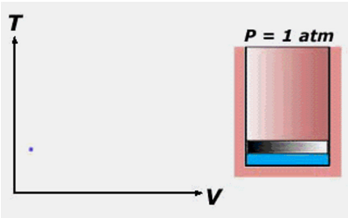
Chapter 2



Processes and Process Variables

Course Learning Outcomes

At the end of this course students will be able to

- Calculate the **composition** in term of mole fractions when the composition of a mixture is given in term of mass fractions and vice versa.
- Determine the **average molecular weight** of a mixture from the mass or molar composition of the mixture.

3.1 Mass and Volume

- ***Density*** **(ρ) is mass per unit volume**
  - kg/m^3, g/cm^3, and lb_m/ft^3
  - use to relate mass and volume
- ***Specific Volume*** **is volume per unit mass**
  - m^3/kg, cm^3/g, and ft^3/lb_m
  - an inverse of density
- ***Specific Gravity*** **is the ratio of density ρ and ρ_{ref}**
  - $SG = \rho / \rho_{ref}$
  - The reference ρ most commonly used is water at 4.0 °C
  - $\rho_{ref}(H_2O, 4.0\ °C) = 1.000\ g/cm^3$
    $1000\ kg/m^3$
    $62.43\ lb_m/ft^3$

Specific gravity of some compounds are listed in Table B.1

Mass,Volume, specific gravity and density - Test yourself

- What is the unit of specific gravity?
- If a substance A and substance B each have a density of 1.34 g/cm^3, must 3 cm^3 of A have the same mass as 3 cm^3 of B?
- If a substance A and substance B each have a specific gravity of 1.34, must 3 cm^3 of A have the same mass as 3 cm^3 of B **?**
- What happens to the specific gravity and hence density of a liquid if its temperature increases**?**

Mass, Volume and Density

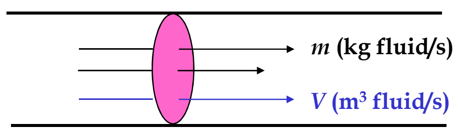
- ***Example*** **– Calculate the density of mercury in lb_m/ft^3 from a tabulated specific gravity, and calculate the volume in ft^3 occupied by 215 kg of mercury.**

Test yourself

- **If dibromopentane (DBP) has a specific gravity of 1.57, what is the density in (a) g/cm^3 (b) lb_m/ft^3 and (c) kg/m^3?**

Flowrate

- *Flow rate* **– rate at which material is transported through process line**
  - *Mass flow rate* **(mass/time) kg/s or lb_m/s**
  - *Volumetric flow rate* **(volume/time) m^3/s or ft^3 /s**
- **The mass and volume is related by the fluid *density* (ρ)**
- **The *density* (ρ) of a fluid can be used to convert known *volumetric flow rate* to the *mass flow rate* and vice versa**



Chemical Composition

- *Atomic Weight* **– the mass of atom on a scale that assign ^{12}C a mass exactly 12.**
- *Molecular Weight* **–the sum of atomic weight of atoms that constitute a molecule**
  - *Atomic weight* **of Oxygen (O) = 16**
  - *Molecular Weight* **of molecular Oxygen (O_2) = 32**
- *Gram-mole* **– amount whose mass is equal to its molecular weight**
  - **units used – gmol, lb_m-mole, kmol**
  - **If *Molecular weight* of a substance is *M*, then there are *M* kg/kmol, *M* g/mol and *M* lb_m/lb-mole of this substance**
  - **Carbon monoxide (CO) has a molecular weight of 28;**
    - 1 mol of (CO) therefore contains 28 g
    - 1 lb_m-mole of (CO) contains 28 lb_m and
    - 1 kgmol of (CO) contains 28 kg

Molecular Weight

- **Example** : 34 kg of ammonia (NH_3): M = 17 are equivalent to

  4 lb-moles of ammonia are equivalent to

- *One gram-mole of any species contains 6.02 x 10 ^{23} (Avogadro's number) molecules of that species*

