CHBE 241 Material and Energy Balances
Department of Chemical and Biological Engineering
The University of British Columbia

Midterm Examination (1hr 50min) **Wednesday, 31 October 2007**

Answer all 5 questions. Present all you calculations!

1. (5%) In Germany, auto fuel consumption is legislated to be 5.97 L/100 km. In the United States, the government requires that the automobile fleet average 27.5 miles/gallon. If the average German drives 20 km per day, what is the savings in gasoline usage (L per year per driver) that is achieved in Germany, compared to the US standard?

2. (15%) Water flows into a tank. The water flow rate $\dot{m}_w$ (kg/h) is a function of time t (h). How much water (kg) is in the tank in 1 hour:

   (a) If $\dot{m}_w = 1 + t$ and the tank is initially empty?

   (b) If $\dot{m}_w = e^t$ and the tank initially contains 10 kg water?

   (c) If $\dot{m}_w = 2 + \sin t$, tank initially contains 20 kg of water and the flow rate out of the tank is 5 kg/h?

3. (25%) You have to prepare a broth for a fermenter to grow antibiotic-producing cells. The broth should be an aqueous solution containing 15 wt% glucose, 5 wt% phosphate, 5 wt% nitrate, and various trace nutrients. A custom supplier sells the required blend for \$16/kg, but your boss suspects you can produce the blend in-house for less. Several commercial powders are available as raw ingredients, to be mixed with water as needed. The mass compositions and costs are:

	"Fast-Feed"	"Super-Gro"	"Formula N"
Glucose (wt%)	45	0	1
Phosphate (wt%)	2	35	12
Nitrate (wt%)	1	15	57
Trace nutrients (wt%)	3	8	0
Inerts (wt%)	49	42	30
Cost (\$/kg)	20	10	15

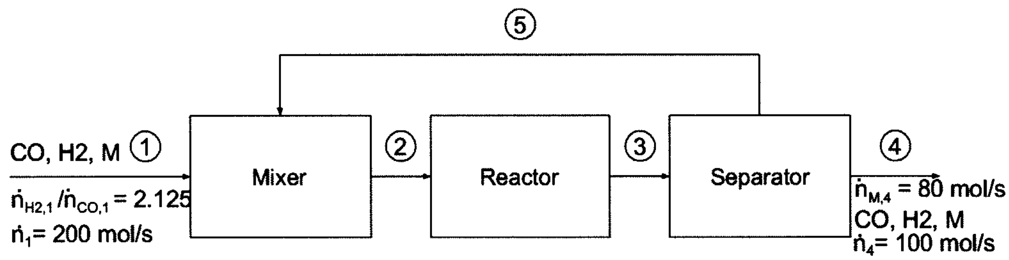
   (a) Suggest a combination of these powders that will produce the desired broth composition. Give the mass of powders and water required per kilogram of broth. Do the DOF analysis first.

   (b) What is the maximum savings per kilogram broth? (Assume water is free.) If the mixing equipment and storage tanks for preparing a 20-kg batch cost \$1500, how many batches will you need to make to pay for the equipment before you begin to see real savings?

4. (30%) Carbon monoxide and hydrogen are partially converted to methanol in a reactor operating at steady-state, according to the following reaction

$$CO + 2H_2 = CH_3OH.$$

The total flow rate of the feed stream (stream 1) is 200 mol/s, and the total flow rate of the product stream (4) is 100 mol/s. The ratio of flow rates hydrogen/CO in the feed stream is 2.125/1. Unreacted gases are recycled; the flow rate of methanol in the product stream is 80 mol/s. Calculate the flow rates of all three components in the feed stream (1) and the product stream (4).



Before you calculate the flow rates, do the DOF analysis for the system you want to use in your calculation.

5. (25%) A liquid mixture, coming from a reactor for the biodiesel production, containing 60 mol% methanol (M), 25 mol% biodiesel (B), 10 mol% glycerol (G), and the balance T (triolein—a raw material for biodiesel production) is fed to a distillation column (DC1). The distillate (Dist1) contains 97 mol% M, 2 mol% G, and no T. 99% of M in the feed is recovered in this stream. The bottom product (Bot1) is fed to a gravity separator (GS), where two liquid phases are formed and glycerol (together with small quantities of M and B) is separated in liquid phase 2 (LP2). 98% of G, 90% of M, 1% of B and no T from Bot1 is recovered in LP2. Stream LP1 (the other product stream from GS) is fed to the second distillation column (DC2). The distillate from the second column (Dist2) contains 98.5% of B in the feed to this column. The composition of Dist2 is 99.65 mol% B and the balance M and G. Fractional recovery of G in the bottom stream Bot2 is 0.90.

