

Name: Solin

Final Exam

**ChBE 2100A
Chemical Process Principles**

Monday, July 27, 2015

The exam consists of 5 problems worth the points indicated (68 points total). Please write your final answers in the space provided in the specified units, or box them if no space provided. Be sure to state all assumptions made for full credit. If you need additional space, use blank sheets and staple them to the end of the exam with your work clearly labeled with the question number and letter and your name. Use the accompanying packets for equations/notes and unit conversions/data from tables (includes entire Felder & Rousseau appendix except B.6 Steam Tables listed by pressure). Please don't write on the packets and return them with your exam. Good luck!

Honor Code:

I commit to uphold the ideals of honor and integrity by refusing to betray the trust bestowed upon me as a member of the Georgia Tech community.

Signature

#1 (4 points)

a. Explain why heat is released and absorbed when reactions occur.

Energy is ^(required) absorbed when bonds break & energy is released when bonds form. Both of these happen during a reaction but the net release or absorption depends on which of these quantities is greater.

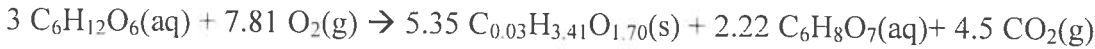
b. Humid air (30°C) has a dew point of 27°C. Is the relative humidity at, above or below 100%? Explain why by defining the dew point.

Below 100%. If the air was saturated (100% humidity), then the temperature would be equal to the dew point temperature.

Since water condenses upon cooling + $T > T_{\text{dew point}}$, it is below 100% (as opposed to above, also supersaturated air >100% generally does not exist). The dew point is the temp at which the 1st drop of water forms as you cool air at constant P.

#2 (26 points) 11 + 15

Citric acid ($C_6H_8O_7$) is used in the preparation of many foods, pharmaceuticals, soft drinks, and personal-care products. Although it can be harvested from citrus juice, modern commercial production uses fermentation of sugars by the fungus *Aspergillus niger*. A continuous fermentation process is used to produce citric acid (as well as biomass ($C_{0.03}H_{3.41}O_{1.70}$) and carbon dioxide), followed by filtration to remove the biomass, and crystallization to collect the citric acid from solution. A simplified version of the chemical reaction is shown below. Do not be alarmed that the numbers are not whole numbers, you treat them the way you treat any (whole) numbers in a chemical reaction. This is typical of bioprocesses.