Conversion of mass flowrate to molar flow rate

- The molecular weight of a species can be used to relate the mass flow rate to corresponding molar flow rate
- Example: If ammonia (NH_3): M = 17 flows through a pipeline at a rate of 100 kg/h the molar flowrate of the of are equivalent to

  If the output stream of a reactor contains NH_3 flowing at a rate of 850 lb-moles/min, the corresponding flowrate is

Mass and Mole Fractions

- Process streams occasionally contain more than one substance
- To define the composition of mixture we need

  Mass Fraction :

$$x_A = \frac{\text{mass of A}}{\text{total mass}}\left(\frac{\text{kg A}}{\text{kg total}} \text{ or } \frac{\text{g A}}{\text{g total}} \text{ or } \frac{\text{lb}_\text{m}\text{ A}}{\text{lb}_\text{m}\text{ total}}\right)$$

  Mole Fraction :

$$y_A = \frac{\text{moles of A}}{\text{total moles}}\left(\frac{\text{kmol A}}{\text{kmol total}} \text{ or } \frac{\text{mol A}}{\text{mol total}} \text{ or } \frac{\text{lb-moles A}}{\text{lb-moles total}}\right)$$

The *percent by mass* of A is 100 x_A, and the *mole percent* of A is 100 y_A

Average Molecular Weight

- *Average molecular weight* - Average of molecular weight $\overline{M}$ of a mixture
- Base on *mole fraction*

$$\overline{M} = y_1 M_1 + y_2 M_2 + \ldots = \sum_{\text{all components}} y_i M_i$$

- Base on *mass fraction*

$$\frac{1}{\overline{M}} = \frac{x_1}{M_1} + \frac{x_2}{M2} + \ldots = \sum_{\text{all components}} \frac{x_i}{Mi}$$

- Test your self

  a. Calculate the average molecular weight of hydrocarbon gas mixture having the molar composition of 90% methane, 5% ethane and 5% propane.

  b. Using the average molecular weight obtained from question (a), calculate the percent mass composition of methane, ethane and propane.

Concentration

- ***Mass concentration*** is the mass of component per unit volume of the mixture (g/cm^3, lbm/ft^3 or kg/m^3)
- *Molar concentration* is the number of moles of the component per unit volume of the mixture (mol/cm^3, $lb\text{-}mole/ft^3$ or $kmol/m^3$)
- *Molarity* is the value of the molar concentration of the solute expressed in ***gram-moles solute/liter solution***
  - 2-molar solution of *A* contains 2 mol *A*/ liter solution
- Concentration factor can be used to relate *mass* (*molar*) flow rate of a component of a continuous stream to the total volumetric flow rate of the stream

- **Given:** 6 liters of 0.02-molar solution of NaOH contains

$$\frac{6\ \text{liters}}{} \left| \frac{0.02\ \text{mol NaOH}}{\text{liter}} \right. = \boxed{0.12\ \text{mol NaOH}}$$

Conversion of mass, molar and volumetric flow rate

A 0.5 molar aqueous solution of sulfuric acid flows into a process unit at a rate of 1.25 m^3/min. The specific gravity of the solution is 1.03. Calculate

(1) the mass concentration of H_2SO_4 in kg/m^3,

(2) the mass flow rate of H_2SO_4 in kg/s, and

(3) the mass fraction of H_2SO_4

Solution for (2) and (3)

Parts per Million (ppm) and Parts per Billion (ppb)

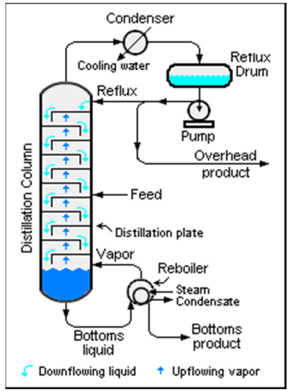
- Concentration of trace species (present in extremely small amount) in mixtures of gases or liquids
- **Defined as mass ratios (usually for liquid) or mole ratio (usually for gases)**
- Signify how many parts (e.g. gram, moles) of the species present per million or billion parts (gram, moles) of the mixture
- If y_i is the fraction of component *i* in the gas or liquid mixture, then by definition

$$ppm_i = y_i \times 10^6$$

$$ppb_i = y_i \times 10^9$$

Example: Use of ppm

- The current OSHA limit for HCN in air is 10.0 ppm. A lethal dose of HCN in air (from the Merck Index) is 300 mg/kg of air at room temperature. How many mg HCN/kg air is the 10.0 ppm? What fraction of the lethal dose is 10.0 ppm?