   (a) Draw and label a block flow diagram of this process and do the degree of freedom analysis to prove that for an assumed basis of calculation (e.g., flow rate of the feed stream), molar flow rates and compositions of all process streams can be calculated from the given information. Write the material balance equations to calculate unknown process variables. Do not perform the calculations.

   (b) Calculate

      i. The percentage of the biodiesel (B) in the process feed (i.e., the feed to DC1) that emerges in the distillate from the second column.

      ii. The percentage of triolein (T) in the process feed that emerges in the bottom product (Bot2) from the second column.

MT1

① US ; 27.5 mi/gal ⇒

$$\frac{1\ \text{gal}}{27.5\ \text{mi}} \cdot \frac{3.785\ \text{L/gal}}{1.609\ \text{km/mi}} \cdot \frac{100\ \text{km}}{100\ \text{km}} = \frac{3.785\times 100}{27.5\times 1.609}\ \frac{\text{L}}{100\ \text{km}} = 8.55\ \frac{\text{L}}{100\ \text{km}}$$

$$\Delta\ \text{L/yr/dri} = \left(\frac{8.55 - 5.97}{100}\right)\times 365\times 20 = 188.34$$

② (a) $\frac{dm_{w,sys}}{dt} = \dot{m}_w = 1+t \qquad m_{w,sys} = 0 \text{ at } t=0$

$$\int_0^{m_{w,sys,f}} dm_{w,sys} = \int_0^1 (1+t)\,dt$$

$$t = 1 \qquad m_{w,sys,f} = \left(t + \frac{t^2}{2}\right)\Big|_0^1 = 1 + \frac{1}{2} = 1.5\ \text{kg}$$

(b) $\frac{dm_{w,sys}}{dt} = \dot{m}_w = e^t \qquad m_{w,sys} = 10\ \text{kg at } t=0$

$$\int_{10}^{m_{w,sys,f}} dm_{w,sys,f} = \int_0^1 e^t\,dt$$

$$m_{w,sys,f} - 10 = e - 1$$

$$m_{w,sys,f} = 9 + e = 11.72\ \text{kg}$$

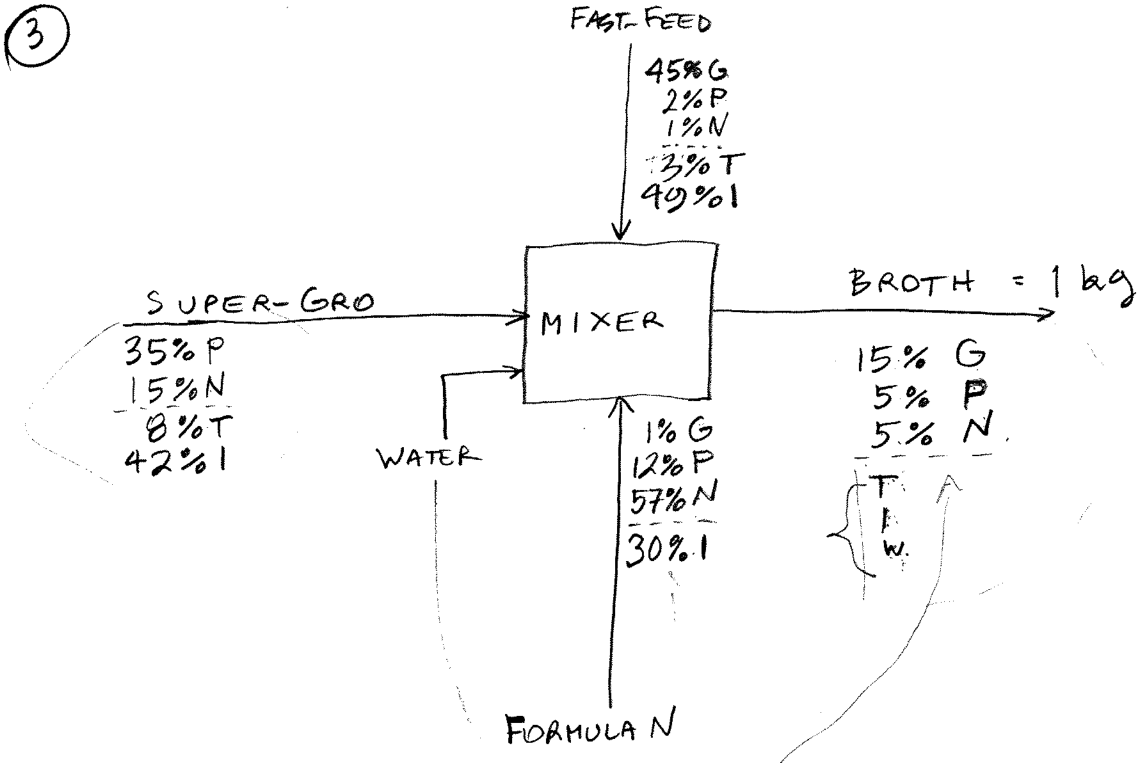
(c) $\frac{dm_{w,sys}}{dt} = \dot{W}_w - \dot{W}_{w,out} = 2 + \sin(t) - 5 \qquad m_{w,sys} = 20 \text{ at } t = 0$

