

Material Balance Calculations

(Incorporating calculations of ideal gas laws, unit operations and chemical reactions etc.)

THEORETICAL BACKGROUND

Ideal Gas Law :

$$PV = nRT$$

where, P = Total pressure of system

V = Volume

n = Number of moles

T = Absolute temperature

R = Universal gas constant

Values of universal gas constant (R).

In different units, the values of universal gas constant are as under :

<i>Unit</i>	<i>Numerical value of R</i>
$\frac{(\text{atm.}) (\text{lit.})}{\text{gm mole } ^\circ\text{K}}$	0.08205
$\frac{(\text{atm.}) \text{ m}^3}{\text{kg. mole } ^\circ\text{K}}$	0.08205
$\frac{(\text{atm.}) (\text{cc})}{\text{gm mole } ^\circ\text{K}}$	82.05
$\frac{(\text{Psi}) \text{ ft}^3}{\text{lb. mole } ^\circ\text{R}}$	10.73
$\frac{(\text{atm.}) \text{ ft}^3}{\text{lb. mole } ^\circ\text{R}}$	0.73
$\frac{(\text{mm Hg}) \text{ lit.}}{\text{gm mole } ^\circ\text{K}}$	62.359
$\frac{\text{kcal}}{\text{kg. mole } ^\circ\text{K}}$	1.987

<i>Unit</i>	<i>Numerical value of R</i>
$\frac{\text{B Thu}}{\text{lb. mole } ^\circ\text{R}}$	1.987
$\frac{\text{kJ}}{\text{kg. mole } ^\circ\text{K}}$	8.314
$\frac{\text{J}}{\text{gm mole } ^\circ\text{K}}$	8.314

Properties of gas mixtures :

(1) **Amagat's law.** If v_i is the volume of pure component i , present in the mixture, total volume of gas, V , is given by

$$V = \sum v_i.$$

(2) **Dalton's law.** If p_i is the partial pressure of the i th component of the mixture and y_i is its mole fraction in the mixture, the total pressure (P_T) is,

$$P_T = \sum p_i$$

Also,
$$p_i = P_T y_i.$$

(3) **Average molecular weight (M_{av})**

$$M_{av} = \sum M_i Y_i$$

where, M_i = Molecular weight of i th component

Y_i = Mole fraction of i th component.

Properties of ideal and non-ideal solutions :

(1) **Rault's law.** Rault's law holds good for ideal and dilute solutions. According to this law, the vapour pressure of the solvent in a solution is directly proportional to the mole fraction of the solvent.

Mathematically,

$$p_i = P_i x_i$$

where, p_i = equilibrium partial pressure

P_i = vapour pressure of a solvent in a solution

x_i = mole fraction of the solvent.

(2) **Henry's law.** According to this, for non-ideal solution (low concentration of gas in liquid), the partial pressure of solute gas is proportional to the mole fraction of the solute in the solution.

Mathematically,

$$p_i = H_i x_i$$

where, H_i = Henry's law constant

x_i = Solute mole fraction

Terminology used in chemical reactions :

Limiting reactant. A reactant which decides the conversion in a reaction.

Excess reactant. A reactant which is present in excess of the stoichiometric amount in a reaction.

In the reaction, $C + O_2 \rightarrow CO_2$, carbon is the limiting reactant and oxygen which is supplied generally in excess of the theoretical amount is the excess reactant.

Conversion and yield (in percentage)

$$\text{Conversion} = \frac{\text{Moles of reactants consumed in reaction}}{\text{Moles of reactants charged}} \times 100$$

This takes into account the reactants consumed for the production of main and by-products in a reaction.

$$\text{Yield} = \frac{\text{Moles of reactants converted to main product}}{\text{Moles of reactant taking part in the reaction}} \times 100.$$

Recycle, by-pass and purge streams :

These streams are encountered in industrial processes involving both physical operations and chemical reactions.

Recycle stream. It refers to a process stream that conducts material exiting or downstream from a unit back to the inlet or upstream of the same unit, the objective being either to control a process parameter or to increase yield, conversion with respect to a particular reactant. (Fig. 1.1)

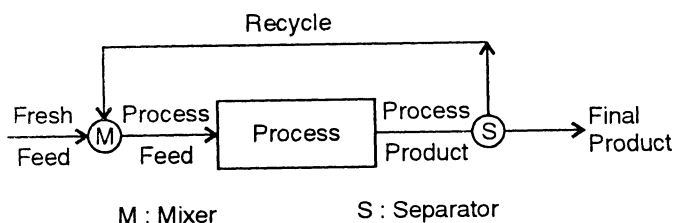


Fig. 1.1. A recycle stream.

Bypass stream. It is a stream that skips one or more stages of the process and goes directly to another stage with the purpose of controlling the composition of a final exit stream. (Fig. 1.2)

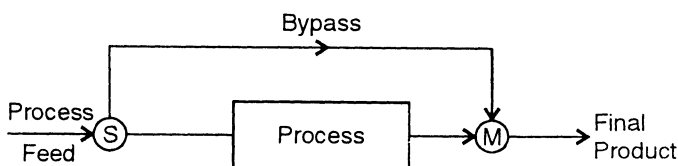


Fig. 1.2. A bypass stream.

Purge stream. A stream bled off to remove an accumulation of certain inerts or unwanted materials that might otherwise build up in the recycle stream is called a purge stream. It is generally associated with a recycle stream. (Fig. 1.3)

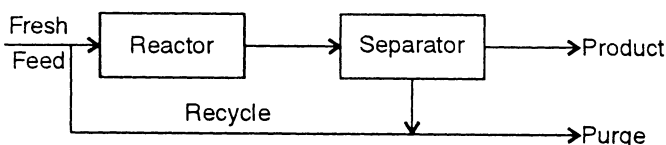


Fig. 1.3. A purge stream.

Ex. 1. A compound whose molecular weight is 103 analyzes as following (percentage weight basis) :

C—81.5 ; H—4.9 ; N—13.6.

What is its formula ?

(A.M.I.E. Exam. May 1974 E ; A.M.I.E. Exam. 1991 Summer)

Solution :

Basis : 103 kg of the compound (1 kg mol)

$$\text{Amount of carbon} = \frac{81.5}{100} \times 103 = 83.95 \text{ kg.}$$

$$\text{Kg atoms of carbon} = \frac{83.95}{12} = 6.995 \approx 7.0$$

$$\text{Amount of hydrogen} = \frac{4.9}{100} \times 103 = 5.05 \text{ kg.}$$

$$\text{Kg atoms of hydrogen} = \frac{5.05}{1.0} = 5.05 \approx 5.0$$

$$\text{Amount of nitrogen} = \frac{13.6}{100} \times 103 = 14.008$$

$$\text{Kg atoms of nitrogen} = \frac{14.008}{14} \approx 1.0$$

Hence formula of the compound is $\text{C}_7\text{H}_5\text{N}$.

Ex. 2. By electrolyzing a mixed brine a mixture of gases is obtained at the cathode having the following percentage composition by weight :

Cl_2 — 67

Br_2 — 28

O_2 — 5

Using the ideal gas law, calculate :

(a) Composition of the gas by volume.

(b) Density of the mixture in grams per litre at 25°C and 740 mm of Hg pressure.

(c) *Specific gravity of the mixture, (air = 1.0) Atomic weights :
Cl—35.5, Br—80.0, O—16.0. (A.M.I.E. Exam. May 1974)*

Solution :

Basis : 1 gm of the gas mixture.

(a) Composition of gas by volume.

Constituents	Amount		Mol % (\equiv Vol. %)
	gm.	gm. mol.	
Cl ₂	0.67	0.00943	74.02
Br ₂	0.28	0.00175	13.74
O ₂	0.05	0.00156	12.24
Total	1.00	0.01274	100.00

(b) 1 gm of mixture contains 0.01274 mol.

$$P = 740 \text{ mm of Hg.}$$

$$T = 25^{\circ}\text{C} = 298^{\circ}\text{K}$$

$$R = \frac{760 \times 22.4}{273} = 62.4 \frac{(\text{mm. Hg}) (\text{lit.})}{(\text{gm. mol}) (^{\circ}\text{K})}$$

$$\begin{aligned} \text{Hence, } V &= \frac{nRT}{P} && [\text{from ideal gas law}] \\ &= \frac{0.01274 \times 62.4 \times 298}{740} = 0.32 \text{ lit.} \end{aligned}$$

$$\text{Density} = \frac{1}{0.32} = 3.12 \text{ gm/lit.}$$

(c) Assuming ideal behaviour for air, volume of 1 gm mol at 25°C and 1 atmosphere

$$= \frac{760 \times 22.4 \times 298}{740 \times 273} = 25.11 \text{ litres.}$$

$$\text{Mol. wt. of air} = 28.84$$

$$\text{Density of air} = \frac{28.84}{25.11} = 1.15 \frac{\text{gm}}{\text{lit}}$$

Specific gravity of the mixture

$$= \frac{3.12}{1.15} = 2.71.$$

Ex. 3. *In the Deacon process for the manufacture of chlorine, a dry mixture of hydrochloric acid gas and air is passed over a heated catalyst which promotes oxidation of the acid. Air is used in 30% excess of that theoretically required.*

(a) Calculate the weight of air supplied per kg. of acid.

(b) Calculate the composition by weight of the gas entering the reaction chamber.

(c) Assuming that 60% of the acid is oxidized in the process, calculate the composition by weight of the gases leaving the chamber.

(A.M.I.E. Exam. May 1974 and Sambalpur Uni. 1982)

Solution :

Basis : 1 kg of dry HCl gas.

Reaction: $4 \text{HCl} + \text{O}_2 \rightarrow 2\text{Cl}_2 + 2\text{H}_2\text{O}$

(a) $4 \times 36.5 \text{ kg HCl require } 32 \text{ kg O}_2$

$$1 \text{ kg HCl require } \frac{32}{146} = 0.219 \text{ kg.}$$

$$\text{Theoretical air} = 0.219 \times \frac{100}{23} = 0.953 \text{ kg.}$$

$$\text{Air supplied (30\% excess)} = 0.953 \times 1.3 = 1.24 \text{ kg.}$$

$$(b) \text{ Wt. of O}_2 \text{ supplied} = 1.24 \times 0.23 = 0.285 \text{ kg.}$$

$$\text{Wt. of N}_2 \text{ supplied} = 1.24 \times 0.77 = 0.955 \text{ kg}$$

Analysis of gas entering reaction chamber :

Constituents	Amount, kg	Wt. %
HCl	1.000	44.66
O ₂	0.285	12.73
N ₂	0.955	42.61
Total	2.24	100.00

(c) Composition of the gases leaving the reaction chamber :

Reaction is 60% complete

$$\text{HCl converted} = 0.6 \text{ kg.}$$

From the chemical reaction,

$$\text{Chlorine formed} = \frac{142}{146} \times 0.6 = 0.583 \text{ kg}$$

$$\text{Water vapour} = \frac{36}{146} \times 0.6 = 0.148 \text{ kg}$$

$$\text{Oxygen used} = \frac{32}{146} \times 0.6 = 0.132 \text{ kg}$$

$$\text{Oxygen left} = 0.285 - 0.132 = 0.153 \text{ kg}$$

Analysis of gases leaving :

Constituents	Wt., kg.	Wt. %
HCl	0.400	17.87
O ₂	0.153	6.86
N ₂	0.955	42.62
Cl ₂	0.583	26.04
H ₂ O	0.148	6.61
Total	2.239	100.00

Ex. 4. A solution contains 50% benzene, 30% toluene and 20% xylene by weight at a temperature of 100°C. The vapours are in contact with the solution. Calculate the total pressure and the molar percentage compositions of the liquid and the vapour. The vapour pressures and molecular weights are as follows :

Components	Vapour pressure at 100°C	Mol. wt.
Benzene	1340 mm of Hg	78
Toluene	560 mm of Hg	92
Xylene	210 mm of Hg	106

(A.M.I.E. Exam. 1974 May, 1975 May and 1975 Winter ;
Sambalpur Uni. 1969 and 1975)

Solution :

Basis : 100 kg of solution.

Molar percentage composition of liquid :

Constituents	Amount kg	Mol. wt.	Mol.	Mol. %
Benzene	50	78	0.641	55.45
Toluene	30	92	0.326	28.20
Xylene	20	106	0.189	16.35
Total	100		1.156	100.00

Calculation of partial pressure :

By Rault's law,

$$p = \text{V.P.} \times \text{Mol. fraction in liquid}$$

where, p = partial pressure.

$$p_{\text{benzene}} = 1340 \times 0.5545 = 743.0 \text{ mm Hg}$$

$$p_{\text{toluene}} = 560 \times 0.2820 = 157.9 \text{ mm Hg}$$

$$p_{\text{xylene}} = 210 \times 0.1635 = 34.3 \text{ mm Hg}$$

$$\begin{aligned}\text{Total pressure} &= \Sigma p = 743.0 + 157.9 + 34.3 \\ &= 935.2 \text{ mm of Hg}\end{aligned}$$

Vapour composition :

$$y = \frac{p}{\text{Total pressure}}$$

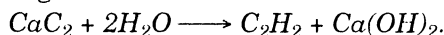
where, y = Mol. fraction in vapour.

$$Y_{\text{benzene}} = \frac{743}{935.2} = 0.7945 \approx 79.45\%$$

$$Y_{\text{toluene}} = \frac{157.9}{935.2} = 0.1688 \approx 16.88\%$$

$$Y_{\text{xylene}} = \frac{34.3}{935.2} = 0.0367 \approx 3.67\%.$$

Ex. 5. The gas acetylene is produced according to the following reaction by treating calcium carbide with water :

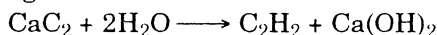


Calculate the number of hours of service that can be derived from 1.0 kg of carbide in an acetylene lamp burning 60 litres of gas per hour at a temperature of 20°C and a pressure of 740 mm Hg.

(A.M.I.E. Exam. Winter 1974 ; A.M.I.E. Exam. 1991 Summer)

Solution :

Basis : 1 kg of carbide.



