Processes & Process Variables

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Process

- **Process-** any operation that cause a physical or chemical change in a substance. Can consist of several process unit.
- Chemical/bioprocess engineering is responsible to design and operate the process.
  - Design

    Formation of process flow sheet/layout

    Specification of individual process unit

    Associated operating variables
  - Operation: running day-to-day process

Process variables

A physical or chemical quantity that is usually measured and controlled in the operation of a water, wastewater, or industrial treatment plant. Common process variables are -

- Temperature
- Pressure
- Density
- Flow rate
- Chemical composition

Temperature

- Temperature of a substance in a particular state of aggregation (solid, liquid, or gas) is a measure of the average kinetic energy possessed by the substance molecules.
- Some temperature measuring devices based on substance properties include electrical resistance of a conductor (resistance thermometer), voltage at the junction of two dissimilar metals (thermocouple), spectra of emitted radiation (pyrometer), and volume of a fixed mass of fluid (thermometer).
- The following relationship may be used to convert a temperature expressed in one defined scale unit to its equivalent in another;

$$T(°K) = T(°C) + 273.25$$
$$T(°R) = T(°F) + 459.67$$
$$T(°R) = 1.8\,T(°K)$$
$$T(°F) = 1.8\,T(°C) + 32$$

Temperature

Example: Consider the interval from 20°F to 80°F.

(a) Calculate the equivalent temperature in °C and the interval between them

(b) Calculate directly the interval in °C between the temperature

$$T(°C) = \frac{T(°F) - 32}{1.8}$$

$$T_1(20°F) = \left(\frac{20-32}{1.8}\right)°C = -6.7°C$$

$$T_2(80°F) = \left(\frac{80-32}{1.8}\right)°C = 26.6°C$$

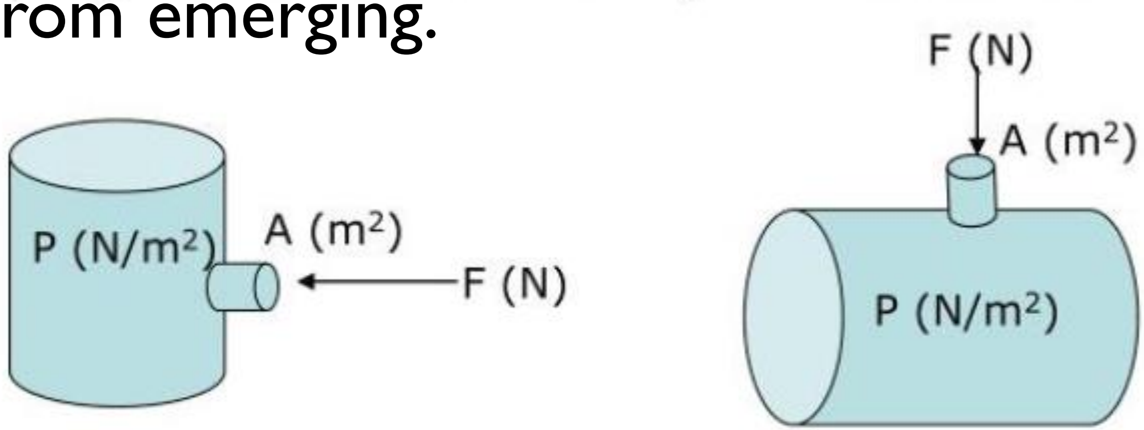
$$\Delta T = T_2 - T_1 = 26.6 - (-6.7) = 33.3°C$$

$$\Delta T(°C) = \Delta T(°F) \times \frac{1°C}{1.8°F}$$

$$= (80-20)°F \times \frac{1°C}{1.8°F} = 33.3°C$$

Pressure

- A pressure is the ratio of a force to the area on which the force acts (P= F/A).
- Pressure units: N/m^2, $dynes/cm^2$, lb_f/in^2, psi, Pa.
- The fluid pressure may be defined as the ratio F/A, where F is the minimum force that would have to be exerted on a frictionless plug in the hole to keep the fluid from emerging.



