ChBE 3210A
Transport Processes II
Spring 2014

Exam #2
April 3, 2014
6:00-8:00pm

The exam consists of two parts. The first part is closed book, closed notes, no calculator. After 30 minutes, the first answer sheets will be collected. At that point, books, notes and calculators may be used for the second part of the exam.

The use of wireless devices (*e.g.*, cell phones, IR transmitters/receivers) is not permitted at any time during the exam.

To receive full credit on each problem, it is advised to start with the (appropriate) full form of the balance equation(s) needed to solve the problem. Label all variables and equations. Include a brief word description to explain each step in your problem, stating *all assumptions.* Present your solution clearly. Numerical answers without units or explanations will not receive credit.

NAME: ________________________________

The work presented here is solely my own. I did not receive any assistance nor did I assist other students during the exam. I pledge that I have abided by the above rules and the Georgia Tech Student Code of Conduct.

Signed: ________________________________

Problem I	**_____/14**
Problem II	**_____/11**
Problem III	**_____/33**
Problem IV	**_____/27**
Problem V	**_____/15**
Total	**_____/100**

Problem I (14 points)

Answer the following TRUE/FALSE questions by circling the correct answer. If you want to change your answer, scratch out the old answer, rewrite "TRUE / FALSE" and circle the correct answer. Make sure that it is clear to which question your answer belongs.

Each correct answer is worth 2 points, leaving the question blank yields no points and incorrect answers lead to a penalty of -1 point.

A/ A cylindrical Arnold diffusion cell is partially filled with a volatile pure liquid A. The top of the tube is exposed to a continuous flow of inert, insoluble carrier gas B. At (pseudo) steady state, the molecular transport of A in the Arnold cell can be described as equimolar counter-diffusion.

TRUE / FALSE

B/ If the molecular flux of species A is zero ($\mathbf{N}_A = 0$), molecules of A are not moving relative to the lab framework.

TRUE / FALSE

C/ In air, the mole fraction of oxygen is lower than the weight fraction..

TRUE / FALSE

D/ If the Biot number for mass transfer of species A from a gas mixture into a solid flat plate of thickness 2L ($Bi_m = k_c \cdot L/D_{AB}$) is much greater than one, the mass transfer resistance of A outside the plate is negligible.

TRUE / FALSE

E/ Liquid A is evaporating from a cylindrical surface into a stagnant bulk gas B; once steady state is achieved, the mass flux $n_{A,r}$ increases with increasing distance from the surface.

TRUE / FALSE

F/ If Sc = 1, the thicknesses of the concentration boundary layer, δ_c, and thermal boundary layer, δ_{th}, must be equal.

TRUE / FALSE

G/ For equimolar counter-diffusion in a binary mixture of A and B, $\mathbf{J}_A = \mathbf{N}_A$.

TRUE / FALSE

Problem II (11 points)

A/ A wet, rectangular piece of cloth (4 by 8 inches) is placed on a flat table surface and dry air (5) is blown parallel to the tabletop surface under laminar flow conditions in order to dry the cloth.

i) If your objective is to minimize drying time, what are the optimal location and orientation of the cloth? Should it be placed close to or far away from the table edge that faces the air flow? How should the cloth be oriented relative to the air flow? Define the ideal placement by providing a top-down view of the cloth on the table top and briefly explain your answer.

ii) Which part of the cloth will dry first? Indicate this in the sketch provided above and explain your answer.

B/ Steel is hardened through a process called carburization: at a very high temperature (2) (~ 1000 ºC) the steel is exposed to a carbon-containing gas stream that creates a sudden jump in carbon concentration at the steel surface. Diffusion then transports the carbon into the steel, creating a layer with increased hardness once the steel is cooled down again. For hardening, it is generally not necessary to carburize the entire bulk steel object; it is usually sufficient to only change the hardness of the surface layer.

If the diffusion coefficient of carbon in steel at 1000 ºC is $3{\cdot}10^{-7}$ cm^2/s, estimate the thickness of the hardened layer that is created after exposing a thick steel plate to the high-carbon gas stream for 10 hours..

