# R & D NOTES

# On the Regeneration of Fixed Absorber Beds

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Recent papers (Zwiebel et al., 1972; Garg and Ruthven, 1973, 1974) have considered the problem of isothermal desorption in fixed beds and were concerned with the effect of nonlinear isotherms on the adsorption/desorption curves. Using an adsorbate free fluid under comparable conditions to adsorption, they showed that the desorption curves were not as sharp when the isotherm was of favorable shape. These papers are important because although there are many theoretical and experimental publications about adsorption in fixed beds those previously concerned with desorption or regeneration are limited and use semi-empirical heat balance methods (Cappell et al., 1944; Carter, 1966a). Continuous fixed-bed adsorption is a cyclic process which is dependent upon satisfactory desorption before a bed can be reused. For dual adsorbers it is then usually necessary to speed up desorption by using a hot fluid (thermal swing) because the heat of desorption is a large proportion of the heat requirements when high adsorption loading occurs. In practice even distribution throughout the bed is not obtained because changeover from a used adsorber to a fresh one is usually made at the breakpoint. A high loading will thus be obtained at the adsorption inlet end of the bed approaching zero at the outlet. Under these conditions the direction of regeneration, whether in the same or in the reverse direction to the adsorption flow, will affect the desorption curves. For beds evenly saturated throughout, they will be identical whatever the direction of regeneration flow. The author is currently investigating nonisothermal regeneration problems and has also carried out experimental and theoretical studies of adiabatic adsorption in fixed beds (Carter, 1966b, 1968a,b; Carter and Barrett, 1972). The theoretical model included boundary-layer and adsorbed phase rate control for mass transfer. When diffusion in the pore space of the adsorbent is the significant adsorbed phase rate mechanism, it was shown that an effective diffusion coefficient could be described by

$$D \simeq \frac{D_p \epsilon_g \rho_f}{K \rho_g} \tag{1}$$

The product $KD$ would then be substantially constant and temperature and concentration independent over a limited range of conditions. This was shown to be so for water vapor adsorbed on activated alumina, giving excellent predictions for adiabatic adsorption in fixed beds on both a small and a large scale. It was also noted that the values of $D$ were much lower than the thermal diffusivity of the granules (approximately $0.3 \times 10^{-5}$ cm²/s against $1 \times 10^{-3}$ cm²/s, respectively) so that temperature gradients in them would be negligible compared with adsorbate concentrations and only boundary-layer heat transfer would be controlling. The equations may also be used for adiabatic desorption, and in their dimensionless form are first the mass balance and rates of diffusion through the fluid-film, fluid/adsorbent interface, and in the adsorbent granules:

$$\frac{\delta \bar{v}_0}{\delta T_0'} = -\frac{\delta u}{\delta Z} \tag{2}$$

$$= u - v_{0,s} K_0/K \tag{3}$$

$$= -\frac{K_0}{K} N \left( \frac{\delta v_0}{\delta R} \right)_{R=1} \tag{4}$$

$$\frac{\delta v_0}{\delta T_0'} = \frac{K_0}{K} \frac{N}{3} \left( \frac{\delta^2 v_0}{\delta R^2} + \frac{2}{R} \frac{\delta v_0}{\delta R} \right) \tag{5}$$

The sensible and latent heat balance gives

$$\frac{\delta \Theta_g}{\delta T_0'} = -\frac{\delta \Theta_f}{\delta Z} \frac{K_0 C_f}{C_g + w^*_{0,i} v_0 C_a} - \frac{\delta u}{\delta Z} \frac{w_{0,i} \lambda_a}{C_g + w^*_{0,i} v_0 C_a} \tag{6}$$

and the rate of sensible heat transfer between the fluid and solid phases is

$$-\frac{\delta \Theta_f}{\delta T_0'} = (\Theta_f - \Theta_g)\, X\, (Sc/Pr)^{2/3} \tag{7}$$

The derivation of this equation makes use of the analogy:

$$j_h = X j_d \quad \text{so that,} \quad h = k_y C_f X\, (Sc/Pr)^{2/3} \tag{8}$$

Equations (2) to (7) are coupled hyperbolic and parabolic partial differential equations whose integration from known boundary conditions by an implicit finite difference method has been described previously in detail (Carter, 1966b). $X = 1.0$ was used and $K_0/K$ calculated from

$$\frac{K_0}{K} = u^{1-\beta} \exp\left(-\lambda_1 \beta M/R(1/\Theta_g' - 1/\Theta'_{g,0})\right) \tag{9}$$

derived from

$$w^* = \alpha (y/y_{\mathrm{satn}\Theta_g})^\beta \tag{10}$$

The latter represented the temperature and concentration adsorption equilibria with reasonable accuracy but over a wide temperature range might be a serious limitation.

