THE UNIVERSITY OF JORDAN

The University of Jordan
Faculty of Engineering & Technology
Chemical Engineering Department

# Chemical Engineering Principles (0905211)

## Material Balance
## Part 1: Basics and Balance on Single unit process

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## Content

# Process Classifications

A. Based on how the process varies with time

   a. **Steady state process:** the process variable do not change with time but may change with location

   b. **Unsteady state (transient) process:** the process variables change with time

B. Based on how the process was built to operate

   a. **Continuous process:** The inputs (feed) and outputs (products) flow continuously through the process all the time.

      System is open, and usually modeled as steady flow.

   b. **Batch process:** Feed is charged into a system. The system works on the feed until processing is complete. Products are then removed .

      System is closed, with no material transfer across system boundaries except during charging and product removal.



   c. **Semibatch process:** Hybrid of batch and continuous.

      In one form the feed is added continuously, but the product is removed all at once.

      In other cases the feed is charged into the vessel in one step, but the products are removed continuously during the run.

Continuous processes may be modeled either as transient or as steady state

Batch and semibatch processes require transient models (they never reach a steady state).

# The General Balance Equation

It is the Law of Conservation of Mass, i.e. Mass can neither be created nor destroyed

$$\begin{pmatrix}\text{Accumulation}\\ \text{within system}\end{pmatrix} = \begin{pmatrix}\text{Flow In}\\ \text{through system boundaries}\end{pmatrix} - \begin{pmatrix}\text{Flow Out}\\ \text{through system boundaries}\end{pmatrix} + \begin{pmatrix}\text{Generation}\\ \text{within system}\end{pmatrix} - \begin{pmatrix}\text{Consumption}\\ \text{within system}\end{pmatrix}$$

[=] mass/time

**Accumulation = In – Out + Generation – Consumption**

Applies to total mass, components, energy, etc.



The system is any process or portion of a process chosen by the engineer for analysis.

An open system: In which material flows across the system boundary during the interval of time being studied;

A closed system: if there are no flows cross the system boundary, in or out.

Accumulation is usually the rate of change of holdup within the system, i.e. the change of material within the system. It may be

i. Positive (material is increasing),
ii. Negative (material decreasing), or
iii. Zero (steady state).

Rules used to simplify the general material balance equation:

- If the system is at steady- state,

  set accumulation= 0

- If the balanced quantity is total mass,

  set generation = 0 and consumption = 0

  (low of conservation of total mass)

- If the balanced substance is non reactive species, (neither a reactive nor a product),

  set generation = 0 and consumption = 0

**Input through system boundary** = **Output through system boundary**

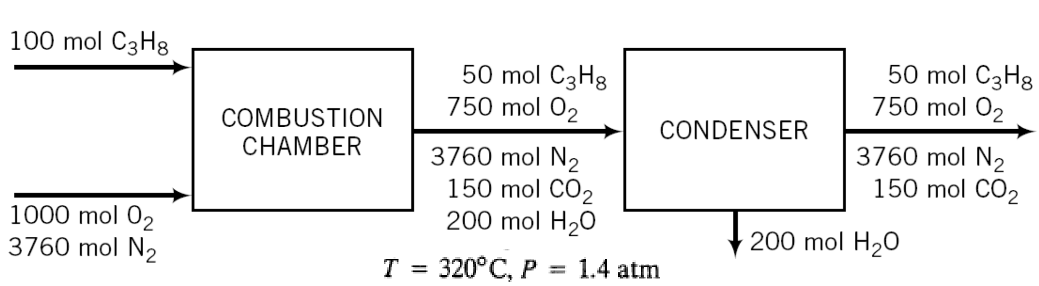


## Example

If 35,000kg of whole milk containing 4% fat is to be separated in a 6 hour period into skim milk with 0.45% fat and cream with 45% fat, what are the flow rates of the two output streams from a continuous centrifuge which accomplishes this separation?

# Flowcharts

- Flowchart is a convenient way of organizing process information for subsequent calculations.
- Use boxes to symbolize unit processes or process units and directed lines to represent material or information flows.
- To benefit from flowchart in material balance equation, we must:
  - Write the values and units of all known stream variables at the locations of the streams on the chart.
  - Assign algebraic symbols to unknown stream variables and write these variables names and their associated units on the chart.



## Notations

The use of consistent notation is generally advantage.

- For example:

  m: mass, $\dot{m}$ : mass flow rate

  n : moles, $\dot{n}$ : mole flow rate

  v : volume, $\dot{V}$ : volumetric flow rate

  x : component fractions (mass or mole) in liquid streams.

  y : component fractions in gas streams.