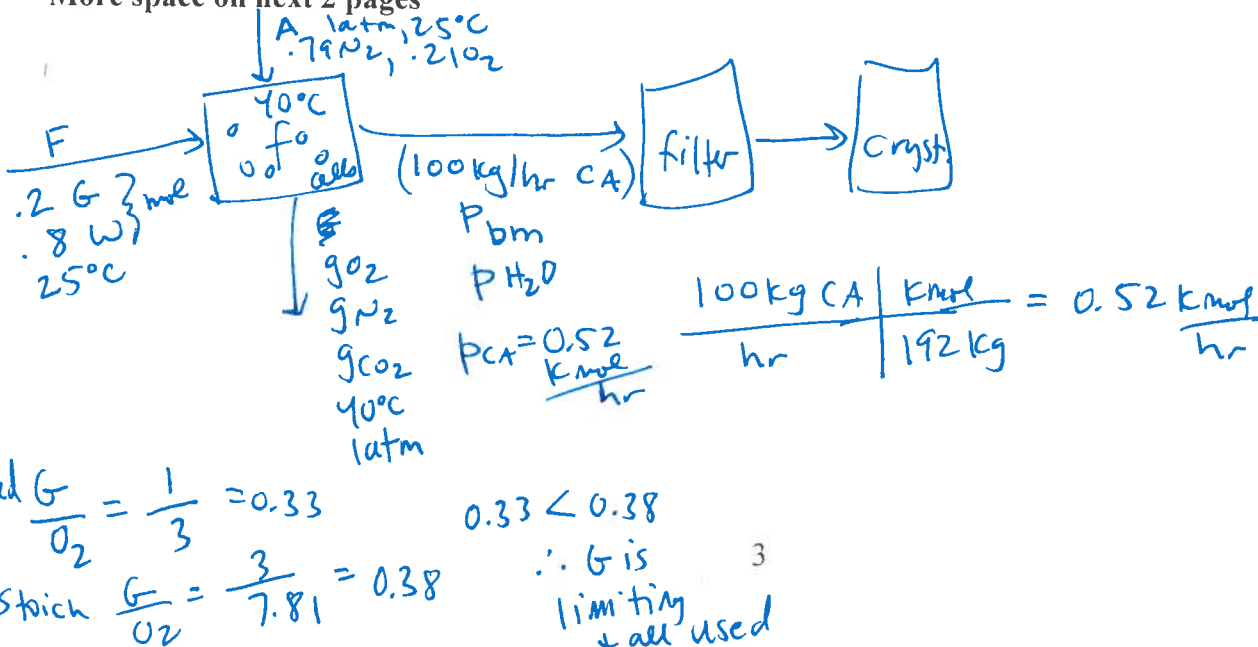
The feed to the fermenter is a $25^\circ C$ aqueous solution containing 20mol% glucose ($C_6H_{12}O_6$) and the rest water. Also added to the fermenter is an air stream at 1 atm, $25^\circ C$ that provides a molar flow rate of oxygen three times that of glucose. The cells are already in the fermenter, they are immobilized there and do not enter or exit (like a catalyst). All of the limiting reactant is consumed. The fermenter operates at $40^\circ C$, and the two streams that leave the fermenter are also at that temperature. The CO_2 formed by fermentation exits with the remaining gases in the gas exit stream (at 1 atm). All the other reaction products exit in the liquid stream, which contains 100 kg/hr citric acid. Any unreacted reactants or inerts remain in the same phase that they entered in (i.e. all water remains in liquid stream, all N_2 remains in gas stream) since the components are not in the reactor long enough to achieve equilibrium or measureable transfer between gas and liquid phases. The liquid exit stream is sent through a filter which removes all the cell mass produced in the reaction, and the remaining liquid (still at $40^\circ C$) goes to the crystallizer. Molecular weights and enthalpy information for all species not in the appendix is given below. You may just use the "a" term for heat capacities. The heat capacity of biomass can be approximated as 2 kJ/kg $^\circ C$.

Calculate for this process:

- a. Flow rate of air required in m^3/hr . 241 m^3/hr
 b. Heat added/removed (specify which) to/from the reactor in kJ/hr. -561,078 kJ/hr

Species	MW (g/mol)	$\Delta \hat{H}_f^\circ$ (kJ/mol)	$\Delta \hat{H}_s^\circ$ (kJ/mol) (for all r values)
glucose (s)	180	-1006.8	+9.9
citric acid (s)	192	-1543.8	+22.6
biomass (s)	24.6	-59.9	n/a

More space on next 2 pages



Extent of rxn: out = in + ξ

$$\text{inerts: } .8F = p_{H_2O} = .8(3.45) = 2.76 \text{ kmol/hr} \quad (5)$$

$$.79A = g_{N_2}$$

$$G: O = .2F - 3\xi \quad F = \frac{3\xi}{.2} = 3.45 \text{ kmol/hr} \quad (4)$$

$$O_2: g_{O_2} = .21A - 7.81\xi = .21(9.86) - 7.81(0.23) = 0.27 \frac{\text{kmol}}{\text{hr}} \quad (7)$$

$$CA: p_{CA} = 0 + 2.22\xi \rightarrow \xi = 0.23 \text{ kmol/hr} \quad (6)$$

$$BM: p_{BM} = 0 + 5.35\xi = 1.23 \text{ kmol/hr} \quad (2)$$

$$CO_2: g_{CO_2} = 0 + 4.5\xi = 1.04 \text{ kmol/hr} \quad (3)$$

$$\text{extra info: } \frac{G}{O_2} = \frac{.2F}{.21A} = \frac{1}{3} \rightarrow .2F(3) = .21A \quad A = \frac{.2(3)}{.21} F = 9.86 \frac{\text{kmol}}{\text{hr}} \quad (8)$$