Process and Process Equipment in Chemical Industry

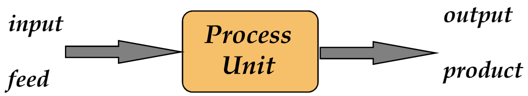
Course Learning Outcomes

At the end of this course students will be able to

1. Describe **chemical engineering process terms** such as distillation, absorption, scrubbing, liquid extraction, crystallization, adsorption and leaching.
2. Explain **various types of equipment** involved in chemical engineering processes

Process and Process Unit

- *Process* - any operation that causes a physical or chemical change in a substance or a mixture of substances
- Material enters a process is referred as *input* or *feed*
- Material leaves is called as *output* or *product*
- *Process Unit* is an apparatus for carrying out the process



Process Units

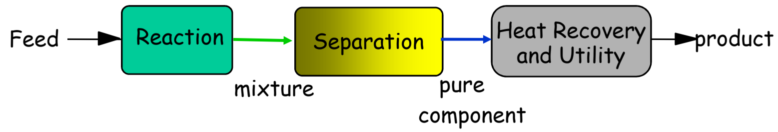
Adsorption
Absorption
Distillation
Extraction
Filtration
Stripping
Evaporation
Condensation
Crystallization
Heating
Cooling

Absorber
Adsorber
Boiler
Compressor
Decanter
Distillation column
Dryer
Heat exchanger
Fan

Pump
Scrubber
Settler
Stripper
Evaporator
Condenser
Vaporizer
Mixer
Reactor

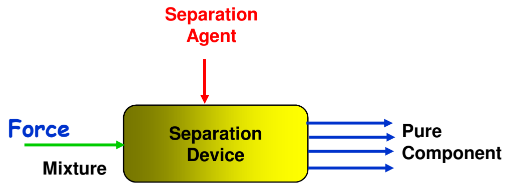
Process

- **Overall schematic of chemical process industry**



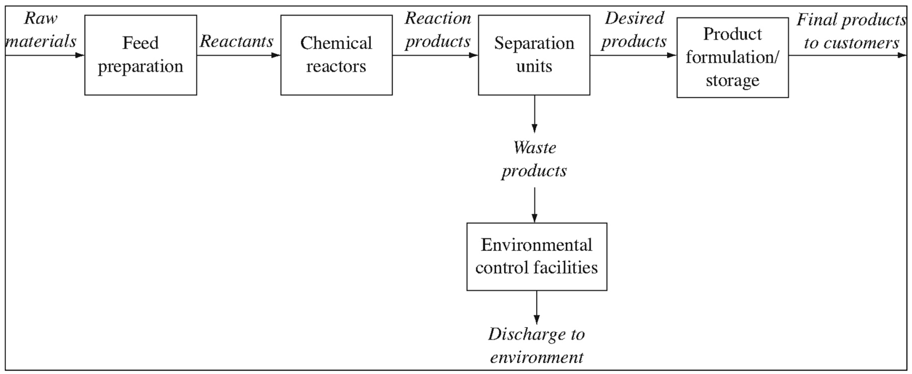
- **Characteristic of Separation Process**

