Chapter 12

Liquid – Liquid and Fluid – Solid Separation Processes

This chapter includes examples of adsorption processes where one or more components of a gas or liquid stream are adsorbed on the surface of an adsorbent material. The following problem module illustrates pressure swing adsorption process for purifying hydrogen for proton – exchange membrane fuel cells.

12.3-1 Hydrogen Purification in Pressure Swing Adsorption Process

Example 12.3-1 Hydrogen Purification in Ethanol – Reforming Process

The dry reformate stream coming from an ethanol reforming process contains 70 mole % H_2 and 30 mole % CO_2. Lopes et al. [1] study the adsorption of CO_2 on a packed bed of activated carbon with a length of 0.267 m. The bed contains 245.6 kg of adsorbent material consisting of activated carbon, with a particle diameter of 2.9 mm. The average flow rate of the dry reformate is $5\times10^{-5}\,\frac{m^3}{s}$ and has a density of $0.587\frac{kg}{m^3}$.

Use the data in the following table to determine the time required to reach the break – point concentration $\left(\frac{C}{C_0}=0.01\right)$, the time equivalent to the total capacity of the bed, and the time equivalent to the usable capacity of the bed up to the break – point time. Also calculate the length and capacity of unused bed after the break-point time. What is the saturation capacity of the bed?

Breakthrough Concentration of CO_2 in the packed bed

t(s)	C/C_0
0	0
27	0.0063
187	0.0125
480	0.0358
600	0.1391
613	0.3487
640	0.4249
667	0.4884
747	0.5600
853	0.6661
973	0.7168
1067	0.7611
1200	0.8055
1360	0.8561

t(s)	C/C_0
1493	0.8814
1640	0.9066
1827	0.9318
1933	0.9444
2107	0.9569
2240	0.9695
2373	0.9757
2560	0.9819
2707	0.9817
2853	0.9879
3120	0.9940
3280	0.9938
3440	1.0000
3600	1.0000

Strategy

The break-through and capacity of the packed bed can be determined using the design equations given in Section 12.3D of Geankoplis.

Solution

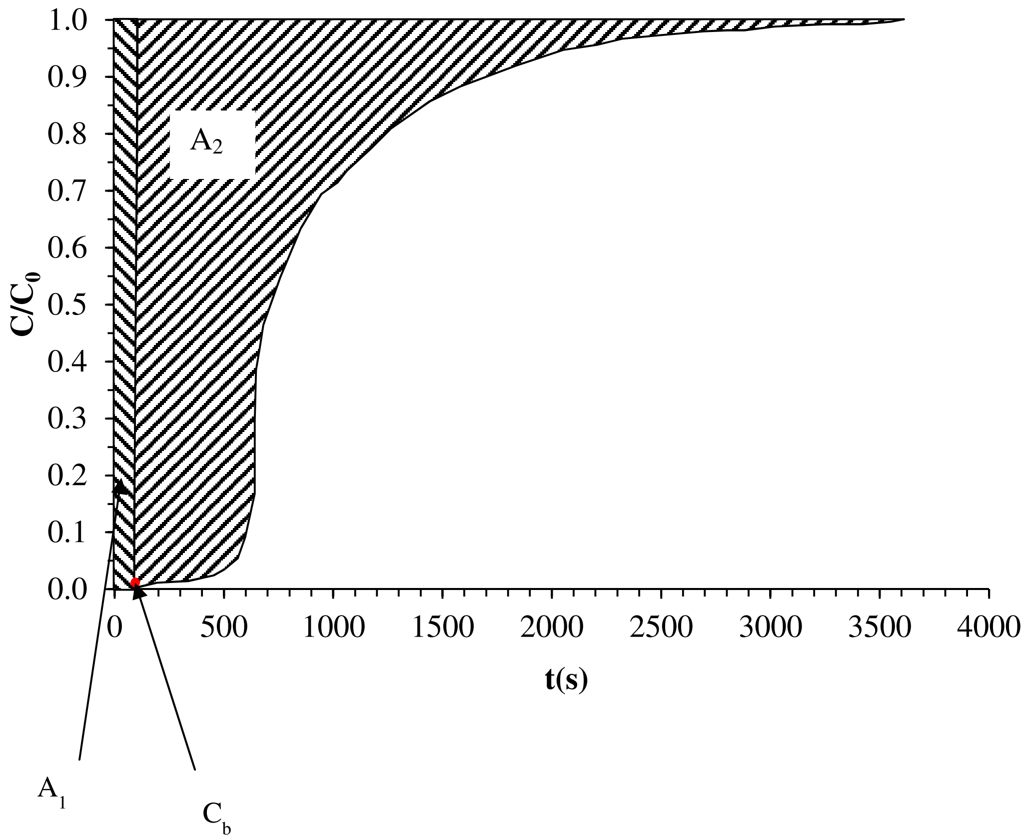
First, the break – point time can be obtained from the tabulated data, at the point where $\frac{C}{C_0}=0.01$ to be equal to $\boxed{t_b = \_\_\_\_\_\_\_ \text{ s}}$