Air entering is ideal gas

$$\dot{V} = \frac{nRT}{P} = \frac{9.86 \frac{\text{kmol}}{\text{hr}} (25+273K) (0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot K} | \frac{1000 \text{ mol}}{1 \text{ kmol}} | \frac{1 \text{ m}^3}{1000 \text{ L}})}{1 \text{ atm}}$$

$$\dot{V} = 241 \text{ m}^3/\text{hr}$$

Ebal: open, steadystate, thermal terms dominate (reaction, ΔT)

$$\Delta \dot{H} + \Delta \dot{E}_K + \Delta \dot{E}_P = \dot{Q} - \dot{W}_s$$

negligible
compared to thermal
termsno
moving
parts

Pick heat of rxn method

Refs: Glu(aq), $O_2(g)$, BM(s), CA(aq), $CO_2(g)$, $N_2(g)$ all at 25°C , 1 atm

$$\Delta \dot{H}_r = 5.35 \Delta \hat{H}_f^\circ \text{ biomass(s)} + 2.22 \Delta \hat{H}_f^\circ \text{ CA(aq)} + 4.5 \Delta \hat{H}_f^\circ \text{ CO}_2(g) - 3 \Delta \hat{H}_f^\circ \text{ glu(aq)} - 7.81 \Delta \hat{H}_f^\circ \text{ O}_2(g)$$

$$\Delta \hat{H}_f^\circ \text{ CA(aq)} = \Delta \hat{H}_f^\circ \text{ CA(s)} + \Delta \hat{H}_s^\circ = -1543.8 + 22.6 = -1521.2 \text{ kJ/mol CA}$$

$$\Delta \hat{H}_f^\circ \text{ glu(aq)} = \Delta \hat{H}_f^\circ \text{ glu(s)} + \Delta \hat{H}_s^\circ = -1006.8 + 9.9 = -996.9 \text{ kJ/mol glu}$$

$$\Delta \dot{H}_r = 5.35(-59.9) + 2.22(-1521.2) + 4.5(-393.5) - 3(-996.9) - 7.81(0) = -2477.6 \text{ kJ/mol}$$

species	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}
Glu (aq)	.2 (3.45) 0.69 kmol/hr	0	—	—
O ₂ (g)	.21 (9.86) 2.07 kmol/hr	0	0.27 $\frac{\text{kmol}}{\text{hr}}$	\hat{H}_1
N ₂ (g)	.79 (9.86) 7.79 kmol/hr	0	7.79 $\frac{\text{kmol}}{\text{hr}}$	\hat{H}_2
BM BM (s)	—	—	1.23 $\frac{\text{kmol}}{\text{hr}}$	\hat{H}_3
CA (aq)	—	—	0.52 kmol/hr CA (+ 2.76 kmol/hr H ₂ O)	\hat{H}_4
CO ₂ (g)	—	—	1.04 $\frac{\text{kmol}}{\text{hr}}$	\hat{H}_5

from bottom of

$$Q = -561078 \frac{\text{kJ}}{\text{hr}}$$

 \hat{H}_1 : ref same as B.8 so just interpolate

$$\hat{H}_1 = 0 + \frac{(40-25^\circ\text{C})}{(100-25^\circ\text{C})} (2.24 - 0 \frac{\text{kJ}}{\text{mol}}) = 0.45 \frac{\text{kJ}}{\text{mol}} \text{O}_2 \left(\frac{1000 \text{ mol}}{\text{kmol}} \right) = 450 \frac{\text{kJ}}{\text{kmol}} \text{O}_2$$

 \hat{H}_2 : ref same as B.8 so interpolate

$$\hat{H}_2 = 0 + \frac{(40-25^\circ\text{C})}{(100-25^\circ\text{C})} (2.19 - 0 \text{ kJ/mol}) = 0.44 \frac{\text{kJ}}{\text{mol}} \text{N}_2$$

\hat{H}_3 : ref BM(s) 25°C \longrightarrow act BM(s) 40°C

$$\hat{H}_3 = \int_{25^\circ\text{C}}^{40^\circ\text{C}} 2 \text{ kJ/kg} \cdot \left(\frac{24.6 \text{ kg}}{\text{kmol}} \right) dT = 49.2 \frac{\text{kJ}}{\text{kmol}} (40-25^\circ\text{C}) = 738 \frac{\text{kJ}}{\text{kmol}} \text{BM}$$