64 kg calcium carbide gives 26 kg C_2H_2

1 kg calcium carbide gives $\frac{26}{64}$ kg C_2H_2

$$= \frac{26}{64} \times \frac{1}{26} \text{ kg mol } \text{C}_2\text{H}_2 = 0.0156 \text{ kg mol.}$$

Assuming ideal gas behaviour for C_2H_2 ,

Volume of gas produced at 20°C and 740 mm of Hg is to be calculated.

$$\begin{aligned}R &= \frac{pV}{nT} = \frac{760 \times 22,400}{1 \times 273} \\ &= 62,358.9 \frac{(\text{mm Hg}) (\text{lit.})}{(\text{kg mol}) (^\circ\text{K})}\end{aligned}$$

$$\begin{aligned}\text{Volume of acetylene} &= \frac{nRT}{P} \\ &= \frac{0.0156 \times 62,358.9 \times (273 + 20)}{740} \\ &= 385.8 \text{ litres.}\end{aligned}$$

$$\text{No. of hours of service} = \frac{385.8}{60} = 6.43.$$

Ex. 6. *The spent acid from a nitrating process contains 33% H_2SO_4 36% HNO_3 and 31% water by weight. This acid is to be strengthened by the addition of concentrated sulphuric acid containing 95% H_2SO_4 and concentrated nitric acid containing 78% HNO_3 . The strengthened mixed acid is to contain 40% H_2SO_4 and 43% HNO_3 . Calculate the quantities of spent and concentrated acids that should be mixed together to yield 1500 kg of the desired mixed acid.*

(A.M.I.E. Exam. Summer 1975,
Winter 1978 and Summer 1979)

Solution :

Basis : 1500 kg of the desired mixed acid.

Let, x = wt. of waste acid (in kg) required

y = wt. of conc. H_2SO_4 (in kg) required

z = wt. of conc. HNO_3 (in kg) required

Overall material balance is,

$$x + y + z = 1500 \quad \dots(1)$$

Sulphuric acid balance is,

$$0.33x + 0.95y = 0.4 \times 1500 = 600 \quad \dots(2)$$

Nitric acid balance is,

$$0.36x + 0.78z = 0.43 \times 1500 = 645 \quad \dots(3)$$

$$\text{From Eq. (2),} \quad y = \frac{600 - 0.33x}{0.95} \quad \dots(4)$$

$$\text{From Eq. (3),} \quad z = \frac{645 - 0.36x}{0.78} \quad \dots(5)$$

Putting (4) and (5) in Eq. (1)

$$x + \frac{600 - 0.33x}{0.95} + \frac{6.45 - 0.36x}{0.78} = 1500$$

$$\begin{aligned} \text{or,} \quad x - (0.347x + 0.462x) \\ = 1500 - (631.58 + 826.92) \end{aligned}$$

$$\text{or} \quad 0.191x = 41.5$$

$$\text{Therefore,} \quad x = \frac{41.5}{0.191} = 217.3 \text{ kg.}$$

$$\text{From (4),} \quad y = 556.1 \text{ kg.}$$

$$\text{From (5),} \quad z = 726.6 \text{ kg.}$$

Weights of waste (spent) acid, conc. H_2SO_4 and conc. HNO_3 required are 217.3, 556.1 and 726.6 kg respectively.

Ex. 7. *After a crystallization process a solution of calcium chloride in water contains 62 parts of CaCl_2 per 100 parts of water.*

Calculate the weight of this solution necessary to dissolve 250 kg. of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ crystal at a temperature of 25°C . Solubility of CaCl_2 at 25°C is 7.38 kg. mol of CaCl_2 per 1000 kg of water.

(A.M.I.E. Exam. 1975 Summer and Sambalpur Univ. 1977 May)

Solution :

Let, M = wt. of solution obtained from the crystallization process.

C = wt. of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ crystals dissolved.

S = wt. of final solution obtained after dissolving the crystals

Overall material balance is,

$$S = M + C \quad \dots(1)$$

Mol. wt. of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O} = 219$.

Let x_S , x_M , and x_C represent the solid fractions in S , M and C respectively.

$$x_S = \frac{7.38 \times 111}{7.38 \times 111 + 1000} \quad [\text{Mol. wt. of } \text{CaCl}_2 = 111]$$

$$= 0.45$$

$$x_M = \frac{62}{100 + 62} = 0.383$$

$$x_C = \frac{111}{219} = 0.507$$

Since, $C = 250$,

Therefore, $S = M + 250$.

Calcium chloride balance gives,

$$Sx_S = Cx_C + Mx_M \quad \dots(2)$$

or, $(M + 250) 0.45 = 250 \times 0.507 + M \times 0.383$

Solving, $M = 212.7$ kg.

Weight of the solution required = 212.7 kg.

Ex. 8. A solution of potassium dichromate in water contains 13% $\text{K}_2\text{Cr}_2\text{O}_7$ by weight, 1000 kg of this solution is evaporated to remove some amount of water. The remaining solution is cooled to 20°C . If the yield of $\text{K}_2\text{Cr}_2\text{O}_7$ crystals is 80%, calculate the amount of water evaporated. Solubility of $\text{K}_2\text{Cr}_2\text{O}_7$ is 0.390 kg mole per 1000 kg water (at 20°C). Atomic weights : K 39, Cr 52.

(A.M.I.E. Exam. 1975 Winter and Sambalpur Uni. 1978 May)

Solution :

Basis : 1000 kg of 13% $\text{K}_2\text{Cr}_2\text{O}_7$ solution,

Assumption : No water of crystallization with $\text{K}_2\text{Cr}_2\text{O}_7$ crystals.

Let, F = amount of feed solution, kg.

E = amount of evaporation, kg.

C = amount of crystals formed, kg.

M = amount of mother liquor left after crystallization, kg.

Mol. wt. of $K_2Cr_2O_7$ = 294.

$$x_F = 0.13$$

$$x_C = 1.0$$

$$x_M = \frac{0.39 \times 294}{0.39 \times 294 + 1000} = 0.103$$

$K_2Cr_2O_7$ in original solution = 130 kg.

Yield of crystals = 80% = $130 \times 0.8 = 104$ kg

So, $C = 104$ kg

Overall material balance gives,

$$F = E + M + C = E + M + 104 \quad \dots(1)$$

or, $M = (F - E - 104) = (1000 - E - 104) = 896 - E$

$K_2Cr_2O_7$ balance gives,

$$F x_F = M x_M + C x_C \quad \dots(2)$$

(Since, $x_E = 0$, $E x_E$ term is not there)

So, $1000 \times 0.13 = (896 - E) \times 0.103 + 104$

i.e. $0.103 E = 92.29 + 104 - 130$

$$E = 643.6 \text{ kg.}$$

Amount of water evaporated = 643.6 kg.

Ex. 9. 1000 kg of sodium carbonate solution containing 25% Na_2CO_3 is subjected to evaporative cooling, during which process 15% of the water present in the solution is evaporated. From the concentrated solution Na_2CO_3 , $10H_2O$ crystallizes out. Calculate how much crystals would be produced if the solubility of Na_2CO_3 , $10H_2O$ is 21.5 gm per 100 gm of water. (Sambalpur Uni. 1982 May)

Solution :

Basic : 1000 kg of sodium carbonate 25% solution (F).

Let C = crystals formed.

E = evaporated water

M = mother liquor.

Water present in the solution = 750 kg.

Water evaporated = $750 \times 0.15 = 112.5$ kg.

$$F = C + E + M = C + 112.5 + M$$

or, $1000 - 112.5 = C + M$.

i.e., $M = (887.5 - C)$

Mol. wt. of Na_2CO_3 , $10\text{H}_2\text{O} = 286$

$$x_C = \frac{106}{286} = 0.371$$

$$x_M = \frac{21.5}{121.5} = 0.177$$

Na_2CO_3 balance is,

$$F x_F = M x_M + C x_C$$

$$1000 \times 0.25 = (887.5 - C)0.177 + 0.371 C$$

Solving, $C = 479.4 \text{ kg.}$

Crystals formed = 479.4 kg.

Ex. 10. *Phosphorous is prepared by heating in the electric furnace a thoroughly mixed mass of calcium phosphate, sand and charcoal. In a certain charge silica used is 10% in excess of that theoretically required to combine with all the calcium to form the silicate and the charcoal used is 40% in excess of that required to combine as carbon monoxide, with the oxygen that would accompany all the phosphorous as the pentoxide.*

(i) Calculate the composition of the original charge.

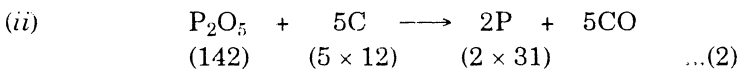
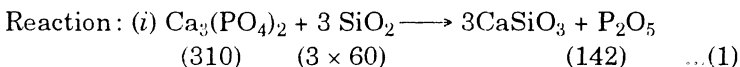
(ii) If the decomposition of the phosphate is 90% complete and the reduction of the pentoxide is 70% complete, calculate the amount of phosphorous produced per 100 kg of charge.

Atomic weights : P—31.0, Si—28.0, Ca—40.0.

(A.M.I.E. Exam. 1975 Winter)

Solution :

Basis : 1 kg mol of calcium phosphate decomposed.



310 kg of $\text{Ca}_3(\text{PO}_4)_2$ require 180 kg of SiO_2

Since SiO_2 is 10% excess.

so, SiO_2 supplied = $180 \times 1.1 = 198 \text{ kg}$

142 kg. of P_2O_5 require 60 kg carbon.

Since charcoal (carbon) is 40% excess.

So carbon supplied = $60 \times 1.4 = 84 \text{ kg.}$

(i) Charge analysis :

Constituents	Amount, kg	Wt. %
$\text{Ca}_3(\text{PO}_4)_2$	310	52.36
SiO_2	198	33.45
Charcoal	84	14.19
Total	592	100.00

(ii) 100 kg. of charge contains 52.36 of calcium phosphate

Since the phosphate decomposition is 90%

Amount of P_2O_5 formed (reaction - 1)

$$= 52.36 \times 0.9 \times \frac{142}{310} = 21.58 \text{ kg.}$$

Reduction of P_2O_5 is 70% complete.

P_2O_5 reduced $= 21.58 \times 0.7 = 15.11 \text{ kg.}$

From reaction (2),

142 kg P_2O_5 produces 62 kg. P.

15.11 P_2O_5 produces $\frac{62}{142} \times 15.11 = 6.6 \text{ kg.}$

Amount of phosphorous produced = 6.6 kg.

Ex. 11. Calculate the volume occupied by 1 gm mole of water vapour at 900°C and 100 atm. (i) by the perfect gas law, and (ii) using Van der Waal's equation. The Van der Waal's constants for water are :

$$a = 5.404 (\text{litre})^2 (\text{atm.}) / (\text{gm. mol})^2$$

$$b = 0.3049 (\text{litre} / \text{gm. mol})$$

$$\text{Van der Waal's equation is : } \left(P + \frac{a}{V^2} \right) (V - b) = RT.$$

(A.M.I.E. Exam. 1976 Winter)

Solution :

$$R = \text{gas constant} = 0.082 \frac{(\text{lit.}) (\text{atm.})}{(\text{gm. mol}) (^\circ\text{K})}$$

$$T = 1173^\circ\text{K}, P = 100 \text{ atm.}$$

$$n = 1.0 \text{ gm mol.}$$

(a) Let V = volume in litres.

By perfect gas law,

$$V = \frac{nRT}{P} = \frac{0.082 \times 1173}{100} = 0.963 \text{ lit.}$$

(b) For Van der Waal's equation, V is solved by trial and error

$$\left(P + \frac{a}{V^2} \right) (V - b) = RT = 0.082 \times 1173 = 96.3$$

Let $V = 1.0$ lit.

L.H.S. $= 102.25 \neq$ R.H.S.

Let $V = 0.94$ lit.

L.H.S. $= 96.58 \approx 96.3$

Hence the volume occupied = **0.94 litre.**

Ex. 12. Bottled liquid gas of the following composition is sold for house-hold use :

Component	<i>n</i> -Butane	Propane	Ethane
Composition, Mole %	50	45	5
V. Pr. at 30°C, bar	3.4	10.8	46.6

Determine (i) the pressure of the system and the equilibrium vapour composition at 30°C and (ii) if all the ethane be removed from the liquid, the pressure of the system and the vapour composition at 30°C. Assume Rault's law is applicable.

(A.M.I.E. Exam. Summer 1976)

Solution :

Basis : 1 kg. mole of the bottled gas.

Components	Mol frac. in liquid	Vapour pr., bar	Partial pr., bar
<i>n</i> -butane	0.50	3.4	1.7
propane	0.45	10.8	4.86
ethane	0.05	46.6	2.33

(i) Pressure of the system

$$= \Sigma \text{ partial pressure} = 8.89 \text{ bar.}$$

Equilibrium vapour composition :

$$y = \frac{\text{Partial pressure}}{\text{Pressure of the system}}$$

$$y_{\text{butane}} = \frac{P_{\text{butane}}}{\text{Total pressure}}$$

$$= \frac{1.70}{8.89} \times 100 = 19.12\% \text{ m}$$

$$\text{Similarly, } y_{\text{propane}} = \frac{4.86}{8.89} \times 100 = 54.67\% \text{ m}$$

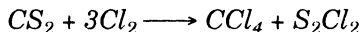
$$y_{\text{ethane}} = \frac{2.33}{8.89} \times 100 = 26.21\% \text{ m}$$

(ii) If ethane is removed, the liquid left will be
 $= 1.0 - 0.05 = 0.95 \text{ kg mol.}$

Components	Amount mol	Mol% in liquid	p.p., bar	Vapour comp. mol%
Butane	0.50	52.63	1.789	25.91
Propane	0.45	47.37	5.116	74.09
Total	0.95	100.00	6.905	100.00

Pressure of the system = $\Sigma p.p. = 6.905 \text{ bar.}$

Ex. 13. Carbon tetrachloride is made as following :



The product gases are found to contain

	CCl_4	S_2Cl_2	CS_2	Cl_2
Mol%	23.3	23.3	1.4	32.0

Calculate (i) The percentage of the excess reactants used.