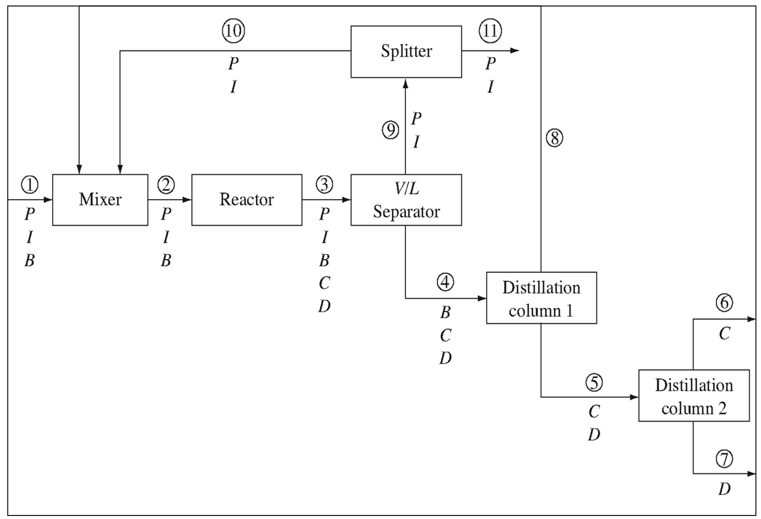
Consist of

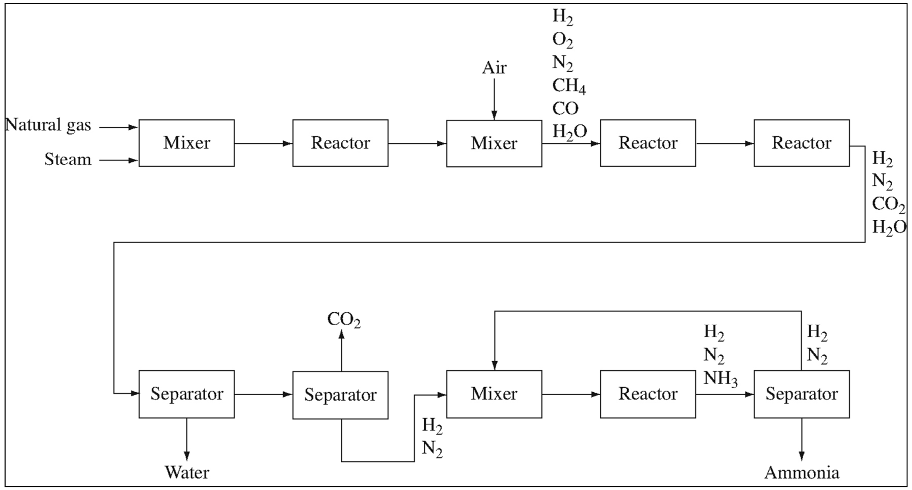


Separating Agent

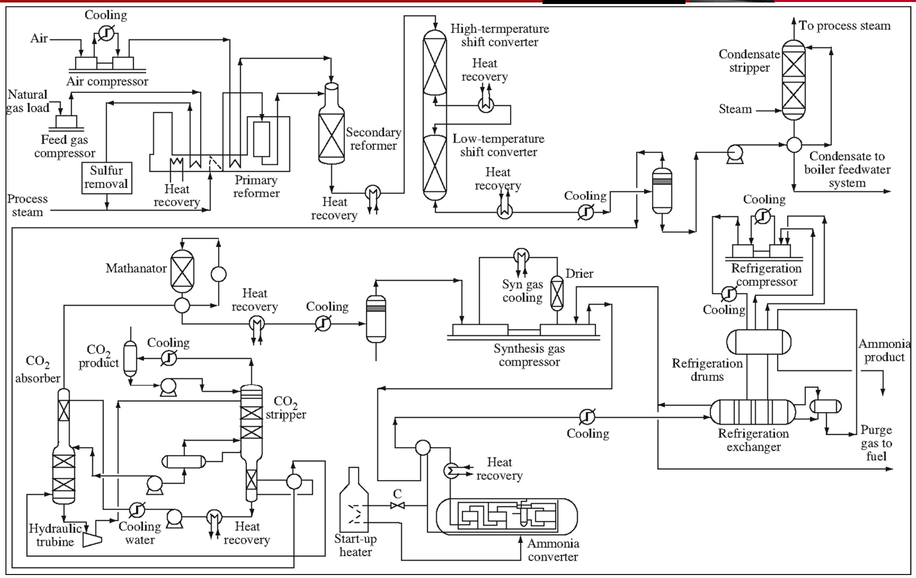
(i) Heat
(ii) Solvent
(iii) Pressure
(iv) Gravity or Mechanical





