ChBE 3210A
Transport Processes II
Spring 2015

Final Exam
Friday May 1, 2015
8:00 - 10:50am

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, a 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. 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 Honor Code.

Signed: _______________________________

Problem I	**_____/ 10**
Problem II	**_____/ 10**
Problem III	**_____/ 20**
Problem IV	**_____/ 20**
Problem V	**_____/ 18**
Problem VI	**_____/ 22**
Total	**_____/100**

Problem I (10 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 1 point, leaving the question blank yields no points and incorrect answers lead to a penalty of -0.5 point.

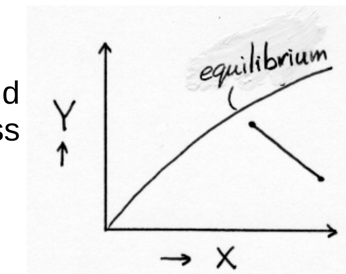
A/ If the molar flux of species A is zero ($\vec{\mathbf{N}}_A = 0$), individual molecules of A are not moving relative to the lab framework.

TRUE / FALSE

B/ The Chilton-Colburn analogy between convective momentum and mass transfer, $0.5 \cdot C_f = j_D$, can only be applied in the absence of form drag.

TRUE / FALSE

C/ The figure on the right shows the equilibrium and operating lines for a continuous contact tower in terms of solute-free gas and liquid stream compositions; it can be concluded from the graph that mass transfer in the tower occurs from the liquid to the gas phase in counter-current operation.



TRUE / FALSE

D/ In air at atmospheric conditions (1 atm, 20°C), the diffusion coefficient of ethane is larger than that of *n*-butane.

TRUE / FALSE

E/ A bubble column is used for stripping species A from a liquid waste stream into a gas stream; the total mass transfer rate (in mol/hr) of A from liquid to gas is independent of bubble size, provided that the total gas volume in the column (hold up) is kept the same.

TRUE / FALSE

F/ For flow along the length of a large cylinder (for example, the body of an airplane in flight) it is reasonable to use convective heat and mass transfer correlations for a flat plate.

TRUE / FALSE

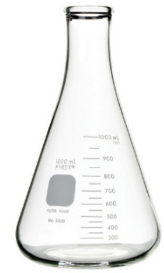
G/ A very small (<< 1) Biot modulus for mass transfer indicates that the diffusive mass transfer resistance inside an object is negligible compared to the convective mass transfer resistance between the surrounding fluid and the object.

TRUE / FALSE

H/ The Hatta number is a dimensionless group that compares the rate of a surface reaction in a medium to the diffusion coefficient of the limiting reactant in that medium.

TRUE / FALSE

Problem I *(continued)*



I/ The Erlenmeyer flask on the right is used for evaporation of ethanol, similar to the typical Arnold cell set-up: a small amount of pure ethanol is added to partially fill the flask and dry air is then blown across its opening. At (pseudo) steady state, the diffusive ethanol flux will be the same everywhere in the vapor phase inside the flask.

TRUE / FALSE

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

TRUE / FALSE

Problem II (10 points)

A/ Draw the temperature profile (*T* as a function of position along the tube) for a counter flow
(3) double pipe heat exchanger in which ethylene glycol is heated from 50°F to 93°F, using saturated steam that enters at 280°F and exits the heat exchanger as subcooled water at 190°F. List key features of your diagram for full credit.

B/ When you apply water and rubbing alcohol to your skin, you experience different
(2) temperature sensations, even if both liquids are taken from containers that are at room temperature. Which of these two liquids feels colder and why?

Problem II *(continued)*

C/ On cold winter days, a thin layer of ice sometimes forms on the inner surface of the
(3) windows in your house. Explain briefly why this phenomenon:

i) always occurs on the inner surface of the window (i.e. inside the house)

and

ii) is more likely to be observed near the bottom of the window than at the top.

D/ A slab of green gelatin gel is prepared by adding food colorant during its preparation
(2) process. The flat gel slab of thickness d = 10 mm is then immersed in a large bath of pure water, which is well-stirred and refreshed continuously. The gelatin slab is exposed to the water on all sides. Over time, the green food colorant leeches out of the gelatin gel slab.

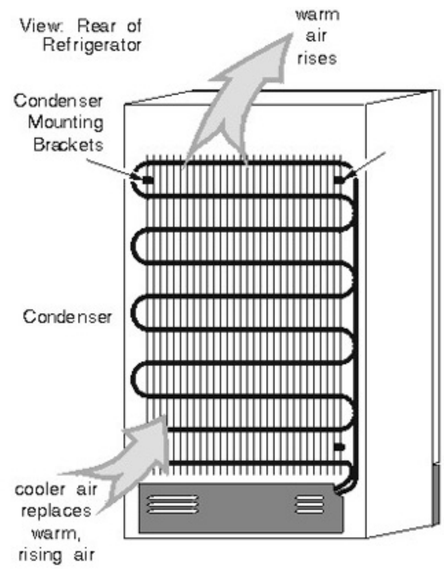
In a graph, sketch as a function of time the cumulative amount of food colorant that has leeched out of the gelatin slab. *List key features of your sketch to receive full credit.*

PART II **Name:** ____________________

Problem III: Refrigerator (20 points)

A refrigerator transfers heat to the surrounding air by pumping condensing refrigerant through a copper tube (outer diameter 10 mm, wall thickness 0.5 mm, thermal conductivity 300 W/(m·K)), which winds along the back of the refrigerator and is exposed to the surrounding air (see figure on the right). The refrigerant (R-113) is condensing at 321 K along the length of the copper tube with a convective heat transfer coefficient of 2000 W/(m^2·K). See hand-out for R-113 physical properties.