(ii) The percentage of conversion.

(iii) The kg of CCl_4 produced per 100 kg of Cl_2 converted.

(A.M.I.E. Exam. Summer 1976)

Solution :

Basis : 100 kg mol of product gas.

Product gas analysis :

Components	Mol
CCl_4	23.3
S_2Cl_2	23.3
CS_2	1.4
Cl_2	32.0

In this case CS_2 is the limiting reactant and Cl_2 is the excess reactant. From the product analysis, it is seen that 23.3 kg mols of CS_2 have been converted.

(i) CS_2 unconverted = 1.4 kg mol

(ii) Percentage conversion

$$= \frac{23.3 \times 100}{23.3 + 1.4} = 94.33$$

Chlorine required for complete conversion of

$$\text{CS}_2 = 24.7 \times 3.0 = 74.1 \text{ kg mol.}$$

Chlorine used $= 23.3 \times 3 = 69.9 \text{ kg mol.}$
 Chlorine in product $= 32.0$
 Total chlorine used $= 69.9 + 32.0 = 101.9 \text{ kg mol}$
 Excess chlorine used $= 101.9 - 74.1$
 $= 27.8 \text{ kg. mol.}$

(i) Percentage of the excess reactant used

$$= \frac{27.8}{74.1} \times 100 = 37.52$$

(ii) From the reaction,

$3 \times 71.0 \text{ kg of Cl}_2 \text{ yield } 154 \text{ kg of CCl}_4$

$$100 \text{ kg of Cl}_2 \text{ yield } \frac{154}{3 \times 71.0} \times 100$$

$$= 72.3 \text{ kg of CCl}_4.$$

Ex. 14. Stock containing 1.562 gm of water per gm of dry stock is to be dried to 0.099 gm. For each gm of stock (dry basis) 52.5 gm of dry air pass through the drier, leaving at a humidity of 0.0525. The fresh air is supplied at a humidity 0.0152. Calculate the fraction of air recirculated. (Sambalpur Uni. 1979 May)

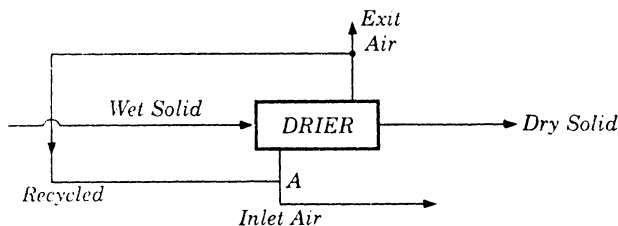


Fig. 1.4

Solution :

Basis : 1 gm of dry stock.

Assumption : The humidity values are taken as $\frac{\text{gm water}}{\text{gm dry air}}$

$$\text{Initial water content of stock} = 1.562 \frac{\text{gm H}_2\text{O}}{\text{gm dry stock}}$$

$$\text{Final water content of stock} = 0.099 \frac{\text{gm H}_2\text{O}}{\text{gm dry stock}}$$

$$\text{Water removed in the drier} = 1.562 - 0.099$$

$$= 1.463 \frac{\text{gm}}{\text{gm of dry stock}}$$

$$\text{Dry air used} = 52.5 \frac{\text{gm}}{\text{gm of dry stock}}$$

Water taken away by 52.5 gm dry air in the drier = 1.463 gm.

So, change in humidity of air

$$= \frac{1.463}{52.5} = 0.0279 \frac{\text{gm}}{\text{gm dry air}}$$

$$\text{Exit humidity of air} = 0.0525 \frac{\text{gm H}_2\text{O}}{\text{gm. dry air}}$$

$$\begin{aligned} \text{Inlet humidity of air} &= 0.0525 - 0.0279 \\ &= 0.0246 \frac{\text{gm H}_2\text{O}}{\text{gm. dry air}} \end{aligned}$$

Let y gm of dry exit air be recycled

So, fresh dry air = $(52.5 - y)$ gm.

A humidity balance at point A gives,

$$0.0525 y + (52.5 - y)0.0152 = 0.0246 \times 52.5$$

$$\text{Hence, } y = 13.23$$

$$(52.5 - y) = 39.27$$

$$\text{Fraction of air recycled} = \frac{13.23}{52.50} = 0.252.$$

Ex. 15. Air at 1 atm., 35°C and 90% humidity is to be conditioned to 23.9°C and 60% humidity by cooling part of the air to 10°C and mixing it with uncooled air. The resulting mixture will be reheated to 23.9°C. For 1000 litres/min. of air at 23.9°C and 60% humidity, calculate (i) the volume of entering air, and (ii) the percentage of entering air that is by-passed.

Following data are available :

At 23°C 60% humidity,

$$y = 0.018 \frac{\text{kg moles H}_2\text{O}}{\text{kg moles dry air}}$$

At 35°C 90% humidity,

$$y = 0.053 \quad ,$$

At 10°C, 100% humidity,

$$y = 0.012 \quad , \quad (\text{A.M.I.E. Exam. Winter 1976})$$

Solution :

Basis : 1000 litres/min. of conditioned air at 23.9°C and 60% humidity.

Assuming ideal gas law holds good for both water vapour and dry air, moles of air and accompanied water vapour are calculated.

Let n = no. of mol at 23.9°C and 60% humidity.

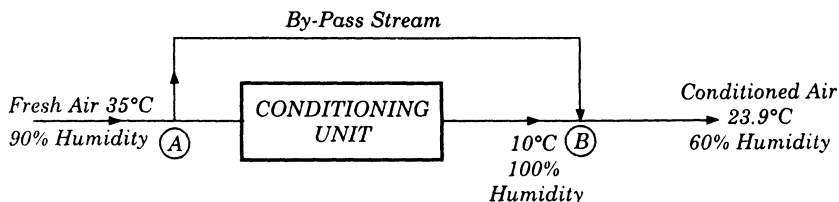


Fig. 1.5

$$n = \frac{PV}{RT} = \frac{1 \times 1000}{0.082 \times (273 + 23.9)}$$

$$= 41.07 \text{ gm mol/min.}$$

$$\text{Amount of dry air} = \frac{1.0}{1.018} \times 41.07 = 40.344 \frac{\text{gm mol}}{\text{min.}}$$

$$\text{Amount of water vapour}$$

$$= \frac{0.018}{1.018} \times 41.07 = 0.726 \text{ gm. mol/min.}$$

Amount of dry air remains unchanged. Let y gm mol of dry air be contained in the bypass stream.

Hence, dry air associated with fresh air stream = $(40.344 - y)$ gm. mols.

A water vapour balance at point B gives,

$$y \times 0.053 + (40.344 - y) \times 0.012 = 0.726$$

Solving $y = 5.902$ gm mol (by-pass stream)

$$\begin{aligned} \text{Main stream dry air} &= 40.344 - y \\ &= 34.442 \text{ gm mol.} \end{aligned}$$

(a) Amount of water vapour corresponding to inlet conditions
 $= 40.344 \times 0.053 = 2.138$ gm mol.

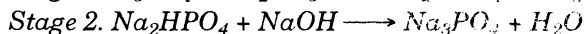
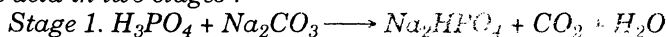
$$\begin{aligned} \text{Total gm mol of humid air at the entry} \\ &= 40.344 + 2.138 = 42.482 \end{aligned}$$

$$\begin{aligned} \text{Volume at the inlet} &= \frac{nRT}{P} = \frac{42.482 \times 0.082 \times (273 + 35)}{1.0} \\ &= 1072.93 \text{ litres.} \end{aligned}$$

(b) % entering air by passed

$$= \frac{5.902}{40.344} \times 100 = 14.63.$$

Ex. 16. Sodium phosphate is produced by neutralizing phosphoric acid in two stages :



The process is carried out as follows :

Soda ash (Na_2CO_3) is dissolved in water and the solution is reacted with commercial phosphoric acid containing 85% H_3PO_4 (rest water) to complete the first stage of reaction.

The second stage of the reaction is carried out by reacting the disodium phosphate solution with 50% caustic lye (NaOH) resulting in a trisodium phosphate solution having a concentration of 20%. To produce 1 tonne (1000 kg) of the trisodium phosphate, calculate :

(a) The composition of the soda ash solution fed ;

(b) The ratio in which phosphoric acid (85%) and the soda ash solution to be mixed ;

(c) The weight of caustic lye needed ;

(d) If Na_2CO_3 be added 10% in excess in the first stage how much of the caustic lye should be added in the second stage,

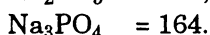
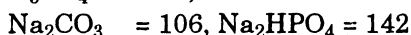
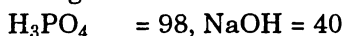
Atomic weights $P = 31, Na = 23, C = 12,$

$O = 16, H = 1.$ (A.M.I.E. 1976 Summer)

Solution :

Basis : 1 tonne of trisodium phosphate produced.

Molecular weights are as follows :



Since the compositions are independent of the amount of Na_3PO_4 produced, hence for the solution of (a) and (b), another convenient basis of 100 kg of phosphoric acid is used. From the reactions, for 100 kg H_3PO_4 ,

$$\begin{aligned} \text{Na}_2\text{CO}_3 \text{ used} &= \frac{106}{98} \times 85 \text{ (since } \text{H}_3\text{PO}_4 \text{ is 85\% acid)} \\ &= 91.94 \text{ kg} \end{aligned}$$

$$\text{Na}_2\text{HPO}_4 \text{ produced} = \frac{142}{98} \times 85 = 123.16 \text{ kg}$$

$$\text{Water produced} = \frac{18}{98} \times 85 = 15.61 \text{ kg (in stage 1)}$$

$$\text{NaOH required} = \frac{40}{142} \times 123.16 = 34.69 \text{ kg}$$

$$\text{Na}_3\text{PO}_4 \text{ produced} = \frac{164}{142} \times 123.16 = 142.24 \text{ kg}$$

$$\text{Water produced} = \frac{18}{142} \times 123.16 = 15.61 \text{ kg (in stage 2)}$$

Since, caustic lye is a 50% NaOH solution, water with caustic soda = 34.69 kg.

Na_3PO_4 is 20% solution. Let x kg water is associated with Na_3PO_4 .

$$\frac{142.24}{x + 142.24} = \frac{20}{100}$$

Hence, $x = 568.96 \text{ kg}$

(amount of water with final product)

Water produced = $15.61 + 15.61 = 31.22 \text{ kg}$.

Water with caustic lye = 34.69 kg .

Water with H_3PO_4 = 15.00 kg .

Let $y = \text{kg water with } \text{Na}_2\text{CO}_3 \text{ solution}$.

Water balance gives,

$$31.22 + 34.69 + 15.0 + y = 568.96$$

$$y = 488.05 \text{ kg}$$

(a) Soda ash solution contains 488.05 kg water.

$$\text{Composition of solution} = \frac{91.94}{91.94 + 488.05} \times 100 = 15.85\%.$$

(b) Amount of soda ash solution

$$= 91.94 + 488.05 = 579.99 \text{ kg}.$$

Ratio of soda ash solution and phosphoric acid

$$= 579.99 : 100 = 5.8 : 1.0$$

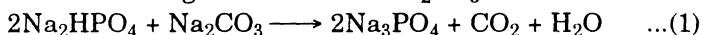
(c) 142.24 kg of Na_3PO_4 require 34.69 kg of NaOH

$$1000 \text{ kg of } \text{Na}_3\text{PO}_4 \text{ require } \frac{34.69}{142.24} \times 1000 = 243.88 \text{ kg NaOH}$$

Since it is a 50% solution,

$$\text{Weight of caustic lye needed} = \frac{243.88}{0.5} = 487.76 \text{ kg}.$$

(d) When Na_2CO_3 is in excess of that required in the first stage, it is used in the second stage in place of NaOH to produce trisodium phosphate. Thus the consumption of caustic lye is reduced. The second stage reaction with Na_2CO_3 will be



142.24 kg of Na_3PO_4 require 91.94 kg Na_2CO_3

$$1000 \text{ kg of } \text{Na}_3\text{PO}_4 \text{ require } \frac{91.94}{142.24} \times 1000 = 646.37 \text{ kg}.$$

Na_2CO_3 used is 10% excess.

$$\text{Na}_2\text{CO}_3 \text{ used} = 646.37 \times 1.1 = 711 \text{ kg}.$$

$$\begin{aligned} \text{Amount of } \text{Na}_2\text{CO}_3 \text{ reacting in the second stage} &= 711 - 646.37 \\ &= 64.63 \text{ kg}. \end{aligned}$$

From the above equation (1),

106 kg Na_2CO_3 produce $2 \times 164 \text{ kg}$ Na_3PO_4

$$64.63 \text{ kg } \text{Na}_2\text{CO}_3 \text{ produce } \frac{2 \times 164}{106} \times 64.63 = 200 \text{ kg } \text{Na}_3\text{PO}_4$$

Amount of Na_3PO_4 produced by $\text{NaOH} = 1000 - 200 = 800 \text{ kg}$.

164 kg Na_3PO_4 require 40 kg of NaOH

800 kg Na_3PO_4 require $\frac{40}{164} \times 800 = 195.12 \text{ kg}$. NaOH

Amount of 50% caustic lye needed

$$= \frac{195.12}{0.5} = 390.24 \text{ kg}.$$

Ex. 17. SO_2 reacts with pure O_2 to form SO_3 . If the reaction is carried out with 100% excess oxygen as necessary for complete oxidation, but under such low temperature and pressure that the reaction goes only 60% to completion, calculate :

(i) The mole fraction of SO_2 , O_2 and SO_3 in reactants and products

(ii) The weight fraction of the three gases in reactants and products.

(iii) The average molecular weights of reactants and products.

(iv) The partial pressure of the products if the total pressure is 2 atm.

(v) If the products were cooled to 20°C and the pressure reduced to 720 mm Hg., what volume of gas would be obtained from 100 kg of SO_2 .

(A.M.I.E. Exam. Summer, 1977)

Solution :

Basis : 100 gm. mol. of SO_2 gas.

