CHEMICAL ENGINEERING

Process Calculations

Comprehensive Theory
with Solved Examples *and* Practice Questions

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Email : infomep@madeeasy.in | **Web :** www.madeeasypublications.org

Process Calculations

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Introduction and Basic Concepts

CHAPTER

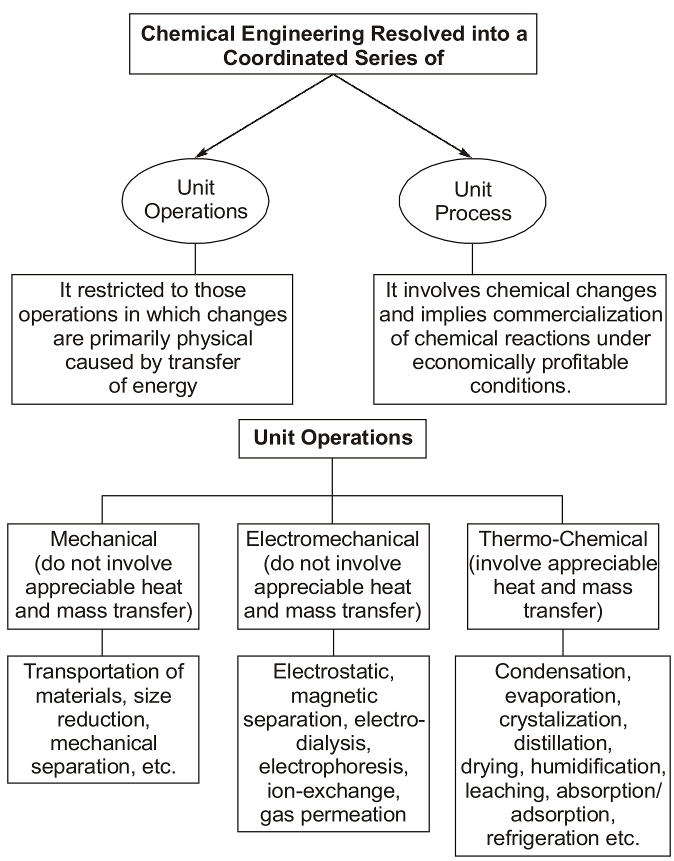
1

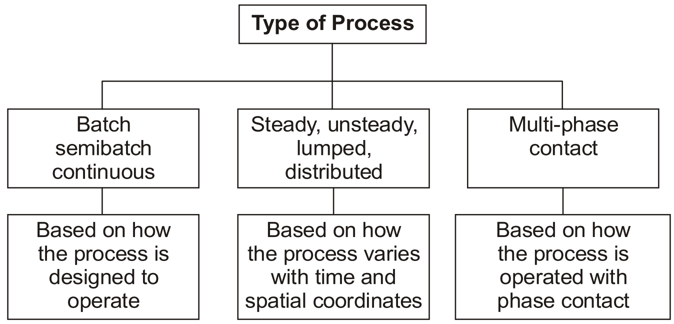
LEARNING OBJECTIVES

The reading of this chapter will enable the students

- To understand unit and dimensions.
- To understand the basic chemical calculations.
- To understand about ideal gas law and their applications.
- To understand about Raoult's and Henry's law for gas-liquid system.

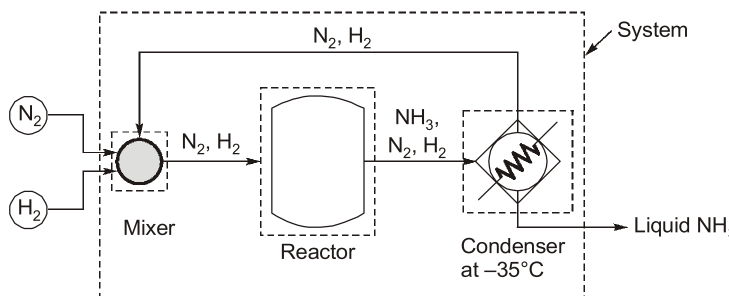
1.1 INTRODUCTION





What is System?

- Any specified arbitrary portion or whole of a process analyzing the problem is defined as system.
- It depends on what information is provided and what needs to be determined.
- A system may contain more than one process unit.
- In figure, the entire process is a system which consists of three process units.



