BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE, PILANI, PILANI CAMPUS
CHEMICAL ENGINEERING DEPARTMENT
Course Title: Process Design Principles - I (CHE F314)
Comprehensive Examination (Closed Book)

Marks: 50 ` **Date: 26/12/22** **Time: 75 mins**

Note: Make suitable assumptions by clearly stating them, if necessary. Write all steps clearly.

1. **(2 + 3 + 3 = 8 Marks)**
   (a) **Name the process synthesis step** that will be selected for increasing the pressure and temperature of raw material and recycling stream up to 500 Psia and 1150°F in the HDA process for producing benzene from toluene.
   (b) Two reaction pathways (alternatives) are available to produce a product. The first alternative has a low yield and produces the less expensive by-product but has the advantage of the use of a single reactor, and the process occurs at a few hundred degrees centigrade. The second alternative has a higher yield and involved two reactions that occurred at different operating conditions (atmospheric pressure and moderate temperature) and hence, utilizes two reactor systems and produces a less expensive by-product. **Which alternative will be selected and why**?
   (c) A stream of a component whose boiling point is 0°C and 300°C at 1 atm and 30 atm, respectively. Which operations are required to convert this stream from 600°C and 30 atm to 50°C and 2 atm? **Write only the steps involved**.
2. **(4 Marks)**
   A stream containing 25 mol/h of benzene and 1000 mol/h of air was fed to the absorption column. Benzene is recovered as per the heuristic by water as solvent. The water flow rate to the distillation column is 1000 mol/h. Based on the heuristic, what should be the **total flow rate of the gaseous stream leaving the absorption column in mol/h.** Assume that there are no evaporation losses for water in the absorption column.
3. **(4 Marks)**
   Aniline ($C_6H_5NH_2$) is produced from the vapor phase reduction of nitrobenzene. To produce 100 lbmol/hr of aniline which mode (**batch vs continuous**) of operation would you suggest as per the heuristic. Provide proper justification for your answer.
4. **(4 Marks)**
   Consider the components and the destinations given below with their normal boiling points for a gas phase reaction. **Identify the groups and the number of possible recycle streams**? Provide justification for your answer.

Component	Boiling Point (°C)	Destination Code
A	111	Valuable by product
B	-161	Reactant-recycle to R2
C	253	Reactant-recycle to R1
D	-253	Reactant-recycle to R1
E	80	Reactant-recycle to R2
F	-270	Reactant-recycle to R1
G	180	By-product as fuel

5. **(4 Marks)**
   Acetone is produced by dehydrogenation of isopropanol (IPA) as follows:
   $$(CH_3)_2CHOH \rightarrow (CH_3)_2CO + H_2$$
   The heat of reaction at 570°F and 1 atm is 25,800 Btu/mol. Calculate the reactor heat load for producing 200 lb-mol/h of acetone, if conversion is 0.75 and also **suggest whether direct heating or heat carrier is required**?

6. **(4 Marks)**

   How many reactors are required for the following reaction system? Justify your answer.

   $A \rightarrow B$ $\quad 500^{\circ}C,\ 10\,\text{atm}$

   $B \rightarrow C + D$ $\quad 500^{\circ}C,\ 10\,\text{atm}$

   $C + E \rightarrow F$ $\quad 500^{\circ}C,\ 5\,\text{atm, Catalyst A}$

   $C + F \rightarrow G + H$ $\quad 500^{\circ}C,\ 5\,\text{atm, Catalyst B}$

   $A + I \rightarrow J$ $\quad 500^{\circ}C,\ 5\,\text{atm}$

7. **(4 Marks)**

   In a mass integration process, the source and target mass fractions of H_2S (solute) in a given rich stream are 0.07 and 0.0005, respectively, and the total flow rate is 0.9 kg/s. The ammonia (solvent) is used as a lean stream for the recovery of H_2S. If the following linear equilibrium equation applies: $y = 1.45\ x$ (where y and x are equilibrium mass fractions of H_2S in the rich and lean stream, respectively), then **calculate the approach to equilibrium compositions of H_2S in the lean stream corresponding to the source and target mass fractions of H_2S in the rich stream**. Assume $\Delta x_{min} = 0.0001$.