The room temperature is 20°C and when the air temperature is measured near the top of the condenser coil, where it is warmest, it is found to be 40°C. According to the manufacturer of the copper tubing, the convective heat transfer coefficient on the air side is 20 W/(m^2·K).



A/ If the required cooling rate of the refrigerator is 250 W, calculated the minimum flow
(4) rate (in kg/hr) of saturated refrigerant that must be pumped through the tube. What are the corresponding average velocities in the tube (in m/s) if the refrigerant is: *a)* 100% saturated vapor, or *b)* 100% saturated liquid?

B/ Show with a simple calculation that the thermal resistance of the copper tube is negligible.
(3)

C/ Calculate the length of the copper tube that is needed to achieve the required cooling rate,
(7) assuming that there is no need to use a correction factor for this system.

D/ You are rather skeptical about the accuracy of the conveniently nice value of 20 W/(m^2·K)
(3) for the external heat transfer coefficient and want to get a better estimate for this value yourself. After a 15 minute Google search, you still cannot find a correlation function for refrigerator coils. Therefore, you will have to use one of the correlations in your hand-out. Explain which correlation you would pick for this case and at which temperature you would evaluate air properties. **Do not attempt to actually calculate *h*!!!!**

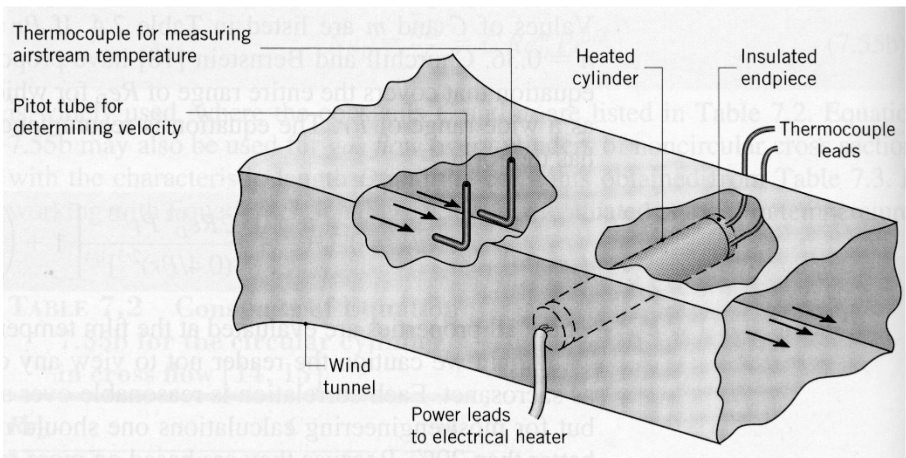
E/ A common problem with refrigerators is dust build-up on the coil, which can be accounted for
(3) as “fouling”. Calculate the value of the fouling factor for which the performance of the refrigerator (as measured by cooling rate) would decrease by 10%.

BONUS QUESTION:
F/ The refrigerator manual specifies that the back of the refrigerator must be kept away from the
(2) wall by a minimum distance. Explain why this installation guideline exists.

Problem IV: Convection in wind tunnel (20 points)

A small wind tunnel set-up is used to test correlation functions for heat and mass transfer. The figure below shows the experiment: a horizontal cylinder is oriented perpendicular to the air flow, and sensors are placed upstream of the cylinder to measure the velocity and temperature of the airstream.

The cylinder itself has a diameter of 1.5 cm and length of 0.50 m, and contains an electric heating element that can be used to heat the cylinder. The uniform surface temperature of the cylinder, which is made of a thermally conductive material, can also be measured with a thermocouple.



In the first set of experiments, the power consumption of the electric heater is 250 W. Some of this energy is lost through radiation and via conduction from the ends of the cylinder to the tunnel wall, which are imperfectly insulated; these cumulative energy losses are estimated to account for 10% of the supplied electrical power.

A/ With an airstream velocity of 10 m/s and air temperature of 25°C, it is found that the surface (5) temperature of the cylinder is 130°C. Determine the <u>average</u> convective heat transfer coefficient based on this measurement.

B/ Compare this experimental result with the convective heat transfer coefficient that can be (5) calculated from correlations.

