Name: Sohn Solution

Exam #2

ChBE 2100A
Chemical Process Principles

Wednesday, July 1, 2015

The exam consists of 4 problems worth the points indicated (42 points total). Please write your final answers in the space provided in the specified units, or box them if no space provided. 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.

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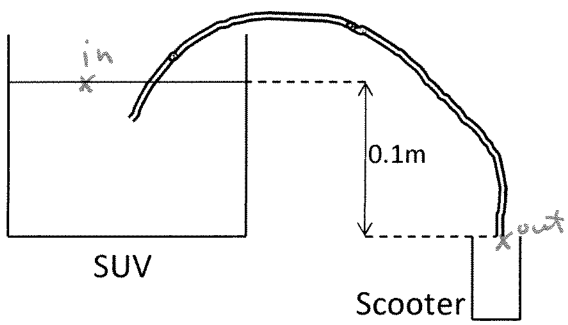
Signature

#1 (8 points)
You are driving on a country road when you see a teenager with a scooter on the side of the road, out of gas. You are in a hurry but you stop to help. You have a full tank of gas and some 1/4" (diameter = 0.00625 m) tubing. Luckily, you are driving an SUV, so the gas tank is higher and much much larger than the tubing diameter (drawing not to scale). Almost immediately after you make a bad safety decision and suck on the tubing to get the gas flowing, the flow is steady and driven by gravity. What is the flow rate in gal/min from your tank if the height difference between the gas in the SUV tank and end of the tubing is 0.1 meters? The density of gasoline is 740 kg/m^3. The gasoline has little friction with the tubing.



Moving fluid → mechanical terms more important

$$\frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z + \cancel{\hat{F}} = \cancel{-\frac{\dot{W}_s}{\dot{m}}}$$

Bernoulli

$$\frac{\cancel{P_{out} - P_{in}}}{\rho} + \frac{u_{out}^2 - \cancel{u_{in}^2}}{2} + g(\underbrace{z_{out}}_{=0} - \underbrace{z_{in}}_{=0.1\,m}) = 0$$

$P_{out} = P_{in} = atm$ tank >>> tubing → $u_{in} \lll u_{out}$, $u_{in} \approx 0$

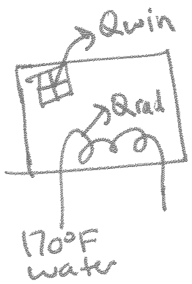
$$u_{out} = \sqrt{-2g(-z_{in})} = \sqrt{2gz_{in}} = \sqrt{2\,(9.8\,\tfrac{m}{s^2})(0.1\,m)} = 1.4\ m/s$$

$$\dot{V} = uA = 1.4\ m/s\left(\pi\left(\frac{.00625\,m}{2}\right)^2\right) = 4.3\times10^{-5}\ \frac{m^3}{s}$$

$$\dot{V} = 4.3\times10^{-5}\ \frac{m^3}{s}\cdot\frac{60\,s}{1\,min}\cdot\frac{264.17\,gal}{1\,m^3} = \boxed{0.68\ \frac{gal}{min}}$$

#2 (11 points)

Dr. Champion lives in an old house, built in 1925. It has radiators in every room and hot water from a boiler in the basement flows through the radiators and heats the air in each room. This method of heating is quite efficient. The water temperature is stable at 170°F. The design of the radiators gives heat to the air in the room according to the relationship, $Q = UA_{radiator}(T_{water} - T_{room})$, where $UA_{radiator}$ = 50 BTU/min. However, since it is an old house and the windows are also original, some heat from the room is lost to the outdoors according to a similar relationship, $Q = UA_{windows}(T_{room} - T_{outside})$, where $UA_{windows}$ = 35 BTU/min. If the air temperature in the living room is 60°F when the radiator water flow valve is opened, how long will it take for the temperature to reach 70°F? The temperature outside on this particular winter day is 18°F. The living room is 10ft x 12 ft x 9ft. Though heat is lost through the windows, no air leaves through the windows and the doors to the living room are closed. The heat capacity at constant volume (C_v) of air is approximately 28 J/g°C. If needed, recall that for gases $C_p = C_v + R$.



Thermal E balance: Q is important, no Ep, E

T (air) changes w/ time → unsteady state

air in room is closed system, well-mixed

$$M C_v \frac{dT}{dt} = \dot{Q} - \cancel{\dot{W}}$$

no work

initial condition
T = 60°F @ t = 0 min

$$\frac{dT}{dt} = \frac{1}{MC_v}\left[+\dot{Q}_{rad} - \dot{Q}_{win}\right] = \frac{1}{(82\,lb)(21.7\,\frac{BTU}{lb \cdot °F})}\left[50\,\frac{BTU}{min}(170°F - T) - 35\,\frac{BTU}{min}(T-\right.$$