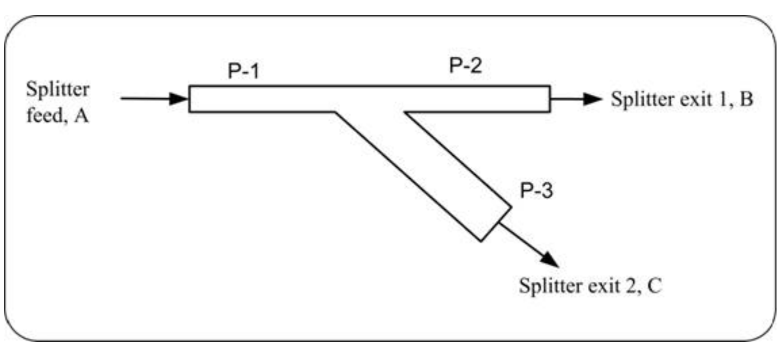




## Process units (basic functions)

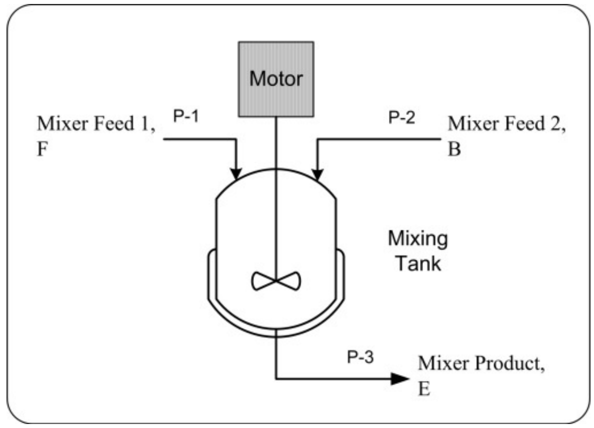
**Splitter (Divider)**

- Total mass balance is A = B + C
- The compositions of the three streams are the same ,but the mass flow rate may be different.
- There is only one independent material balance.



## Mixer (Blender)

- There are two or more entering streams and only one exit stream.
- The streams can by in any phase.

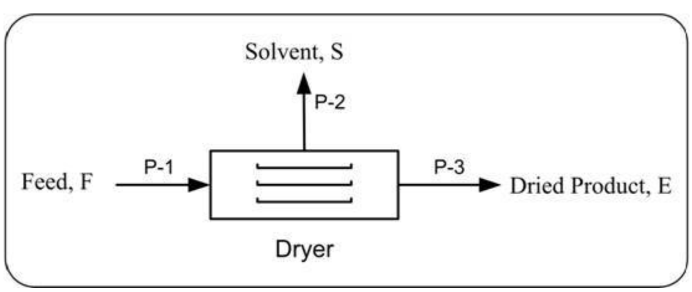






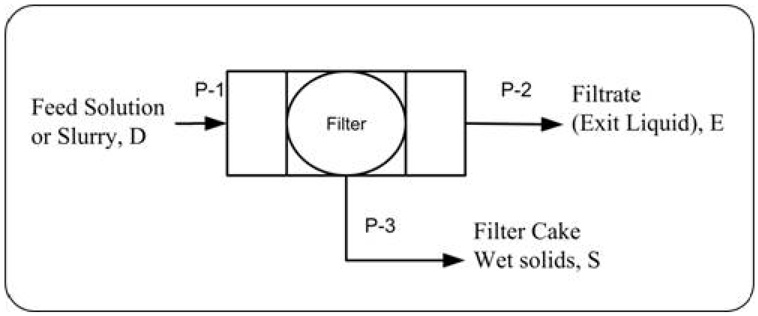

## Dryer (Direct heating)

- Solvent stream leaves as a pure vapor and free of solids.
- Exit dried solids are in the solid phase.
- Dried solids may not be solvent free.
- Feed can be solid, slurry or solution.



## Filter

- Filtrate, the exit liquid, is free of solids.
- Filtrate is saturated with soluble component.
- The filter cake leaves with some liquid attached.
- Concentration of stream E and the liquid attached to the filter cake is the same.

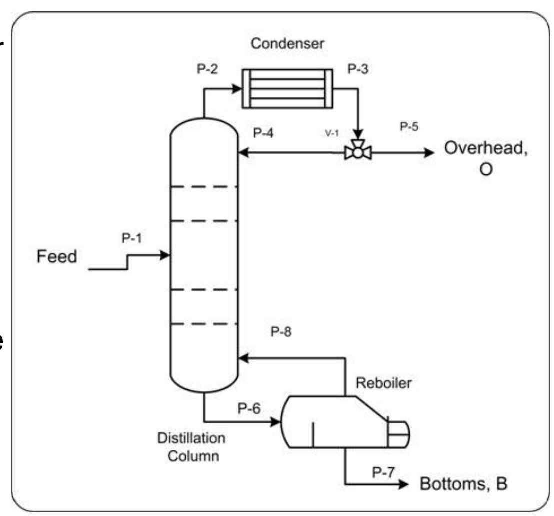




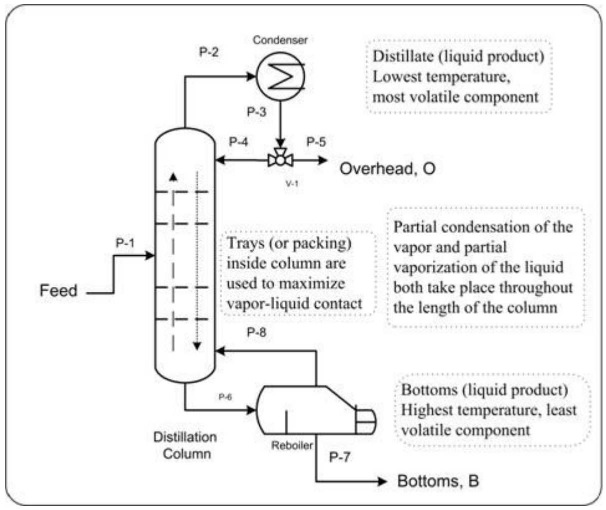

## Distillation Column

- A method of separating a substance that is in solution from it's solvent based on differences in their volatilities or separating a liquid from a mixture of liquids having different boiling points.