Reaction: $\text{SO}_2 + \frac{1}{2} \text{O}_2 \longrightarrow \text{SO}_3$.

Oxygen required = 50 gm mol.

Oxygen supplied (by 100% excess) = $50 \times 2 = 100 \text{ gm mol}$.

Reaction is 60% complete

SO_3 formed = 60 gm mol.

(a) Oxygen left = $100 - 30 = 70 \text{ gm mol}$

Analysis of reactants :

Constituents	Mol.	Mol fraction
SO_2	100	0.500
O_2	100	0.500

Analysis of products :

<i>Constituents</i>	<i>Mol</i>	<i>Mol fraction</i>
SO ₂	40	0.235
SO ₃	60	0.353
O ₂	70	0.412

(b) Weight fraction of reactant gases :

<i>Constituents</i>	<i>Mol.</i>	<i>Wr. in gm</i>	<i>Wt. fraction</i>
SO ₂	100	6400	0.667
O ₂	100	3200	0.333

Weight fraction of product gases :

<i>Constituents</i>	<i>Mol.</i>	<i>Wr. in gm</i>	<i>Wt. fraction</i>
SO ₂	40	2560	0.267
SO ₃	60	4800	0.500
O ₂	70	2240	0.233

(c) Average molecular weight of reactants

$$= 0.5 \times 64 + 0.5 \times 32 = 48.0$$

Average molecular weight of products

$$= 0.353 \times 80 + 0.235 \times 64 + 0.412 \times 32$$

$$= 56.46$$

(d) Partial pressure = Total pressure \times Mol fraction.

$$\text{p.p. SO}_2 = 2 \times 0.235 = 0.470 \text{ atm.}$$

$$\text{p.p. SO}_3 = 2 \times 0.353 = 0.706 \text{ atm}$$

$$\text{p.p. O}_2 = 2 \times 0.412 = 0.824 \text{ atm}$$

$$(e) 100 \text{ gm SO}_2 = \frac{100}{64} = 1.56 \text{ gm mol}$$

100 gm mol of SO₂ yield 170 gm mol of product

$$1.56 \text{ gm mol of SO}_2 \text{ yield } \frac{170}{100} \times 1.56 = 2.65 \text{ gm mol of product}$$

$$\text{Volume of gas} = \frac{nRT}{P}$$

$$= \frac{2.65 \times 62.36 \times (273 + 20)}{720} = 67.25 \text{ litres.}$$

So, gas produced for 100 kg of SO₂

$$= 67.25 \times 1000 = 67,250 \text{ litres.}$$

Ex. 18. Two pure organic chemicals A and B are introduced into the apparatus as shown in the figure below for the purpose of making the compound AB. Stream flows are adjusted so that mole ratios of A to B in the reactor is 4 : 1. At the temperature and pressure employed, this mole ratio effects complete consumption of B, 90% of the B forms AB, the desired product. The remainder forms A_2B , a useless by product. A_2B is incapable of further reaction. The effluent stream from the reactor is cooled to 20°C , at which temperature A and AB are completely immiscible. A_2B however is soluble in A and in AB. The distribution coefficient is

$$k = \frac{C_{AB}}{C_A} = 6$$

where, $C_{AB} = \text{mol } A_2B / \text{mol } AB$

$C_A = \text{mol } A_2B / \text{mol } A$.

Calculate the amount of all material flowing in each numbered stream, per 100 mole of desired product AB in stream 4.

(A.M.I.E. Exam. Summer 1977)

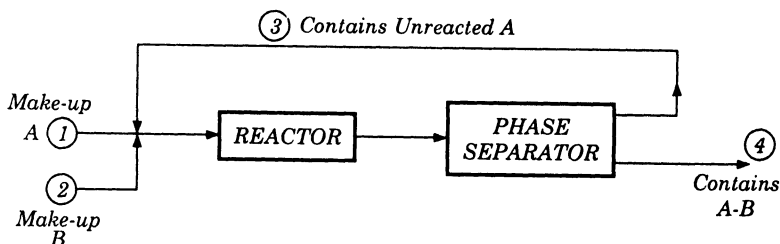
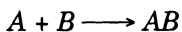


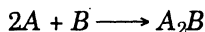
Fig. 1.6

Solution :

Basis : 100 mol of B reacted.



Since, 90% of B forms AB, 90 mol of B reacts with 90 mol of A to give 90 mol AB



10 mol B reacts with 20 mol A to give 10 mol A_2B

Mole of A reacted = 90 + 20 = 110

For 90 mol AB produced, 110 mol A reacted

100 mol AB produced = $\frac{110}{90} \times 100 = 122$ mol A reacted

Stream (1) = 122 mol.

Mol of B required for 100 mol AB,

$$= \frac{100}{90} \times 100 = 111$$

Stream (2) = 111 mol.

The only place that A_2B can leave the process is with AB . After start-up, the recycle stream composition will change constantly until a steady state has been reached. Under steady state conditions,

$$\text{Mol } A_2B \text{ with stream (4)} = \frac{10}{90} \times 100 = 11.0$$

So, stream (4) will have $100 + 11 = 111$ mol

Calculation for Stream (3) :

Stream (3) and (4) are in equilibrium with respect to the concentration of A_2B .

$$C_{AB} = \frac{11}{100}$$

$$\frac{C_{AB}}{C_A} = 6 \text{ (given)}$$

$$C_A = \frac{11}{600} = \frac{\text{mol } A_2B}{\text{mol } A}$$

$$\frac{\text{mol } A}{\text{mol } B} = \frac{4}{1} ; \text{mol } A = 4 \times 111 = 444$$

make-up A is 122 mol.

Hence recycle $A = 444 - 122 = 322$ mol

$$C_A = \text{concentration of } A_2B \text{ in stream (3)} \\ = 11/600$$

$$\text{Mol. } A_2B \text{ in stream (3)} = \frac{11}{600} \times 322 = 5.90$$

So, stream (4) will have

(i) 100 mol AB ; (ii) 11 mol A_2B

Stream (3) will have

(i) 322 mol A ; (ii) 5.9 mol A_2B .

Ex. 19. 1000 kg of an impure limestone which analysis 96% CaCO_3 and 4% inert material is reacted with a sulphuric acid solution containing 70% sulphuric acid and 30% water. The reacting mass is heated and all the CO_2 generated is driven off together with some of the water. The analysis of the final solid 'cake' is

CaSO_4 —86.54%

CaCO_3 —3.11%

H_2SO_4 —1.35%

H_2O —6.23%

Inerts—2.77%.

Calculate :

(a) *the degree of completion of the reaction*

(b) *mass of acid solution fed*

(c) *mass of gas driven off*

(d) *composition of gases driven off.*

(Sambalpur Uni. 1976 May)

Solution :

Basis : 100 kg of cake formed.

Reaction : $\text{CaCO}_3 + \text{H}_2\text{SO}_4 \longrightarrow \text{CaSO}_4 + \text{CO}_2 + \text{H}_2\text{O}$

Amount of CaSO_4 formed = 86.54 kg.

$$\text{CaCO}_3 \text{ consumed} = \frac{100}{136} \times 86.54 = 63.63 \text{ kg.}$$

CaCO_3 unconverted = 3.11

(a) Degree of completion of the reaction

$$= \frac{63.63}{63.63 + 3.11} = 95.34$$

$$(b) \text{ Acid used} = \frac{98}{136} \times 86.54 = 62.36 \text{ kg.}$$

Acid in cake = 1.35 kg.

Acid supplied = 62.36 + 1.35 = 63.71 kg.

Lime stone used = 63.63 + 3.11 + 2.77 = 69.51 kg.

69.51 kg limestone require 63.71 kg H_2SO_4

1000 kg limestone require

$$= \frac{63.71}{69.51} \times 1000 = 916.56 \text{ kg } \text{H}_2\text{SO}_4$$

$$\text{Acid solution fed} = \frac{916.56}{0.7} = 1309.37 \text{ kg.}$$

$$(c) \text{ Water in acid} = 1309.37 - 916.56 = 392.81 \text{ kg.}$$

$$\text{Water formed} = \frac{18}{100} \times 63.63$$

$$= 11.45 \text{ kg (per 69.51 kg, limestone)}$$

Total water formed by reaction

$$= \frac{11.45}{69.51} \times 1000 = 164.72 \text{ kg.}$$

Amount of water (acid solution and reaction)

$$= 392.81 + 164.72 = 557.53 \text{ kg.}$$

Water left in cake per 1000 kg limestone

$$= \frac{6.23}{69.51} \times 1000 = 89.63 \text{ kg.}$$

$$\text{Water evaporated} = 557.53 - 89.63 = 467.9 \text{ kg.}$$

$$\text{CO}_2 \text{ formed} = \frac{44}{100} \times 63.63 = 28.00 \text{ kg.}$$

For 1000 kg of limestone,

$$\text{CO}_2 \text{ formed} = \frac{28}{69.51} \times 1000 = 402.82 \text{ kg.}$$

$$\begin{aligned} \text{Mass of gas driven off} &= 467.90 (\text{H}_2\text{O}) + 402.82 (\text{CO}_2) \\ &= 870.72 \text{ kg.} \end{aligned}$$

(d) Composition of gases driven off :

Constituents	Weight, kg	Kg. mol.	Mol%
CO ₂	402.82	9.155	26.06
H ₂ O	467.90	25.994	73.95
	Total	35.149	100.00

Ex. 20. For 1000 lit / sec of a gaseous mixture of the following composition :

CH₄ – 10%, C₂H₆ – 30%, H₂ – 60% (all by volume) at 30°C and 2000 mm Hg gauge, calculate,

(a) the mole fraction of each component

(b) the concentration of each component, $\frac{\text{gm mol}}{\text{CC}}$

(c) the partial pressure of each component

(d) the molar density of the mixture

(e) the mass flow rate of the mixture

(f) the average molecular weight of the gas.

(A.M.I.E. Ch. Engg. Exam., C.P.P. March 1983)

Solution :

Basis : 1000 lit of the gaseous mixture.

Pressure = 2000 mm Hg gauge

= 2760 mm Hg absolute.

(a) Let n_{CH_4} , $n_{\text{C}_2\text{H}_6}$, n_{H_2} be the moles of the components.

From ideal gas law :

$$\begin{aligned} n_{\text{CH}_4} &= \frac{PV}{RT}, R = 62.36 \frac{\text{mm Hg lit.}}{\text{gm mol } ^\circ\text{K}} \\ &= \frac{2760 \times (1000 \times 0.1)}{62.36 \times (273 + 30)} = 14.61 \text{ gm mol} \\ n_{\text{C}_2\text{H}_6} &= \frac{2760 \times (1000 \times 0.3)}{62.36 \times 303} = 43.82 \text{ gm mol} \\ n_{\text{H}_2} &= \frac{2760 \times (1000 \times 0.6)}{62.36 \times 303} = 87.64 \text{ gm mol} \end{aligned}$$

$$\begin{aligned}\text{Mol fraction of CH}_4 &= \frac{14.61}{14.61 + 43.82 + 87.64} \\ &= \frac{14.61}{146.07} = 0.10\end{aligned}$$

$$\text{Mole fraction of C}_2\text{H}_6 = \frac{43.82}{146.07} = 0.30$$

$$\text{Mol fraction of H}_2 = \frac{87.64}{146.07} = 0.60$$

(b) Concentration of CH₄

$$= \frac{14.61}{1000 \times 1000} = 1.46 \times 10^{-5} \frac{\text{gm mol}}{\text{cc}}$$

$$\text{Concentration of C}_2\text{H}_6 = \frac{43.82}{1000 \times 1000} = 4.38 \times 10^{-5} \frac{\text{gm mol}}{\text{cc}}$$

$$\text{Concentration of H}_2 = \frac{87.64}{1000 \times 1000} = 8.76 \times 10^{-5} \frac{\text{gm mol}}{\text{cc}}$$

(c) Partial pressure of CH₄

$$= 0.1 \times 2760 = 276 \text{ mm Hg}$$

Partial pressure of C₂H₆

$$= 0.3 \times 2760 = 828 \text{ mm Hg}$$

Partial pressure of H₂ = 0.6 × 2760 = 1656 mm Hg

(d) Molar density of the mixture

$$= \frac{146.07}{1000} = 0.146 \frac{\text{gm mol}}{\text{lit}}$$

(e) Mass flow rate of the mixture.

Constituents	Mol	Mol wt	Weight
CH ₄	14.61	16	233.76
C ₂ H ₆	43.82	30	1314.60
H ₂	87.64	2	175.28
		Total	1723.64

Mass flow rate of the gaseous mixture

$$= 1723.64 \text{ gm} = 1.724 \text{ kg.}$$

(f) Average molecular weight

$$= 16 \times 0.1 + 30 \times 0.3 + 2 \times 0.6 = 11.8.$$

Ex. 21. 4000 kg of KCl are present in a saturated solution at a temperature of 80°C. The solution is cooled to 20°C in an open tank. The solubilities of KCl at 80°C and 20°C are 55.0 and 35.0 parts per 100 of water respectively. Calculate :

(a) Assuming water equal to 3% by weight of solution is lost by evaporation, weight of crystals obtained.

(b) The yield of crystals neglecting loss by evaporation.

KCl crystallizes without any water of crystallisation.

(A.M.I.E. Exam. 1978 Summer)

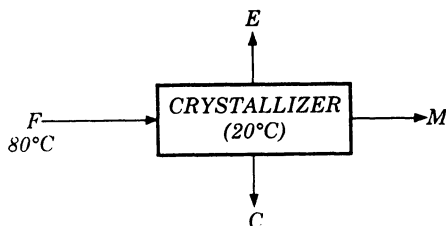


Fig. 1.7

Solution :

Molecular weight of KCl crystals

$$= 39 + 35.5 = 74.5$$

Let F , M , E and C represent the amounts of feed, mother liquor, evaporation and crystals and x_F , x_M , x_E and x_C their solid fractions respectively.

$$x_E = 0 \quad x_F = \frac{55}{100 + 55} = 0.355$$

$$x_C = 1.0 \quad x_M = \frac{35}{100 + 35} = 0.259$$

Overall material balance is,

$$F = E + M + C \quad \dots(1)$$

$$\text{KCl balance is, } Fx_F = Mx_m + Cx_C \quad \dots(2)$$

Amount of KCl in feed = 4000 kg.