Pressure

- Hydrostatic pressure, P is the pressure exerted by a fluid at equilibrium at any point of time due to the force of gravity

$$P = \rho g h$$

- Pressure head, is the height of a hypothetical column of the fluid that would exert the given pressure at its base if the pressure at the top were zero.
- The equivalence between a pressure P (force/area) and the corresponding head P_h (height of a fluid) is given by:

$$\textbf{P (force/area)} = \rho_{fluid}\, g P_h \textbf{ (head of fluid)}$$

Absolute & Gauge Pressure

- Relationship between absolute pressure and gauge pressure is

$$P_{absolute} = P_{gauge} + P_{atmosphere}$$

- The atmosphere pressure can be thought of as the pressure at the base of a column of fluid(air) located at the point measurement (e.g. at sea level)
- A typical value of the atmospheric pressure at sea level, 760.0 mm Hg, has been designated as a standard pressure of 1 atmosphere.
- The fluid pressure referred to so far are all absolute pressures, in that a pressure of zero corresponds to a perfect vacuum.
- The pressure relative to atmospheric pressure is called the gauge pressure.

Density & specific gravity

The density of a substance is the mass per unit volume of the substance (kg/m^3, g/cm^3, lb_m/ft^3, etc.). The specific volume of a substance is the volume occupied by a unit mass of the substance; it is the inverse of density. Densities of pure solids and liquids are essentially independent of pressure and vary relatively slightly with temperature.

The density of a substance can be used as a conversion factor to relate the mass and volume of a quantity of the substance. For example, the density of carbon tetrachloride is 1.595 g/cm^3; the mass of 20.0 cm^3 of CCl_4 is therefore,

$$\frac{20.0\ \text{cm}^3 \mid 1.595\ \text{g}}{\mid \text{cm}^3} = 31.9\ \text{g}$$

and the volume of 6.20 lb. of CCl_4 is

$$\frac{6.20\ \text{lb}_m \mid 454\ \text{g} \mid 1\ \text{cm}^3}{\mid 1\ \text{lb}_m \mid 1.595\ \text{g}} = 1760\ \text{cm}^3$$

Density & specific gravity

The specific gravity of a substance is the ratio of the density ρ of the substance to the density ρ_{ref} of a reference substance at a specific condition.

Calculate the density of mercury in lb_m/ft^3 at 20°C (specific gravity of mercury at 20°C as 13.546). Calculate the volume in ft^3 occupied by 215 kg of mercury.

$$\rho_{Hg} = (13.546)\left(62.43\frac{lb_m}{ft^3}\right) \bullet = 845.7\frac{lb_m}{ft^3}$$

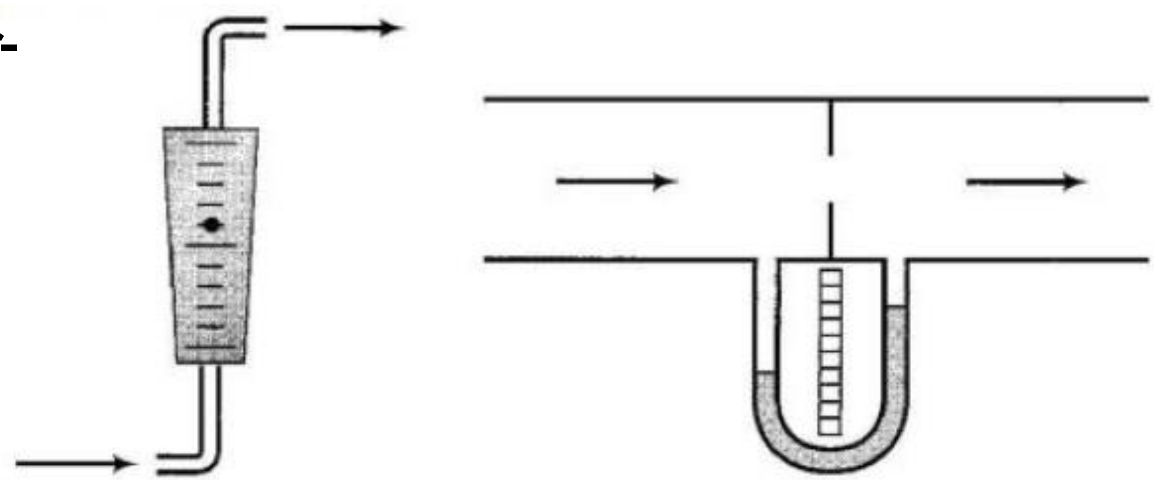
$$V = \frac{215\ kg}{} \left| \frac{1\ lb_m}{0.454\ kg} \right| \frac{1\ ft^3}{845.7\ lb_m} = 0.560\ ft^3$$

Flow Rate

- Row rate- the rate at which a material is transported through a process line. It can be expressed as mass flow rate (mass/time) or volumetric flow rate (volume/time)
- The density of a fluid can be used to convert a known volumetric flow rate of a process stream to the mass flow rate of that stream or vice versa.