Air in room is ideal
n_{air} not changing w/ time
So use $T_{initial}$, $P_{initial}$

$$n_{air} = \frac{PV}{RT} = \frac{(1\,atm)(10 \times 12 \times 9\,ft^3)}{\left(0.7302\,\frac{ft^3 \cdot atm}{°R \cdot lb\text{-}mol}\right)(60 + 460\,°R)}$$

n_{air} = 2.8 lb-mol

$$MW_{air} = .79\,MW_{N_2} + .21\,MW_{O_2} = .79(28\,lb/lb\text{-}mol) + .21(32\,lb/lb\text{-}mol) = 28.84\,\frac{lb}{lb\text{-}mol}$$

$$M_{air} = 2.8\,lb\text{-}mol\left(28.84\,\frac{lb}{lb\text{-}mol}\right) = 82\,lb$$

$$C_v = 28\,\frac{J}{g \cdot °C} \left|\frac{9.486 \times 10^{-4}\,BTU}{1\,J}\right| \frac{453.593\,g}{1\,lb} \left|\frac{1.8\,°C}{1\,°R}\right| = 21.7\,\frac{BTU}{lb \cdot °F}$$

or F

#2

#4 More Space

$$\frac{dT}{dt} = 0.03(170 - T) - 0.02(T - 18) = 5.46\,\frac{°F}{min} - \frac{0.05}{min}\,T$$

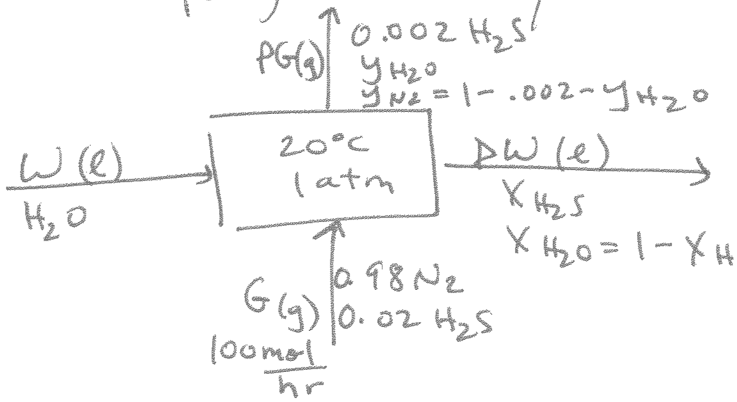
$$\int_{60°F}^{70°F} \frac{dT}{5.46 - 0.05\,T} = \int_{0\,min}^{t} dt$$

$$-\frac{1}{0.05}\Big[\ln[5.46 - 0.05(70)] - \ln(5.46 - 0.05(60))\Big] = t - 0$$

$$\boxed{t = 4.5\ min}$$

#3 (10 points)
Hydrogen sulfide (H_2S) is a very toxic gas, which smells like rotten eggs, and can be present in crude petroleum or natural gas. A nitrogen stream from a refinery is contaminated with 2mol% H_2S, the remainder is N_2, and is cleaned in an absorber. In the absorber, water contacts the gas and H_2S is absorbed into the water, while N_2 is not absorbed at the absorber operating conditions. The absorber operates at 20°C and 1 atm, at which conditions the Henry's law constant for H_2S in water is 18 atm. If 100 mol/hr of contaminated gas needs to be processed, how much clean water is required?

forgot ≈ in product gas $y_{H_2S} = 0.002$



PG + DW streams are in contact → in equilibrium

→ gas is saturated with water

→ water is saturated with H_2S

Equilibrium relationships

for H_2O : $X_{H_2O} \simeq 1$, Raoult

$$y_{H_2O} P = \underbrace{X_{H_2O}}_{(1-X_{H_2S})} \underbrace{P^*_{H_2O}(20°C)}_{17.535 \text{ mmHg}}$$

$$y_{H_2O} = \frac{(1-.0001)\, 17.535 \text{ mmHg}}{760 \text{ mmHg}}$$

$$y_{H_2O} = 0.02$$

for H_2S : $X_{H_2S} \approx 0$, Henry

$$y_{H_2S} P = X_{H_2S} H_{H_2S}(20°C)$$

$$0.002 (1 \text{ atm}) = X_{H_2S} (18 \text{ atm}) \qquad X_{H_2S} = 0.0001$$

mass balances:

total $W + 100 \frac{mol}{hr} = PG + DW$

H_2O $W = 0.02\, PG + (1-.0001)\, DW$

N_2 $.98 (100 \text{ mol/hr}) = (1-.002-.02)\, PG$

$PG = 100.2$ mol/hr

$0.02(100.2) + (1-.0001)\,DW + 100 = 100.2 + DW$

$1.804 = DW - 0.9999\, DW$

$DW = 18040$ mol/hr

$W = 100.2 + 18040 - 100 = \boxed{18040.2 \text{ m/h}}$

#4 (13 points)

The type, size and shape of crystals that form depends on many things including the temperature drop between the feed solution and the operation temperature of the crystallizer. In order to obtain the desired crystals of ammonium chloride, a solution that is saturated at 50°C is heated to 80°C before entering a continuous crystallizer, which operates at 20°C. The solution is heated by flowing it through a heater that has steam running through it. The steam and the solution do not mix, they are separated by pipe walls but heat transfers between them. The streams running in and out of the heater are shown in the figure below, but the crystallizer is standard so no streams are drawn. A solubility chart is provided for your convenience. If you use it to solve this problem, you must show your work on the chart (do not use the chart in the notesheet). There is more space for work on the next page.