- The characteristics of the distillation column:
  - The distillate have the more volatile components.
  - The bottom have the less volatile components.
  - Boiling used for separation.
  - Perfect separation is impossible.



- At the distillate:
  - The more volatile species to the gas phase with low temperature. Then, outside the column the liquid product condensed by the condenser.
- At the bottom:
  - The less volatile species to the liquid phase with high temperature. Then, outside the column the liquid product go to the reboiler.

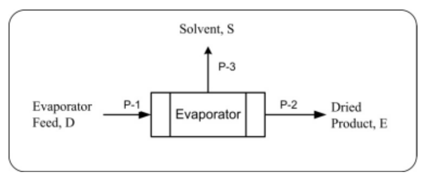


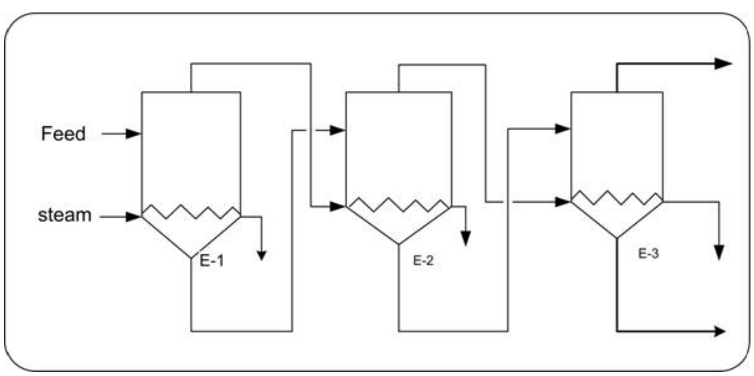





## Evaporator

- Evaporation is widespread technological process from food to chemicals.
- The multiple-effect evaporators allow decreasing consumption of energy for a concentration.

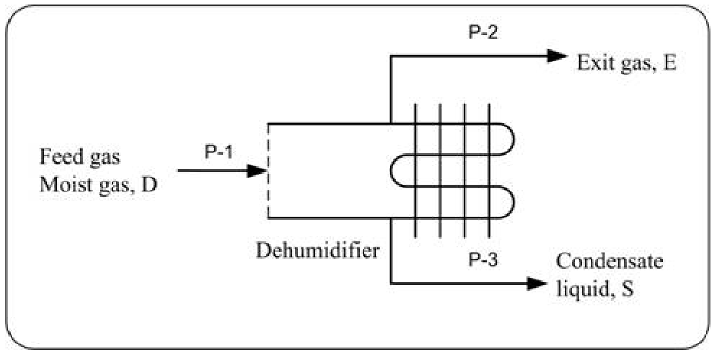



Multiple-effect evaporators

## Dehumidification

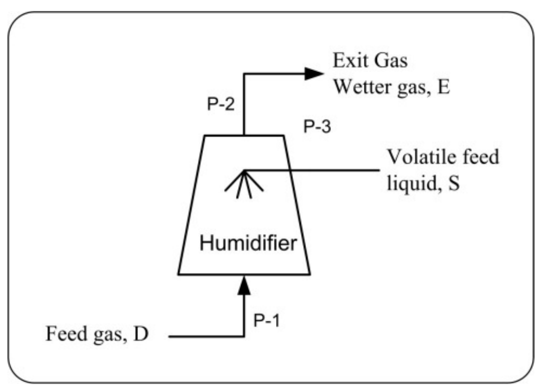
- The dehumidifier is a device that reduces the level of humidity in air with internal cooling and heating coils.
- In dehumidification processes:
  - Feed stream contains a condensable component and a non-condensable component.
  - Condensate is a liquid with the condensable component only.
  - At the Temp. & P of the process the dry gas exit stream is saturated with the condensable component.





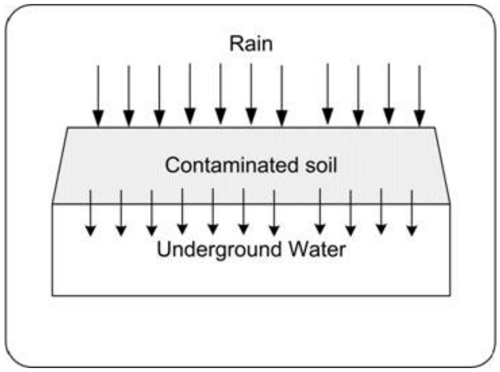

## Humidifier

- Humidifier is a device that increases the amount of moisture in indoor air or a stream air by allowing water to evaporate from a pan or a wetted surface or by circulating air through an air-washer compartment that contain moisture.
- The characteristics of the humidifier:
  - The feed gas is not saturated.
  - The liquid is evaporated in the process unit.
  - The vapor exit product may or may not be saturated.