$$\int_{20}^{m_{w,sys,f}} dm_{w,sys} = \int_0^1 (\sin(t) - 3)\,dt$$

$$m_{w,sys,f} = 20 - \cos(t)\Big|_0^1 - 3t\Big|_0^1 = 20 - 0.54 + 1 - 3$$

$$m_{w,sys,f} = 17.46\ \text{kg}$$

③



(a) DOF:

stream v. $5+4+1+4+6 = 20$

system v. 0

$\Sigma_v = 20$

Specified flows 1 ← basis you should assume, not given

Specified stream comp. $4+3+0+3+3 = 13$

System performance 0

MBE's 6

$\Sigma_{eqs} = 20$

DOF = 20 − 20 = 0 ⇒ we can solve the system.

G: $0.45\times FF + 0.01\times FN = 0.15\times B = 0.15$ (1)

P: $0.02\times FF + 0.35\times SG + 0.12\times FN = 0.05$ (2)

N: $0.01\times FF + 0.15\times SG + 0.57\times FN = 0.05$ (3)

This is a system of 3 linear equations in 3 unknowns. Solution

FF = 0.332 kg; SG = 0.105 kg; FN = 0.054 kg

$\Sigma = 0.492$ kg ⇒ $w = 1 - 0.492 = 0.508$ kg

(b) cost/kg = 0.332 × \$20 + 0.105 × \$10 + 0.054 × \$15

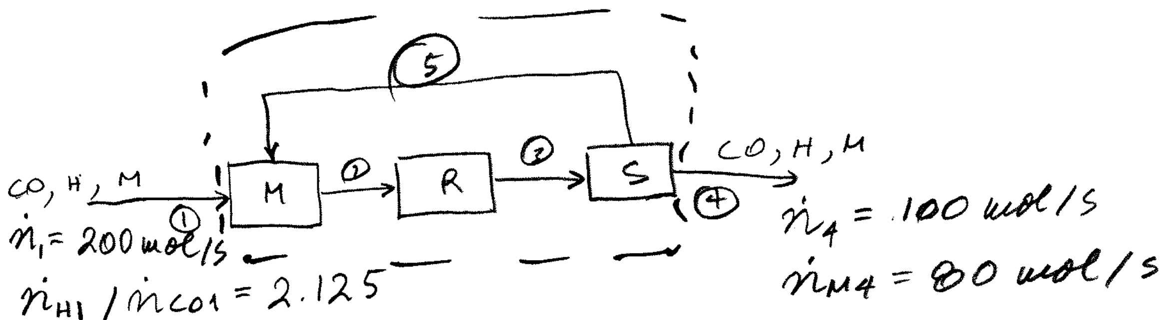
cost/kg = \$8.51

savings per batch $= 20\ kg \times (\$16 - \$8.51) = \$149.83$

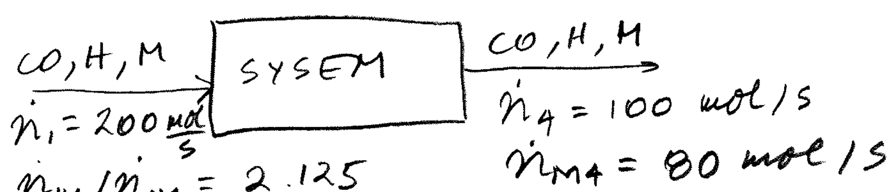
# of batches $= \$1500 / \$149.83 = \sim 10$

