Processes and Process Variables
• Process: Any operation or series of operations by which a particular objective is accomplished.
  e.g. Operations that cause a physical or chemical change in a substance or mixture.

The material entering a process: input, feed
The material leaving a process: output, product

If there are multiple steps, each will be a process unit with its own process streams (I,O)

You design (formulation of a flowsheet and specifications) or operate (day-to-day running of process) a process.
VARIABLES

• Mass and Volume:
• Density = mass / volume
• Specific volume = volume occupied by unit mass = 1/\rho (density)

• If \rho = 1.595 \text{g/cm}^3, \text{volume} = 20.0 \text{cm}^3,
• \rightarrow \text{mass} = 20.0 \text{cm}^3 \times 1.595 \text{g/cm}^3 = 31.9 \text{g}

• Specific gravity = \rho_{\text{subs.}} / \rho_{\text{ref.subs.}} (at specific conditions)
  \rightarrow \text{SG} = \rho / \rho_{\text{ref.}}
• \rho_{\text{ref}} = \rho_{\text{H}_2\text{O}(l)} (4^\circ\text{C}) = 1.000 \text{g/cm}^3 = 62.43 \text{lb}_m/\text{ft}^3
• \text{SG} = 0.6 (20^\circ/4^\circ) \text{ SG} = 0.6 at 20^\circ\text{C with reference to 4}^\circ\text{C}
Example:

• Calculate the density of mercury in lb\textsubscript{m}/ft\textsuperscript{3}, if its SG=13.546  \(20^\circ/40^\circ\)

• Calculate the volume in ft\textsuperscript{3} occupied by 215 kg of mercury.

\[ \rho_{\text{Hg}} = 13.546 \times (62.43 \text{ lb}_m/\text{ft}^3) = 845.7 \text{ lb}_m/\text{ft}^3 \]

\[ V = \frac{m}{\rho_{\text{Hg}}} \]

\[ = 215 \text{ kg} \times \frac{1 \text{ lb}_m}{0.454 \text{ kg}} \times \frac{1 \text{ ft}^3}{845.7 \text{ lb}_m} \]

\[ = 0.560 \text{ ft}^3 \]

For solids and liquids \( \rho \neq \rho(T,P) \)

For gases it is obvious

For mercury \( \rho \) is depended on \( T \):

\[ V(T) = V_0 \left(1 + 0.18 \times 10^{-3} T + 0.0018 \times 10^{-6} T^2\right) \]
3.1.1 Example: \( m = 215 \text{ kg}, \ V = 0.560 \text{ ft}^3 \) at 20°C

\[
V(T) = V_o \left( 1 + 0.18 \times 10^{-3} T + 0.0018 \times 10^{-6} T^2 \right)
\]

What volume would the mercury occupy at 100°C?

1. If it is contained in a cylinder (\( D = 0.25 \text{ in} \)), what change in height would be observed as the mercury is heated from 20°C to 100°C?

\[
V(100^\circ C) = V_o [1 + 0.18\times 10^{-3}(100) + 0.0018\times 10^{-6}(100)^2]
\]
\[
V(20^\circ C) = V_o [1 + 0.18\times 10^{-3}(20) + 0.0018\times 10^{-6}(20)^2]
\]
\[
= 0.560 \text{ ft}^3
\]

Solving for \( V_o \) from the 2nd equation and substituting it into the 1st yields.

\[ \rightarrow V(100^\circ C) = 0.568 \text{ ft}^3 \]

\[
V_{cyl} = \pi \frac{D^2}{4}
\]

\[
H(100^\circ C) - H(20^\circ C) = \frac{[V(100^\circ C) - V(20^\circ C)]}{(\pi D^2/4)}
\]
\[
= 23.5 \text{ ft}
\]
Flow Rate

Mass an Volumetric Flow Rate:

- Material move between process units, between a production facility and a transportation depot. The rate at which a material is transported through a process line is the flow rate. Blood flows in the arteries with a specific flow rate.
- Mass flow rate $\rightarrow$ (mass/time)
- Volumetric flow rate $\rightarrow$ (volume/time)

\[ \rho = \frac{m}{V} = \frac{\dot{m}}{\dot{V}} \]

\[ n = \frac{n}{t} \]
Flow Rate Measurement

- Flowmeter: A device that reads continuously flow rate in the line.

\[ \text{The larger the flow rate the higher the float rises} \]

\[ \text{Fluid pressure drops from the upstream to the downstream} \]
• Chemical Composition: The properties of a mixture depend on mixture compositions.
• Moles and Mole Weight: A g-mole (or mol in SI units) of a species is the amount of that species whose mass in grams is numerically equal to its MW. e.g. CO has a MW of 28.
  • 1 mol of CO contains 28 g
  • 1 lb-mole CO contains 28 lb
  • 1 ton-mole CO contains 28 tons
• e.g. NH$_3$ has a MW of 17.
• 34 kg of ammonia is;
  34 kg NH$_3$ (1 kmol NH$_3$/17 kg NH$_3$) = 2 kmol NH$_3$
• **Example: Conversion between Mass and Moles**