\hat{H}_4 : ref CA(aq) 25°C \longrightarrow act CA(aq) 40°C

$$\hat{H}_4 = \int_{25^\circ\text{C}}^{40^\circ\text{C}} 75.4 \times 10^{-3} \frac{\text{kJ}}{\text{mol}^\circ\text{C}} \left| \frac{1000 \text{ mol}}{\text{kmol}} \right| dT = 75.4 (40-25^\circ\text{C}) = 1131 \frac{\text{kJ}}{\text{kmol}} \text{aq soln}$$

 \hat{H}_5 : ref same as B.8, interpolate

$$\hat{H}_5 = 0 + \frac{(40-25^\circ\text{C})}{(100-25^\circ\text{C})} (2.90 - 0) \frac{\text{kJ}}{\text{mol}} \left| \frac{1000 \text{ mol}}{\text{kmol}} \right| = 580 \frac{\text{kJ}}{\text{kmol}} \text{CO}_2$$

$$\dot{Q} = \Delta \dot{H} = \dot{Q} \Delta \hat{H}_r + \sum_{out} n \hat{H} - \sum_{in} n \hat{H} = 0.23 \frac{\text{kmol}}{\text{hr}} (-2477.6 \frac{\text{kJ}}{\text{mol}} \left| \frac{1000 \text{ mol}}{\text{kmol}} \right|) + 0.27 \frac{\text{kmol}}{\text{hr}} (450 \frac{\text{kJ}}{\text{kmol}} \text{O}_2) + 7.79 \frac{\text{kmol}}{\text{hr}} (440 \frac{\text{kJ}}{\text{kmol}} \text{N}_2) + 1.23 \frac{\text{kmol}}{\text{hr}} (738 \frac{\text{kJ}}{\text{kmol}}) + (0.52 + 2.76 \frac{\text{kmol}}{\text{hr}} \text{ total soln}) (1131 \frac{\text{kJ}}{\text{kmol}} \text{ aq soln}) + 1.04 \frac{\text{kmol}}{\text{hr}} (580 \frac{\text{kJ}}{\text{kmol}} \text{CO}_2)$$

#3 (12 points)

A room temperature extraction process is used to remove acetone from water. A 125 kg feed mixture of acetone and water is added to a tank along with pure methyl isobutyl ketone (MIBK). The total mixture is stirred well and left to sit until two phases come to equilibrium and separate. One phase has a mass of 165 kg and contains 70 wt% MIBK.

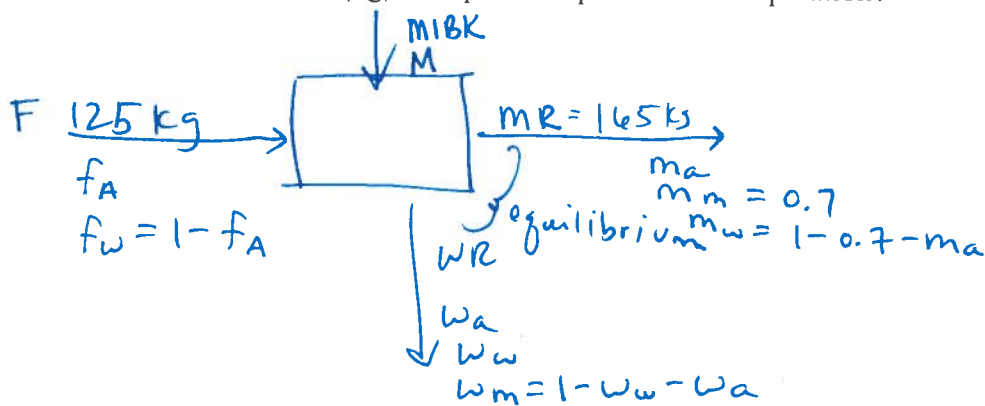
(a) Why do two phases form?

Water + MIBK are partially immiscible in each other (so as long as acetone is not the majority ~~species~~, they will separate)

(b) Why is acetone present in both phases, but more in the MIBK-rich phase than the water-rich phase?

acetone is more soluble in MIBK than water. (You can tell this because the equilibrium tie lines go higher on the MIBK side.)

(c) How much MIBK (kg) is required to perform this separation?