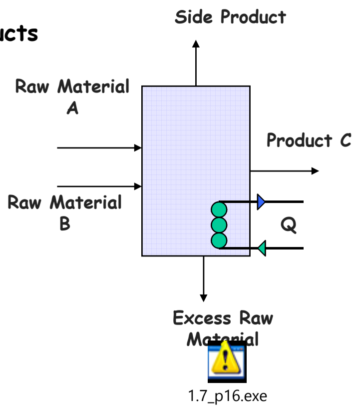


Process Flow Diagram



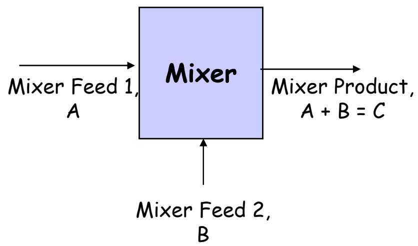
Reaction

- Raw materials reacted to form products
- Mechanism
  - Material balance
  - Energy balance
- Type of reactions
  - Exothermic (releasing heat)
  - Endothermic (absorbing heat)
- Example
  - $S + O_2$ ---> SO_2
- Equipment : Reactor

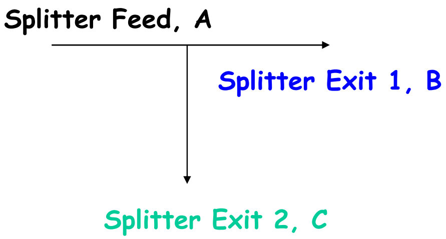


Mixing

- There are two or more entering streams
- There is only one exit stream, a “mixed” stream
- The streams can be any phase, gas, liquid or solid.
- The total balance is A + B = C
- Involving material balance



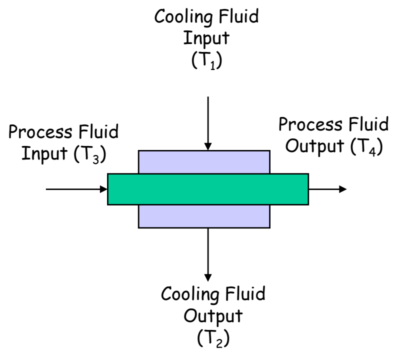
Splitting



- The total balance is A = B + C
- Composition of Streams A, B and C is the same for each.
- There is only one independent material balance since all compositions are equal.
- Involving material balance

Cooling

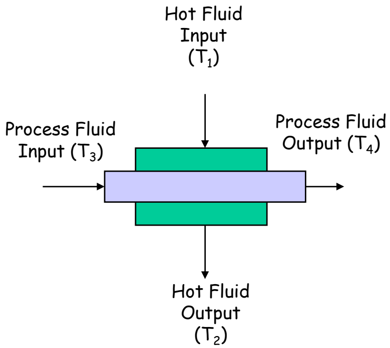
- Process fluid being cooled
- Heat being transferred from process fluid to the cooling fluid
- Mechanism
  - Heat balance
- Equipment : Heat Exchanger, Cooler



$T_3 > T_4 > T_2 > T_1$

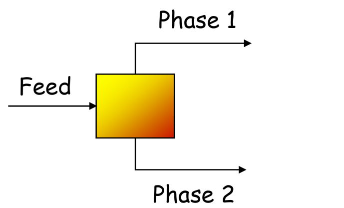
Heating

- Process Fluid is being heated
- Heat is being transferred being from Hotter Fluid to Process Fluid
- Mechanism
  - Heat balance.
- Equipment : Heat Exchanger