(4)

$$CO + 2H_2 = CH_3OH$$



DOF: Not enough information to analyse separate units. Our system is



Stream v.	3 + 3 =	6
System v.		1
		7
Specified flows		3
Spec. stream comp.		1
Sys. performance		0
MBE's		3
		7

DOF = 7 − 7 = 0 (solvable)

MBE's

CO: $\dot{n}_{CO,in} = \dot{n}_{CO,out} + \xi$ (1)

H: $\dot{n}_{H,in} = \dot{n}_{H,out} + 2\xi$ (2)

M: $\dot{n}_{M,in} = \dot{n}_{M,out} - \xi$ (3)

also: $\dot{n}_{in} = \dot{n}_{out} - \sum_{i=1}^{3} \nu_i \xi$

$$200 = 100 - (-1-2+1)\xi = 100 + 2\xi$$

$$\xi = \frac{200-100}{2} = 50 \text{ mol (s)}$$

from (3)

→ $\dot{n}_{M,in} = 80 - 50 = 30$ mol/s

$\dot{n}_{CO,in} + \dot{n}_{H,in} = \dot{n}_{in} - \dot{n}_{M,in} = 200 - 30 = 170$

$\dot{n}_{H,in} = 2.125 \times \dot{n}_{CO,in}$

$3.125\, \dot{n}_{CO,in} = 170 \Rightarrow$

→ $\dot{n}_{CO,in} = 54.4$ mol/s

→ $\dot{n}_{H,in} = 2.125 \times 54.4 = 115.6$ mol/s

from (2)

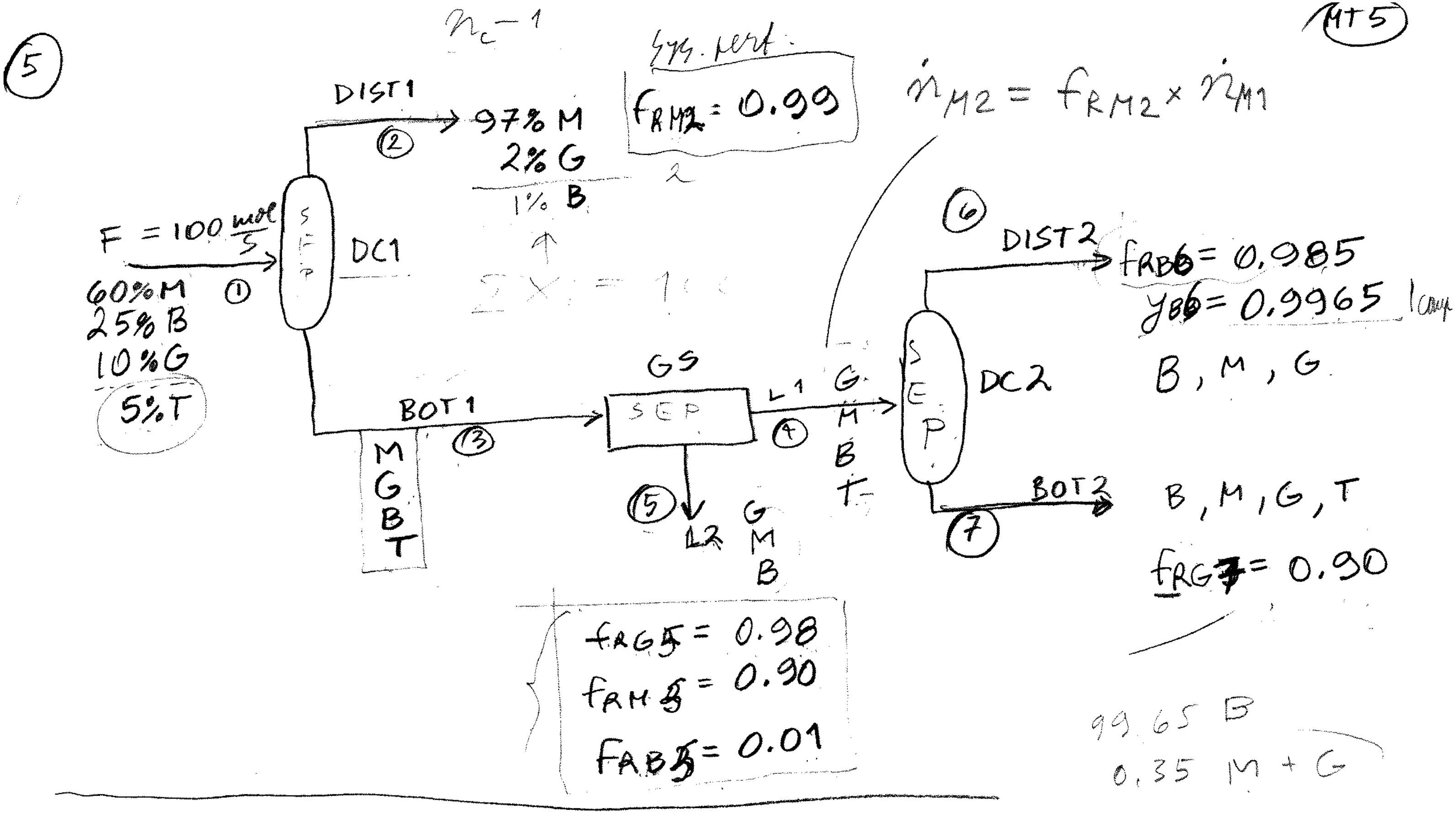
→ $\dot{n}_{H,out} = \dot{n}_{H,in} - 2 \times \xi = 115.6 - 100 = 15.6 \frac{mol}{s}$