The initial and boundary conditions for adsorption on a freshly regenerated bed cooled to the inlet temperature are

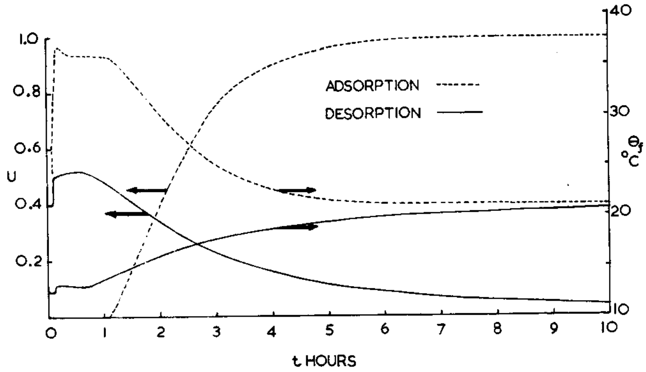

**Fig. 1. Adsorption and desorption curves with 21.1°C inlet temperature.**

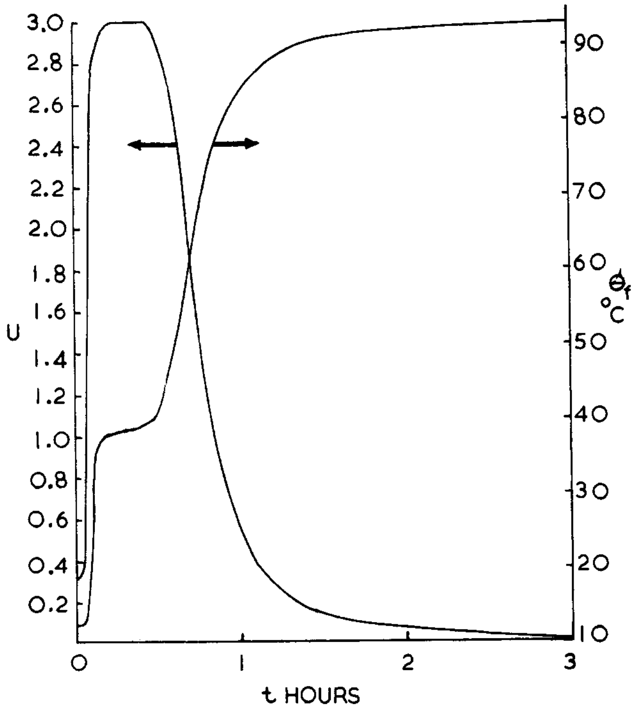

**Fig. 2. Desorption curves with 93.3°C inlet temperature.**

$$T_0' = 0, \quad Z > 0 : u = \exp - Z, \quad \bar{v}_0 = 0,$$

$$\Theta_f = \Theta_g = \Theta_{f,\text{ad}} \quad (11)$$

$$T_0' > 0, \quad Z = 0 : u = 1.0, \quad \Theta_f = \Theta_{f,\text{ad}}$$

For desorption of a fully saturated bed by an adsorbate free fluid at the adsorption inlet temperature they are

$$T_0' = 0, \quad Z > 0 : u = 0, \quad \bar{v}_0 = 1.0,$$

$$\Theta_f = \Theta_{f,\text{ad}}, \quad \Theta_g = \Theta_{f,\text{ad}} \quad (12)$$

$$T_0' > 0, \quad Z = 0 : u = 0, \quad \Theta_f = \Theta_{f,\text{de}} (= \Theta_{f,\text{ad}})$$