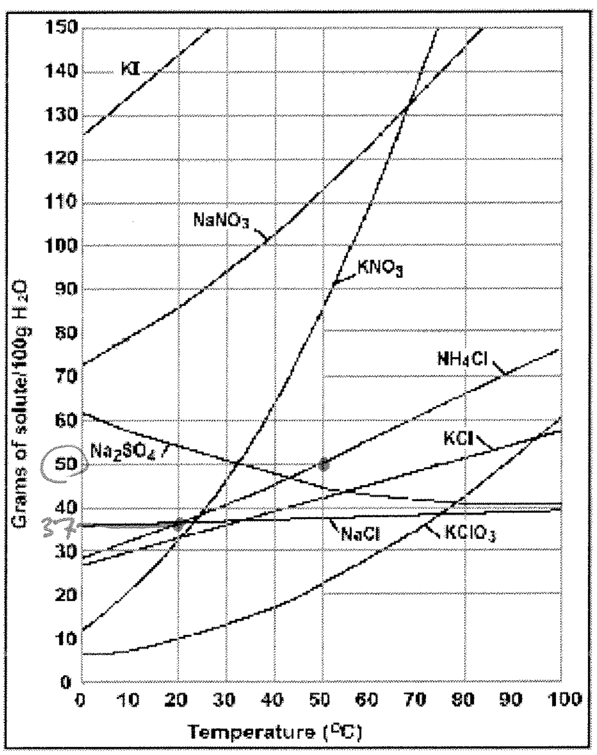
(a) Why do crystals form in the crystallizer?

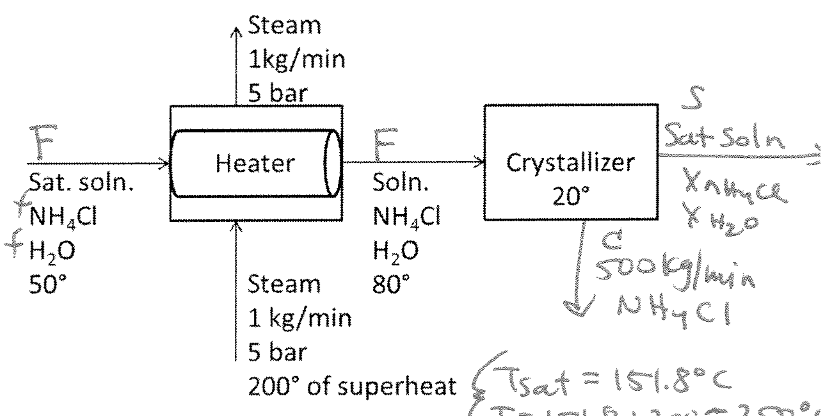
The solution that is saturated at 50°C would be supersatura at 20°C & the only way to get back to equilibrium (saturation) is for crystals to precipitate & reduce the concentration of salt in water to the saturation conc at 20°C.

(b) The steam transfers 313 kJ/min of heat to the solution. What is the temperature of the steam exiting the heater?

200°C

(c) If 500 kg/min of anhydrous crystals are desired, what is the flow rate of the feed solution to the crystallizer?





b) Energy balance, thermal terms important (heating) + open system

$$\Delta \dot{H} + \cancel{\Delta \dot{E}_k} + \cancel{\Delta \dot{E}_p} = \dot{Q} - \dot{W}_s$$

less important than thermal terms

no work mentioned

$$\Delta \dot{H} = \dot{Q}$$

system is steam so $\dot{Q}$ is ⊖ (lost to surr.)

$$\dot{m}(\hat{H}_{out} - \hat{H}_{in}) = \dot{Q}$$

More space →

$$1\ \text{kg/min}\left(\hat{H}_{out} - \underbrace{3168\ \tfrac{kJ}{kg}}_{B.7}\right) = -313\ \tfrac{kJ}{min}$$

#4 More Space

$\hat{H}_{out} = 2855 \frac{kJ}{kg}$ from B.7 at 5 bar $\rightarrow T = 200°C$

Feed is saturated at 50°C $\rightarrow \frac{50g\ NH_4Cl}{100g\ H_2O}$

$f_{NH_4Cl} = \frac{50}{50+100} = 0.33$ $\quad f_{H_2O} = 1 - .33 = .67$

Exit soln is saturated at 20°C $\rightarrow \sim \frac{37g\ NH_4Cl}{100g\ H_2O}$

$x_{NH_4Cl} = \frac{37}{37+100} = 0.27$ $\quad x_{H_2O} = 1 - .27 = 0.73$

Mass balances

total: $F = S + 500$ kg/min

~~NH_4Cl~~

water: $.67F = .73S$ $\quad F = 1.09S$

$1.09S = S + 500$

$0.09S = 500$

$$\boxed{S = 5555.6 \text{ kg/min}}$$