So, $Fx_F = 4000$

$$\text{i.e. } F = \frac{4000}{0.355} = 11,268 \text{ kg}$$

$$(a) E = 0.03 F = 0.03 \times 11,268 = 338 \text{ kg.}$$

From Eqn. (1),

$$(11,268 - 338 - C) = M \quad \dots(3)$$

Putting Eqn. (3) in (2),

$$4000 = (10,930 - C) \times 0.259 + C$$

or

$$C = 1578 \text{ kg.}$$

$$(b) \text{ When } E = 0, M = (11,268 - C)$$

$$\text{Eqn. (2) gives } 4000 = (11,268 - C) \times 0.259 + C$$

$$\text{Solving, } C = 1460 \text{ kg.}$$

Ex. 22. A natural gas having the composition CH_4 —94%, C_2H_6 —3% and N_2 —3% is piped from the well at 25°C and 3.0 atm. pressure. Assuming that the ideal gas law is obeyed, find out :

(a) Partial pressure of N_2 .

(b) Volume of N_2 per 100 cu.m of gas.

(c) Density of the gas. (A.M.I.E. Exam., 1978 Winter)

Solution :

Basis : 100 m^3 of gas at 25°C and 3 atm

Volume % = mole %

From ideal gas law and Dalton's law of partial pressure,

Partial pressure = Mole fraction \times Total pressure

(a) Partial pressure of N_2 = $0.03 \times 3.0 = 0.09$ atm

(b) Volume of N_2 per 100 m^3 of gas = 3 m^3 (measured at 3 atm and 25°C).

(c) n = No. of moles = $\frac{PV}{RT}$

$$R = 0.082 \frac{\text{Atm m}^3}{\text{kg mol } ^\circ\text{K}}$$

$$n_{\text{CH}_4} = \frac{3 \times 94}{0.082(273 + 25)} = 11.54 \text{ kg mole}$$

$$n_{\text{C}_2\text{H}_6} = \frac{3 \times 3}{0.082 \times (273 + 25)} = 0.37 \text{ kg mol}$$

$$n_{\text{H}_2} = \frac{3 \times 3}{0.082 \times (273 + 25)} = 0.37 \text{ kg mol}$$

The analysis is as follows :

Constituents	Kg mol	Mol wt	Weight
CH_4	11.54	16	184.64
C_2H_6	0.37	30	11.10
N_2	0.37	28	10.36
Total	12.28		206.10

$$\begin{aligned} \text{Density of the gas} &= \frac{\text{Weight}}{\text{Volume}} \\ &= \frac{206.10}{100} = 2.06 \text{ kg/m}^3 = 2.06 \text{ gm/lit.} \end{aligned}$$

Ex. 23. Nitrogen hydrogen mixture with a molar ratio of 1 : 3 is used for the manufacture of NH_3 , where 18% conversion is achieved. After separating NH_3 from product, the unconverted gases are recycled. The feed contains 0.2 mole of argon per 100 moles of N_2

– H_2 mixture. The toleration limit of argon entering the reactor is 6 parts to 100 parts of $N_2 - H_2$ mixture by volume. Calculate,

(a) the fraction of recycle that must be continually purged ;

(b) the overall yield of ammonia

At. wt. $H = 1$; $O = 16$; $N = 14$; $C = 12$.

(Sambalpur Uni. 1978 May)

Solution :

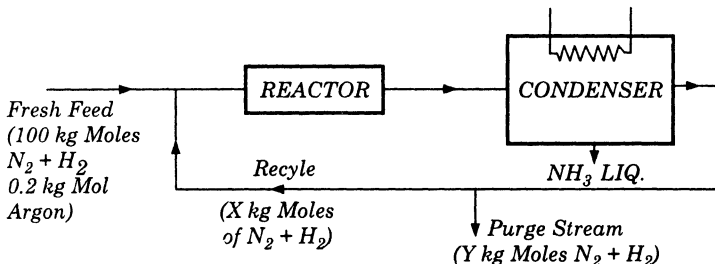


Fig. 1.8

Basis : 100 kg, mol of $N_2 - H_2$ in fresh feed.

Let x kg mol of N_2 and H_2 are recycled to the reactor and y kg mol of N_2 and H_2 are purged.

Amount of N_2 and H_2 entering the reactor
 $= (100 + x)$ kg. mol.

Amount of N_2 and H_2 leaving $= 0.82 (100 + x)$

Amount of NH_3 formed $= \frac{0.18 (100 + x)}{2}$

Argon in fresh feed $= 0.2$ kg. mol.

Argon in total feed $= \frac{6}{100} (100 + x)$ kg mol

$= 0.06 (100 + x)$ kg mol

Mol of argon

Moles of N_2 and H_2 leaving the condenser

$= \frac{0.06 (100 + x)}{0.82 (100 + x)} = 0.073$

Moles of argon in purge stream $= 0.073 \times (y)$

When a steady state of operation is attained the argon purged is equal to the argon in the fresh feed supply.

Hence $0.073 y = 0.2$

and $y = 2.74$ kg mol

A $(N_2 + H_2)$ balance around the purge point gives,

$0.82 (100 + x) = x + y = x + 2.74$

or $x = 440$ kg mol.

(a) the fraction of recycle purged

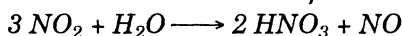
$$= \frac{y}{x} = \frac{2.74}{440} = 0.0062.$$

(b) the overall yield of ammonia

$$= \frac{0.18}{2} (100 + x)$$

$$= 0.09 (100 + 440) = 48.6 \text{ kg mol.}$$

Ex. 24. Air is passed through an electric arc and some of the Nitrogen is fixed as NO. The hot gases leaving the arc are having a pressure of 750 mm Hg and 2 per cent NO by volume. The gases are then cooled to 26°C and NO is further oxidized to NO₂ and 66 percent of this NO₂ is associated as N₂O₄. The gases are then passed through an absorption tower where Nitric acid is formed as given below :



The NO liberated is reoxidized in part and more Nitric acid is formed.

(a) Calculate the analysis of the hot gases leaving the arc.

(b) Calculate the partial pressure of NO₂ and N₂O₄ in the gases entering the absorption apparatus.

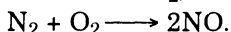
(c) Calculate the weight of HNO₃ formed per 1000 cu m of the gases entering the absorption system if the conversion to nitric acid of the combined Nitrogen in the furnace is 85 per cent complete.

(Sambalpur Uni. 1981 May)

Solution :

Basis : 100 kg mol of air to the arc.

Let x kg. mol is fixed as NO₂,



Oxygen used = x kg mol

NO formed = $2x$ kg mol

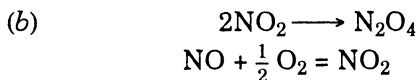
$$\frac{\text{Mol NO}}{\text{Total moles}} = \frac{\text{Vol. NO}}{\text{Total mol}} = \frac{2x}{(100 - 2x) + 2x}$$

or
$$\frac{2x}{100} = \frac{2}{100}$$

Hence, $x = 1.0$; NO formed = 2.0 kg mols.

(a) Analysis of hot gases leaving the arc :

Constituents	Kg mol	Mol%
NO	2.0	2.0
N ₂	78.0 (79 - 1.0)	78.0
O ₂	20.0 (21 - 1.0)	20.0
Total	100.0	100.0



Complete conversion of NO is assumed

Hence NO_2 formed = 2.0 kg mol.

O_2 used = 1.0 kg mol

O_2 left = 20 - 1.0 = 19 kg mol.

66% of NO_2 remain as N_2O_4 .

i.e. 1.32 kg mol remain as N_2O_4

N_2O_4 formed = $\frac{1.32}{2} = 0.66$ kg mol

NO_2 left = 2.0 - 1.32 = 0.68 kg mol

Composition of gas entering absorber

Constituents	Kg mol	Mol %
N_2	78.00	79.32
O_2	19.00	19.32
NO_2	0.68	00.69
N_2O_4	0.66	00.67
Total	98.34	100.00

Partial pressure of NO_2

= Total pressure \times Mole fraction

= $750 \times 0.0069 = 5.18$ mm Hg

Partial pressure of N_2O_4

= $750 \times 0.0067 = 5.03$ mm Hg

(c) Assuming ideal gas law,

$$n = \frac{PV}{RT} = \frac{\frac{750}{760} \times 1000}{0.082 (273 + 26)} = 40.25 \text{ kg mol.}$$

Amount of NO_2 = $40.25 \times 0.0069 = 0.278$ kg mol

3 kg mol of NO_2 yield 2 kg mol HNO_3

0.278 kg mol of NO_2 yield $\frac{2}{3} \times 0.278 \times 0.85$

= 0.158 kg mol. (conversion is 85%)

Weight of HNO_3 formed

= $0.158 \times 63 = 9.95$ kg.

Ex. 25. Pure CO_2 may be prepared by treating limestone with aqueous H_2SO_4 . The limestone contains CaCO_3 and MgCO_3 , and the

remaining is insoluble matter. The acid is 12% H_2SO_4 . The residue from the process had the following composition :

$CaSO_4$ —8.56%

$MgSO_4$ —5.23%

H_2SO_4 —1.05%

Inerts—0.53%

CO_2 —0.12%

Water—84.51%

If during the process the mass was warmed and CO_2 and water vapour were removed, calculate :

(a) composition of lime stone used.

(b) % excess acid used.

(c) calculate the weight and analysis of the material distilled from the reaction mass per 1000 kg of limestone treated.

(A.M.I.E. Exam., 1979 Winter)

Solution :

Basis : 100 kg of limestone.

Reactions : $CaCO_3 + H_2SO_4 \longrightarrow CaSO_4 + CO_2 + H_2O$

$MgCO_3 + H_2SO_4 \longrightarrow MgSO_4 + CO_2 + H_2O$

Let the limestone contain x kg $CaCO_3$ and y kg $MgCO_3$.

Insoluble matter = $[100 - (x + y)]$ kg.

Let z = amount of residue formed.

Inert balance gives,

$$100 - (x + y) = 0.0053 z \quad \dots(1)$$

$$Mg SO_4 \text{ formed} = \frac{120}{84} y = 1.43 y$$

$$CaSO_4 \text{ formed} = \frac{136}{100} x = 1.36 x$$

$$\text{So,} \quad 1.43 y = 0.0523 z \quad \dots(2)$$

$$\text{and} \quad 1.36 x = 0.0856 z \quad \dots(3)$$

$$\text{From (2),} \quad y = 0.0366 z$$

$$\text{From (3),} \quad x = 0.0629 z$$

From (1),

$$x + y + 0.0053 z = 100$$

$$\text{or,} \quad 0.0629 z + 0.0366 z + 0.0053 z = 100$$

$$\text{Solving,} \quad z = 954.2 \text{ kg}$$

$$\text{Hence,} \quad y = 34.92 \text{ kg}$$

$$\text{and} \quad x = 60.00 \text{ kg}$$

$$\text{Inerts in limestone} = 100 - (60 + 34.92) = 5.08 \text{ kg.}$$

(a) Limestone analysis :

<i>Constituents</i>	<i>Amount, kg</i>	<i>Percentage</i>
CaCO ₃	60.00	60.00
Mg CO ₃	34.92	34.92
Insolubles	5.08	5.08
Total	100.00	100.00

$$(b) \text{H}_2\text{SO}_4 \text{ in residue} = 954.2 \times 0.0105 = 10.0 \text{ kg.}$$

$$\text{CO}_2 \text{ in residue} = 954.2 \times 0.0012 = 1.15 \text{ kg.}$$

$$\text{H}_2\text{SO}_4 \text{ used for CaCO}_3 = \frac{98}{100} \times 60 = 58.8 \text{ kg.}$$

$$\text{H}_2\text{SO}_4 \text{ used for MgCO}_3 = \frac{98}{84} \times 34.92 = 40.7 \text{ kg.}$$

$$\text{Total H}_2\text{SO}_4 \text{ used} = 58.8 + 40.7 = 99.5 \text{ kg.}$$

$$\text{Percentage excess acid used} = \frac{10}{99.5} \times 100 = 10.05$$

(c) CO₂ and water are distilled in the process

CO₂ balance,

$$\text{CO}_2 \text{ from CaCO}_3 = \frac{44}{100} \times 60 = 26.4 \text{ kg}$$

$$\text{CO}_2 \text{ from Mg CO}_3 = \frac{44}{84} \times 34.92 = 18.3 \text{ kg}$$

$$\text{CO}_2 \text{ produced per 100 kg limestone} = 26.4 + 18.3 = 44.7 \text{ kg.}$$

$$\text{CO}_2 \text{ produced per 1000 kg limestone} = 447 \text{ kg.}$$

$$\begin{aligned} \text{CO}_2 \text{ in residue for 1000 kg limestone} \\ = 1.15 \times 10 = 11.5 \text{ kg.} \end{aligned}$$

$$\text{CO}_2 \text{ distilled} = 447 - 11.5 = 435.5 \text{ kg.}$$

Water balance :

$$\text{Water from CaCO}_3 = \frac{18}{100} \times 60 = 10.8 \text{ kg.}$$

$$\text{Water from MgCO}_3 = \frac{18}{84} \times 34.92 = 7.48 \text{ kg.}$$

Water formed by the two reactions

$$= 10.8 + 7.48 = 18.28 \text{ kg.}$$

Water formed for 1000 kg limestone

$$= 18.28 \times 10 = 182.8 \text{ kg.}$$

$$\text{Acid used per 100 kg limestone} = 109.5 \text{ kg. (99.5 + 10)}$$

$$\text{Acid for 1000 limestone} = 1095 \text{ kg.}$$

$$\text{Water with acid} = 1095 \times \frac{88}{12} = 8030 \text{ kg.}$$

$$\begin{aligned} \text{Water in residue (formed from 1000 kg limestone)} \\ = 954.2 \times 10 \times 0.8451 = 8063.9 \text{ kg.} \end{aligned}$$

$$\begin{aligned} \text{Water evaporated} &= (\text{water with acid} \\ &\quad + \text{water formed} - (\text{water with residue})) \\ &= (8030 + 182.8) - 8063.9 = 148.9 \text{ kg.} \end{aligned}$$

Analysis of the materials distilled—

Constituents	Wt, kg (per 1000 kg limestone)	Wt%
CO ₂	435.5	74.52
H ₂ O	148.9	25.48
Total	584.4	100.00

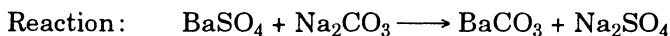
Ex. 26. *In order to obtain barium in a pure form that may be put to solution the natural sulphate, barytes, is fused with sodium carbonate. A quantity of barytes containing only pure barium sulphate and infusible matter, is fused with an excess of pure, anhydrous soda ash. Upon analysis of the fusion mass it is found to contain 11.3% barium sulphate, 27.7% sodium sulphate and 20.35% sodium carbonate. The remainder is barium carbonate and infusible matter.*

(a) *Calculate the percentage composition of the original barytes.*

(b) *Calculate the percentage completion of the conversion of the barium sulphate to the carbonate and the complete analysis of the fusion mass.*

(c) *Calculate the percentage excess in which the sodium carbonate was used above the amount theoretically required for reaction with all the barium sulphate.*

Solution :



$$\text{Mol. wt. : } \text{BaSO}_4 = 233.4, \text{Na}_2\text{CO}_3 = 106$$

$$\text{BaCO}_3 = 197.4, \text{Na}_2\text{SO}_4 = 142$$

Basis : 100 kg of barytes.