From ternary phase diagram for MIBK-H₂O-Acetone on equilibrium curve at 70% MIBK: Acetone = 25%.
Cross on tie line to other side: Acetone = 16% water = 82%.

Mass balances

$$\text{total } F + M = MR + WR \quad \left. \begin{array}{l} 125 \text{ kg} \\ 165 \text{ kg} \end{array} \right\} \text{ solve to get } M$$

$$M = 0.7 MR + (1 - .82 - .16) WR$$

$$A: f_A (125 \text{ kg}) = .25 MR + 0.16 WR$$

$$40 \text{ kg} + WR = 0.7(165) + 0.02 WR$$

$$0.98 WR = 75.5$$

$$WR = 77 \text{ kg}$$

$$M = 40 \text{ kg} + WR$$

$$M = 40 + 77 = 117 \text{ kg}$$

To prepare a cold drink during this hot Atlanta summer, you put a few ice cubes (2 oz, -10°C) into 8 oz of 25°F water in a very well insulated thermos. What is the temperature of the water when the ice melts? The heat capacity of ice is $\sim 1.9 \text{ kJ/kg}^{\circ}\text{C}$. You may just use the “a” term for heat capacities.

$$\Delta U + \cancel{\Delta KE} + \cancel{\Delta PE} = \cancel{Q} - \cancel{W}$$

thermos well insulated
not moving no moving parts

ref state: water (l) 25°C

Species	n_{in}	\hat{H}_{in}	n_{out}	\hat{H}_{out}
ice	n_1	\hat{H}_1	—	—
water		0	n_2	\hat{H}_2

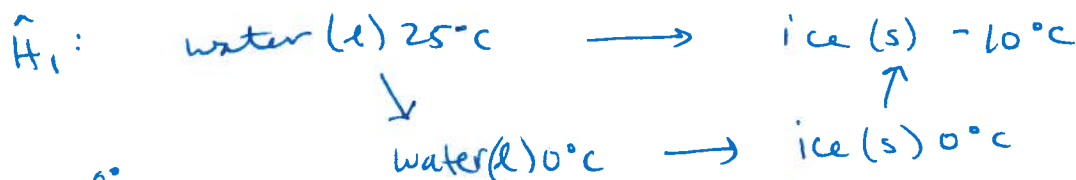
$$\text{1a: } \frac{20\text{z}}{35.273920\text{z}} \times 1\text{kg} = 0.057\text{ kg} = n_1 = \frac{0.057\text{ kg}}{18\text{ kg}} \times \frac{1\text{ kmol}}{1\text{ kmol}} \times \frac{1000\text{ mol}}{1\text{ kmol}} = 3.2\text{ mol}$$

water:

H_2O	1 kg	kmol	1000 mol
	35.27342 oz	18 kg	1 kmol

 $\frac{1000}{18} = 12.6 \text{ mol}$

$$n_2 = \text{ice} + \text{water} = 3.2 + 12.6 = 15.8 \text{ mol}$$



$$\hat{H}_1 = \int_{25^\circ}^{0^\circ} 75.4 \times 10^{-3} \frac{\text{kJ}}{\text{mol}^\circ\text{C}} dT - 6.0095 \frac{\text{kJ}}{\text{mol}} + \int_0^{-10} 1.9 \frac{\text{kJ}}{\text{kg}^\circ\text{C}} \left| \frac{18 \text{ kg}}{\text{kmol}} \right| \left| \frac{1 \text{ kmol}}{1000 \text{ mol}} \right| dT$$

$$\hat{H}_1 = 75.4 \times 10^{-3} \frac{\text{kJ}}{\text{mol} \cdot ^\circ\text{C}} (0 - 25^\circ\text{C}) - 6.0095 \text{ kJ/mol} + 0.0342 \frac{\text{kJ}}{\text{mol} \cdot ^\circ\text{C}} (-10 - 0) = -8.24 \frac{\text{kJ}}{\text{mol}}$$



$$\hat{H}_2 = \int_{25}^T 75.4 \times 10^{-3} \frac{\text{kJ}}{\text{mol} \cdot ^\circ\text{C}} dT = 75.4 \times 10^{-3} \frac{\text{kJ}}{\text{mol} \cdot ^\circ\text{C}} (T - 25^\circ\text{C})$$

