3.044 Problem Set 6

Continuous Flow Reactors

Due Monday April 11, 2005

1. Batch and continuous flow reactors (40)

   In a batch or continuous flow reactor, the productivity is defined as the flow rate, or the volume divided by total time. Here we'll discuss a reactor with a homogeneous first-order reaction throughout volume V with rate constant k and target conversion of reactant A given by $C_{A,out}/C_{A,in} = 0.05$.

   (a) Write expressions for the productivity (flow rate) of plug flow and perfect mixing continuous reactors. (8)

   (b) Write an expression for productivity of a batch reactor with downtime t_d for emptying and reloading between batch processes. (8)

   (c) For a given volume, which of these three has the best productivity, and how much better is it than the others? (Give a ratio of productivities.) (8)

   (d) Which is likely to give the best product uniformity? (8)

   (e) Give one advantage of batch reactors over continuous reactors. (8)

2. Evaporation of volatile impurities during electron beam melting (25)

   Cadmium, lead and zinc are impurities present in the sponge titanium feedstock of an electron beam furnace. We would like to assess the effectiveness of the process at removing these impurities.

   Reaction rate coefficients may be calculated by equations which we will discuss later; for now, the following table gives equilibrium vapor pressures, pure material evaporation fluxes, and evaporation reaction rate coefficients (assuming unit activity coefficients):

Element	$\bar{p}_v$, torr	J_{ev}, $\frac{\text{mol}}{\text{m}^2 \cdot \text{s}}$	k'', $\frac{\text{m}}{\text{s}}$
Cd	1.81×10^5	2.21×10^5	2.59
Pb	787	709	8.29×10^{-3}
Zn	9.56×10^4	1.53×10^5	1.79

   (a) For a furnace with a flow rate of 22 $\frac{\text{cm}^3}{\text{sec}}$ and hearth surface area of 0.25 m^2, calculate the ratio of concentration in the product to concentration in the feedstock for each of these elements assuming plug flow behavior. (10)

   (b) Repeat part 2a assuming perfect mixing behavior. (10)

   (c) Does electron beam melting effectively remove these impurities from sponge titanium? (5)

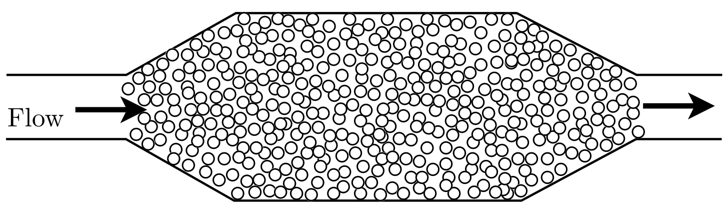
3. Flow through a catalytic reactor (35)

CuO is a good catalyst for the reaction

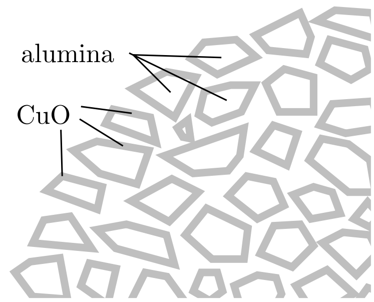
$$2CO(g) + O_2(g) \Rightarrow 2CO_2(g)$$

CuO is coated on the internal surfaces of porous Al_2O_3 spheres of radius R, so the gases containing CO and O_2 can diffuse in through the pores with diffusivity D and react on the internal CuO surfaces. (The Al_2O_3 is used as a substrate because of its high strength and stability at the high temperatures reached due to combustion; porous CuO would sinter into dense solid spheres at such temperatures.)

Catalytic combustor



Sphere cross-section



Because the spheres are a lot smaller than the reactor, you can treat this as a homogeneous chemical reaction throughout a porous solid. Assume for this problem that CO is the limiting reagent, and the rate of reaction is proportional to its concentration with "homogeneous" rate constant k, so $G_{CO} = -kC_{CO}$. And assume that the spheres take up 60% of the reactor volume, and are very porous but with small channels allowing very little flow.

(a) Estimate the hydraulic radius and low-velocity permability $\mathcal{P}$ of a packed bed of spheres with 2 mm diameter with solid volume fraction 0.6 using the tube bundle approximation. (10)

(b) The actual permeability as measured by flowing water slowly through the device ends up being 10% higher than the value calculated in part 3a. Give a reason why this might happen here. (7)

(c) Using the tube bundle model of flow through this packed bed of spheres, and based on what you know of average and maximum flow velocities in a tube, sketch the concentration at the outlet vs. time of an inert tracer injected at time $t = 0$. Assume that the longitudinal mixing due to nonuniform velocity is much larger than due to diffusion, in other words, that the molecular diffusivity D is approximately zero. (10)

(d) Do you think this reactor will behave more like plug flow or perfect mixing? Explain your answer. (8)