• How many of each of the following are contained in 100 g CO$_2$ (M=44.01) (a) mol CO$_2$; (b) lb-moles CO$_2$; (c) mol C

• $100 \text{ g} \left( \frac{1 \text{ mol CO}_2}{44.01 \text{ g CO}_2} \right) = 2.273 \text{ mol CO}_2$

• $2.273 \text{ mol CO}_2 \left( \frac{1 \text{ lb-mol}}{453.6 \text{ mol}} \right) = 5.011 \times 10^{-3} \text{ lb-mole CO}_2$

• $2.273 \text{ mol CO}_2 \left( \frac{1 \text{ mol C}}{1 \text{ mol CO}_2} \right) = 2.273 \text{ mol C}$

• Calculate the flow rate in kmol CO$_2$/h if flow rate = 100 kg/h CO$_2$

• $100 \text{ kg CO}_2 / \text{h} \left( \frac{1 \text{ kmol CO}_2}{44.01 \text{ kg CO}_2} \right) = 2.27 \text{ kmol CO}_2/\text{h}$
Masses and Mole Fractions and Average Molecular Weight

• Process input or output streams can contain mixtures of liquids or gases, solutions of one or more solutes in a solvent. You need mass fraction and mole fraction to define the compositions:

• Mass fraction; \( x_A = \frac{\text{mass of } A}{\text{total mass}} \)

• Mole fraction; \( y_A = \frac{\text{moles of } A}{\text{total moles}} \)
• Example: A solution contains 20% X and 25% Y by mass.

• Calculate the mass of X in 220 kg of solution:
  \[220 \text{ kg solution} \times 0.20 \frac{\text{kg X}}{\text{kg solution}} = 44 \text{ kg X}\]

• Calculate the mass flow rate of A in stream flowing at a rate of 53 \text{ lb}_m/\text{h}:
  \[53 \text{ lb}_m/\text{h} \times 0.20 \frac{\text{lb}_m \ X}{\text{lb}_m \ \text{solution}} = 10.6 \text{ lb}_m \ X/\text{h}\]
The Average Molecular Weight

\[ \overline{M} = y_1 \cdot M_1 + y_2 \cdot M_2 + \ldots = \sum_{\text{all comp.}} y_i \cdot M_i \]

\[ \frac{1}{M} = \frac{x_1}{M_1} + \frac{x_2}{M_2} + \ldots = \sum_{\text{all comp.}} \frac{x_i}{M_i} \]

Where;

\( x_i \) = Mass fraction

\( y_i \) = Mole fraction

\( M_i \) = Molecular weight of component
Concentration

- Mass concentration = mass of a component / volume of the mixture
- Molar concentration = moles / volume
- Molarity = molar concentration of solute / volume of solution
- Parts per million (ppm), and parts per Billion (ppb) are used to express the concentration of trace species.

- \( \text{ppm}_i = y_i \times 10^6 \)
- \( \text{ppb}_i = y_i \times 10^9 \)
Example: In normal living cells, the nitrogen requirement for the cells is provided from protein metabolism. When individual cells are commercially grown, \((\text{NH}_4)_2\text{SO}_4\) is usually used as the source of nitrogen. Determine the amount of \((\text{NH}_4)_2\text{SO}_4\) consumed in a fermentation medium in which the final cell concentration is 35 g/L in a 500 L volume of the fermentation medium. Assume cells contain 9 wt% N, and that \((\text{NH}_4)_2\text{SO}_4\) is the only N source.

Basis: 500 L solution containing 35 g/L cell concentration,

\[
500L \times \frac{35g}{cell} \times \frac{0.09g}{N} \times \frac{1gmol}{N} \times \frac{1gmolNH4SO4}{1gmolN} \times \frac{132g(\text{NH}_4)2\text{SO}_4}{1gmol(NH_4)2SO4}
\]

\[= 14,850 \text{ g } (\text{NH}_4)_2\text{SO}_4\]
A solution of HNO₃ in water has a specific gravity of 1.10 at 25° C. The concentration of HNO₃ is 15 g/L of solution. What is the:

a) Mole fraction of HNO₃ in the solution?
b) ppm of HNO₃ in the solution? (Take 1 L and 100 g of solution)

Basis: 1 L →

(15 g HNO₃/1 L solution) (1 L/1000 cm³) (1 cm³/1.10 g solution)

= 0.01364 g HNO₃/g solution

(Assume SG = ρ_{solution})
Basis: 100 g solution;  
The mass of water in the solution is:  
100 – 1.364 = 99.986 g H₂O