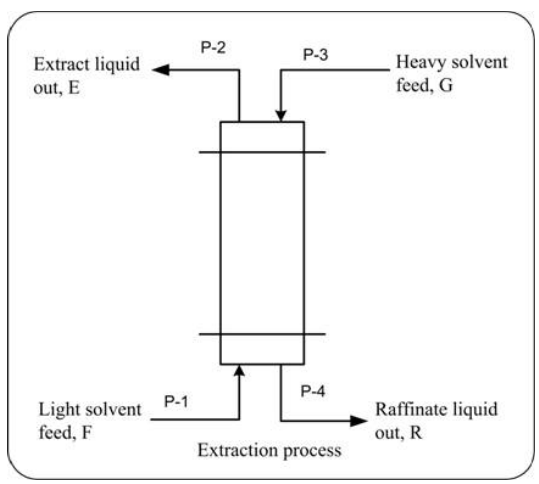
## Leaching and Extraction

- Leaching is the removal of materials by dissolving them away from solids.
- Leaching of toxic materials into groundwater is a major health concern.
- The leaching process in the industries is called extraction.






- The leaching processes:
  - The two liquid solvent must be immiscible.
  - They must have different specific gravity.
  - At least one component is transferred from one solvent to other by difference in solubility.
  - The process called liquid-liquid extraction but if one of the feed streams is a solid, the process called Leaching or liquid-solid extraction.



## Absorption (gas absorption) Desorption

- In gas absorption a soluble component is absorbed by contact with a liquid phase in which the component is soluble.

- This system is used for scrubbing gas stream of components such as:
  - Sulphur dioxide 4
  - Carbon dioxide
  - Ammonia
- We used water , amines and potassium carbonate to remove $CO_2$ from air or natural gas.

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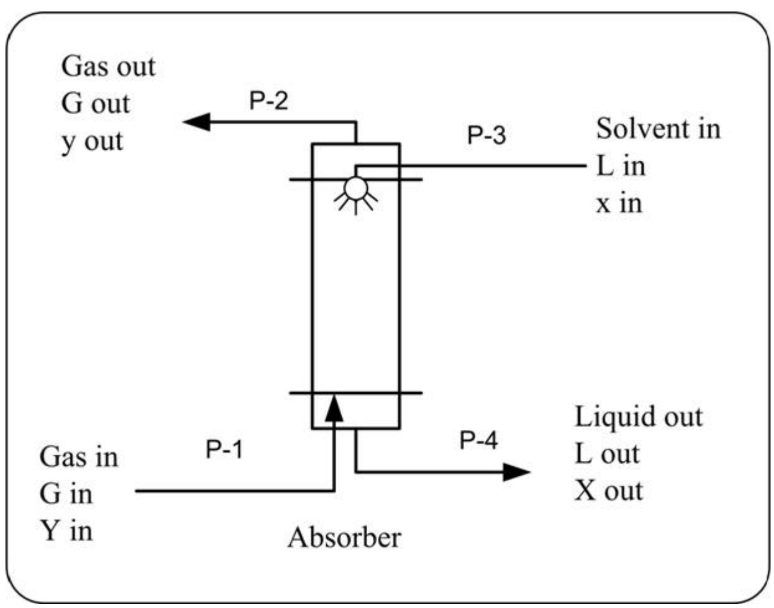
## Absorption (gas absorption) Desorption

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## Cont. Absorption system

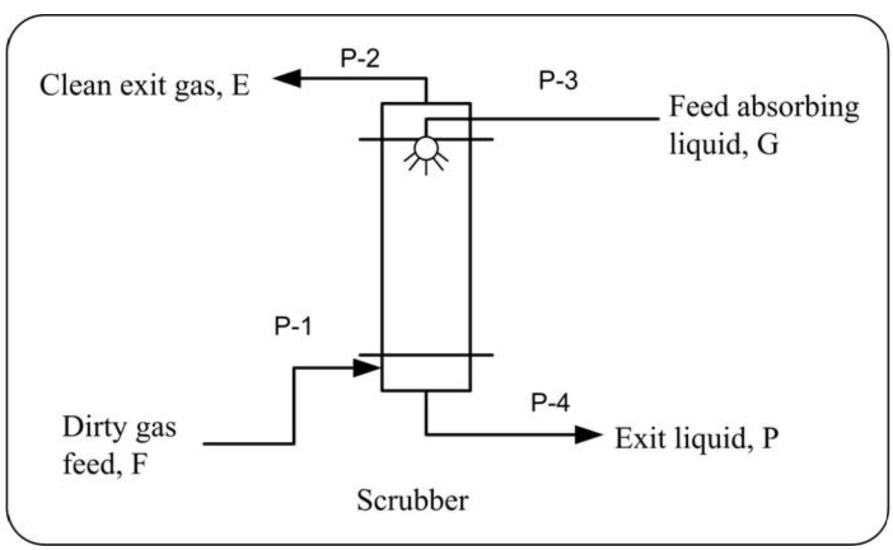
### The characteristics of the absorption processes:

- The purpose of the unit is to have the liquid absorb a component from the feed gas.
- An absorber is often called a scrubber.
- The liquid stream flows down through the tower by the gravity.
- The gas stream is pumped upwards through the tower.
- No carrier gas is transferred to the liquid.
- Generally no liquid solvent is transferred to the gas stream.
- Desorption is the same process as a gas absorption except that the component transferred leaves the liquid phase and enters the gas phase.
- Absorber is sometimes called stripper.





## Flow sheet of scrubber



## Partial condenser

- A partial condenser partly (not completely) condense a vapor stream.
- In the partial condensers:

  The feed stream contains only condensable vapor components.