In a second set of experiments, the validity of the Chilton-Colburn analogy is tested. In order to do so, the <u>heater element is disconnected</u> and the cylinder is wrapped with a layer of fabric that is kept moist during the experiment. The thickness of the fabric can be neglected, so that the cylinder diameter remains 1.5 cm. The airstream (again at 10 m/s and 25°C) has a relative humidity of 30%. At steady state, the surface temperature of the cylinder is found to be 5.0°C.

C/ What should the surface temperature of the cylinder be if the Chilton-Colburn correlation (10) was perfectly accurate? You may use a saturated vapor pressure for water of 0.015 atm, latent heat of water evaporation of 2500 kJ/kg, and Sc = 0.6.

Problem V: Absorption column (18 points)

Waste gas from a reactor contains 5 mol% ethylene oxide (EO) and 10 mol% CO_2, the remaining 85 mol% being nitrogen. For economical and environmental reasons, it is desirable to recover the EO from the gas stream. The EO recovery is achieved by scrubbing the waste gas with water in a countercurrent absorption tower.

The countercurrent absorber operates at 20 atm and 30°C, using pure water as liquid feed. The total gas feed rate is 3 mol/s and the absorber is operated at $L_S/G_S = 3.0$. Under these conditions, 98% of the EO in the gas stream is recovered; the absorption of nitrogen and carbon dioxide into the water stream can be neglected.

A/ Calculate the molar fractions of ethylene oxide in the gas and liquid outlet streams
(5) and the molar flow rate of water.

There is no equilibrium data available for EO and water at 20 atm and 30°C, but it is known that a modified Henry's law describes the solution equilibrium under these process conditions quite well:

$$y_{EO}^* = C \cdot x_{EO}$$

In an attempt to find the equilibrium constant C, the process operator gradually reduces the flow rate of pure water into the column, while keeping the gas flow rate and gas feed composition the same.

B/ What happens (qualitatively) to the EO concentrations in the gas and liquid outlet streams
(2) when L_S/G_S is gradually decreased? Explain your answers briefly.

When L_S/G_S reaches 1.5, the liquid outlet concentration suddenly stops changing. When that happens, the EO concentration in the gas outlet is found to be 1%.

C/ Based on this information, determine the equilibrium constant C.
(6)

***If you did not find an answer for C/, you may use C* = 1.5.**

D/ At the top of the tower, near the water inlet, 25% of the mass transfer resistance is in
(5) the liquid phase. Determine the concentration of ethylene oxide on the liquid side of the the gas-water interface ($x_{EO,i}$) near the water inlet for the operating conditions used in part A/ ($L_S/G_S = 3.0$).

Problem VI: Controlled evaporation through ceramic tubes (22 points)

A porous, thick-walled ceramic tube (inner diameter D_i = 1 cm; outer diameter D_o = 2 cm) is utilized to introduce species A into a gas stream at a controlled rate via evaporation.

The outer surface of the ceramic tube is immersed in pure liquid A. Liquid A cannot enter the porous ceramic, but evaporates at the ceramic-liquid interface and diffuses in gaseous form through the porous ceramic wall. The effective diffusion coefficient of A in the ceramic tube is $D_{A,wall} = 10^{-3}$ cm^2/s. When A reaches the inner surface of the ceramic tube, it is swept up by a flowing stream of carrier gas B, which moves through the core of the tube at an average velocity of 1 cm/s.

The carrier gas stream is at 298 K and 1 atm, and its physical properties can be approximated as those of air. Although the saturated vapor concentration of A, $c_{A,sat}$, is unknown under these conditions, experiments have shown that the saturated vapor *pressure* $p_{A,sat}$ does not exceed 0.02 atm.

The concentration of A in the carrier gas stream is negligible at the entrance of the ceramic tube, but gradually changes along its length. You may assume that the concentration of A is constant <u>in the gas stream inside the tube</u>, *i.e.* across the cross-section of the hollow core of the tube.

A/ (6) Define a control volume and coordinate system, and then simplify the general differential equation for mass transfer and Fick's rate equation for the mass transport of A through the ceramic wall. Assume steady state.

B/ (6) Use the differential equations from part A/ to derive an expression for the *local molar flux* of A at the inner surface of the ceramic wall as a function of the *local molar concentration* of A inside the tube, $c_A(z)$.

If you did not find an answer in part B/, you can use the expression:

$$|N_A|_{inner\ wall}(z) = \alpha\cdot(c_{A,sat} - c_A(z))$$

where α = 3.0·10^{-5} m/s is a constant that depends on the tube dimensions and other physical parameters.

C/ (7) Calculate the length L of ceramic tube if the concentration of A at the tube exit must reach 50% of its saturated value: $c_A(L) = 0.5\cdot c_{A,sat}$.

D/ (3) You have serious doubts about the assumption that the concentration of A is constant *across the cross-section of the tube core* at every location along the tube. Assuming that you know the value of α in the equation above, how would you prove/disprove this assumption. You don't have to do any actual calculations, but must describe your strategy and potential conclusion in sufficient detail for someone to do the work.