1.2 UNIT AND DIMENSIONS

Unit	Dimensions
• The "unit" indicates what the measured quantity represents.	• The "dimension" is the measurable quantity that the unit represents. Example : length, mass, time and temperature
• A measured or counted quantity has a numerical value and a unit.	• It also be calculated by multiplying or dividing other dimensions. Example : length/time = velocity, $length^3$ = volume and $mass/length^3$ = density
• Measurable units are specific values of dimensions that have been defined by convention. Example: grams for mass, seconds for time and centimeters for length	

The system of units composed of (1) Base units, (2) Derived units and (3) Multiple units.

1. **Base units:** These are the units for basic quantities such as length, mass, time, etc.
2. **Derived units:** These are the units obtained by multiplying and dividing base units. e.g., cm^2, m/s, etc.

3. **Multiple units:** These are the units which are multiple or fractions of base units. e.g., hour, minute, second, etc.

Unit Systems

The various systems of units and the basic/fundamental quantities associated with them are given below:

Fundamental Quantity	Systems of Units				Dimensions
	SI	MKS	CGS	FPS	
Length	Meter (m)	Meter (m)	Centimeter (cm)	Foot (ft)	L
Mass	Kilogram (kg)	Kilogram (kg)	Gram (g)	Pound (lb)	M
Time	Second (s)	Second (s)	Second (s)	Second (s)	θ
Temperature	Kelvin (K)	Celsius (°C)	Celsius (°C)	Fahreinheit (°F)	T

°C = Degrees Celsius
K = Kelvin
SI = International system of units

Symbolic abbreviations of the units are given in brackets.

(i) **Force:** According to Newton's law of motion, force is proportional to the product of mass and acceleration.

$$F \propto m.a$$
$$F = k\, m.a$$

In CGS system, dyne is defined as the force necessary to accelerate one gram mass at 1 cm/s^2.
In the SI system, Newton (N) is defined as the force necessary to accelerate one kilogram mass at 1 m/s^2. The engineer's unit of force in the MKS system is kilogram-force (kgf). The kilogram force is the force necessary to accelerate 1 kg mass at 9.81 m/s^2.
In the SI system, the unit of force has been named as Newton (N) in honour of the scientist Newton. 1 N is equal to 1 (kg.m)/s^2.

(ii) **Kilogram force (kgf):** The **kilogram force** is a metric unit of force (kgf). The kilogram-force is equal to a mass of one kilogram multiplied by the standard acceleration due to gravity on Earth, which is defined as exactly 9.80665 meter per second^2. Then one (1) kilogram-force is equal to 1 kg × 9.80665 meter per second^2 = 9.80665 kilogram × meter per second^2 = 9.80665 newton (1 N).
Note: A kilogram-force (kgf), also called kilopond (kp), is a gravitational metric unit of force.

(iii) **Pressure:** Pressure is defined as the force per unit area.

$$P = \frac{F}{A}$$

The units of pressure in SI, MKS and FPS systems are N/m^2 (known as Pascal, abbreviated as Pa), kgf/cm^2 and lbf/in^2 (psi) respectively. The relationship between the absolute, atmospheric and gauge pressure is

Absolute pressure = Gauge pressure + Atmospheric pressure

Gauge pressure:

SI unit = N/m^2 (or Pa)

$$\text{CGS unit} = \text{dyn/cm}^2$$
$$\text{AES unit} = \text{lbf/in}^2 \text{ (or psi)}$$

- The gauge pressure of the fluid which is the pressure of the fluid relative to atmospheric pressure (reference pressure).
- A gauge pressure of 0 indicates that the absolute pressure of the fluid is equal to the atmospheric pressure.

$$P_{\text{absolute}} = P_{\text{gauge}} + P_{\text{atmospheric}}$$

Types of Pressures

- Atmospheric pressure: P_{atm}, is the pressure caused by the weight of the earth's atmosphere. Often atmospheric pressure is called barometric pressure.
- Absolute pressure: P_{abs}, is the total pressure. An absolute pressure of 0.0 is a perfect vacuum. Absolute pressure must be used in all calculations, unless a pressure difference is used.
- Gauge pressure: P_{gauge}, is pressure relative to atmospheric pressure.
- Vacuum pressure: P_{vacuum}, is a gauge pressure that is below atmospheric pressure.