  The exit streams, L and V , are in equilibrium.

  Condensation is caused by cooling and / or increasing the pressure.



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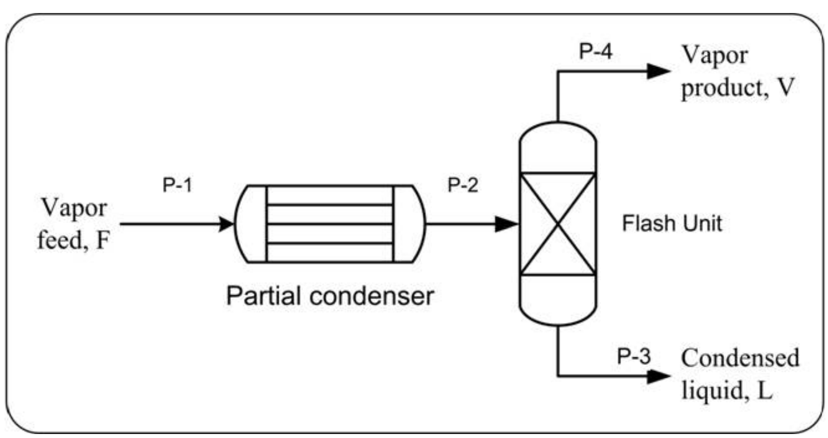
## Flow sheet of partial condenser



## Flash Vaporizer/ Distillation

- Flash vaporizer/distillation splits a liquid feed into vapor and liquid-phase products.
- The characteristics of the flash units:

  The process flow sheet is the same as a partial condenser except the feed is a liquid.

  Vaporization is caused by reducing the pressure and /or heating.

  The vapor and the liquid streams are in equilibrium.



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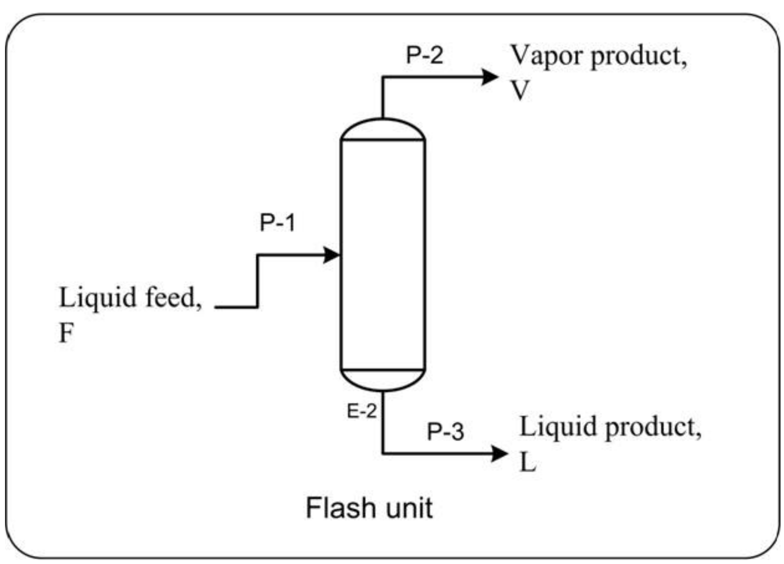
## Flash unit

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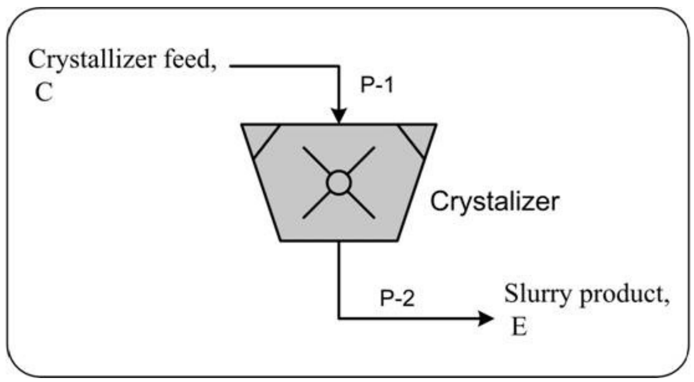
## Crystallizer

- Solid crystals are formed in the unit by a change in temperature.
- The flow sheet for crystallizer is a combination crystallizer-filter so as to separate solid crystals for solution.








## Reactors: (chemical reactor ,combustor ,furnace ,reformer)

- *In reactive processes:*

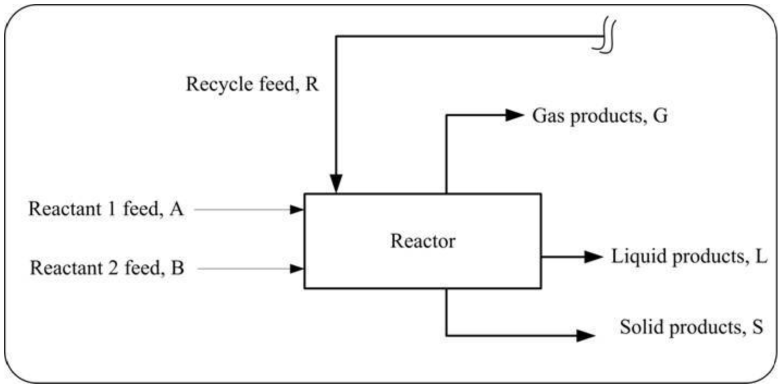
  If a single reaction takes place , put the conversion in the box.