Let x = amount of BaSO₄ in barytes

y = amount of BaSO₄ converted

z = amount of BaSO₄ in fusion mass.

Infusible matter in barytes = $(100 - x)$ kg.

% infusible and BaCO_3 in fusion mass

$$= 100 - (27.7 + 11.3 + 20.35) = 40.65$$

$$\text{BaCO}_3 \text{ formed} = \frac{197.4}{233.4} \times y = 0.846 y$$

$$\text{BaCO}_3 + \text{infusible} = 0.846 y + (100 - x)$$

$$\text{Na}_2\text{SO}_4 \text{ formed} = \frac{142}{233.4} y = 0.608 y.$$

Barium sulphate balance gives,

$$x - y = 0.113 z \quad \dots(1)$$

BaCO_3 and infusible are,

$$0.846 y + (100 - x) = 0.4065 z \quad \dots(2)$$

$$\text{Na}_2\text{SO}_4 \text{ amount is, } 0.608 y = 0.277 z \quad \dots(3)$$

From (1) with the help of (3),

$$x = 0.113 z + \frac{0.277}{0.608} z = 0.569 z \quad \dots(4)$$

Solving, $z = 169.6$ kg

From (4), $x = 96.5$ kg

From (3), $y = 77.3$ kg

Infusible in barytes = $100 - 96.5 = 3.5$ kg.

(b) Barytes composition is as follows :

Constituents	Amount, kg	Weight, %
BaSO_4	96.5	96.5
Infusibles	3.5	3.5
Total	100.0	100.0

(b) Since, BaSO_4 converted = 77.3 kg.

$$\text{BaCO}_3 \text{ formed} = \frac{197.4}{233.4} \times 77.3 = 65.3 \text{ kg}$$

$$\text{Na}_2\text{SO}_4 \text{ formed} = \frac{142}{233.4} \times 77.3 = 46.7 \text{ kg}$$

$$\text{Na}_2\text{CO}_3 \text{ used} = \frac{106}{233.4} \times 77.3 = 35.1 \text{ kg}$$

Na_2CO_3 in fusion mass

$$= 169.6 \times 0.2035 = 34.5 \text{ kg}$$

BaSO_4 unconverted

$$= 96.5 - 77.3 = 19.2 \text{ kg}$$

% completion of the conversion of BaSO_4 to BaCO_3

$$= \frac{77.3}{96.5} \times 100 = 80.1.$$

Analysis of fusion mass :

<i>Constituents</i>	<i>Amount, kg</i>	<i>Weight, %</i>
BaSO_4	19.2	11.32
Na_2SO_4	46.8	27.70
Na_2CO_3	34.5	20.35
BaCO_3	65.3	38.57
Infusibles	3.5	2.07
Total	169.3	100.01

(c) Total Na_2CO_3 supplied

$$= \text{Na}_2\text{CO}_3 \text{ used} + \text{Na}_2\text{CO}_3 \text{ in fusion mass} \\ = 35.1 + 34.5 = 69.6 \text{ kg.}$$

Na_2CO_3 required theoretically for complete conversion

$$= \frac{106}{233.4} \times 96.5 = 43.83 \text{ kg.}$$

Na_2CO_3 in excess = $69.6 - 43.83 = 25.77 \text{ kg.}$

$$\% \text{ excess } \text{Na}_2\text{CO}_3 \text{ used} = \frac{25.77}{43.83} \times 100 = 58.80.$$

Ex. 27. A limestone has the following composition :

CaCO_3 —93%, MgCO_3 —6% and insoluble—1%,

Calculate :

(a) How many kg of CaO will be obtained from 2000 kg of limestone ?

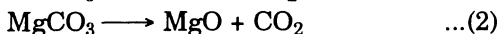
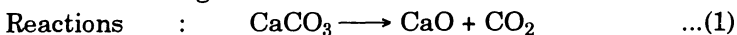
(b) Kg of CO_2 available per kg of limestone

(c) Kg of limestone required for the manufacture of 1000 kg of CaO .

(A.M.I.E. Exam., Summer, 1979)

Solution :

Basis : 100 kg limestone.



(a) 100 kg CaCO_3 yield 56 kg CaO

$$93 \text{ kg } \text{CaCO}_3 \text{ yield } \frac{56}{100} \times 93 = 52.08 \text{ kg}$$

100 kg limestone gives 52.08 kg CaO

2000 kg limestone gives $\frac{52.08}{100} \times 2000 = 1041.6$ kg.

(b) CO_2 produced from reaction (1)

$$= \frac{44}{100} = 0.44 \text{ kg/kg CaCO}_3$$

CO_2 produced from reaction (2)

$$= \frac{44}{84} = 0.524 \text{ kg/kg MgCO}_3$$

Total CO_2 formed from one kg limestone

$$= 0.44 \times 0.93 + 0.524 \times 0.06 = 0.44 \text{ kg.}$$

(c) 52.08 kg CaO is manufactured from 100 kg limestone.

1000 kg CaO will be obtained from

$$\frac{100}{52.08} \times 1000 = 1920 \text{ kg limestone.}$$

Ex. 28. In a lime manufacturing process pure calcium carbonate is burnt with coke containing 83% carbon, producing a gas of 26.5% CO_2 , 5% O_2 and balance N_2 . Compute :

(i) The ratio of lime produced to coke burnt.

(ii) The percentage excess air used.

(iii) Amount of stack gas obtained per ton of lime produced.

(Sambalpur Uni. 1975 May ; A.M.I.E. Exam. 1991 Summer)

Solution :

Basis : 100 kg mol of flue gas.

Reactions : $\text{C} + \text{O}_2 \longrightarrow \text{CO}_2$... (1)

$\text{CaCO}_3 \longrightarrow \text{CaO} + \text{CO}_2$... (2)

Oxygen balance,

$$\text{N}_2 \text{ in flue gas} = 100 - (26.5 + 5.0) = 68.5 \text{ kg mol.}$$

$$\text{O}_2 \text{ supplied by air} = 68.5 \times \frac{21}{79} = 18.2 \text{ kg mol.}$$

O_2 reported in flue gas (as O_2 and CO_2)

$$= 26.5 + 5 = 31.5 \text{ kg mol.}$$

O_2 as CO_2 from CaCO_3 decomposition

$$= 31.5 - 18.2 = 13.3 \text{ kg mol.}$$

(a) CaCO_3 decomposed

$$= 13.3 \text{ kg mol.}$$

CaO obtained = $13.3 \times 56 = 744.8$ kg.

Total CO_2 in flue = 26.5 kg mol.

CO_2 from limestone = 13.3 kg mol.

CO_2 from coke = $26.5 - 13.3 = 13.2$ kg mol.

Kg atom carbon = $13.2 \times 12 = 158.4$ kg C

Amount of coke required

$$= \frac{158.4}{0.83} = 190.8 \text{ kg.}$$

$$\frac{\text{Lime produced}}{\text{Coke burnt}} = \frac{744.8}{190.8} = 3.9.$$

(b) Theoretical amount of oxygen required for coke to burn completely = 13.2 kg mol.

Oxygen supplied = 18.2 kg mol.

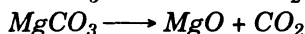
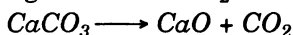
$$\% \text{ excess air used} = \frac{18.2 - 13.2}{13.2} \times 100 = 37.88.$$

(c) 744.8 kg lime gives 100 kg mol flue gas

$$1000 \text{ kg lime gives } \frac{100}{744.8} \times 1000 = 134.26 \text{ kg mol flue gas}$$

Flue gas/ton of lime produced = 134.26 kg mol.

Ex. 29. Limestone is a mixture of calcium and magnesium carbonates and inert material. Lime is made by calcining the carbonates i.e. heating them until CO_2 is driven off by the reactions

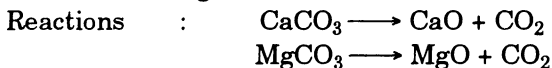


When 100 kg of limestone is calcined, 44 kg of CO_2 is obtained. If the limestone contains 10% inerts, calculate the complete analysis.

(Sambalpur Uni. 1978 May)

Solution :

Basis : 100 kg limestone calcined.



Amount of inert material = 10 kg.

Amount of MgCO_3 and CaCO_3
 $= 100 - 10 = 90 \text{ kg.}$

Let x kg be the amount of CaCO_3

Hence, $\text{MgCO}_3 = (90 - x) \text{ kg.}$

A CO_2 balance is made :

$$\begin{aligned} \text{CO}_2 \text{ produced from } x \text{ kg CaCO}_3 \\ = \frac{44}{100} x = 0.44x \text{ kg.} \end{aligned}$$

$$\begin{aligned} \text{CO}_2 \text{ produced from } (90 - x) \text{ kg MgCO}_3 \\ = \frac{44}{84} (90 - x) \text{ kg} = (47.14 - 0.524x) \text{ kg.} \end{aligned}$$

$$\begin{aligned}\text{Total CO}_2 \text{ produced} &= 0.44x + 47.14 - 0.524x \\ &= (47.14 - 0.084x) \text{ kg}\end{aligned}$$

$$47.14 - 0.084x = 44$$

or,

$$x = 37.38 \text{ kg}$$

$$\therefore 90 - x = 90 - 37.38 = 52.62 \text{ kg.}$$

Composition of limestone :

Constituents	Amount, kg	% Wt
CaCO ₃	37.38	37.38
MgCO ₃	52.62	52.62
Inert	10.00	10.00
Total	100.00	100.00

Ex. 30. 5 kg of limestone is mixed with one kg of coke and is being burnt in a kiln with 200% excess air. The composition of limestone and coke are given below :

Lime Stone	Coke
CaCO ₃ —84.5%	Carbon—76%
MgCO ₃ —11.5%	Ash—21%
Inerts—4.0%	Moisture—3%

The calcination of CaCO₃ is 95% complete and MgCO₃ is 90% complete.

(a) Calculate the composition of lime leaving the furnace.

(b) Calculate the composition of the gas leaving the furnace.

(Sambalpur Uni. 1976 May and 1981 May)

Solution :

Basis : 5 kg limestone and one kg coke.

Assumption : (a) Complete combustion of coke.

(b) All the solid fractions are associated with the lime leaving the furnace.

$$\text{CaCO}_3 \text{ in limestone} = 5.0 \times 0.845 = 4.225 \text{ kg.}$$

$$\text{CaCO}_3 \text{ decomposed} = 4.225 \times 0.95 = 4.014 \text{ kg.}$$

$$\begin{aligned}\text{CaCO}_3 \text{ undecomposed (accompanies the lime stream)} \\ = 4.225 - 4.014 = 0.211 \text{ kg.}\end{aligned}$$

$$\text{MgCO}_3 \text{ in limestone} = 5.0 \times 0.115 = 0.575 \text{ kg}$$

$$\text{MgCO}_3 \text{ decomposed} = 0.575 \times 0.90 = 0.518 \text{ kg}$$

$$\begin{aligned}\text{MgCO}_3 \text{ undecomposed (accompanies the lime stream)} \\ = 0.575 - 0.518 = 0.057 \text{ kg.}\end{aligned}$$

(a) Amount of lime produced :

$$\text{CaO obtained} = 4.014 \times \frac{56}{100} = 2.248 \text{ kg.}$$

$$\text{MgO obtained} = 0.518 \times \frac{40}{84} = 0.247 \text{ kg.}$$

$$\text{Inerts from limestone} = 5 \times 0.04 = 0.2 \text{ kg.}$$

$$\text{Ash from coke} = 0.21 \text{ kg.}$$

Lime composition :

<i>Constituents</i>	<i>Amount kg.</i>	<i>Wt.%</i>
CaO	2.248	70.85
MgO	0.247	7.78
CaCO ₃	0.211	6.65
MgCO ₃	0.057	1.80
Inerts	0.200	6.30
Ash	0.210	6.62
Total	3.173	100.00

(b) Flue gas obtained :

$$\text{CO}_2 \text{ from CaCO}_3 = 4.014 \times \frac{44}{100} = 1.766 \text{ kg}$$

$$\text{CO}_2 \text{ from MgCO}_3 = 0.518 \times \frac{44}{84} = 0.271 \text{ kg.}$$

$$\text{CO}_2 \text{ from coke} = 0.76 \times \frac{44}{12} = 2.787 \text{ kg.}$$

$$\text{Total CO}_2 \text{ formed} = 1.766 + 0.271 + 2.787 = 4.824 \text{ kg.}$$

Oxygen balance :

$$\text{O}_2 \text{ used by coke} = 0.76 \times \frac{32}{12} = 2.027 \text{ kg.}$$

O₂ supplied by 200% excess air

$$= 2.027 \times 2 = 4.054 \text{ kg.}$$

$$\text{N}_2 \text{ supplied} = 4.054 \times \frac{77}{23} = 13.572 \text{ kg.}$$

$$\text{O}_2 \text{ excess} = 4.054 - 2.027 = 2.027 \text{ kg.}$$

$$\begin{aligned} \text{Moisture from coke (present as water vapor in flue gas)} \\ = 0.03 \text{ kg.} \end{aligned}$$

Fuel gas analysis (wet) :

Constituents	Wt., kg	Kg mol	Mol%
CO ₂	4.824	0.110	16.67
O ₂	2.027	0.063	9.55
N ₂	13.572	0.485	73.48
H ₂ O	0.030	0.002	0.30
Total	20.453	0.660	100.00

Ex. 31. A high purity limestone is burnt in a lime-kiln which is fired externally with a coal containing 75.5% C, 5.5% H, 1.6% N, 1.1% S, 7.6% O and rest ash. The stack gas analysis is 20.2% CO₂, 7.1% O₂ and the rest N₂. Calculate :

- (i) Kg of limestone burnt per kg of coal
(ii) Excess air used for combustion.

