ChBE 3210A
Transport Processes II
Spring 2015

Exam #2
April 2, 2015
6:00-8:00pm

The exam consists of two parts. The first part is closed notes, no calculator. After 30 minutes, the first answer sheets (Problems I + II) will be collected. For the remainder of the exam, cheat sheet (one sided, 8.5 x 11”), hand-out and calculators may be used..

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 carefully. 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	**_____/16**
Problem II	**_____/14**
Problem III	**_____/32**
Problem IV	**_____/38**
Total	**_____/100**

Problem I: TRUE/FALSE (16 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.

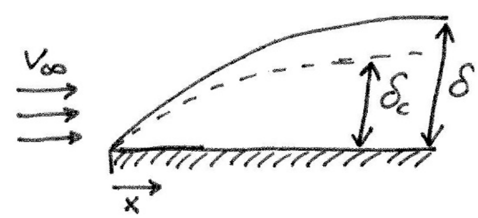
A/ On the surface of a solid catalyst, gas A is transformed into gas B according to the following reaction: A (g) → 2 B (g). If mass transfer to the catalyst surface is reaction-limited, the appropriate boundary condition is: $y_{A,surface} = 0$.

TRUE / FALSE

B/ The Schmidt number is the mass transfer equivalent of the Stanton number.

TRUE / FALSE

C/ The figure on the left shows the momentum and concentration boundary layer thickness as a function of location for laminar flow across a flat plate. It can be concluded that Sc > 1.



TRUE / FALSE

D/ The Chilton-Colburn analogy between heat and mass transfer, $j_D = j_H$, is not valid in the presence of form drag.

TRUE / FALSE

E/ The diffusion coefficient D_{AB} of molecule A in medium B increases with increasing temperature, regardless of whether B is a liquid or gas.

TRUE / FALSE

F/ For oxygen dissolved in water, the mass fraction of oxygen is always larger than the mole fraction of oxygen.

TRUE / FALSE

G/ The diffusion coefficient of oxygen in water will be higher than in maple syrup, if both fluids are at the same temperature.

TRUE / FALSE

H/ For laminar flow across a flat plate, both the convective heat and mass transfer coefficients between the plate and the bulk flow, resp. h and k_c, increase with and increasing distance from the leading edge of the plate.

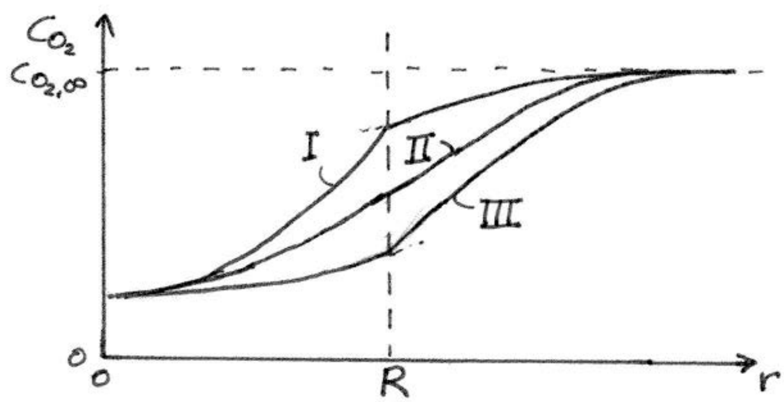
TRUE / FALSE

Problem II (14 points)

A/ During one of the in-class problem solving sessions, we discussed the oxygen concentration
(3) profile in and around a spherical microorganism (radius *R*) that consumes oxygen to sustain its metabolism. In class, we discussed two extreme cases: diffusion-limited and reaction-limited transport of oxygen from the bulk medium into the microorganism. In reality, however, neither of these cases is actually correct: <u>oxygen transport in and around microorganisms is neither diffusion- nor reaction-limited under steady-state conditions</u>.

The figure below shows three different potential concentration profiles for the "in between" scenario described above; $r = 0$ denotes the center of the organisms. Which of these three concentration profiles (I, II or III) is the most correct? Explain your answer.

You can assume that the oxygen solubility in the bulk medium and inside the microorganism is essentially the same. However, the oxygen diffusivity inside the microorganism is quite a bit lower ($D_{org} = 2.0 \cdot 10^{-9}$ m^2/s) than in the surrounding medium, which is essentially water ($D_{bulk} = 4.0 \cdot 10^{-9}$ m^2/s).



B/ In part A/, why is the oxygen diffusivity inside the microorganism quite a bit lower
(1) than in the surrounding medium?

<u>Problem II (continued)</u>

C/ When you buy a helium-filled Mylar balloon at the supermarket, the balloon will slowly
(2) deflate over time, because the helium slowly diffuses through the Mylar skin. Is it appropriate to describe the helium transport through the Mylar as "pseudo steady state"? Explain your answer.

D/ In one of the research labs on campus, a graduate student temporarily stores a toxic liquid in
(3) a plastic vial with wall thickness d = 1 mm. Because the toxic liquid is slightly soluble in the plastic, the vial does not provide safe permanent storage for this toxic liquid. The graduate student realizes the danger and closely monitors the vial; after one week, he detects the first traces of toxic material at the outer surface of the vial. Because he needs to keep his samples around for at least 4 weeks to complete the experimental studies, this leakage is problematic. The student decides to order new plastic vials of the same material, but with a thicker wall. What is the minimum wall thickness that he should consider in order to provide safe storage for 4 weeks? Explain your answer.

E/ Although there are four different ways to describe fluxes in mass transfer (***N***, ***n***, ***J*** and ***j***),
(2) almost all homework and exam problems in this course use ***N***. Explain <u>briefly</u> why there is such a preference for using ***N***.