  A reactor is often named by the reaction taking place.

  A reactor sometimes preceded by a fictitious mixer if the combined reactor feed is specified or must be determined.

  Multiple exit streams are shown to remind you to watch for exit streams that separate because of their different phases.
- A chemical reactor carries out a chemical reaction that converts molecular species in the input to different molecular species in the output where chemical compound looses it's identity.

## Reactors




- There are various type of reactor used in industry, the most common type ones are:
  - Batch reactor
  - Plug flow reactor
  - Packed bed reactor
  - Continuous stirred tank reactor
  - Fluidized bed reactors



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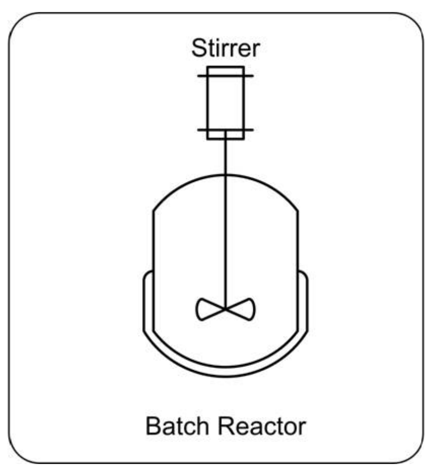
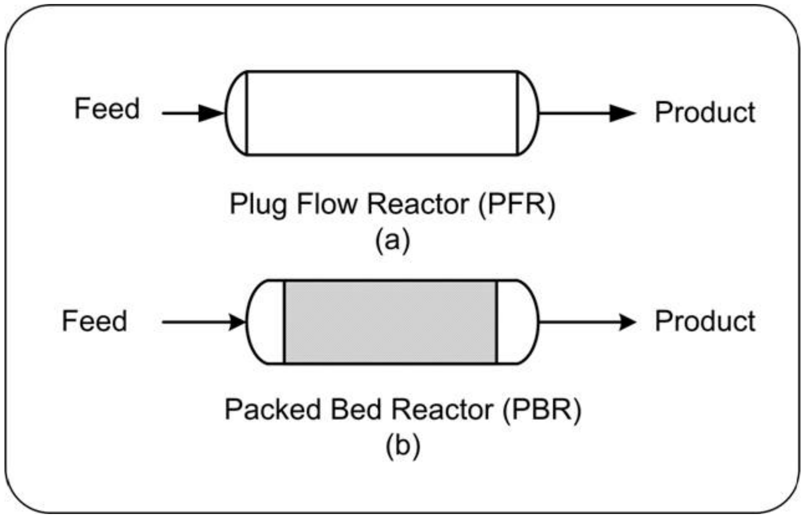
## Batch reactor

- key characteristics of batch reactors:
  - Un steady state operation (by definition ).
  - No spatial variation of concentration or temperature i.e.
  - -lumped parameter system
  - - used for small scale operation
  - - suitable for slow reaction
  - - used for liquid-phase reaction
  - - charge-in/clean-up times can be large.



## Plug flow reactor & Packed bed



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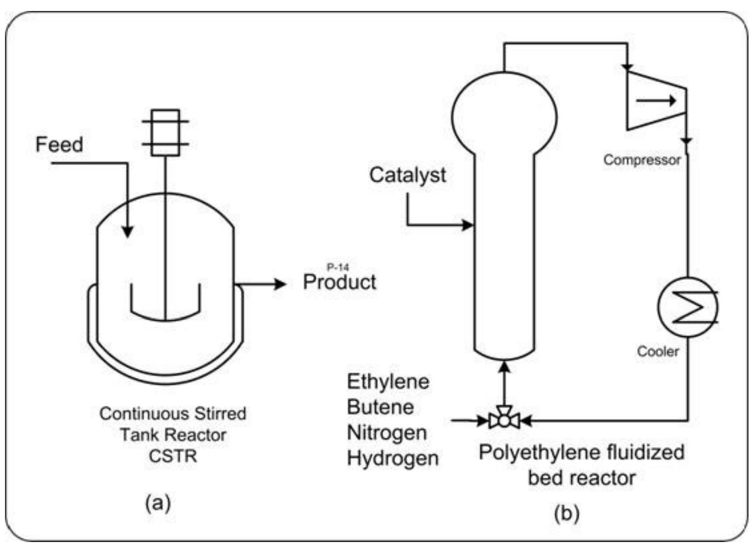
## Continuous stirred tank reactor and Fluidized bed reactor



## Example

A mixture containing 10% Ethanol (E) and 90% $H_2O$ (W) by weight is fed to a distillation column at the rate of 1000 kg/h. The distillate contains 60% Ethanol and the distillate is produced at a rate one tenth that of the feed. Draw and label a flowchart of the process. Calculate all unknown stream flow rates and composition?

## Type of balance

1. Differential Balances:
   - The balance describes what happening in a system at an instant in time, i.e.
   - written in terms of rates of change of the specified quantity with respect to time(rate of input, generation, …etc)
   - Usually the best choice for a continuous process.
   - When formulated for an instant in time, the result is an ordinary differential equation.

- Example: a worker said I get paid $10.0/hr.



