Introduction to Chemical Engineering

Problem Sheet 2 – Week 3 – September 26 2025

Goals:

- Consolidating Your Foundations on Non-Reactive Systems
- Learn how to manipulate the key concepts of Reactive Systems seen in class today

This week's exercise is designed to strengthen your understanding of material balances on non-reactive systems, whether using mass balances or mole balances, and apply the fundamental concepts and definitions related to reactive systems.

Remarks:

- A splitter/splitting point **does not alter the composition of the input and output streams**; it only divides the total flow rate of the input stream into several output streams with different flow rates (see Problem 2)

Problem 1: Pure Ethanol (Material Balance – Single Unit – Non-reactive)

Suppose you want to make 1000 kg/h of pure ethanol by separating a mixture that contains 60% water and 40% ethanol. To help with the separation, you add a pure benzene stream to the distillation column. This helps remove the water from the ethanol.

The distillate that comes out of the top of the distillation column has 75% benzene, 24% water, and the rest is ethanol. As mentionned above, the process also produces pure ethanol.

Start by drawing a labeled flowchart of the process and then determine how much benzene needs to be fed into the distillation column.

Problem 2: Distillation with Reflux (Material Balance – Multiple Units – Non-reactive)

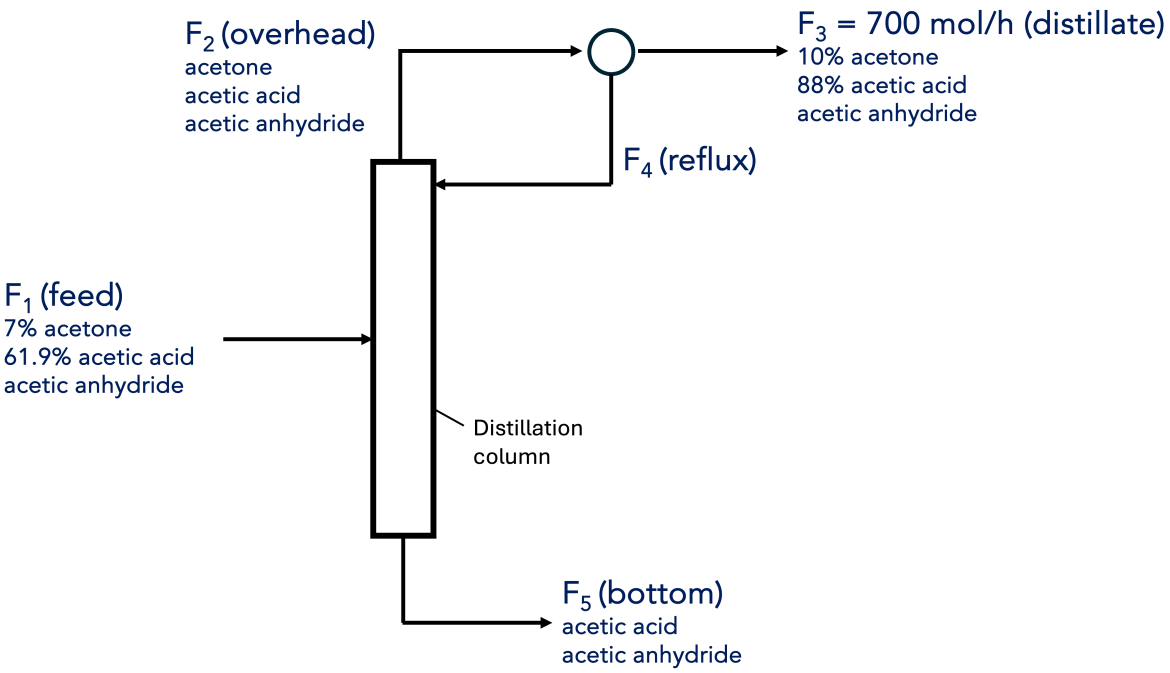
You are tasked with calculating all the flow rates in a distillation system, where a three-component mixture is separated. The feed mixture consists of 7% acetone, 61.9% acetic acid, and 31.1% acetic anhydride (all percentages are in mol %).

The overall system is designed to produce:

- A **bottoms stream** with **no acetone**
- A **distillate stream** of **700 mol/h**, containing **10% acetone** and **88% acetic acid** (in mol %).

Additionally, **60% of the overhead** is returned as **reflux** to the column.

You are required to calculate all the flows within the system (in mol/h), assuming that all compositions are given in mol %



Problem 3: Orange juice (Material Balance – Multiple Units – Non-reactive)

Fresh orange juice contains **12.0 wt% solids** (the solids include sugars, fibers, and other non-water components) and **88% water**. Concentrated orange juice contains **42.0 wt% solids** and **58% water**. Initially, the juice was concentrated using a single evaporation process, but this caused many of the **volatile flavor compounds** to escape with the water, resulting in a flat-tasting concentrate.