Flow Rate

- The mass flow rates of process streams must be known for many process calculations, but it is frequently more convenient to measure volumetric flow rates than mass flow rate. Therefore, the density is used to convert volume flow rate to mass flow rate.
- Flow meter is a device mounted in a process line that provides a continuous reading of the flow rate in the line.
- Two commonly used flow meter are (a) rotameter and (b) orifice meter-



(a) (b)

Problem-I

*** A blower delivers air at 323K and 750mm Hg pressure. 10 kg of ammonia are added every minute to the air. A sample of the gaseous mixture taken downstream indicates 67.1% nitrogen, 17.9% oxygen and 15% ammonia. Compute the flow rate of air delivered by the blower in cubic meters per minute.

Chemical Composition

- **Moles and Molecular Weight**
  - Atomic weight of element- mass of an atom based on carbon isotope ^{12}C
  - Molecular weight of compound- sum of the atomic weights of atoms that constitute a molecule of the compound
  - Moles= Mass /Molecular Weight
  - Unit for moles are g-mole, kmol, lb-mole, etc, (*g-mole is same as mol*)

Chemical Composition

- **Moles and Molecular Weight**
  - If the 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.
  - The molecular weight may thus be used as a conversion factor that relates the mass and the number of moles of a quantity of the substance.
  - One gram-mole of any species contains 6.02×10^{23} (Avogadro's number) molecules of that species

Chemical Composition

1. What is the molar flow rate for 100kg/h CO_2 (M=44) fed to the reactor?

$$\frac{100\text{kg } CO_2}{\text{h}} \times \frac{1 \text{ kmol } CO_2}{44 \text{ kg } CO_2} = \frac{2.27 \text{ kmol } CO_2}{\text{h}}$$

2. What is the mass flow rate of 8501b-moles/min CO_2?

$$\frac{850 \text{ lb-moles } CO_2}{\text{min}} \times \frac{44 \text{ lb}_m \text{ } CO_2}{1 \text{ lb-moles } CO_2} = \frac{37\,400 \text{ lb}_m \text{ } CO_2}{\text{min}}$$

3. How many gram of O_2 consist in 100g of CO_2?

$$100 \text{ g } CO_2 \times \frac{1\text{mol } CO_2}{44 \text{ g } CO_2} \times \frac{1 \text{ mol } O_2}{1 \text{ mol } CO_2} \times \frac{32 \text{ g } O_2}{1 \text{ mol } O_2} = 72.73 \text{ g } O_2$$

4. Find the number of molecules of CO_2 in 1008 of CO_2?

$$100 \text{ g } CO_2 \times \frac{1\text{mol } CO_2}{44 \text{ g } CO_2} \times \frac{6.02 \times 10^{23} \text{ Molecules}}{1 \text{ mol } CO_2} = 1.37 \times 10^{24} \text{ Molecules}$$

Chemical Composition

- **Mass and Mole Fractions**
  - Mass fraction: x_A= mass of A / total mass Unit: kg A/kg total; g A/g total; lb_m A/lb total
  - Mole fraction: V_A moles of *A*/ total moles Unit: kmol A/ kmol total; lb-moles A/lb-mole total
  - The percent by mass of A is 100xA, and the mole percent of A is100yA.
  - Calculation:
    - assuming as a basis (e.g.100 kg or 100 lbm)
    - using the known mass fractions to calculate and converting these masses to moles
    - taking the ratio of the moles of each component to the total number of moles

Note that the numerical value of mass or a mole fraction does not depend on the mass units in the numerator and denominator as long as these units are the same.

Chemical Composition

Example: A mixture of gases has the following mass composition: O_2 -16%; CO-4%; CO_2 -17%; and N_2 63%. What is the molar composition?