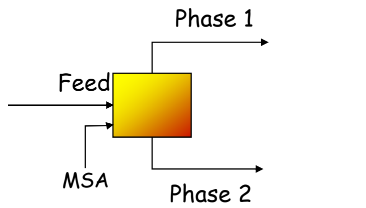


$T_1 > T_2 > T_4 > T_3$

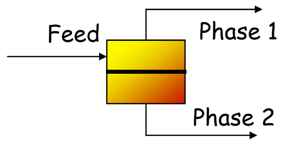
Separation



Separation by phase creation

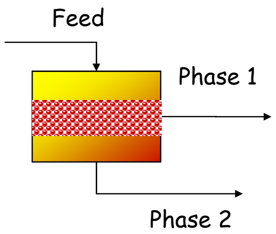


Separation by phase addition

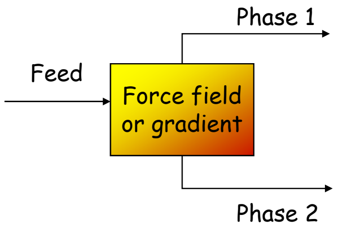


Separation by barrier

Separation



Separation by solid agent



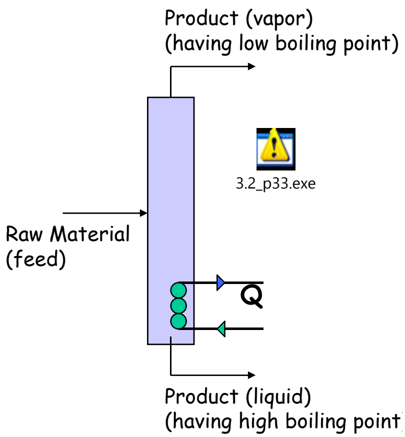
Separation by Force Field or Gradient

Separation Processes and Separating Agents by Phase Creation or Addition

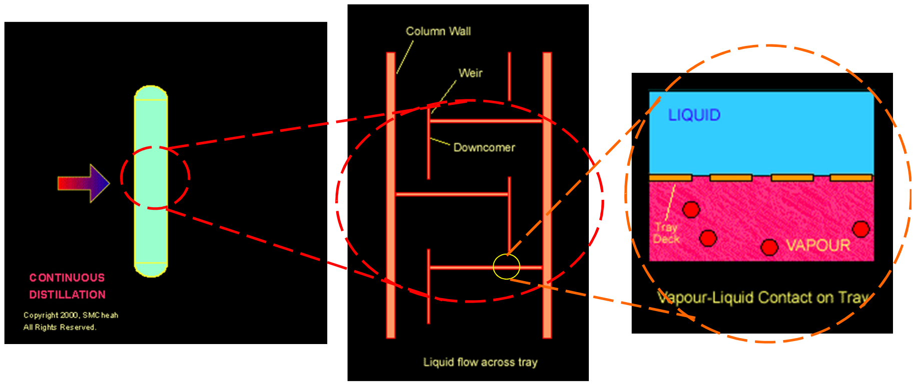
Process	Separating agent(s)	Application(s)
Absorption	Solvent	Removal of CO_2 and H_2S from natural gas with amine solution.
Adsorption	Solid Adsorbent/resin	Separation of meta- and paraxylene, air separation, water demineralization
Distillation	Heat	Propylene/propane separation, production of gasoline from crude oil, and air separation.
Evaporation	Heat	Water desalination and manufactured of sugars.
Stripping	Stripping Gas	Removal of benzene from wastewaters.
Extraction	Solvent	Recovery of benzene, toluene, xylenes from gasoline reformate, removal of caffeine from coffee.
Drying	Heat	Drying of ceramics, plastics and foods.

Distillation

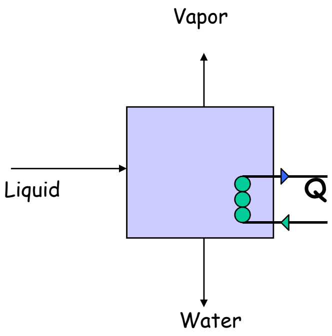
- Raw Material (liquid or gas) is being separated by using
  - Heating
  - Contact between 2 phases (vapor & liquid)
- Material and energy balance needs to solve simultaneously
- If there is no packing and stages in the distillation column normally it is called flash column.
- Use to separate raw oil to gasoline, tar and coke.