(A.M.I.E. Exam., 1979 Summer)

Solution :

Basis : 100 kg of coal fired.

Let, limestone decomposed = z kg mols.
stack gas (dry) produced = y kg mole.
air used for combustion = x kg mol.

Oxygen required for coal :

Constituents	Amount, kg	O ₂ reqd., kg.
C	75.5	201.33
H	5.5	44.00
S	1.1	1.1
Total O ₂ reqd. =		246.43 kg.
		= 7.70 kg mol

O₂ in coal = 7.6 kg = 0.24 kg mol.

O₂ to be supplied by air = $7.70 - 0.24 = 7.46$ kg mol.

Nitrogen balance,

N₂ in coal = 1.6 kg = 0.06 kg mol.

N₂ from air = $0.79 x$

N₂ in flue gas = $0.727 y$

Hence, $0.06 + 0.79 x = 0.727 y$... (1)

or, $x = \frac{0.727 y - 0.06}{0.79}$... (2)

Oxygen balance,

$$\text{O}_2 \text{ required} = 7.46 \text{ kg mol.}$$

$$\text{O}_2 \text{ in flue gas} = 0.071 y$$

$$\text{O}_2 \text{ from air} = 0.21 x$$

$$\text{Hence, } 0.21 x = 7.46 + 0.071 y \quad \dots(3)$$

$$\text{or, } x = \frac{0.071 y + 7.46}{0.21} \quad \dots(4)$$

From (2) and (4),

$$\frac{0.727 y - 0.06}{0.79} = \frac{0.071 y + 7.46}{0.21}$$

$$\text{Solving, } y = 60.86 \text{ kg mol}$$

$$\text{Amount of } \text{CO}_2 = 60.86 \times 0.202 = 12.29 \text{ kg mol}$$

$$\text{CO}_2 \text{ from coal} = \frac{75.5}{12} = 6.29 \text{ kg mol.}$$

$$\text{CO}_2 \text{ from limestone} = 12.29 - 6.29 = 6.00 \text{ kg mol}$$

$$z = 6.00 \text{ kg mol.}$$

$$\text{Limestone burnt} = 6.0 \text{ kg mol} = 6 \times 100 = 600 \text{ kg.}$$

(Taking limestone as pure CaCO_3)

$$(a) \frac{\text{Limestone burnt}}{\text{Coal used}} = \frac{600}{100} = 6.0$$

$$(b) \text{ From Eqn. (4) } x = 56.1 \text{ kg mol.}$$

Theoretical air required

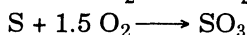
$$= 7.46 \times \frac{100}{21} = 35.52 \text{ kg mol.}$$

$$\text{Excess air used} = \frac{56.1 - 35.52}{35.52} \times 100 = 57.94\%.$$

Ex. 32. 200 kg of pure sulphur is burnt with 25 per cent air in excess of that required to convert all the sulphur to sulphur dioxide, 4.5 percent of sulphur is oxidized to sulphur trioxide and 95.5 per cent to sulphur dioxide. The air is assumed to be dry. Calculate the composition (in mole per cent) of the gas leaving the burner. (Sambalpur Uni. 1976 May)

Solution :

Basis : 200 kg of sulphur.



Oxygen balance :

$$\text{kg atom of sulphur } \frac{200}{32} = 6.25$$

$$\text{O}_2 \text{ required} = 6.25 \text{ kg mol.}$$

$$\text{O}_2 \text{ supplied} = 6.25 \times 1.25 = 7.81 \text{ kg mol}$$

Sulphur converted to $\text{SO}_3 = 6.25 \times 0.045 = 0.28 \text{ kg atom.}$

O_2 used $= 0.28 \times 1.5 = 0.42 \text{ kg mol.}$

Sulphur converted to $\text{SO}_2 = 6.25 \times 0.955 = 5.97 \text{ kg atom.}$

O_2 used for $\text{SO}_2 = 5.97 \text{ kg mol.}$

Total O_2 used $= 5.97 + 0.42 = 6.39 \text{ kg mol}$

O_2 in excess $= 7.81 - 6.39 = 1.42 \text{ kg mol.}$

Burner gas analysis :

N_2 supplied $= 7.81 \times \frac{79}{21} = 29.38 \text{ kg mol.}$

SO_3 formed $= 0.28 \text{ kg mol.}$

SO_2 formed $= 5.97 \text{ kg mol.}$

O_2 excess $= 1.42 \text{ kg mol.}$

Constituents	Amount, kg. mol	% mol
SO_3	0.28	0.76
SO_2	5.97	16.11
O_2	1.42	3.83
N_2	29.38	79.30
Total	37.05	100.00

Ex. 33. The gases from a sulphur burner in a sulphuric acid plant has the composition :

SO_2 —6.5%, SO_3 —2.78%

O_2 —10.65%, N_2 —80.07%

(a) What was the percentage completion of oxidation of S to SO_3 ?

(b) What was the % excess O_2 supplied over that required to complete oxidation to SO_3 .

(c) The gas is passed through a series of converters so that all the SO_2 is oxidized to SO_3 . Calculate the composition of the gas leaving the converters.

(d) The gas leaves the converters at 65°C and 740 mm Hg. Calculate the volume of gas leaving the converters per 1000 kg of pure sulphur burned.
(Sambalpur Uni. 1978 May)

Solution :

Basis : 100 kg mol of burner gas.

(a) SO_2 in burner gas $= 6.5 \text{ kg mol.}$

SO_3 in burner gas $= 2.78 \text{ kg mol.}$

% completion of the oxidation of S to SO₃

$$= \frac{2.78}{2.78 + 6.5} \times 100 = \frac{2.78}{9.28} \times 100 = 29.96$$

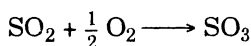
(b) O₂ supplied = $80.07 \times \frac{21}{79} = 21.28 \text{ kg mol}$

O₂ required for complete conversion of S to SO₃
 = $9.28 \times 1.5 = 13.92 \text{ kg. mol}$

O₂ in excess = $21.28 - 13.92 = 7.36 \text{ kg mol}$

% excess O₂ supplied = $\frac{7.36}{13.92} \times 100 = 52.87.$

(c) Let it be assumed that all SO₂ is converted to SO₃ in the converters.



O₂ required for 6.5 kg mol of SO₂
 = $6.5 \times \frac{1}{2} = 3.25 \text{ kg mol.}$

O₂ left after SO₃ conversion
 = $10.65 - 3.25 = 7.40 \text{ kg mol}$

Converter gas analysis :

Constituents	Kg mol	Mole %
SO ₃	9.28	9.59
O ₂	7.40	7.65
N ₂	80.07	82.76
Total	96.75	100.00

(d) Sulphur converted = 9.28 kg atoms
 = 296.96 kg.

296.96 kg sulphur yield 96.75 kg mol of gas

1000 kg sulphur yield $\frac{96.75}{296.96} \times 1000 = 325.8 \text{ mol of gas}$

Volume of gas obtained

$$\begin{aligned}
 &= \frac{n RT}{P} \text{ (from ideal gas law)} \\
 &= \frac{325.8 \times 0.082 \times (273 + 65)}{740/760} \\
 &= 9273.9 \text{ m}^3.
 \end{aligned}$$

Ex. 34. In the manufacture of sulphuric acid by the contact process, iron pyrites, FeS₂, are burned in dry air, the iron being

oxidized to Fe_2O_3 . The SO_2 thus formed is further oxidized to trioxide by conducting the gases mixed with air over a catalytic mass of platinum black at a suitable temperature. It will be assumed that in the operation sufficient air is supplied to the pyrites burner so that the oxygen shall be 40% in excess of that required if all the sulphure actually burned were oxidized to trioxide. Of the pyrites charged, 15% is lost by falling through the grate with the cinder and not burned.

(a) Calculate the weight of air to be used per 100 kg of pyrites charged.

(b) In the burner and a contact shaft connected with it, 40% of sulphur burned is converted to the trioxide. Calculate the composition by weight of the gases leaving the contact shaft.

(c) By means of the platinum catalyst mass, 96% of the sulphur dioxide remaining in the gases leaving the contact shaft is converted to the trioxide. Find the total weight of sulphur trioxide formed per 100 kg of pyrites charged. (Sambalpur Uni. 1979 May)

Solution :

Process flow chart is as follows :

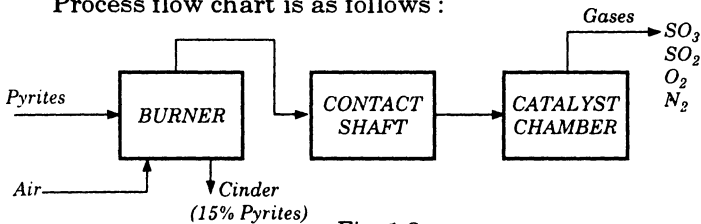
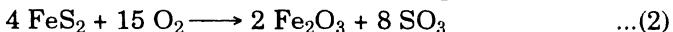
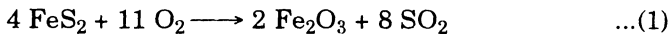


Fig. 1.9

Basis : 100 kg of pyrites charged

Reactions (a) In burner and contact shaft :



(b) In catalyst chamber



(a) 15 kg pyrites escaped unburnt.

Pyrites burnt = $100 - 15 = 85$ kg.

Oxygen required by reaction (2),

$$= \frac{15 \times 32}{4 \times 120} \times 85 = 85 \text{ kg.}$$

Oxygen supplied by 40% excess air

$$= 85 \times 1.4 = 119 \text{ kg.}$$

$$\text{Amount of air supplied} = 119 \times \frac{100}{23} = 517.4 \text{ kg.}$$

(b) 40% of FeS_2 burned is converted to SO_3

FeS_2 converted by reaction (1) is 60%

FeS_2 converted to $\text{SO}_2 = 85 \times 0.6 = 51 \text{ kg.}$

SO_2 formed $= 51 \times \frac{8 \times 64}{4 \times 120} = 54.4 \text{ kg.}$

O_2 consumed $= 51 \times \frac{11 \times 32}{4 \times 120} = 37.4 \text{ kg.}$

FeS_2 converted to $\text{SO}_3 = 85 \times 0.4 = 34 \text{ kg.}$

SO_3 formed $= 34 \times \frac{8 \times 80}{4 \times 120} = 45.33 \text{ kg.}$

O_2 consumed $= 34 \times \frac{15 \times 32}{4 \times 120} = 34.00 \text{ kg.}$

Total O_2 consumed $= 37.4 + 34.0 = 71.4 \text{ kg.}$

Oxygen unused $= 119 - 71.4 = 47.6 \text{ kg.}$

N_2 with air $= 517.4 \times \frac{77}{100} = 398.4 \text{ kg.}$

Analysis of the gases (by weight) leaving the contact shaft :

Constituents	Amount, kg	Wt. %
SO_2	54.40	9.97
SO_3	45.33	8.31
O_2	47.60	8.72
N_2	398.40	73.00
Total	545.73	100.00

(c) SO_2 converted to SO_3 by catalyst

$= 54.4 \times 0.96 = 52.22 \text{ kg.}$

Amount of SO_3 formed $= 52.22 \times \frac{80}{64} = 65.28 \text{ kg.}$

Total amount of SO_3 formed

$= 45.33 + 65.28 = 110.61 \text{ kg.}$

Ex. 35. The SO_3 absorption tower in sulphuric acid plant uses sulphuric acid (98% H_2SO_4 by weight) as a liquid absorbent because, SO_3 is partially soluble in 98% acid. As shown in the figure, the 98% acid is fed into the tower where it absorbs SO_3 leaving as 99% acid. Make up water dilutes this acid back to 98% and is partly withdrawn as product and the rest is recycled to the absorber.

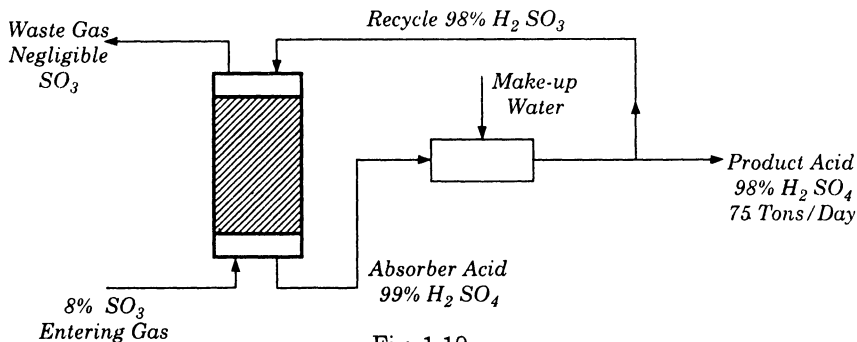


Fig. 1.10

(a) Calculate the flow rate of make-up water

(b) The weight of 98% acid recycled into the tower in a plant producing 75 tons/day of 98% H₂SO₄. (Sambalpur Uni. 1982 May)

Solution :

Basis : 1 hr operation.

$$\text{Product acid} = \frac{75 \times 1000}{24} = 3125 \text{ kg}$$

$$\begin{aligned} \text{H}_2\text{SO}_4 \text{ content of product acid} \\ = 3125 \times 0.98 = 3062.5 \text{ kg.} \end{aligned}$$

Let x be the equivalent amount of 99% acid.

$$x \times 0.99 = 3062.5$$

or

$$x = 3093.4 \text{ kg.}$$

$$\text{Mol. of 100\% acid} = \frac{3062.5}{98} = 31.25 \text{ mol of SO}_3$$

31.25 mol of SO₃ are converted to 3093.4 kgs of 99% H₂SO₄ in the absorber after receiving water from 98% acid

Water required in the absorber

$$= 3093.4 - (80 \times 31.25) = 593.4 \text{ kg.}$$

Water given by 98% H₂SO₄ is 1 kg/100 kg.

