The UNIVERSITY OF BRITISH COLUMBIA

Department of CHEMICAL and BIOLOGICAL ENGINEERING

CHBE 241: MATERIAL and ENERGY BALANCES

MIDTERM – EXAMINATION

October 24, 3 – 5 PM

Instructions:

- Hand calculators are allowed
- The only allowed material is the one page of formula sheet provided to you before the exam.
- Solve individually all 2 problems.
- If any of these rules are not respected, it will be dealt with according to University Policy on student ethics during examination.

*** *use a maximum of two significant figures after the decimal point* ****

Problem 1 (60% of the mark):

Hydrogen sulfide and other sulfur compounds are removed from natural gas (CH_4) by various so-called 'sweetening processes' that upgrade the otherwise lower quality 'sour' natural gas. A proposed process to remove H_2S from a natural gas stream is by reaction with SO_2:

$2H_2S_{(gas)} + SO_{2(gas)} \rightarrow 3S_{(solid)} + 2H_2O_{(gas)}$.

In a reactor a gas stream containing $20\%_{mol}$ H_2S and $80\%_{mol}$ CH_4 is combined with a separate stream of pure SO_2. The reactor produces two streams: a gas stream and a pure solid sulfur (S) stream with a production rate of 5000 lb/h of $S_{(solid)}$. The molar mass of S: 32 g/mol.

In the product gas stream the molar ratios are: SO_2 / H_2S is equal to 3, and H_2O / H_2S is equal to 10. Calculate and perform the following by assuming steady-state operation:

a) Perform DOF analysis to evaluate if you have enough information to perform process engineering calculations.
b) Calculate the molar flow rate of $S_{(solid)}$ in the product stream (expressed in kmol/h).
c) Calculate the extent of reaction.
d) Calculate the molar feed rates of H_2S and SO_2 in the reactor.
e) Calculate the fractional conversion of H_2S and demonstrate which reactant is the limiting reactant.

Problem 2 (40% of the mark):

A distillation (separator) column is fed with 2000 liter/h of liquid mixture containing 45% benzene (**B**) and 55% toluene (**T**) by mass. The specific gravity of the feed liquid mixture is 0.87 (with respect to the density of water at 4 ^{0}C).

Two product streams leave the distillation column: i) a top stream that contains 95 mol% **B**, and ii) a bottom stream where the fractional recovery of **B** is 0.08.

The molar mass of benzene (**B**) is: 78 kg/kmol; the molar mass of toluene (**T**) is: 92 kg/kmol.

Calculate the following by assuming steady state operation:

a) The mass flow rates of the top and bottom product streams, respectively.
b) The fractional recovery of **B** in the top stream.
c) The composition in mass fractions of the bottom product stream.

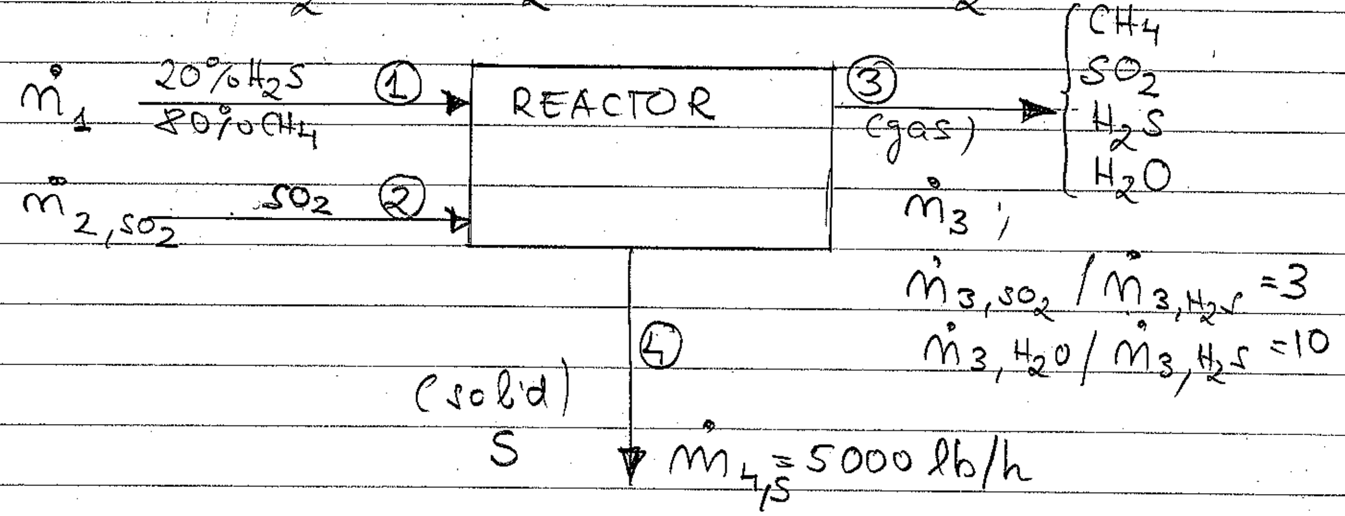
Marking scheme:

Problem 1: a) 10%; b) 5%, c) 10%, d) 20%, e) 15%

Problem 2: a) 20%, b) 10%, c) 10%

PROBLEM 1 (based on H. 10.2/p.267)

$$2H_2S + SO_2 \longrightarrow 3S + 2H_2O$$



a) DOF

	$N_{VARIABLES}$
stream components	8 (= 2 (①) + 1 (②) + 4 (③) + 1 (④))
system variables	1 (chemical reaction)
TOTAL =	9

	$N_{EQUATIONS}$
basis production rate	1 ($\dot{m}_4$)
stream composition eqns. (independent eqns.)	3 (= 1 (①) + 2 (③))
material balance eqns.	5 (5 species: H_2S, CH_4, SO_2, H_2O, S)
TOTAL =	9

DOF = $N_V - N_e = 9 - 9 = \underline{0}$ // FULLY SPECIFIED SYSTEM

⇒ CAN BE SOLVED

b) $\dot{n}_{4,S} = \frac{\dot{m}_{4,S}}{MW_S}$, $MW_S = 32 \frac{kg}{kmol}$

$\dot{m}_{4,S} = 5000 \ lb/h = 2270 \ kg/h$

NOTE: $1 \ lb = 0.454 \ kg$

$\dot{n}_{4,S} = \frac{2270}{32} = \underline{70.94 \ kmol/h}$ //

c) Strategy: write down MBE for each chemical species at steady-state.

The general form of the MBE is:

$\dot{n}_{i,OUT} = \dot{n}_{i,IN} + \nu_i \xi$, where

ν_i : stoichiometric coeff. of species i
ξ : extent of reaction

For S: $\dot{n}_{4,S} = \underset{0}{\dot{n}_{IN,S}} + 3\xi$,

hence $\xi = \frac{\dot{n}_{4,S}}{3} = \underline{23.65 \ kmol/h}$ //

d) continue with MBE for species

For H_2S: $\dot{m}_{3,H_2S} = \dot{m}_{1,H_2S} - 2\xi$

For SO_2: $\dot{m}_{3,SO_2} = \dot{m}_{2,SO_2} - \xi$

also we know that $\dfrac{\dot{m}_{3,SO_2}}{\dot{m}_{3,H_2S}} = 3$

For H_2O: $\dot{m}_{3,H_2O} = \underset{0}{\cancel{\dot{m}_{1,H_2O}}} + 2\xi$

also we know that $\dfrac{\dot{m}_{3,H_2O}}{\dot{m}_{3,H_2S}} = 10$

For CH_4: $\dot{m}_{1,CH_4} = \dot{m}_{3,CH_4}$

$\dot{m}_{3,H_2O} = 2 \times 23.65 = 47.3 \ \frac{kmol}{h}$ $\longleftarrow$ INTRODUCE NUMERICAL VALUES

$\dot{m}_{3,H_2S} = \dfrac{47.3}{10} = 4.73 \ \frac{kmol}{h}$

- using MBE for H_2S gives:

$4.73 = \dot{m}_{1,H_2S} - 2 \times 23.65$

$\dot{m}_{1,H_2S} = \underline{52.03 \ kmol/h}$ // (In the feed)

④

$$\dot{m}_{3,SO_2} = 3 \times \dot{m}_{3,H_2S} = 3 \times 4.73 = 14.19 \; \frac{kmol}{h}$$

From SO_2 MBE $\Rightarrow$

$$\dot{m}_{2,SO_2} = 14.19 + 23.65 = 37.84 \; \frac{kmol}{h}$$

(in the feed)

e) $$f_{c,H_2S} = \frac{2\xi}{\dot{m}_{1,H_2S}}$$; 2ξ = consumed H_2S in the reaction

(fractional conversion)

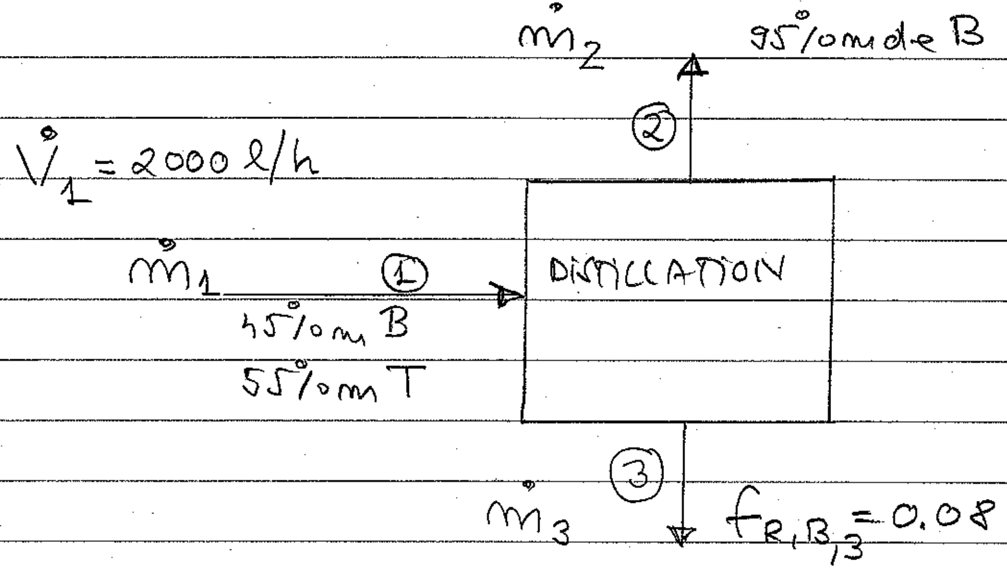
$$f_{c,H_2S} = \frac{2 \times 23.65}{52.03} = 0.91$$