Distillation occurs because of the differences in the vapor pressure (volatility) of the components in the liquid mixture

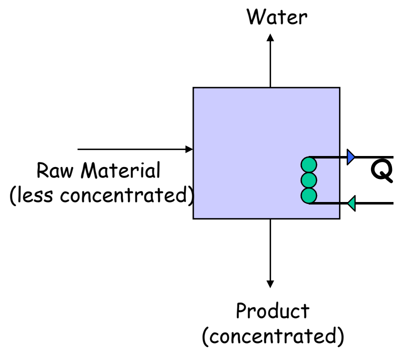


Flash Vaporizer (Flash Distillation)



- Pressure reduction and/or heating will change the liquid into two phases: vapor and liquid.
- Involving heat and energy balances
- Example:
  - Recovery of water from sea water.

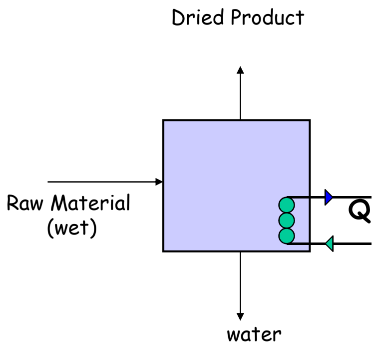
Evaporation



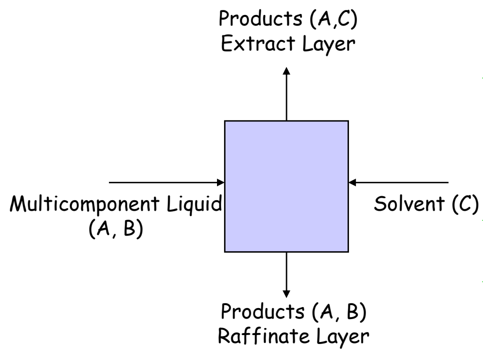
- Heating mechanism will withdraw the water from the raw material
- Process Fluid will become concentrated
- Involving heat and energy balances
- Equipment : Evaporator

Drying

- Water being withdrawn from raw material through heating mechanism
- Involving heat and energy balances
- Example
  - Drying of clothes
  - Process of making dry salted fish



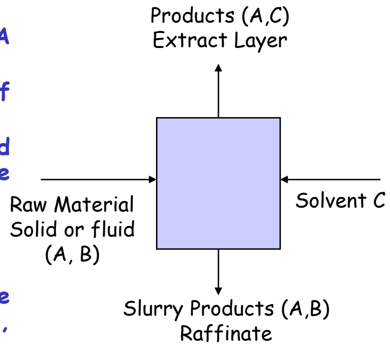
Extraction (Liquid-Liquid)



- Multicomponent Liquid being separated using extraction technique by utilizing solvent
- Terminology:
  - Component A : solute
  - Component C : solvent
  - Component B and C : solution
- Involving material balance
- Example:
  Separation of Water (A), Chloroform (B), using Acetone (C)

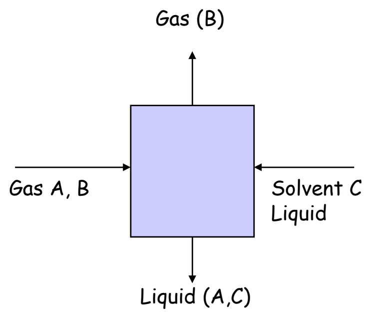
Leaching (Solid Liquid Extraction)

- **Mechanism**
  - Solvent (C) will extract solute A from slurry B
  - Extract layer will consist of components A and C
  - Some of the solute A left behind with solid B is called raffinate layer
- **Involving material balance**
- **Example**
  - production of vegetable oils where organic solvent such as hexane, acetone and ether are being used
  - extraction of oil from peanuts, soybeans, sunflower seeds and palm kernel.



