CHME420
Winter 2016
Exam 3
3/17/16
Time Limit: 125 Minutes

Name (Print): ______________________

This exam contains 9 pages and 4 problems. Check for missing pages.

The exam contains closed book and open book sections. Complete the closed book section and exchange it for the open book section with your instructor. No cell phone use allowed during the exam.

You are required to show your work on each problem. The following rules apply:

- **Read the problem statements carefully**. Do what is requested in each problem. Show your work at every step to communicate your knowledge and thinking process.
- **Organize your work** neatly and coherently in the space provided. Scattered work without a clear order and difficult to understand will receive very little credit.
- **Mysterious or unsupported answers will not receive full credit**. A correct answer that is unsupported by calculations or explanation, will receive no credit; an incorrect answer supported by substantially correct calculations and explanations might still receive substantial partial credit. A correct answer accompanied randomly by an incorrect one will undergo a deduction.
- If you need more space, request extra blank pages from the instructor. Label each additional blank page with your name, the problem number, and the page number for that particular problem. Place your additional pages in the right order and staple them together.

Do not write in this table:

Question	Points	Bonus Points	Score
1	30	0	
2	25	3	
3	25	0	
4	20	3	
Total:	100	6	

Closed book

1. (30 points) Answer the following questions using words and equations if necessary:

   (a) (5 points) You are a newly minted Kettering chemical engineer that just started a very nice job. A fellow newbie gets assigned a mass transport problem in which they have to sort out the consumption rate of species A on a catalytic surface (heterogeneous catalysis). Species A is found in an equimolar mixture of species A, B, C, and D. They show you the following equation for the combined flux and claim they have found a solution with it:

   $$N_{Az} = -cD_A \frac{dx_A}{dz} + x_A \left(N_{Az} + N_{Bz}\right)$$

   Is there a problem with their approach? Explain.

   (b) (5 points) Flue gas is primarily H_2O and CO_2 with traces (parts per million) of CO, NO, NO_2, and SO_2. You are interested in the transport of SO_2 to a catalyst surface. State a simplification you can make that enables the use of the approach to mass transport problems that we learned in class. Explain when it is valid.

   (c) (5 points) You are the lead engineer of a new catalytic process in your company. A report states that the Thiele modulus at the current operating condition is 0.01. Is the process diffusion or reaction controlled? Remember that the Thiele modulus is defined as:

   $$\phi = \frac{\text{reaction rate}}{\text{diffusion rate}}$$

   You want to speed up the process. Would you focus on improving the catalytic activity or speeding up the diffusivity of the reactant?

(d) (5 points) A three component liquid mixture with molar fractions x_a, x_b, and x_c is flowing in a pipe. There are significant concentration gradients in the solution and so each species has a velocity v_a, v_b, and v_c. Write an expression for the mol average velocity (v^*). Is the equation you wrote a vector or a scalar equation?

(e) (5 points) Explain what happens in equimolar counter-diffusion. In what type of situations do we observe this phenomena?

(f) (5 points) You are running an experiment to measure the diffusivity of the vapor of A in air. To accomplish this, you have an amount of liquid A in a tube and you measure the amount of liquid A remaining as a function of time. Why is it likely that the quasi-steady approximation is a good one in this situation?

Open Book

2. (25 points) A falling film of liquid with density $1000\,\mathrm{kg/m^3}$ and viscosity $1.0 \times 10^{-3}\,\mathrm{Pa \cdot s}$ falls vertical over a biological compressed solid from which valuable compound A needs to be extracted (§18.6). The solubility of A in the liquid is $1\,\mathrm{mol/m^3}$ and its diffusivity in the liquid is $1.0 \times 10^{-6}\,\mathrm{m^2/s}$. The thickness of the liquid film is 1.0 mm. Answer the following questions:

   (a) (5 points) What is the flux of A at the end of a piece of compressed solid 1.0 m in Length?

   (b) (5 points) What is the total molar flow of A if the piece of solid in Part (a) is 0.2 m in Width?

   (c) (5 points) The penetration depth (λ) is defined as the value of y at which C_A reaches 1% of C_{A0}. The right hand side of equation (18.6-8) is equal to 0.01 when $\boldsymbol{\eta} = \mathbf{1.6}$. What is the penetration depth of A at the bottom of the solid piece in Part (a)?

   (d) (5 points) Given your answer to Part (c), is our model valid for the current situation? If you could not solve Part (c) assume $\lambda = 1.7\,\mathrm{mm}$ to answer this question.

   (e) (5 points) What is the maximum Length of solid for which the "short contact time" model is valid?

   (f) (3 points (bonus)) Suggest a feasible strategy to improve the rate of extraction of A.

3. (25 points) A sphere of solid A is suspended in liquid B. A is only slightly soluble in B (C_{A0}) and it undergoes a homogeneous, first order reaction with B (rate constant $k_1^{'''}$). Do the following:

   (a) (8 points) Perform a shell balance to obtain a differential equation relating the concentration of A and the radial coordinate r. Do not attempt to solve the differential equation.

   (b) (6 points) Make the differential equation and boundary conditions non-dimensional by using the following definitions: $\breve{r} = r/R$ and $\Theta = C_A/C_{A0}$. The boundary conditions are:

   $$C_A = C_{A0} \quad \text{at} \quad r = R$$
   $$C_A = 0 \quad \text{at} \quad r \to \infty$$

   (c) (5 points) The solution to the differential equation and boundary conditions is:

   $$\frac{C_A}{C_{A0}} = \frac{R}{r}\frac{e^{-br/R}}{e^{-b}}$$

   where $b^2 = k_1^{'''} R^2/D_{AB}$. Derive an expression of the flux of A in the radial direction (N_{Ar}).

   (d) (6 points) It is of interest to estimate the time required for the sphere of A to dissolve completely. Perform a quasi-steady state analysis by relating the rate of dissolution of A to your answer in Part (c). The molar concentration of pure A in solid form is $C_S^{(A)}$. Do not attempt to solve the differential equation. If you could not get the answer to Part (c) use a general expression for N_{Ar} (for example, its mathematical definition).

4. (20 points) A dilute solution of A (with concentration C_{Ai}) passes through a **planar**, catalytic membrane of area S. A reacts within the membrane at a rate per unit volume of $R_A = -k_1^{''} a C_A$ and has an effective diffusivity D_A. The concentration of A at the outlet of the membrane is C_{Ao} and the thickness of the membrane is H. Neglecting any convective terms do the following:

   (a) (3 points) Make a drawing of the membrane that includes the boundaries and a well specified reference frame.

   (b) (3 points) Write the boundary conditions for this problem. Make sure they are consistent with your drawing.

   (c) (6 points) Derive a differential equation relating the concentration of A to the appropriate spatial variable. Do not attempt to solve it.

   (d) (4 points) The solution to the differential equation is:

   $$C_A = C_1 \sinh(N x_1) + C_2 \cosh(N x_1)$$

   where $N^2 = a k_1^{''} / D_A$ and x_1 is the relevant coordinate in your drawing and boundary conditions. Solve for the integration constants.

   (e) (4 points) What is the likely physical significance of a. What is the physical interpretation of D_A?

   (f) (3 points (bonus)) Write an expression for the total amount of A reacted in the membrane (HINT: Think macroscopically).