to determine the limiting reactant compare $\dot{m}_{1,H_2S}$ and $\dot{m}_{2,SO_2}$ with respect to reaction stoichiometry

$$\frac{\dot{m}_{1,H_2S}}{\dot{m}_{2,SO_2}} = \frac{52.03}{37.84} < \frac{\nu_{H_2S}}{\nu_{SO_2}} = \frac{2}{1}$$

clearly, H_2S is fed with a molar rate that is lower than the stoichiometric requirement. $\Rightarrow$ H_2S LIMITING REACTANT!

PROBLEM 2 (based on F&R, 4.3-5/p.102)



a) Clearly $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$ (total MBE) ; [1]

fractional recovery in the bottom:

$$0.08 = f_{R,B,3} = \frac{\dot{m}_{3,B}}{\dot{m}_{1,B}} = \frac{\dot{m}_{3,B}}{0.45\,\dot{m}_1} \quad ; \quad [2]$$

observe

$\dot{m}_1$ can be easily calculated:

$$\dot{m}_1 = \rho_{mix} \cdot \dot{V}_1 \quad ; \text{ where} \quad [3]$$

$$\rho_{mix} = SG \cdot \rho_{H_2O}^{4°C} = 870 \text{ kg/m}^3$$

$$= 1 \text{ g/cm}^3 = 1000 \text{ kg/m}^3$$

Thus,

$$\dot{m}_1 = \underbrace{870 \times 2}_{(kg/m^3)\times(m^3/h)} = \underline{1740 \text{ kg/h}} \Rightarrow$$

From Eq. [2] $\dot{m}_{3,B} = 0.08 \times 0.45 \times 1740$

$$\dot{m}_{3,B} = 62.64 \text{ kg/h}$$

B MBE: $\dot{m}_{1,B} = \dot{m}_{3,B} + \dot{m}_{2,B}$ [4]

Thus, $0.45\,\dot{m}_1 = \dot{m}_{3,B} + \dot{m}_{2,B}$

$\Rightarrow$ $\dot{m}_{2,B} = 0.45\,\dot{m}_1 - \dot{m}_{3,B}$ [5]

$$\dot{m}_{2,B} = 0.45 \times 1740 - 62.64 = \underline{720.36} \text{ kg/h}$$

we also know that in the top stream

$Y_{2,B} = 0.95 = \dfrac{\dot{m}_{2,B}}{\dot{m}_2} = \dfrac{\dot{m}_{2,B}}{MW_B\,\dot{m}_2}$ [6]

(mole fraction)

Thus $\dot{m}_2 = \dfrac{720.36}{78 \times 0.95} = 9.72$ kmol/h [7]

Also, $\dot{m}_2 = \underset{\text{known}}{\dot{m}_{2,B}} + \underset{\text{unknown}}{\dot{m}_{2,T}}$ [8]

However, if $Y_{2,B} = 0.95 \Rightarrow Y_{2,T} = 0.05$

$Y_{2,T} = 0.05 = \dfrac{\dot{m}_{2,T}}{\dot{m}_2} = \dfrac{\dot{m}_{2,T}}{MW_T \cdot \dot{m}_2}$ [9]

$$\dot{m}_{2,T} = 0.05 \times 92 \times 9.72 = \underline{44.71\,kg/h}$$

FROM Eq. [8] therefore:

$$\dot{m}_2 = 720.36 + 44.71 = \underline{765.07\,kg/h} \,\|$$

and from Eq. [1]

$$\dot{m}_3 = 1740 - 765.07 = \underline{974.93\,kg/h} \,\|$$

b) fractional recovery of B in TOP STREAM ②

$$f_{R,B,2} = \frac{\dot{m}_{2,B}}{\dot{m}_{1,B}} = \frac{\dot{m}_{2,B}}{0.45\,\dot{m}_1} \qquad [10]$$

$$f_{R,B,2} = \frac{720.36}{0.45 \times 1740} = \underline{0.92} \,\|$$

Note: the last is easily verified because $f_{R,B,2} + f_{R,B,1} = 0.92 + 0.08 = 1$ as it should be!

c) Mass fraction composition of the bottom stream

$$X_{3,B} = \frac{\dot{m}_{3,B}}{\dot{m}_3} = \frac{62.64}{974.93} = \underline{0.064} \,\|$$

$$X_{3,T} = 1 - X_{3,B} = 0.936 \,\|$$