<table>
<thead>
<tr>
<th></th>
<th>g</th>
<th>MW</th>
<th>g-mole</th>
<th>Mol frac.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNO₃</td>
<td>1.364</td>
<td>63.02</td>
<td>2.164 x 10⁻⁴</td>
<td>3.9 x 10⁻⁵</td>
</tr>
<tr>
<td>H₂O</td>
<td>99.986</td>
<td>18.016</td>
<td>5.550</td>
<td>1</td>
</tr>
</tbody>
</table>

b) Mass fraction is 0.01364 or  

= 13,640/10⁶ or  

= 13,640 ppm
Pressure

- A pressure is the ratio of a force to the area on which the force acts. Units are N/m² (Pa), dynes/cm², lb/in².
- Pressure is defined as the “normal (perpendicular) force per unit area”

\[ P = \frac{F}{A} = \rho \cdot g \cdot h + P_0 \]

- \( P \): static pressure
- \( \rho \): density of fluid
- \( g \): gravity
- \( P_0 \): pressure at the top of the fluid
F (N) : minimum force that would be exerted in the hole to keep the fluid from emerging

A pressure may be expressed as a “head” of a particular fluid; the height of a hypothetical column of this fluid exerting the same pressure at its base if the pressure at the top were zero. e.g. 76 cm of mercury (76 cm Hg). The equivalence between a pressure (P) and its corresponding head $P_h$ is given as:

$$P \text{ (force/area)} = \rho_{\text{fluid}} \cdot g \cdot P_h \text{ (head of fluid)}$$
• Example: Express $2.0 \times 10^5$ Pa in terms of mmHg.

$\rho_{\text{Hg}} = 13.6 \times 1000 \text{ kg/m}^3 = 13600 \text{ kg/m}^3$

$g = 9.807 \text{ g/s}^2$

$$P_h = \frac{P}{\rho_F \cdot g} = 2 \times 10^5 \cdot \frac{N}{m^2} \cdot \frac{m^3}{13600 \cdot \text{kg}} \cdot \frac{s^2}{9.807 \cdot \text{m}} \cdot \frac{1 \cdot \text{kg} \cdot \text{m} / \text{s}^2}{N} \cdot \frac{10^3 \text{mm}}{\text{m}}$$

$$= 1.50 \times 10^3 \text{ mmHg}$$

$$P_h \text{ (mmHg)} = P_0 \text{ (mmHg)} + h \text{ (mm Hg)}$$
Atmospheric, Absolute, and Gauge Pressure

• Atmospheric pressure at sea level, 760 mmHg = 1 atm.
• The fluid pressures are “absolute” pressures if a zero pressure corresponds to a perfect vacuum. Many devices measure the “gauge pressure” of a fluid or the pressure relative to the atmospheric pressure.

\[ P_{\text{gauge}} = 0 \rightarrow P_{\text{absolute}} = P_{\text{atmospheric}} \]

\[ P_{\text{absolute}} = P_{\text{gauge}} + P_{\text{atmospheric}} \]

• psia and psig are commonly used to denote absolute and gauge pressures in lb/in\(^2\)
Open end monomer
Relative (gauge) Pressure

Absolute Pressure
Fluid Pressure Measurement

- Elastic-element method-Bourden tubes
  $7000 \text{ atm} < P < 0$
- Liquid-column methods-manometers
  $P < 3 \text{ atm} \rightarrow \text{ accurate}$
- Electrical Methods-Strain gauges
Open-end

Manometer fluid

Sealed-end

P_1 = P_{atm}

P_2 = 0

Differential
General manometer equation:

\[ P_1 + \rho_1 g d_1 = P_2 + \rho_2 g d_2 + \rho_F g h \]

If \( \rho_1 = \rho_2 = \rho \):
\[ P_1 - P_2 = (\rho_F - \rho) g h \]

(Differential manometer equation)

If both fluids are gases \( \rho_F >> \rho \):
\[ P_1 - P_2 = \rho_F g h \]
Small animals like mice can live at reduced air pressures down to 20 kPa absolute. In a test, a mercury manometer attached to a tank, reads 64.5 cm Hg and the barometer reads 100 kPa. Will mice survive?

\[ P = 100 \text{ kPa} - 64.5 \text{ cmHg} (\frac{101.3 \text{ kPa}}{76 \text{ cmHg}}) \]
\[ = 100 - 86 = 14 \text{ kPa absolute} \]

MICE WILL DIE!
Temperature

- It is a measure of energy (mostly kinetic) of the molecules in a system. Since kinetic energy cannot be measured directly, T must be determined indirectly by measuring some physical property of the substance whose value depends on T.
- 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 a fluid (thermometer)
• Rankine-Fahrenheit Scale $\Delta^\circ F = \Delta^\circ R$
• Kelvin-Celsius Scale $\Delta^\circ C = \Delta^\circ K$
• $\Delta^\circ C / \Delta^\circ F = 1.8$
• $\Delta^\circ K / \Delta^\circ R = 1.8$
• $T(\circ K) = T(\circ C) + 273.15$
• $T(\circ R) = T(\circ F) + 459.67$
• $T(\circ R) = 1.8 \times T(\circ K)$
• $T(\circ F) = 1.8 \times T(\circ C) + 32$