8. **(6+3+2+7 = 18 Marks)**

   100 kmol/h of a reactor effluent stream containing seven components for which the data are given in the following table:

Component	**Composition (mole%)**	**Boiling Point**	**Equilibrium Constant (K_i)**	**Relative Volatility**	**Property**	**Nature**
A	5	-60 °C	100	6	Reactant and Non-corrosive	Hydrocarbon
B	10	-80 °C	150	8.5	Inert and poison to catalyst	Hydrocarbon
C	10	10 °C	0.001	4	By-product and Non-corrosive	Volatile
D	30	35 °C	0.007	3	Reactant and Non-corrosive	Volatile
E	1	-100 °C	200	10	Reactant and Non-corrosive	Hydrocarbon
F	10	-5 °C	0.02	5	Reactant and Corrosive	Volatile
G	34	100 °C	0.0005	2.5	Product and Non-corrosive	Volatile

   Based on the above-mentioned conditions, make the following decisions as per the conceptual design of process synthesis:

   (a) Do we use phase split? Justify your answer. If your answer is yes, then use the sharp split approximation to estimate the approximate vapor and liquid stream flow rates in moles/h after the separation from the flash drum.

   (b) Do we use a vapor recovery system (VRS)? If yes, then what would be the best location for VRS? If not, then why?

   (c) Are any light ends present? If yes, then what would be the destination? If no, then why?

   (d) After the separation from the flash drum, to separate the components from in the liquid stream, draw all possible alternatives of distillation train with reference to column sequencing by utilizing the heuristics of simple column sequencing.

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Marks: 70 ` **Date: 26/12/22** **Time: 105 mins**

Note: Make suitable assumptions by clearly stating them, if necessary. Write all steps clearly.

1. **(25 Marks)**
Ethylene oxide (C_2H_4O) can be produced by the oxidation of ethane (C_2H_6) in the gas phase:
$$C_2H_6 + O_2 \rightarrow C_2H_4O + H_2O$$
The reaction takes place at 450^0C and 370 psia. We desire to produce 900 mols/hr of C_2H_4O. The ratio of the oxygen to the C_2H_6 in the gross feed into the reactor is 10 to 1. Air is supplied to maintain the amount of oxygen in the process. Pure ethane is used as a feed stream. **Draw the recycle structure of the flow sheet and calculate the stream flow rates (inputs, outputs, recycle flows, reactor inlet) and EP_3 in terms of design variables**.

2. **(1+3+3+2+5+4+2+5=25 Marks)**
For the problem given with minimum approach temperature difference, ΔT_{min} = 10 °C, carry out the Energy Integration Analysis using Pinch Technology by determining the following:
(a) Net amount of heat available in the streams based on I law.
(b) Shifted temperature scales diagram with net heat in respective intervals.
(c) Construction of cascade diagram, minimum hot & cold utilities requirement, and Pinch temperature.
(d) Number of heat exchangers based on I & II law analysis.
(e) Hot end design.
(f) Cold end design.
(g) Identification of the loops.
(h) Final heat exchanger network after breaking first loop as per heuristic and restoring ΔT_{min} as and when there is a violation.

Stream No	**Condition**	**FC_p (kW/°C)**	***h* (kW/m² °C)**	**Source Temperature (°C)**	**Target Temperature (°C)**
1	Hot	3	0.25	180	60
2	Hot	1	0.35	150	30
3	Cold	2	0.4	30	135
4	Cold	5	0.45	80	140

3. **(20 Marks)**
To better understand the similarities and differences between the design of a continuous and a batch process, let us consider a very oversimplified design problem where the process consists of only a single reactor. We desire to produce product B by the reaction: $A \rightarrow B$. The cost of A is C_f (\$/mol), we operate 8150 hr/yr for a continuous plant, the desired production rate is P mol/hr, the reaction takes place by a first-order isothermal reaction, the separation of the product from unconverted reactants is free, and we cannot recover and recycle any unconverted reactants. We have to pay for the raw materials and reactor, so our cost model becomes:
$$\text{TAC} = C_f F_F 8150 + C_v V$$
The production rate is related to the fresh feed rate FF and the conversion x by the expression
$$P = F_F x$$

And the reactor volume is given by:

$$V = \frac{F_{\mathrm{F}}}{k\rho_{\mathrm{m}}} \ln \frac{1}{1-x}$$

Thus, we can write

$$\mathrm{TAC} = \frac{8150 C_{\mathrm{f}} P}{x} + \frac{C_{\mathrm{v}}}{k\rho_{\mathrm{m}} x} \ln \frac{1}{1-x}$$

Since the total annual cost becomes unbounded when x approaches either zero or unity, there must be an optimum conversion.

Suppose we do the same process in a batch reactor, where we produce n batches per year for 7500 hr/yr. Derive an expression for the total annual cost in terms of the conversion. Let the time it takes to empty, clean, and refill the reactor be t_{d} and the reaction time per cycle be t_{r}. How do the expressions for the batch process compare to the result for the continuous plant?

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