For a partially saturated bed $\bar{v}_0$ will not equal 1.0 for all Z. To determine the effects of thermal swing regeneration and of adsorbate distribution in the bed on the desorption curves, an example was chosen for which experimental and predicted adsorption curves have been published (Carter, 1968a, Figure 8). This concerned the adsorption of water vapor from an airflow by granular activated alumina (Laporte Industries Ltd.). Details of the adsorption conditions were:

| | |
|---|---|
| Bed depth | 0.228 m |
| Mean granule radius | 0.00147 m |
| Air flow rate | 0.258 kg/m²s |
| Air inlet temperature | 21.1°C |
| Air inlet humidity | 0.0048 kg/kg |
| Equilibrium | $w^* = 0.129(y/y_{\text{satn}\Theta_g})^{0.46}$ |
| Rate data: $KD/b^2$ | 3.25 $h^{-1}$ |
| Heat of adsorption (or desorption) | 2907 kJ/kg |

Desorption calculations were done for a fully saturated bed using the same flow rate, first with dry air at 21.1°C. The adsorption and desorption curves are compared in Figure 1 showing both processes to be strongly nonisothermal. The curves show some similarities. During adsorption the temperature rose to a plateau and then fell after the breakpoint. For desorption a low temperature plateau occurred during the period of maximum outlet concentration. The latter was much lower ($u = 0.53$) than the adsorption inlet value and desorption was a much slower process. Calculations for exactly the same conditions except that $\Theta_{f,\text{de}} = 93.3°\text{C}$ gave the results plotted in Figure 2. The regeneration is now very much quicker, the outlet air flow temperature first having risen to an almost steady value when the outlet concentration reached a maximum ($u = 3.0$). The temperature then rose again to approach the inlet value, but desorption was not completed within the time to reach breakpoint during adsorption (see Figure 1). This would be possible by using a higher temperature still, increasing the maximum outlet concentration further, or an increased regeneration flow rate.

The calculated distribution of moisture on the bed at breakpoint during adsorption was very closely represented by a straight line falling from the equilibrium value at the inlet to zero at the outlet. Thus

$$\bar{v}_0 = 1.0 - Z/Z_{\text{total}} \quad (13)$$

where $Z_{\text{total}}$ is the total dimensionless bed length. It may be noted that this indicates a low average loading sug-

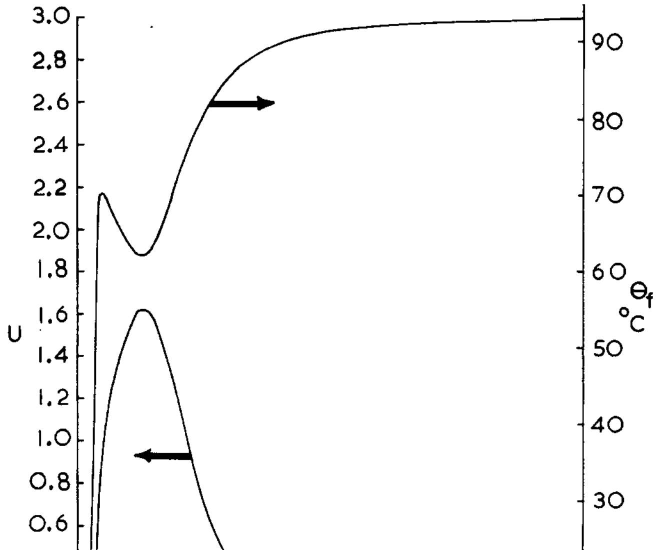

**Fig. 3. Desorption curves for partially saturated bed with 93.3°C inlet temperature in the same direction as adsorption.**