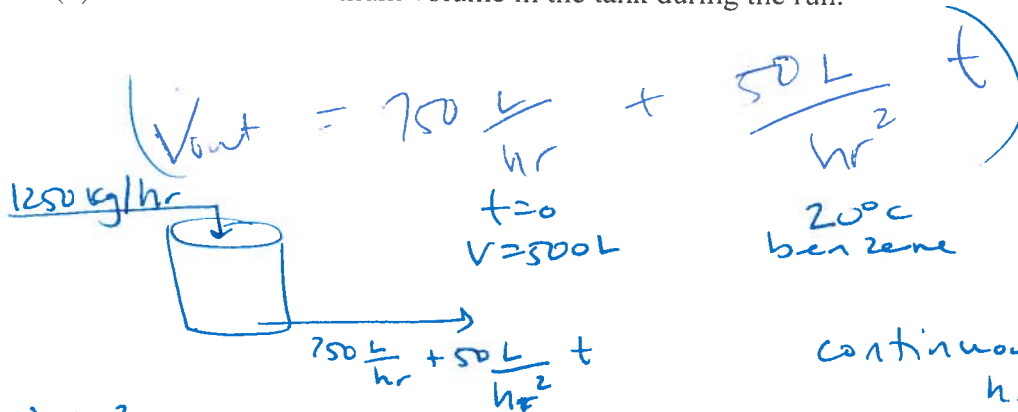
$$0 = 15.8 \text{ mol} \left(75.4 \times 10^{-3} \frac{\text{kJ}}{\text{mol} \cdot ^\circ\text{C}} \right) (T - 25^\circ\text{C}) - 3.2 \text{ mol} \left(-8.27 \frac{\text{kJ}}{\text{mol}} \right)$$

$$-22.1 = T - 25^\circ\text{C} \quad \boxed{T = 2.9^\circ\text{C}}$$

#5 (14 points)

A storage tank holds liquid benzene at 20°C for feed into a complex reactor system. The flow rate into the tank is constant at 1250 kg/hr. Due to the nature of this reactor system, the withdrawal rate of benzene from the tank to feed the process changes over time during the course of a process run. The volumetric flow rate from the tank is $750 \text{ L/hr} + (50 \text{ L/hr}^2)t$ where t is in hours. The tank initially contains 500 L at the start of the run.

- (a) Derive an expression for $V(t)$, the volume of benzene in the tank at any time during the run.
 (b) Calculate the maximum volume in the tank during the run.



benz.
acc = in - out

$$\frac{dM}{dt} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}}$$

$$\frac{d(\rho V)}{dt} = \dot{m}_{\text{in}} - \rho \dot{V}_{\text{out}}$$

$$\rho \frac{dV}{dt} = \dot{m}_{\text{in}} - \rho \dot{V}_{\text{out}}$$

$$\frac{dV}{dt} = \frac{\dot{m}_{\text{in}}}{\rho} - \dot{V}_{\text{out}} = \frac{1250 \text{ kg/hr}}{0.879 \left(\frac{1000 \text{ kg}}{\text{m}^3} \right) \left(\frac{1 \text{ m}^3}{1000 \text{ L}} \right)} - 750 \frac{\text{L}}{\text{hr}} - 50 \frac{\text{L}}{\text{hr}^2} t$$

(1120/hr)

$$\frac{dV}{dt} = 672 \frac{\text{L}}{\text{hr}} - 50 \frac{\text{L}}{\text{hr}^2} t$$

$$\int_{500 \text{ L}}^V dV = \int_{0 \text{ hrs}}^t (672 - 50t) dt$$

$$V - 500 = 672t - \frac{50}{2} t^2$$

$$V = -25t^2 + 672t + 500$$

b. at max $dV/dt = 0$

$$0 = 672 - 50t$$

$$t = 13.4 \text{ hrs}$$

$$\rightarrow V = -25(13.4 \text{ hrs})^2 + 672(13.4) + 500$$

$$V = 5016 \text{ L}$$

continuous, unsteady state,
no rxn

$$M = \rho V \quad \dot{m} = \rho \dot{V}$$

seems to be no ΔT , only benzene
so ρ is constant