Problem II (continued)

C/ Pressure-treated wood can create toxicity for aquatic life. If the wood is immersed in water
(4) for a long time, arsenic can leach from the wood into the surrounding water. Because of the neurotoxicity of arsenic, this can create serious environmental concerns.

For a cylindrical pressure-treated wood pole (radius *R*), sketch in a single graph the concentration of arsenic as a function of time for three locations in the pole after submersion of the pole into water (*t* = 0 marking the moment of submersion):

i) at the center of the pole
ii) halfway between the center and the surface
iii) at the outer surface of the wood

Clearly mark the different curves in your graph.

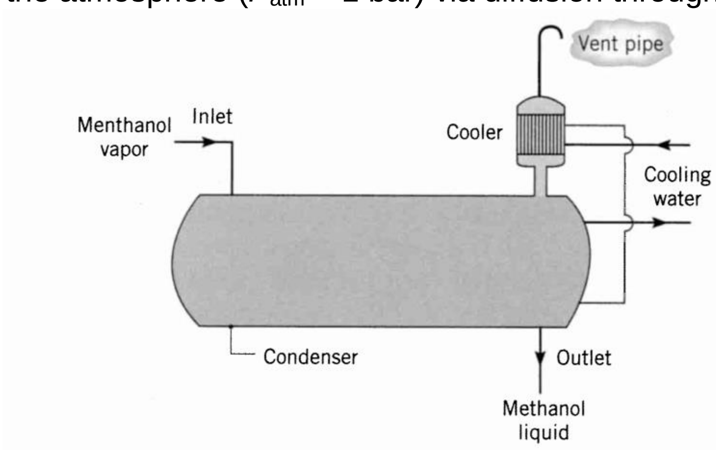
Assume that the initial arsenic concentration in the pole is uniform, that the solubility of arsenic in the water is much greater than in the wood, and that the surrounding body of water is large compared to the volume of the pole.

As usual, *briefly list key features of your graph to receive full credit*.

PART II **Name:** ____________________

Problem III: Methanol venting from condenser unit (33 points)

In a methanol distillation system, a condenser is used to liquefy methanol vapor (see figure below). For safety reasons, the tank has a vent pipe to the atmosphere to control the pressure inside the tank. To minimize the losses of methanol (molecular weight 32 g/mol), a small cooler is installed between the condenser and the vent pipe. The focus of this problem is the methanol loss from the cooler to the atmosphere (P_{atm} = 1 bar) via diffusion through the vent pipe.



The cooler, which operates at 20ºC, contains liquid methanol and saturated methanol vapor in air; the total vapor volume in the cooler is 5 liter and the saturated partial pressure of methanol is 0.15 bar. The vent pipe has an internal diameter d = 4 cm and length L = 50 cm; the entire vent pipe is also at 20ºC.

A/ For the rest of this problem, you may assume that the air in the vent pipe is stagnant.
(2) Explain briefly whether you think this is reasonable or not.

B/ In laboratory experiments, it was found that the diffusion coefficient of air in a saturated
(4) air-methanol mixture at 30ºC and 1 bar is $0.14 \cdot 10^{-4}$ m^2/s.
Estimate the diffusion coefficient of methanol in the vent pipe.

C/ Starting from Fick's rate equation and the general differential equation for mass transfer,
(12) derive an expression (in terms of known parameters) for the molar flux of methanol at the outlet of the vent pipe under steady state conditions.
Do not use numerical values for any of the parameters yet in this part!!!