Problem II (continued)

F/ Farmer Joe protects his crop by spraying insecticide every week. One day, the drum that (3) holds the concentrated aqueous insecticide solution overturns and spills onto a patch of the field. Because the soil is already saturated with water, insecticide enters the soil only via diffusion.

In a graph, sketch how the flux at which the insecticide enters the soil changes as a function of time (t = 0 is the moment of the spill). Draw the flux curve for two scenarios in the same graph: i) a cold day, and ii) a hot day.

To receive full credit, briefly explain key features of your graph, in particular the differences between the two cases.

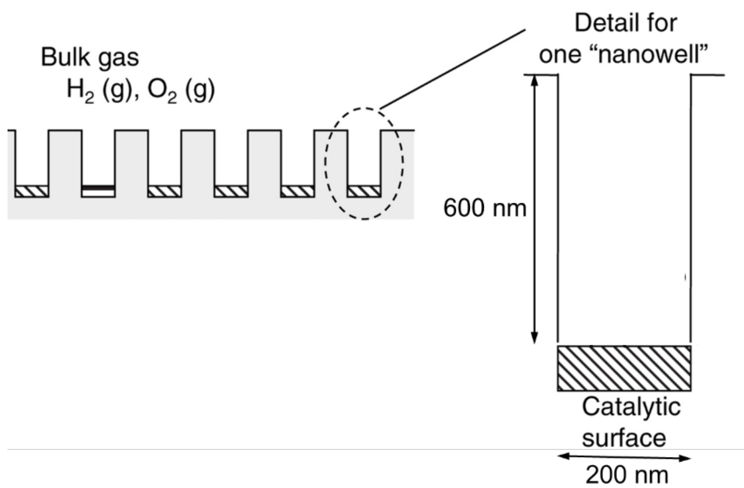
PART II **Name:** ____________________

Problem III: Nanostructured catalyst (32 points)

The figure below shows the design of a novel "nanostructured" catalyst surface for hydrogen conversion. The surface contains an array of cylindrical "nanowells" (diameter 200 nm and depth 600 nm; 1 nm = 10^{-9} m) with a catalytic coating at the bottom of each well, which is where the chemical reaction occurs: 2 H_2 (g) + O_2 (g) → 2 H_2O (g). The conversion reaction within the wells can be considered diffusion-limited.

Dry bulk gas flows across the top of the wells, so that the composition of the gas at the opening of the wells is kept constant (hydrogen mole fraction of 1% and oxygen mole fraction of 99%).

Assume isothermal (100°C) and isobaric (1.5 atm) system conditions; the process can also be considered steady-state.



A/ Estimate the diffusion coefficient of hydrogen in the nanowells. List and explain any
(6) assumptions you make.

B/ Simplify the general differential equation for mass transfer and Fick's rate equation for
(10) hydrogen transport in the nanowells. Clearly explain all your steps.

C/ Derive (*don't solve!*) the differential equation for the hydrogen concentration in the
(5) nanowells and provide boundary conditions that can be used to solve the equation.

D/ Determine the rate at which <u>water</u> is being generated (in mol/m^2·s) on the catalytic surface
(8) at the bottom of the wells.

E/ A process engineer suggests to raise the pressure in the system in order to increase the
(3) hydrogen conversion rate. By which factor will the hydrogen conversion rate change if the pressure is doubled to 3.0 atm? All other conditions are kept constant.

Problem IV: Removal of salt layer (38 points)

NOTE: Many parts of this problem can be solved independently!!!

During operation of a pipeline in a chemical plant, an undesirable salt layer has formed on the inner surface of the pipe (total length L_{tot} = 10 m, inner diameter d = 2.0 cm). This salt layer (thickness δ = 0.1 mm) must be removed during the annual plant maintenance. The salt has a known molecular weight M_w = 100 g/mol.

The plant engineers are considering two different approaches to remove the salt layer:

I) Batch process: fill the pipe with clean water, wait until the stagnant water is almost saturated with salt, replace the saturated water with fresh water, and repeat this process until all salt has been dissolved from the wall.

II) Continous process: flush the pipe with a continuous stream of clean water until the salt layer has been dissolved completely.

The solubility of the salt in water is 100 mol/m^3, and its density is ρ = 2500 kg/m^3, both at the relevant water temperature of 22°C (room temperature).

A/ How many moles of salt must be removed per meter of pipe?
(4)

For the remainder of this problem use 0.25 moles of salt per meter of pipe, if you did not find an answer for part A/.

B/ In literature, the diffusion coefficient for this salt in water is only provided at 60°C:
(4) $D = 2.4 \cdot 10^{-9}$ m^2/s. Calculate the value of D at 22°C.

C/ In the *batch process,* how long does it take for the salt concentration at the center of the
(9) pipe to reach 99% of the solubility limit each time after the pipe has been filled with clean water?

D/ How often must the *batch process* be repeated to dissolve the entire salt layer?
(4) How long will the entire cleaning operation take if the *batch process* is used?

E/ Give a suggestion on how to speed up the batch cleaning process. Explain your answer.
(2)

F/ For the *continuous process*, use analogies between mass and momentum transfer to
(6) estimate the convective mass transfer coefficient (k_c) from the salt layer to the water if the water flows through the pipe at an average velocity of 0.1 m/s.

For the remainder of this problem use $k_c = 6.0 \cdot 10^{-6}$ m/s, if you could not answer part F/.

G/ How long would it take to dissolve the entire salt layer via the *continuous process*?
(7)

H/ Give a disadvantage for each of the two processes.
(2)