Introduction to Chemical Engineering

Problem Sheet 3 – Week 4 – October 3, 2025

Today's session serves as a review and practice opportunity. The aim is to strengthen your ability to analyze chemical processes by revisiting fundamental balance concepts and applying them to increasingly complex systems, from simple reactions to recycle processes.Practice setting up and solving material balances for both reactive and non-reactive systems.

<u>Goals</u>:

- Apply the concepts of limiting reactant identification, fractional conversion, and yield.
- Work with simultaneous reactions, including how to express outlet compositions in terms of extents of reaction and how to calculate selectivity.
- Reinforce the use of degree-of-freedom analysis as a systematic way to check that problems are well-posed.
- Extend balance concepts to a process with recycle and explore how process modifications impact efficiency and economics.

Problem 1: Reactive Systems (Fraction Conversion Specified)

The chlorination of methane occurs by the following reaction:

$$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$$

Determine the product composition if the conversion of the limiting reactant is 67%, and the feed composition in mole % is given as: 40% CH_4, 50% Cl_2, and 10% N_2.

Suggested Steps:

1. Draw diagram process with known data inserted
2. Select a basis
3. Determine limiting reactant:
   Compare maximum extent of reaction for each reactant
4. Degree-of-freedom analysis (good practice)
5. Obtain composition

Problem 2: Reactive Systems (Fraction Conversion to be calculated)

Mercaptans, hydrogen sulfide, and other sulfur compounds are removed from natural gas by various so-called "sweetening processes" that make available otherwise useless "sour" gas. H_2S is known to be toxic in very small quantities and is quite corrosive to process equipment.

A proposed process to remove H2S is by reaction with SO2:

$$\mathrm{H_2S\ (g) + SO_2\ (g) \rightarrow S\ (s) + H_2O}$$

In a test of the process, a gas stream containing 20% H2S and 80% CH4 was combined with a stream of pure SO2. The process produced 5000 kg of S (s), and in the product gas the ratio of SO2 to H2S was equal to 3, and the ratio of H2O to H2S was 10. Determine the fractional conversion of the limiting reactant.

(Hint: **ξ** will have to be calculated from the material balance equations before calculating the fractional conversion)

Suggested Steps:

1. Draw diagram process with known data inserted
2. Determine Basis
3. Degree-of-freedom analysis (good practice)
4. Balance Species, form equations, and solve ☺

Problem 3: Reactive Systems (Simultaneous Reactions)

Formaldehyde (CH_2O) is produced industrially by the catalytic oxidation of methanol according to the following reaction:

$$CH_3OH + O_2 \rightarrow CH_2O + H_2O. \quad (Reaction\ 1)$$

Unfortunately, under the conditions used to produce formaldehyde at a profitable rate, a significant portion of the formaldehyde reacts with oxygen to produce CO and H_2O, that is:

$$CH_2O + O_2 \rightarrow CO + H_2O \quad (Reaction\ 2)$$

Assume that oxygen is twice the stoichiometric amount of oxygen neededed for complete conversion of the CH_3OH to the desired products (CH_2O and H_2O) are fed to the reactor. Also, assume that 90% conversion of the methanol results, and that a 75% yield of the formaldehyde occurs based on the theoretical production of CH_2O by Reaction 1.

Determine the composition of the product gas leaving the reactor.

Problem 4: Reactive Systems (Simultaneous Reactions Again!)

Methane and oxygen react in the presence of a catalyst to form formaldehyde. In a parallel reaction, methane is oxidized to carbon dioxide and water:

$$CH_4 + O_2 \rightarrow HCHO + H_2O \text{ (Reaction 1)}$$

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O \text{ (Reaction 2)}$$

The feed to the reactor contains equimolar amounts of methane and oxygen. Assume a basis of 100 mol feed/s.

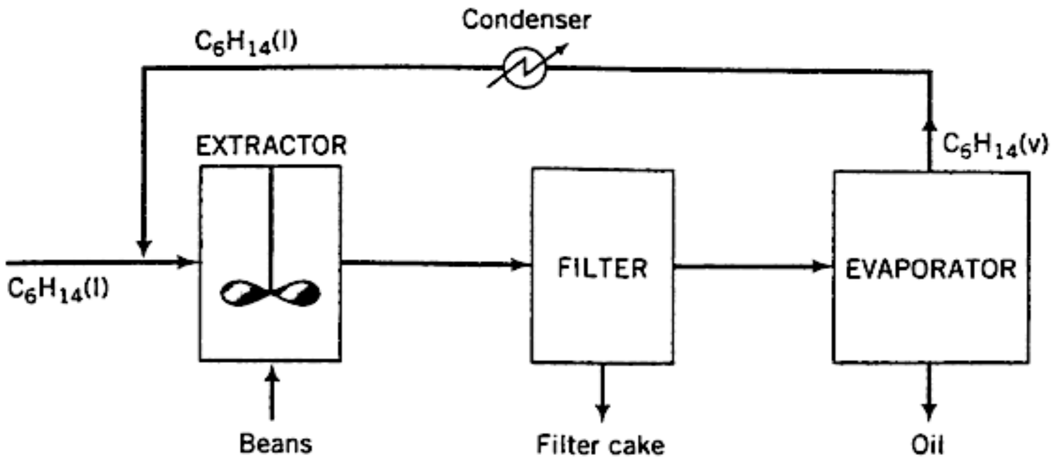
(a) Draw and label a flowchart. Use a degree-of-freedom analysis based on extents of reaction to determine how many process variable values must be specified for the remaining variable values to be calculated.

(b) Derive the expressions for the product stream component flow rates in terms of the two extents of reaction, ξ_1 and ξ_2.

(c) The fractional conversion of methane is 0.900 and the fractional yield of formaldehyde is 0.855. Calculate the molar composition of the reactor output stream and the selectivity of formaldehyde production relative to carbon dioxide production.

Problem 5: Non-Reactive Systems

In the production of a bean oil, beans containing 13.0 wt% oil and 87.0% solids are ground and fed to a stirred tank (the extractor) along with a recycled stream of liquid n-hexane. The feed ratio is 3 kg hexane/kg beans. The ground beans are suspended in the liquid, and essentially all of the oil in the beans is extracted into the hexane.The extractor effluent passes to a filter. The filter cake contains 75.0 wt% bean solids and the balance bean oil and hexane, the latter two in the same ratio in which they emerge from the extractor. The filter cake is discarded and the liquid filtrate is fed to a heated evaporator in which the hexane is vaporized and the oil remains as a liquid. The oil is stored in drums and shipped. The hexane vapor is subsequently cooled and condensed, and the liquid hexane condensate is recycled to the extractor.



(a) Draw and label a flowchart of the process, do the degree-of-freedom analysis, and write in an efficient order the equations you would solve to determine all unknown stream variables, circling the variables for which you would solve.

(b) Calculate the yield of bean oil product (kg oil/kg beans fed), the required fresh hexane feed (kg C_6H_{14}/kg beans fed), and the recycle to fresh feed ratio (kg hexane recycled/kg fresh feed).

(c) It has been suggested that a heat exchanger might be added to the process. This process unit would consist of a bundle of parallel metal tubes contained in an outer shell. The liquid filtrate would pass from the filter through the inside of the tubes and then go on to the evaporator. The hot hexane vapor on its way from the evaporator to the extractor would flow through the shell, passing over the outside of the tubes and heating the filtrate. How might the inclusion of this unit lead to a reduction in the operating cost of the process?

(d) Suggest additional steps that might improve the process economics.