2. Integral Balances : written in terms of the amounts of a specified quantity over a period of time or between two instants of time
   - It describes the overall effect.
   - Often a good choice for batch processes

- Example: a water storage tank at the start contains 5 liters of water, after 30 minutes of water flowing to the tank, it is found to contain 50 liters of water.
  - In this case the accumulated water after 30 minutes is 45 liters of water.
  - Accumulation =(final output – initial input )= 50 - 5 =45 liters

## Basis of calculation

It is an amount or flow rate of one the process stream.  It is recommended to consider that:

1. If a stream amount or flow rates is given in the problem statement, use this as the basis of calculation.
2. If no stream amount or flow rates are known, assume one, preferably a stream of known composition.
3. If mass fraction are known, choose a total mass or mass flow rate of that stream (e.g., 100  kg or 100 kg/h)
4. If mole fraction are known, choose a total number of moles or a molar flow rate.



## General Problem Solving Approach

1. Read the problem thoroughly. Understand what is required for the answer.
2. Make a sketch or flowsheet of the problem.
3. Write down the known and label unknown stream variables.
4. Choose a calculation basis.
5. Check the specification of the problem (degrees of freedom). Can it be solved as is, or is more information needed?
6. Determine what additional data, if any, are needed. Find them.
   - Be sure to indicate the source and applicability of anything you bring from outside.

7. Write the required equations.
   - Material Balances -- NC +1 can be written, NC are independent.
   - Energy Balance
   - Specifications
     i. Assigned values of stream variables.
     ii. Fractional Recoveries.
     iii. Composition Relationships ($x_1$=K*$x_2$).
     iv. Flow Ratios.
   - Physical Properties
   - Constraints
8. Keep track of units. They can help tell if an equation is complete. If the problem units are mixed, you may want convert all quantities to a common set of units, but probably should wait until you're sure which numbers you'll need.
9. Solve the equations for the unknowns.
   - Use a solution strategy. Solve the equations in a planned order. Often, this allows sequential rather than simultaneous solution.
10. Scale the answer.
11. Check the solution. Does it make sense?



## Example

One thousand kilograms per hour of a mixture of benzene (B) and toluene (T) containing 50% benzene by mass is separated by distillation into two fractions. The mass flow rate of benzene in the top stream is 450 Kg B/h and that of toluene in the bottom stream is 475 Kg T/h. The operation is at steady-state. Write balance on benzene and toluene to calculate the unknown component flow rate in the output streams.

## Integral balance on batch process

**In Batch process:**

Feed is charged into a system at $t = t_o = 0.0$, *and thus the initial number of* ***mole of product*** $n = n_o$

The reaction is terminated at **time** $t = t_f$ , the product will be withdrawn and $n = n_f$

Between $n_o$ and $n_f$, no product enters or leaves the reactor

Balance on the product

Accumulation = ~~In~~ – ~~Out~~ + Generation – ~~Consumption~~

Accumulation = Generation

Accumulation = Final output – Initial Input

For any species (reactant or product), the balance equation

Accumulation = Generation – Consumption

Accumulation = Final output – Initial Input

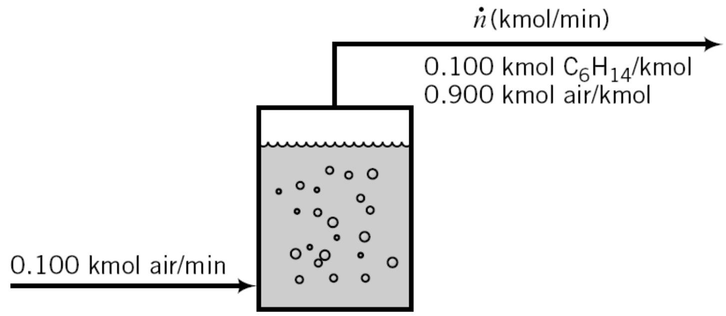
Final output + Consumption = Initial Input+ Generation

*Example*

Two methanol-water mixture are contained in separate flasks. The mixture contains 40.0 wt% methanol, and the second contains 70.0 wt% methanol. If 200g of the first mixture is combined with 150 g of the second, what are the mass and composition of the product?

## Example *Integral Balance on a Semibatch Process*

Air is bubbled through a drum of liquid hexane at a rate of 0.100 kmol/min. The gas stream leaving the drum contains 10.0 mole% hexane vapor. Air may be considered insoluble in liquid hexane. Use an integral balance to estimate the time required to vaporize 10.0 m³ of the liquid.



## Example

An experiment on the growth rate of certain organisms requires an environment of humid air enriched in oxygen. Three input streams are fed into an evaporation chamber to produce an output stream with the desired composition.

A: Liquid water, fed at a rate of 20.0 $cm^3$/min

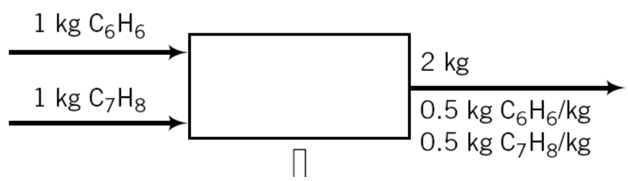
B: Air (21 mole% $O_2$, the balance $N_2$)

C: Pure oxygen, with a molar flow rate one-fifth of the molar flow rate of stream B

The output gas is analyzed and is found to contain 1.5 mole% water.

calculate all unknown stream variables.

