha \sinh \alpha\zeta \sin \beta\zeta + \beta \cosh \alpha\zeta \cos \beta\zeta$
T	temperature
V	interstitial fluid velocity
V_c	interstitial concentration wave velocity $= V/(1+m)$
X	volume fraction or vol% toluene
Z	$L =$ zone length

Lowercase

c	concentration
f	functional relationship between X_S, T, and X_L. (equilibrium isotherm relationship)
m	$A(\partial X_S/\partial X_L)_{T_{\mathrm{av}}}$
m_T	$A(\partial X_S/\partial T)_{X_L}$
n	positive whole integer
p	LaPlace transform operator
q	$\mathscr{D}_c/V_c^2\Delta t$
t	time
z	distance along the axial direction

Greek Letters

α	interparticle void fraction
α	$\sqrt{\dfrac{1+\sqrt{1+16\pi^2n^2q^2}}{2}}$, found in Eqs. (10), (11), and (12)

α_{RV}	constant in solid–liquid isotherm relationship, found in Fig. 8
β	$2\pi nq/\alpha$ as defined immediately above
ε	intraparticle void fraction
ζ	$V_c Z/2$
ξ	$(z - V_c t)/2\mathscr{D}_c t$
ρ	density

Subscripts

avg	average
F	feed concentration
F,av	average feed concentration
F,high	high feed concentration
F,low	low feed concentration
high	high concentration
L	liquid
low	low concentration
S	solid
sinh	$\sinh\left[\sqrt{1 + 4\frac{\mathscr{D}_c p\ V_c Z}{V_c^2\ 2\mathscr{D}_c}}\right]$
cosh	$\cosh\left[\sqrt{1 + 4\frac{\mathscr{D}_c p\ V_c Z}{V_c^2\ 2\mathscr{D}_c}}\right]$

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