$$P_{\text{gauge}} = P_{\text{absolute}} - P_{\text{atmospheric}}$$
$$P_{\text{vacuum}} = P_{\text{atmospheric}} - P_{\text{absolute}}$$
$$P_{\text{absolute}} = P_{\text{atmospheric}} + P_{\text{gauge}}$$

(iv) Work: Work is defined as the product of the force acting on body and the distance travelled by the body in the direction of force applied.
The SI units for work are the joule (J) or Newton meter ($N \times m$), from the function $W = F \times s$ where W is work, F is force, and s is the displacement. The joule is also the SI unit of energy.

$$\text{Joule} = \text{N.m} = \text{kg.m}^2/\text{s}^2$$

(v) Power: Power is the time rate at which work is done or energy is transferred. In calculus terms, power is the derivative of work with respect to time.
The SI unit of power is the watt (W) or joule per second (J/s). Horsepower is a unit of power in the British system of measurement.

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

or

$$P = \frac{W}{t}$$

(vi) Heat: It is a form of energy that flows from one body to another as a result of a difference in temperature. It cannot be stored as such within the system. The units of heat in SI, MKS and CGS systems are Joule (J), kilocalorie (kcal) and calorie (cal) respectively.

Example 1.1 In a multiple effect evaporator system, the second effect is maintained under vacuum of 475 torr (mm Hg). Find the absolute pressure in kPa.

Solution:

$$\text{Absolute pressure} = \text{Atmospheric pressure} - \text{Vacuum}$$
$$= 760 - 475 = 285 \text{ torr (mm Hg)}$$

$$\text{Absolute pressure} = 285 \text{ mm Hg} \times \left(\frac{101.325 \text{ kPa}}{760 \text{ mm Hg}}\right) = 38 \text{ kPa}$$

Example 1.19 Carbon dioxide weighing 1.10 kg occupies a volume of 33 litres at 300 K. Calculate the pressure using the Van der Waals equation of state.

Data: a = 3.60 $(m^3)^2$, kPa/$(kmol)^2$ and $b = 4.3 \times 10^{-2}$ m^3/kmol for CO_2

Solution:

Basis: 1.10 kg of CO_2 gas at 300 K.

The Van der Waals equation is

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT$$

$$\text{Amount of } CO_2 \text{ gas} = 1.10 \text{ kg} = 0.025 \text{ kmol}$$

$$\text{Volume occupied by this gas} = 33 l = 0.033 \text{ m}^3$$

$$\therefore \quad V = \frac{0.033}{0.025} = 1.32 \text{ m}^3/\text{kmol}$$

$$a = 3.60 \,(\text{m}^3)^2 \text{ kPa}/(\text{kmol})^2$$

$$b = 4.3 \times 10^{-2} \text{ m}^3/\text{kmol}$$

$$R = 8.31451 \,(\text{m}^3.\text{kPa})/(\text{kmol.K})$$

$$T = 300 \text{ K}$$

$$\left[P + \frac{3.60}{(1.32)^2}\right][1.32 - 4.3 \times 10^{-2}] = 8.31451 \times 300$$

Solving we get, P = 1951 kPa = 1.951 MPa

Compressibility factor: Compressibility factor (Z) is defined as

$$Z = \frac{PV}{nRT}$$

$$Z = \frac{\text{Actual volume of gas at a given temperture and pressure}}{\text{Volume of the ideal gas at the same } T \text{ and } P}$$

Student's Assignments

Q.1 Convert a pressure of 2 atm to mm Hg.

Q.2 Convert a volumetric flow rate of 2 m^3/s to l/s.

Q.3 Convert 88 kg of carbon dioxide into its amount in molar units.

Q.4 Find the moles of oxygen present in 500 grams.

Q.5 Find moles of K_2CO_3 that will contain 117 kg of K.

Q.6 How many kilograms of carbon are present in 64 kg of methane?

Q.7 98 grams of sulphuric acid (H_2SO_4) are dissolved in water to prepare one litre of solution. Find normality and molarity of solution.