Solution:

Basis: 100g of mixture

Component i	Mass Fraction x_i	Mass m_i	MW M_i	Moles n_i	**Mole Fraction** **yi**
O_2	0.16	16	32	0.500	**0.152**
CO	0.04	4	28	0.143	**0.044**
CO_2	0.17	17	44	0.386	**0.118**
N_2	0.63	63	28	2.250	**0.686**
Total	1.00	100		3.279	**1.000**

Chemical Composition

- **Average Molecular Weight:**
  - The average molecular weight or mean molecular weight of a mixture, *m* (kg/kmol, lbm/lb-mole, etc.), is the ratio of the mass of a sample of the mixture (m_t) to the number of moles of all species (n_t) in the sample.
  - If y_i is the mole fraction of the i th the component of the mixtur $$\overline{M} = y_1 M_1 + y_2 M_2 + \ldots.. = \sum_{\text{all component}} y_i M_i$$
- If x_i is the mass fraction of the i th component of the mixture

$$\frac{1}{\overline{M}} = \frac{x_1}{M_1} + \frac{x_2}{M_2} + \ldots.. = \sum_{\text{all component}} \frac{x_i}{M_i}$$

Chemical Composition

- **Concentration**
  - Mass concentration
  - Molar concentration
  - Molarity
  - Parts per Million (ppm)- to express the concentrations of trace species in gases or liquids
  - Parts per Billion (ppb) - may refer to mass ratios (usual for liquids) or mole ratios (usual for gases)

Stoichiometric Calculations

Stoichiometric calculations are based on the equalization between the ratio of the amount of substance we're interested in, and the ratio of the corresponding absolute values of the stoichiometric numbers. Almost every single stoichiometric task can be solved in five easy steps, and with only a basic knowledge of mathematics.

- Extracting measurement data from the task
- Converting all units of measurement to the same base units
- Writing a balanced reaction
- Determining the stoichiometry of species
- Calculating the desired quantity

Equilateral triangular diagram

Equilateral triangular diagram is used to demonstrate the composition of three component systems. The three components may be designated a, b, and c and their respective mass fraction are $x_{a,}$ $x_{b,}$ and $x_{c;}$ then,

$x_a + x_b + x_c = 1$

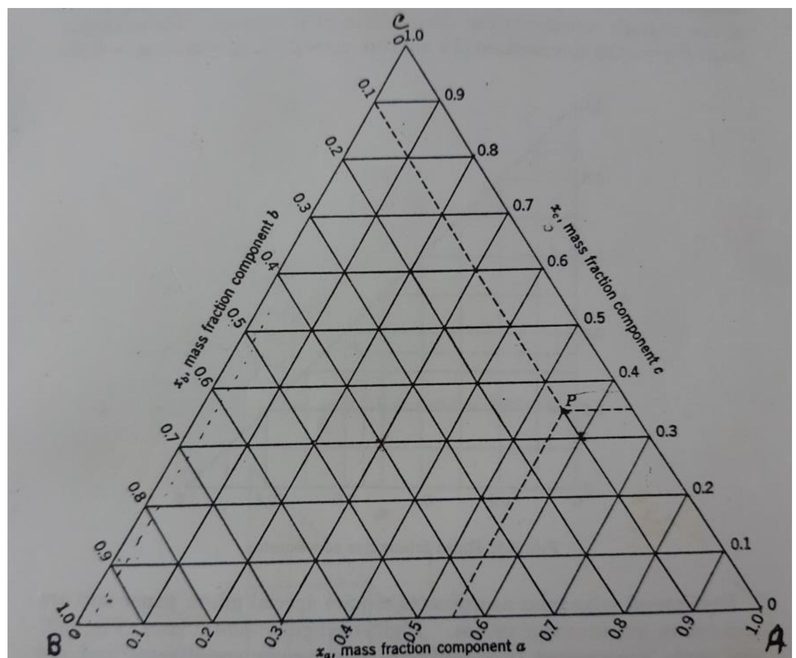


FIG. 3.8. Equilateral triangular coordinates for three-component mixtures.

Graphical addition

If the mixtures of masses M_1 and M_2 are added, a mixture of mass M_3 will result. The composition of M_3 lies on a straight line between the composition of mixture M_1 and M_2. The total mass of M_3 equal the sum of masses of M_1 and M_2.