## Flow chart scaling

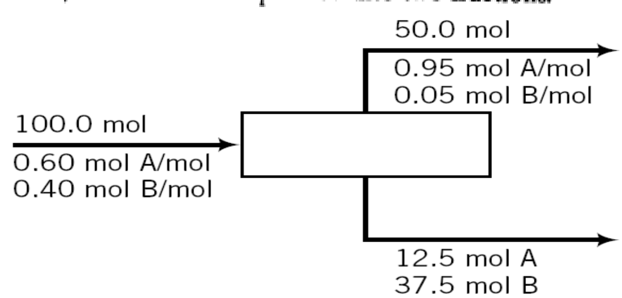



Changing the values of all stream amounts or flow rates by proportional amounts while keeping stream compositions unchanged is refer to as scaling (up or down)



## Example

A 60–40 mixture (by moles) of A and B is separated into two fractions.




It is desired to achieve the same separation with a continuous feed of 1250 lb-moles/h. Scale the flowchart accordingly.

## Example

Suppose 3.0 kg/min of benzene and 1.0 kg/min of toluene are mixed.


What is the output mass flow rate and the stream composition?



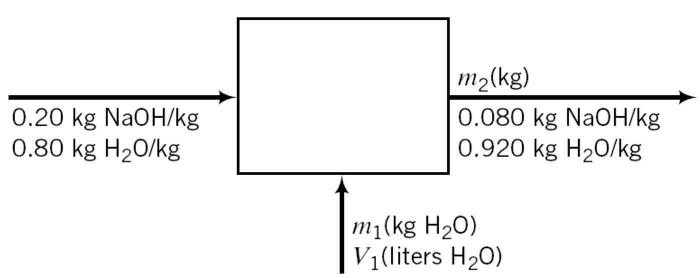
## Keep in mined that, for nonreactive system

1. ***The maximum number of independent equations that can be derived by writing balances on a nonreactive system equals the number of chemical species in the input and output streams.***

2. ***Write balances first that involve the fewest unknown variables.***

## Example ***Balances on a Mixing Unit***

An aqueous solution of sodium hydroxide contains 20.0% NaOH by mass. It is desired to produce an 8.0% NaOH solution by diluting a stream of the 20% solution with a stream of pure water. Calculate the ratios (liters $H_2O$/kg feed solution) and (kg product solution/kg feed solution).



## Degree of freedom analysis

- A degree of freedom Analysis (DFA) is an important tool for systematic analysis of black flow diagrams.
- It shows if the problem is a solvable or not.

1. Draw and completely label a flowchart.
2. Determining number of unknown variables in the chart
3. Determine the number of independent equations relating to them

$$n_{df} = (\,:n_{unknowns} - n_{indep\ eqns})$$

We have three possible results of $n_{df}$:

a. $n_{df}$ = 0.0 The system is completely defined ( Unique solution ).

b. $n_{df}$ > 0.0 The system is under-defined (Infinite number of solutions)

c. $n_{df}$ < 0.0 The system is over-defined (Many boundaries).

## Source of equations

1. Material balances for a non reactive process.
2. Energy balances.
3. Process specifications given in the problem statement.
4. Physical properties and laws.
5. Physical constraints, for examples, for any stream $f$,

$$\sum_f x_i = 1, \sum_f y_i = 1$$

6. Stoichiometric relations.

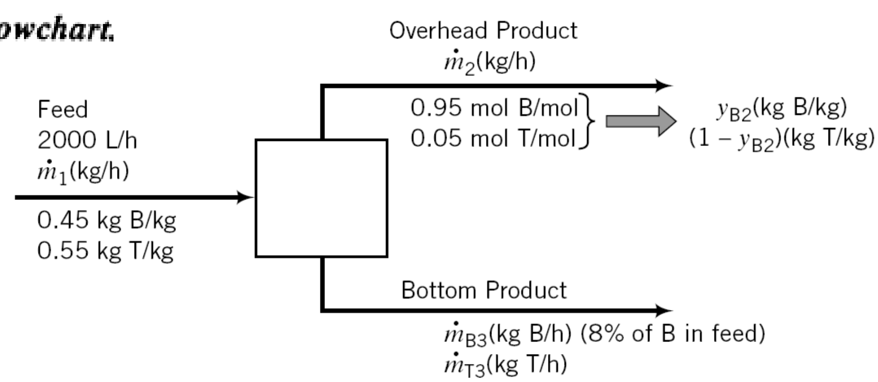
$$2H_2 + O_2 \longrightarrow 2H_2O)$$



## Example **Material Balances on a Distillation Column**

A mixture containing 45% Benzene (B) and 55% Toluene (T) by weight is fed to a distillation column at a rate of 2000 L/hr (SG of the mixture is 0.872). The distillate (top or overhead product) contains 95 mole% B and the bottom produced stream contains 8% of the B fed to the column (meaning that 92% of B leaves with the distillate) . Determine the mass flow rate of the over head product stream and the mass flow rate and composition (in mass fraction) of the bottom product?

***the flowchart.***



Please go back to the text book and try to solve example 4.3-4 (a and b) (p. 100), be ready for **quiz**

## Your task now is to

Synthesis a process to produce vinyl chloride ($C_2H_3Cl$) to a petrochemical plant at a rate of 400,000 ton/year of $C_2H_3Cl$.