1. Lopes, F.V.S., Grande, C.A., Rodrigues, A.E., *Chemical Engineering Science*, 66, 303 – 317 (2011)

The time t_t for the total capacity of the bed can be calculated using the integral of the $\frac{C}{C_0}$ curve as a function of time:

$$t_t = \int_0^\infty \left(1 - \frac{C}{C_0}\right) dt = A_1 + A_2$$

where A_1 and A_2 are the shaded areas shown in the following figure:

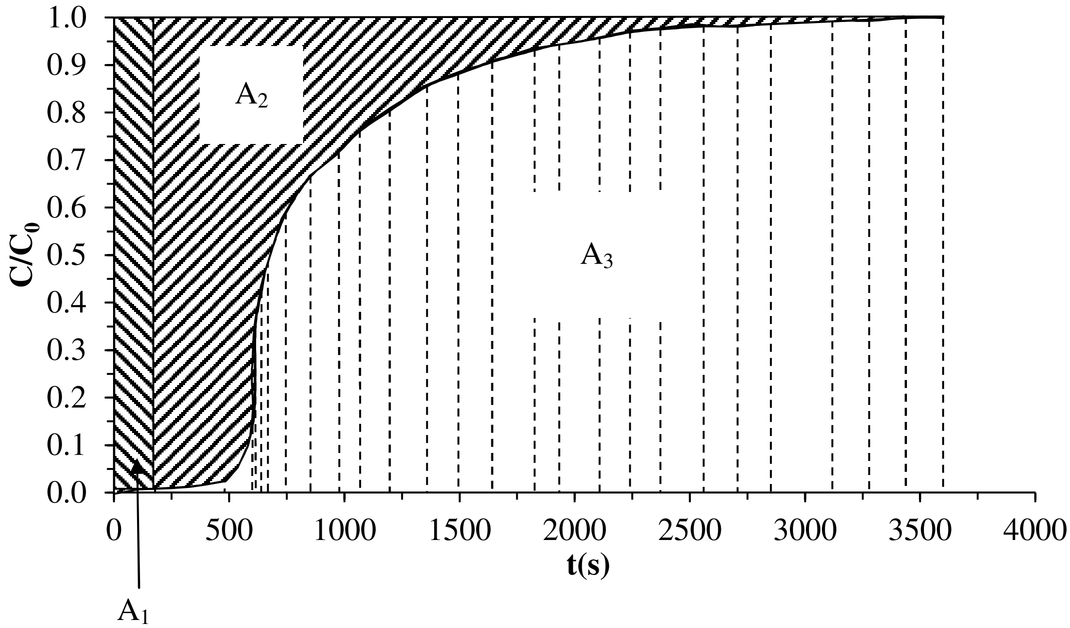


As it can be seen in this figure, we can determine the break – through time by calculating the areas A_1 and A_2. Thus,

$$A_1 = (\_\_\_\_\_\ s - 0s)(1 - \_\_\_)$$

$$A_1 = \_\_\_\_\_\ s$$

To determine the area A_2, we can use the trapezoidal method to calculate the area under the curve and subtract it from the total area A of the rectangle, as shown below:



The area of the rectangle to the right of the break point can be calculated as follows:

$$A = (\_\_\_\_\_\_ \text{ s} - \_\_\_\_\_ \text{ s})(1 - \_\_\_)$$

$$A = 3413 \text{ s}$$

The results for the numerical integration using trapezoidal method will yield:

$$A_3 = \_\_\_\_\_\_\_\_\_\_ \text{ s}$$

Now we can obtain the area A_2 to be:

$$A_2 = A - A_3 = 3413 \text{ s} - \_\_\_\_\_\_\_\_\_\_ \text{ s}$$

$$A_2 = \_\_\_\_\_\_\_\_\_\_ \text{ s}$$

We can substitute the areas A_1 and A_2 into the equation for the break-through time t_t, to obtain:

$$t_t = \_\_\_\_\_\_ \text{ s} + \_\_\_\_\_\_\_\_\_\_ \text{ s}$$

$$\boxed{t_t = \_\_\_\_\_\_\_\_\_\_ \text{ s}}$$

The time equivalent to the available capacity of the bed before the break – point time can be obtained as shown in the following steps:

$$t_u = \int_0^{t_b} \left(1 - \frac{C}{C_0}\right) dt = \_\_\_\_$$

$$\boxed{t_u = \_\_\_\_\_ \ \text{s}}$$

The length of the unused bed can be calculated using Equation 12.3-4 of Geankoplis:

$$H_{UNB} = \left(1 - \frac{t_u}{t_t}\right) H_T$$

where:

H_T = Total length of the packed bed

Substituting the times we calculated and the length of the packed bed into this equation, we get:

$$H_{UNB} = \left(1 - \frac{\_\_\_\_\_ \ \text{s}}{\_\_\_\_\_\_\_\_\_ \ \text{s}}\right)(\_\_\_\_\_\_ \ \text{m})$$

$$\boxed{H_{UNB} = 0.212 \text{ m}}$$

Finally, to determine the saturation capacity of the activated carbon in the bed, we need to obtain the moles of carbon dioxide adsorbed on the bed.

The carbon dioxide can be obtained by multiplying the initial concentration of CO_2 in the gas by the mass of gas in the time t_t of _______ s. Thus,

$$\text{Total } CO_2 \text{ adsorbed} = \frac{0.30 \dfrac{\text{kmol } CO_2}{\text{kmol gas}} \left(5 \times 10^{-5} \dfrac{\text{m}^3}{\text{s}}\right)(\_\_\_\_\_\_\_\_ \ \text{s})\left(0.587 \dfrac{\text{kg gas}}{\text{m}^3}\right)}{\_\_\_\_\_ \dfrac{\text{kg gas}}{\text{kmol gas}}} \left(\_\_\_\_ \dfrac{\text{kg } CO_2}{\text{kmol } CO_2}\right)$$

$$\text{Total } CO_2 \text{ adsorbed} = \_\_\_\_\_\_\_\_ \text{ kg } CO_2$$

The molecular weight of the gas mixture was obtained by multiplying the molar fraction of each component by its corresponding molecular weight and adding the results, as shown below:

$$M_{gas} = y_{H_2}M_{H_2} + y_{CO_2}M_{CO_2} = \_\_\_\_\_\_\left(\_\_\_\_\frac{\text{kg H}_2}{\text{kmol H}_2}\right) + 0.3\left(\_\_\_\_\_\frac{\text{kg CO}_2}{\text{kmol CO}_2}\right)$$

$$M_{gas} = \_\_\_\_\_\_\_\_\frac{\text{kg}}{\text{kmol}}$$

Now we can divide the total CO_2 adsorbed by the mass of activated carbon on the bed. Hence,

$$\text{Saturation Capacity} = \frac{\_\_\_\_\_\_\_\_\ \text{kg CO}_2}{245.6\ \text{kg adsorbent}}$$

$$\boxed{\text{Saturation Capacity} = \_\_\_\_\_\_\_\_\_\_\_\_\ \frac{\text{kg CO}_2}{\text{kg adsorbent}}}$$