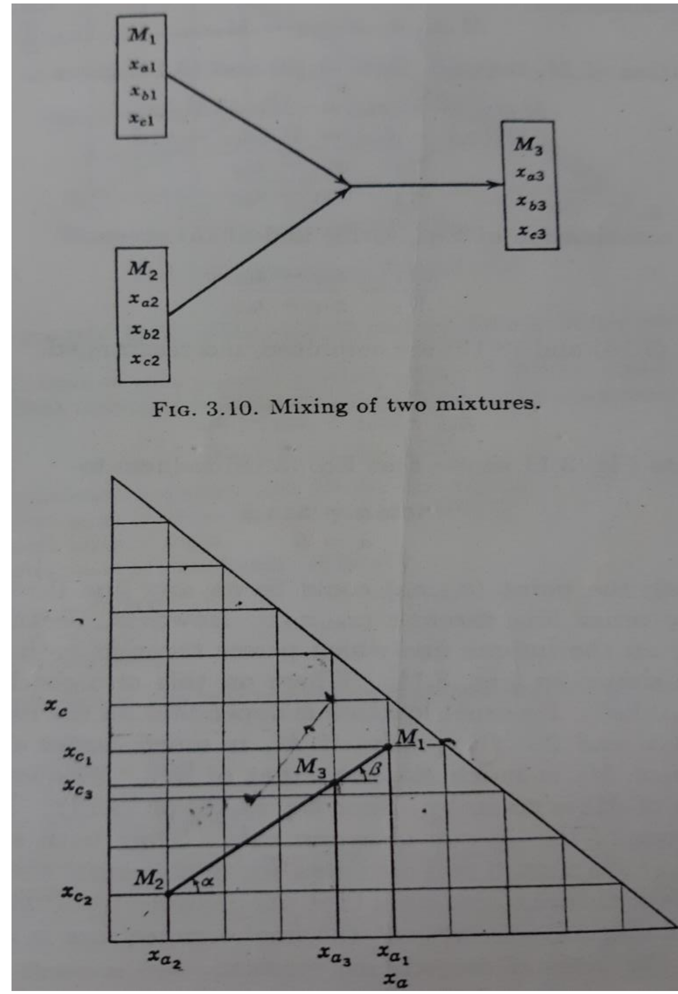


FIG. 3.10. Mixing of two mixtures.

Graphical addition

$$M_1 + M_2 = M_3 \; \ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

Mass fraction for component a,

$$M_1 x_{a1} + M_2 x_{a2} = M_3 x_{a3} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Mass fraction for component c,

$$M_1 x_{c1} + M_2 x_{c2} = M_3 x_{c3} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

From Eq (11) and (111)

$$M_1 x_{a1} + M_2 x_{a2} = (M_1 + M_2) x_{a3}$$

$$M_1 (x_{a1} - x_{a3}) = (x_{a3} - x_{a2}) M_2$$

$$M_1 / M_2 = (x_{a3} - x_{a2}) / (x_{a1} - x_{a3}) \; \ldots\ldots\ldots.(4)$$

Similarly, $M_1 / M_2 = (x_{c3} - x_{c2}) / (x_{c1} - x_{c3}) \; \ldots\ldots\ldots.(5)$

Graphical addition

Combining Eq. (4) and (5)

$$(x_{c1} - x_{c3})/(x_{a1} - x_{a3}) = (x_{c3} - x_{c2})/(x_{a3} - x_{a2})$$

$$\text{Tan } \alpha = \text{Tan} \beta$$

$$\alpha = \beta$$

If M_1 is much larger than $M_{2,}$ then the composition of the M_3 is much closer to that of $M_{1.}$ This is called the inverse lever arm rule. "the composition of the mixtures lies on a straight line between the compositions of the mixtures such that the distance from the composition of one of the original mixtures to the final composition in inversely proportional to the mass of the original mixtures.

Problem-11

It is desired to produce a mixed acid containing 45% H_2SO_4, 30% HNO_3, and 25% H_2O (w%) by mixing sulfuric acid (98% H_2SO_4, 2% H_2O), nitric acid (68% H_2SO_4, 32% H_2O) and water. Calculate the mass of each material required to give 10000 lb of mixed acid.