from (1)

→ $\dot{n}_{CO,out} = \dot{n}_{CO,in} - \xi = 54.4 - 50 = 4.4 \frac{mol}{s}$

	IN	OUT
H	115.6	15.6
CO	54.4	4.4
M	30	80
Σ	200	100

(5)



DOF:

	DC1		GS		DC2		TOTAL		
STREAM VAR.	11		11		11		25		(not 33)
CHEM R.	0		0		0		0		
TOTAL	11		11		11		25		
FLOWS		Assume BASIS 1		0		0		1	ASSUMED
STREAM COMPOSITION		5		0		1		6	
SYSTEM PERFORMANCE		99% M recovered 1		3		2		6	
MBE'S		4		4		4		12	
TOTAL	11	10	11	7	11	7	25	24	

DOF = 11-10 = 1 | DOF = 11-7 = 4 | DOF = 11-7 = 4 | DOF = 25-25 = 0 ⇒ We can solve the system

M

n_{M2} n_{M3}

$$\dot{n}_{M1} = \dot{n}_{M2} + \dot{n}_{M3} = f_{RM1} \times \dot{n}_{M1} + (1 - F_{RM1}) \cdot \dot{n}_{M1}$$

DC1 $\dot{n}_{M2} = f_{RM1} \times \dot{n}_{M1}$

$\dot{n}_{M3} = (1 - f_{RM1}) \times \dot{n}_{M1}$

$$\dot{n}_{M3} = \dot{n}_{M4} + \dot{n}_{M5} = (1 - f_{RM2}) \times \dot{n}_{M3} + f_{RM2} \times \dot{n}_{M3}$$

GS $\dot{n}_{M4} = (1 - f_{RM2}) \times \dot{n}_{M3}$

$\dot{n}_{M5} = F_{RM2} \times \dot{n}_{M3}$

$$\dot{n}_{M4} = \dot{n}_{M6} + \dot{n}_{M7}$$

T

DC1 $\dot{n}_{T1} = \dot{n}_{T3}$ $(= 100 \times 0.05)$

GS $\dot{n}_{T3} = \dot{n}_{T4}$ $(= 5)$

DC2 $\dot{n}_{T4} = \dot{n}_{T7}$ $(= 5)$

In - out + ~~ϕ~~ - ~~ϕ~~ = A

$$\dot{n}_{M1} = \dot{n}_{M2} + \dot{n}_{M3}$$

B

DC1 $\dot{n}_{B1} = n_{B2} + \dot{n}_{B3}$

GS $\dot{n}_{B3} = \dot{n}_{B5} + \dot{n}_{B4} = \dot{n}_{B3} \times F_{RB2} + \dot{n}_{B3}(1 - f_{RB2})$

$\dot{n}_{B4} = \dot{n}_{B3} \times (1 - f_{RB2})$

$\dot{n}_{B5} = \dot{n}_{B3} \times F_{RB2}$

etc.

i)
$$\frac{D2 \cdot y_{B,3}}{F \cdot X_{B,1}} = f_{RB,3} \cdot f_{RB,4} \cdot f_{RB,6} = (1-0.01) \cdot (1-0.01) \cdot 0.985 = 96.5\%$$

ii) 100 %