A new process is introduced to solve this issue. In this process, a fraction of the **fresh juice** (containing **12% solids** and **88% water**) **bypasses the evaporator**, while the remaining juice enters the evaporator and is concentrated to **58 wt% solids** and **42% water**. The concentrated stream from the evaporator is then mixed with the bypassed fresh juice to achieve a final concentration of **42% solids** and **58% water**.

Tasks:

1. **Draw and Label a Flowchart:**
    - You are asked to draw and label a flowchart for this process. Assume that only water is evaporated, meaning the solids and flavor compounds remain unaffected.
    - The species involved include:
        - **Fresh juice** (12% solids, 88% water)
        - **Evaporated juice** (58% solids, 42% water)
        - **Final product** (42% solids, 58% water)
        - **Water vapor** (the water removed by the evaporator)
    - Prove that the subsystem, where the bypass stream splits off from the evaporator feed, has **one degree of freedom** (i.e., one variable that can be controlled independently).
    - Perform a **degree-of-freedom analysis** for:
        - The **overall system**
        - The **evaporator**
        - The **bypass**
        - The **mixing point**
    - List the equations you would need to solve to determine all unknown stream variables. **Circle the variable** for which each equation would solve, but **do not perform any calculations**.

2. **Calculate the Amount of Product and Fraction of Bypassed Feed:**
    - Calculate the amount of **42% concentrate orange juice** produced per **100 kg of fresh juice** fed to the process.
    - Determine the **fraction of the fresh juice** that bypasses the evaporator.

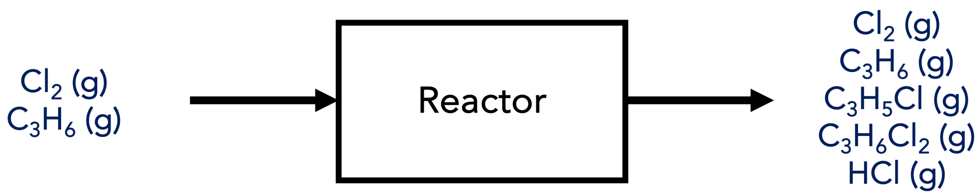
3. **Consider a Different Concentration and Suggest Drawbacks:**
    - The **volatile flavor compounds** are primarily retained in the portion of the fresh juice that **bypasses the evaporator**.
    - Consider how you could improve flavor retention by increasing the solids concentration to **90%** in the evaporator, instead of 58%. This would result in bypassing a larger fraction of the fresh juice.
    - Suggest potential **drawbacks** of this approach

Problem 4: Reactive Systems 101 (Reactive system)

Let's take a quick look at the chemistry of allyl chlorides. The two reactions of interest for this example are:

$$\text{(a)}\quad Cl_2\,(g) + C_3H_6\,(g) \rightarrow C_3H_5Cl\,(g) + HCl\,(g)$$

$$\text{(b)}\quad Cl_2\,(g) + C_3H_6(g) \rightarrow C_3H_6Cl_2\,(g)$$



Species involved:

- C_3H_6 is propylene (propene) (MW = 42.08)
- C_3H_5Cl is allyl chloride (3-chloropropene) (MW = 76.53)
- $C_3H_6Cl_2$ is propylene chloride (1,2-dichloropropane) (MW = 112.99)

The species recovered after the reaction takes place for some time are listed in the table below:

Species	mol
Cl_2	141.0
C_3H_6	651.0
C_3H_5Cl	4.6
$C_3H_6Cl_2$	24.5
HCl	4.6

Based on the product distribution, assuming that no allyl chlorides were present in the feed, calculate the following:

a. How much Cl_2 and C_3H_6 were fed to the reactor in mol?
b. What was the limiting reactant?
c. What was the excess reactant?
d. What was the fraction conversion of C_3H_6 to C_3H_5Cl?
e. What was the selectivity of C_3H_5Cl relative to $C_3H_6Cl_2$?
f. What was the yield of C_3H_5Cl expressed in grams of C_3H_5Cl to the grams of C_3H_6 fed to the reactor?
g. What was the extent of reaction of the first and second reactions?
h. In the application of green chemistry, you would like to identify classes of chemical reactions that have the potential for process improvement, particularly waste reduction. In this example, the waste is HCl(g). The Cl_2 is not considered to be a waste because it is recycled. What is the mole efficiency, i.e., the fraction of an element in the entering reactants that emerges in the exiting products, for chlorine?