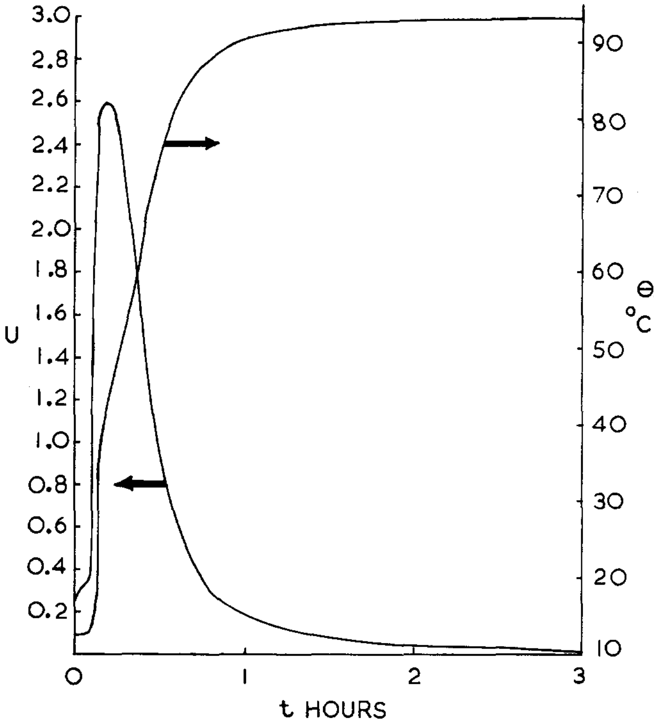

**Fig. 4. Desorption curves for partially saturated bed with 93.3°C inlet temperature in the reverse direction to adsorption.**

gesting the use of longer beds whenever possible in practice. Desorption from this bed using the same flow rate of dry air at 93.3°C in the direction of adsorption gave the outlet curves in Figure 3. In this instance the temperature first rose to a minor peak caused by the heat of re-adsorption of the moisture wave as it moved down the bed. Similar peaks have been observed by the author on large-scale plant and are a loss of sensible heat. This has to be replaced by further regeneration air, lengthening the process and reducing its efficiency, although such a moisture wave may be used to desorb impurities that might otherwise poison the adsorbent if heated to the full regeneration temperature. Using the hot regeneration flow in the reverse direction to adsorption (Figure 4) did not give such a peak and produced a higher maximum outlet concentration ($u = 2.60$ against 1.63) so that desorption was quicker.

These results show the importance of the adsorbate distribution and the temperature and direction of the flow during regeneration. The curves can be expected to be realistic in the temperature range investigated, but for higher values a more accurate representation than Equation (10) of the concentration and temperature dependent adsorption equilibrium would be desirable.

## NOTATION

$A$ = fixed bed cross sectional area
$a$ = external granule area per unit volume of bed
$b$ = mean adsorbent granule radius
$C$ = specific heat
$D$ = effective adsorbed phase diffusion coefficient
$D_p$ = effective pore diffusion coefficient
$G$ = inert fluid flow rate
$h$ = fluid film heat transfer coefficient
$j_h$ = Colborn $j$-factor for heat transfer
$j_d$ = Colborn $j$-factor for mass transfer
$K$ = linear adsorption equilibrium coefficient = $w^*/y$
$k_y$ = fluid film mass transfer coefficient
$M$ = molecular weight of adsorbate
$N$ = dimensionless resistance parameter = $3\rho_b KD/(k_y a b^2)$
$r$ = radius adsorbent granule
$R$ = dimensionless granule radius = $r/b$: or gas constant in Equation (9)
$T_0'$ = dimensionless time = $t' k_y a/(\rho_b K_0)$
$t$ = time
$t'$ = time = $t - z\epsilon_b \rho_f A/G$
$Pr$ = Prandtl group
$Sc$ = Schmidt group
$u$ = dimensionless fluid phase concentration = $y/y_i$
$v$ = dimensionless adsorbed phase concentration = $w/w^*_{0,i}$: $w^*_{0,i} = K_0 y_i$
$w$ = adsorbed phase concentration in granules
$X$ = ratio $j_h/j_d$
$y$ = adsorbate concentration in inert fluid
$Z$ = dimensionless fixed-bed length = $z\, k_y a\, A/G$
$z$ = fixed-bed length

### Greek Letters

$\alpha$ and $\beta$ = constants in equilibrium Equation (10)
$\epsilon$ = voidage fraction
$\Theta$ = temperature
$\Theta'$ = absolute temperature
$\lambda_a$ = heat of adsorption
$\lambda_1$ = latent heat of condensation
$\rho$ = density

### Subscripts

$a$ = adsorbate
ad = adsorption
$b$ = fixed bed
de = desorption
$f$ = fluid
$g$ = adsorbent granule(s)
$i$ = inlet to fixed bed
0 = values based on fluid composition $y_i$ and solids temperature $\Theta_{g,0}$
$s$ = granule surface
satn = saturation at appropriate temperature

### Superscripts

— = average value
$*$ = equilibrium value

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