Q.8 A solution of caustic soda contains 20% NaOH by weight. Taking density of the solution as 1.196 kg/l, find the normality, molarity and molality of the solution.

Q.9 H_2SO_4 solution has a molarity of 11.24 and molality of 94. Calculate the density of solution.

Q.10 At 298 K (25°C) the solubility of methyl bromide in methanol is 44 kg per 100 kg. Calculate : (i) the weight fraction and (ii) the mole fraction of methanol in the saturated solution.

Q.11 Calculate the weight of sulphur dioxide in a vessel having 2 m^3 volume, the pressure and temperature being 97.33 kPa and 393 K (120°C).

Q.12 A certain quantity of gas contained in a closed vessel of volume 1 m^3 at a temperature of 298 K (25°C) and pressure of 131.7 kPa is to be heated such that the pressure should not exceed 303.98 kPa. Calculate the temperature of gas attained.

Q.13 A mixture of nitrogen and carbon dioxide at 298 K (25°C) and 101.325 has an average molecular weight of 31. What is the partial pressure of nitrogen?

Q.14 960 cc of a gas weighs 2.5 g at 750 torr and 300 K (27°C). Calculate the molecular weight of gas.

Q.15 A sample of gas having volume of 10 l at 101.325 kPa pressure and at temperature of 298 K (25°C) is compressed to a high pressure so that its volume reduces by 4.5 l. If the pressure rises by 0.1 MPa, what will be the rise in temperature?

ANSWERS

1. (1520) **2.** (2000) **3.** (2) **4.** (15.625) **5.** (1.5) **6.** (48) **7.** (2, 1) **8.** (5.98, 5.98, 6.25) **9.** (1.2205) **10.** (0.6944, 0.871) **11.** (3.8144) **12.** (687.82) **13.** (82.33) **14.** (65) **15.** (27.6)

Explanation

1. (1520)

Basis : 2 atm pressure.

Conversion factor between atm and mm Hg is 1 atm = 760 mm Hg.

$\therefore$ 2 atm = ?

$$\therefore \quad \text{Pressure} = 2\text{ atm} \times \left(\frac{760\text{ mm Hg}}{1\text{ atm}}\right) = 1520\text{ mm Hg}$$

2. (2000)

Basis : Volumetric flow rate of 2 m^3/s.

Relationship between volume in m^3 and volume in l is

$$1\ m^3 = 1000\ l$$

$\therefore$ Volumetric flow rate

$$= 2\ m^3/s \times \frac{1000\ l}{1\ m^3} = 2000\ l/s$$

3. (2)

Basis : 88 kg of carbon dioxide.

Molecular formula of carbon dioxide = CO_2

Atomic weight: C = 12 and O = 16

Molecular weight of CO_2 = 1 × 12 + 2 × 16 = 44

$$\text{kmol of } CO_2 = \frac{\text{kg of } CO_2}{\text{Molecular weight of } CO_2} = \frac{88}{44} = 2$$

$\therefore$ 88 kg of CO_2 = 2 kmol CO_2

4. (15.625)

Basis : 500 g of oxygen.

Molecular weight of O_2 = 2 × 16 = 32

$$\text{Moles of } O_2 = \frac{500}{32} = 15.625\text{ mol}$$

5. (1.5)

Basis : 117 kg of K.

Atomic weight of K = 39

$$\text{Atoms of K} = \frac{117}{39} = 3\text{ katom}$$

Each mole of K_2CO_3 contains 2 atom of K

2 atom of K ≡ 1 mole of K_2CO_3

2 katom of K ≡ 1 kmol of K_2CO_3

$$\therefore \text{ Moles of } K_2CO_3 = \frac{1}{2} \times 3 = 1.5\text{ kmol}$$

6. (48)

Basis : 64 kg of methane.

Atomic weight of C = 12

Molecular weight of CH_4 = 16

1 katom of carbon ≡ 1 kmol of CH_4

$\therefore$ 12 kg of carbon ≡ 16 kg of CH_4

i.e., in 16 kg of CH_4, 12 kg of carbon are present.

So, amount of carbon present in 64 kg of methane

$$= \frac{12}{16} \times 64 = 48\text{ kg}$$