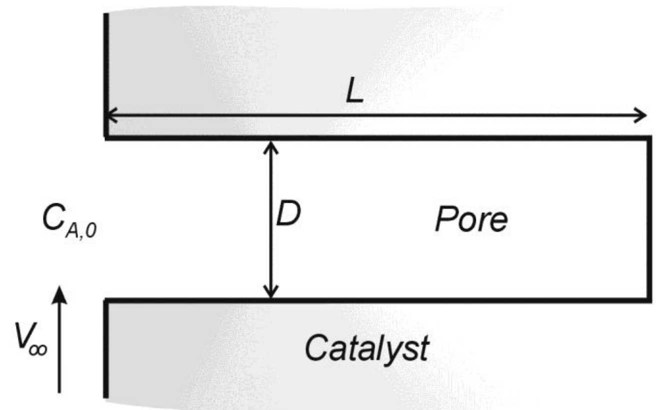
D/ Calculate the weekly losses of methanol through the vent pipe (in moles/week).
(7)

E/ Occasionally, the entire volume of vapor in the cooler (5 liter) is expelled rapidly due to
(4) sudden variations in operating conditions of the distillation process. How many times per week is this allowed to happen, if additional methanol losses from such expulsions cannot be greater than the losses via diffusion through the vent pipe?

F/ During annual maintenance, the vent pipe must be replaced because of corrosion. The
(4) process engineer in charge of this repair can only find pipe stock with an internal diameter of 6 cm. What is the minimum length for the replacement vent pipe if EPA regulations require that the overall methanol losses through diffusion cannot increase after the repair?

Problem IV: Porous Catalysts (27 points)

To enhance the effective surface area -and hence the chemical reaction rate-, catalytic surfaces are often porous. The pores in such materials might be visualized as cylindrical, with diameter D and length L (see figure below). Typically, these pores are narrow: $L >> D$.



Consider a gaseous mixture of species A and inert carrier B, from which A is consumed according to the following chemical reaction at the impermeable pore walls:

$$2\,A\,(g) \rightarrow C\,(g) + D\,(g)$$

The reaction is known to be first order with respect to the concentration of A and the reaction rate per unit surface area may be expressed as $k_1 \cdot C_A$, where k_1 (m/s) is the reaction rate constant and C_A (mol/m^3) the local molar concentration of A.

The concentration of A at the pore mouth, $C_{A,0}$, is kept constant by a gas flow across the pore entrance; this flow also sweeps away the reaction products, $C_{C,0} = C_{D,0} = 0$. The pressure and temperature inside the pore are constant.

A/ Although cylindrical pores with reactive side walls inherently create a two-dimensional (3) diffusion problem with $C_A(r,z)$, it is actually reasonable to treat this process as one-dimensional diffusion with $C_A(z)$, if the pore is narrow ($L >> D$). Explain why this is reasonable.

B/ Define an appropriate coordinate system and simplify Fick's rate equation for species A (7) in the pore at steady state.

C/ The general differential equation for mass transfer is not applicable in this case. Why not? (4) Show that its application leads to an unacceptable result.

D/ Use a mass balance on a differential control volume to derive that the following equation (7) applies inside the pore:

$$\frac{dN_{A,z}}{dz} = -\frac{4k_1}{D} C_A$$

E/ Derive the differential equation for C_A and provide the boundary conditions that should be (6) used to solve the concentration profile $C_A(z)$. *Do not actually solve the differential equation!!!*

Problem V: Leaching of gold from ore (15 points)

The leaching of valuable minerals from ores is a common process in the field of hydrometallurgy.

The extraction of gold from finely ground ore particles with a cyanide solution is a typical example. Assume that the solubility limit of gold in a cyanide solution is much higher than its concentration in the ore particles. Also assume that the reactor in which the extraction is performed is well-mixed, so that the gold concentration in the liquid phase is constant.

A/ (7) If the ore particles can be treated as spheres with a diameter of 4 mm, and the diffusivity of gold in the particles is 10^{-9} m^2/s, estimate how long it will take before the gold concentration in the center of the ore particles drops to 5% of its original value?

B/ (4) A greedy process operator wants to extract even more of the gold. By which factor must the residence time of ore particles in the reactor be increased to extract 99% of gold from the center of the particles?

C/ (4) Instead of increasing the residence time of particles in the reactor, which decreases production capacity, the plant supervisor proposes to grind the ore particles to a different diameter. What would have to be the new particle diameter to achieve the desired effect, *i.e.* 1% of gold remaining in the center of the ore particles without changing the residence time.