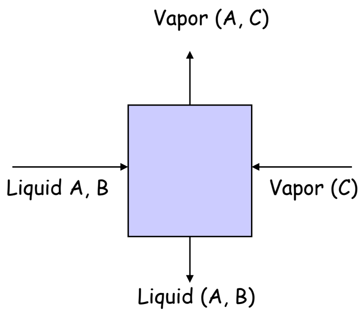
Absorption (Scrubber)

- **Solute (A) being absorbed from gas phase (B) to liquid phase (C)**
- **Involving material balance**
- **Example:**
  - SO_3 being absorbed from air onto water
  - SO_3 dissolved in water will be treated as wastewater



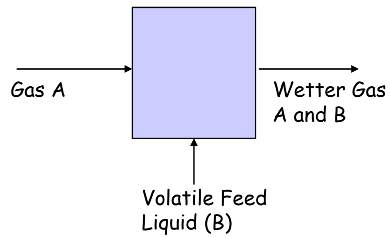
Stripping (Desorber)

- **Solute (A) being absorbed from liquid phase (A, B) to vapor phase (C)**
- **Involving material balance and energy balance**
- **Example:**
  - Steam stripping of naphtha, kerosene, and gas oil side cuts from crude distillation units to remove light ends.



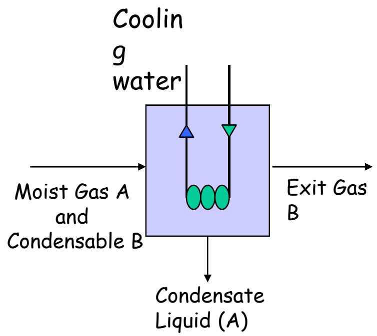
Humidifier

- **The feed Gas (A) is not saturated**
- **Liquid (B) is evaporated in the process unit**
- **The vapor exit (A and B) product may or may not be saturated**
- **Involving material balance**
- **Example:**
  - Humidification of air using H_20



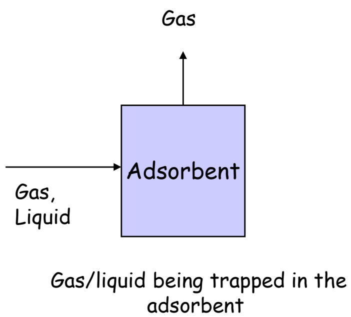
Condenser

- Feed stream contain a condensable component (A) and a non-condensable component (B)
- Condensate is a liquid with the condensable component (A) only.
- The dry gas exit stream is saturated with the condensable component (B) at the temperature and pressure of the process.
- Involving material balance



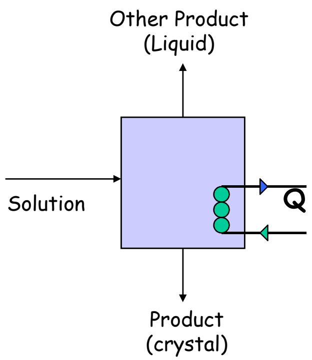
Adsorption

- Process whereby the solid (adsorbent) absorbing liquid from surrounding areas.
- Dry gas is the product
- For separation between gases, pressure is being used to change the phases of the components.
- Involving material balance
- Example
  - Separation of water from air using alumina silica. To decrease the humidity of the air.



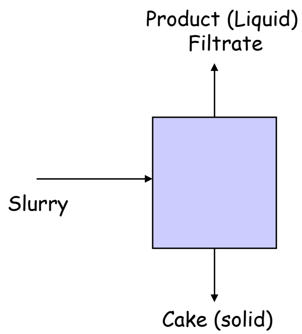
Crystallization

- Saturated solution temperature being lowered down to produce crystal
- Mechanism
  - Material Balance
  - Heat Balance
- Example:
  - Crystallization of p-xylene from p-xylene and m-xylene mixture
  - Crystallization of sugar from sugar solution.



Filtration

- Solid being separated from slurry that contains liquid and solid.
- Mechanism
  - Material Balance
- Example:
  - Separation of palm oil from slurry that contains fiber and oil after the screw press.
  - Process of making coconut milk



Screening

- Solid being separated according to size.
- Fine size solid will pass thru the screen.
- Mechanism
  - Material balance
- Example
  - Separation of coarse sugar and fine sugar.
  - Sieving powder