Acid (98%) required for absorption

$$= 593.4 \times 100 = 59.34 \text{ tons}$$

Total 99% H₂SO₄ produced from the absorber

$$= 59.34 + 3.093 = 62.433 \text{ tons.}$$

(a) Let

W = kg of water added in the dilution tank.

x = amount of 98% H₂SO₄ produced.

SO₃ balance gives,

$$62.433 \times 0.98 \times \frac{80}{98} = x \times 0.99 \times \frac{80}{98}$$

or

$$x = 63.07 \text{ tons.}$$

Overall balance, around dilution tank gives,

$$W + 62.433 = 63.07$$

or,

$$W = 0.637 \text{ tons} = 637 \text{ kg.}$$

(b) Amount of 98% acid produced = 63.07 tons

Weight of 98% product acid = 3.125 tons

Therefore, the weight of 98% acid recycled into the tower
 $= 63.07 - 3.125 = 59.945 \text{ tons.}$

Ex. 36. Rate of heat loss from a horizontal pipe to the atmosphere by both convection and conduction is expressed as

$$\frac{q}{A} = 0.50 \frac{(\Delta T)^{1.25}}{(D_0)^{0.25}}$$

where, q = rate of heat loss, Btu / hr.

A = Area of pipe surface, ft^2

ΔT = Excess of temperature of pipe wall over that of ambient air, $^{\circ}\text{F}$

D_0 = O.D. of the pipe, inch

Express this equation in C.G.S. units (gm., cm., sec., cal., $^{\circ}\text{C}$).

(A.M.I.E. Exam., 1982 Winter)

Solution :

Let Q = rate of heat loss in cal/sec

A' = surface area of pipe in cm^2

$\Delta T'$ = temp. difference in $^{\circ}\text{C}$

D'_0 = O.D. of the pipe, cm

$$\text{So, } q = \frac{3600 Q}{252} \quad (1 \text{ Btu} = 252 \text{ cal})$$

$$A = \frac{A'}{(30.54)^2} \quad (1 \text{ ft.} = 30.54 \text{ cm})$$

$$D_0 = \frac{D'_0}{2.54}$$

$$\Delta T = 1.8 \Delta T'$$

$$\text{L.H.S.} \quad = \frac{q}{A} = \frac{3600 Q / 252}{A' / (30.54)^2}$$

$$\begin{aligned} \text{R.H.S.} &= 0.50 \frac{(\Delta T)^{1.25}}{D_0^{1.25}} \\ &= 0.50 \frac{(1.8 \Delta T')^{1.25}}{\left(\frac{D'_0}{2.54} \right)^{0.25}} \end{aligned}$$

The new equation in C.G.S. units is,

$$\frac{3600 Q / 252}{A' (30.54)^2} = 0.50 \frac{(1.8 \Delta T')^{1.25}}{\left(\frac{D_0'}{2.54} \right)^{0.25}}$$

Simplification yields,

$$\frac{Q}{A'} = 0.0001 \frac{(\Delta T')^{1.25}}{(D_0')^{0.25}}$$

The desired equation is,

$$\frac{Q}{A'} = 0.0001 \frac{(\Delta T')^{1.25}}{(D_0')^{0.25}} .$$

Ex. 37. An evaporator is fed continuously with 50000 kg/hr of a solution containing 10% NaOH, 10% NaCl and 80% water by weight. During the evaporation, water is boiled off and NaCl precipitates as crystals and removed from the remaining liquor. The concentrated liquor leaving the evaporator contains 50% NaOH, 2% NaCl and 48% water.

Calculate : (a) kg of water evaporated per hour,

(b) kg of salt precipitated per hour,

and (c) kg of concentrated liquor produced per hour.

(A.M.I.E. Exam. 1982 Winter)

Solution :

Basis : 1 hour operation.

Let, E = Evaporation, kg

C = crystals formed, kg

P = concentrated product obtained, kg

F = evaporator feed, kg

Overall material balance gives,

$$F = E + C + P$$

$$\text{i.e.} \quad E + C + P = 50000 \quad \dots(i)$$

NaCl balance gives,

$$F x_{\text{NaCl}} = C + P x_{\text{NaCl}}$$

$$50000 \times 0.10 = C + P \times 0.2 \quad \dots(ii)$$

NaOH balance gives,

$$50000 \times 0.1 = P \times 0.50 \quad \dots(iii)$$

From (iii), $P = 10000$ kg

Putting the value of P in (ii)

$$5000 = C + 10000 \times 0.02$$

$$C = 5000 - 200 = 4800 \text{ kg}$$

$$\begin{aligned}
 \text{Evaporation} &= F - C - P \\
 &= 50000 - (4800) - 10000 \\
 &= 35200 \text{ kg.}
 \end{aligned}$$

Answers : (a) Water evaporated = 35200 kg/hr
 (b) Salt precipitated = 4800 kg/hr
 (c) Concentrated liquor produced = 10000 kg/hr.

Ex. 38. A mixture of carbon disulphide vapour and air contains 23.32% CS_2 by volume. Calculate the relative percent saturation and percent saturation of the mixture at 20°C and 740 mm Hg pressure.

Vapour pressure of CS_2 at 20°C = 300 mm Hg.

(A.M.I.E. Exam., 1982 Winter)

Solution :

Total pressure = 740 mm Hg

Partial pressure of CS_2 = p_{CS_2}

$$= 0.2332 \times 740 = 172.57 \text{ mm Hg}$$

P_{CS_2} = Vapour pressure of CS_2 at 20°C

$$= 300 \text{ mm Hg}$$

Y_r = Relative per cent saturation

$$= \frac{p_{\text{CS}_2}}{P_{\text{CS}_2}} \times 100 = \frac{172.57}{300} \times 100 = 57.52$$

Y_p = Per cent saturation

$$= Y_r \times \left[\frac{P_T - P_{\text{CS}_2}}{P_T - P_{\text{CS}_2}} \right]$$

where, P_T = Total pressure.

$$Y_p = 57.52 \times \frac{740 - 300}{740 - 172.57} = 44.6.$$

Ex. 39. Methyl alcohol and ethyl alcohol at 100°C have vapour pressure 2710 mm and 1635 mm Hg respectively. Calculate the total pressure and composition of the vapour in contact with a liquid containing 30% by weight methyl alcohol and 70% by weight ethyl alcohol at 100°C .
 (A.M.I.E. Exam., 1983 Summer)

Solution :

Basis : 100 gm of the liquid.

Liquid analysis :

Constituents	Wt. gm.	Mol. wt.	Mol	Mol. %
CH ₃ OH	30	32	0.938	38.13
C ₂ H ₅ OH	70	46	1.522	61.87
Total	100		2.46	100.00

By Rault's law,

Partial pressure = Vapour pressure \times Mol. fraction in liquid

Partial pressure of CH₃OH

$$= 2710 \times 0.3813$$

$$= 1033.3 \text{ mm Hg.}$$

Partial pressure of C₂H₅OH

$$= 1635 \times 0.6187$$

$$= 1011.6 \text{ mm Hg.}$$

Total pressure $P_T = 1033.3 + 1011.6$

$$= 2044.9 \text{ mm Hg.}$$

Vapour composition :

Constituents	Partial pressure (p)	Mol. fraction $\left(\frac{p}{P_T}\right)$	Mol %
CH ₃ OH	1033.3	0.5053	50.53
C ₂ H ₅ OH	1011.6	0.4947	49.47
Total	2044.9		100.00

Ex. 40. Conditioned air at 760 mm Hg total pressure, 50°C and at a humidity of 0.01 kg water per kg of bone dry air enters a dryer. It leaves the dryer at 760 mm Hg total pressure and 50°C, with 83% relative humidity. Given the vapour pressure of water at 50°C is 92.5 mm Hg. If 50 kg of water enters into the air stream per hour, calculate the weight of bone dry air flowing through the dryer.

(A.M.I.E. Exam., 1983 Winter)

Solution :

Basis : 1 hour operation,

Vapour pressure of water = P

$$= 92.5 \text{ mm Hg.}$$

Partial pressure of water = p .

Relative humidity = 83%

$$\frac{p}{P} = 0.83$$

or,

$$p = 0.83 P = 0.83 \times 92.5 \\ = 76.78 \text{ mm Hg}$$

$$\frac{\text{kg mol water}}{\text{kg mole dry air}} = \frac{\text{p.p. of water vapour}}{\text{p.p. of dry air}} \\ = \frac{76.78}{760 - 76.78} = 0.112$$

$$\therefore \frac{\text{kg. water}}{\text{kg. dry air}} = \frac{0.112 \times 18}{28.84} = 0.07$$

(Mol. wt. of air = 28.84).

Inlet air condition :

$$\frac{\text{kg water vapour}}{\text{kg dry air}} = 0.01$$

Exit air condition :

$$\frac{\text{kg water vapour}}{\text{kg dry air}} = 0.07$$

$$\frac{\text{kg water removed}}{\text{kg bone dry air}} = 0.07 - 0.01 = 0.06$$

Total water entering to air stream = 50 kg.

So, weight of bone dry air flowing through the dryer per hour

$$= \frac{50}{0.06} = 833.3 \text{ kg.}$$

Ex. 41. *It is proposed to recover acetone which is used as a solvent in an extraction process, by evaporation into a stream of nitrogen. The nitrogen enters the evaporator at a temperature of 30°C containing acetone such that its dew point is 10°C. It leaves at a temperature of 25°C with a dew point of 20°C. The barometric pressure is constant at 750 mm Hg. Calculate the vapour concentration of the gases leaving and entering the evaporator, expressed as moles of vapour per mole of vapour-free gas and also the moles of acetone evaporated per mole of vapour-free gas passing through the evaporator.*

Given : Vapour pressure of acetone :

116 mm Hg at 10°C

185 mm Hg at 20°C. (A.M.I.E. Exam., 1984 Summer)

Solution :

Total pressure = 750 mm Hg (= P_T).

At the entry.

Entering temperature = 30°C.

Dew point of acetone = 10°C.

At 10°C, vapour pressure of acetone
= 116 mm Hg.

V.P. = Partial pressure corresponding to dew point
= 116 mm Hg.

$$\frac{\text{Mole acetone}}{\text{Mole acetone} - \text{free gas}} = \frac{\text{P.P. of acetone}}{\text{P.P. of inert}}$$

$$= \frac{116}{P_T - 116} = \frac{116}{750 - 116} = 0.183$$

At the exit,

Dew point = 20°C.

At dew point of 20°C, vapour pressure of acetone
= 185 mm Hg.

$$\frac{\text{Mole acetone}}{\text{Mole of vapour} - \text{free gas}} = \frac{185}{750 - 185} = 0.327.$$

$$\text{So, } \frac{\text{mole acetone evaporated}}{\text{mole of vapour} - \text{free gas}} = 0.327 - 0.183 = 0.144.$$

Ex. 42. A contact sulphuric acid plant burns essentially pure sulphur with air. The products of combustion pass to a converter where some of the SO_2 is converted to SO_3 at high rate owing to the high temperature of the gas. The gas is then cooled and sent to a final converter where the oxidation can be carried further at the lower temperature that is more favourable from the point of greater conversion of SO_2 to SO_3 . The gas from the first converter contained 2.2% SO_2 . The gas from the final converter contained 0.1% SO_2 and 9.3% O_2 .

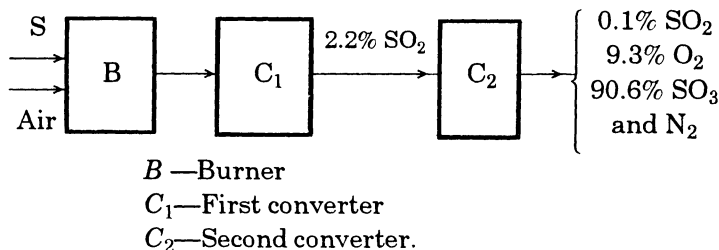
(a) What was the total percentage conversion of SO_2 to SO_3 in the first and the second converters?

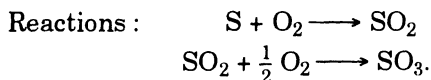
(b) What was the excess air used?

(A.M.I.E. Exam., 1984 Summer)

Solution :

The process flow is as under :





Basis : 100 kg. mole of gas from the second converter.

Let SO_3 in this gas = x kg. mole.

$$\therefore N_2 = 100 - (9.3 + 0.1 + x) \\ = (90.6 - x) \text{ kg mole.}$$

After first converter,

$$SO_2 = 2.2\%.$$

Let mole of SO_3 = y kg mole.

So, SO_2 converted to SO_3 in second converter
 = $(x - y)$ kg mole.

So, oxygen used in second converter
 = $0.5 (x - y)$ kg mole.

O_2 after first converter = $9.3 + 0.5 (x - y)$

N_2 after first converter = $90.6 - x$

SO_2 after first converter = $0.1 + (x - y)$

SO_3 after first converter = y .

Total moles of gas from the first converter
 = $100 + 0.5 (x - y)$.

$$\text{So, } \frac{\text{Moles of } SO_2}{\text{Total moles of converter gas}} \\ = \frac{0.1 + (x - y)}{100 + 0.5 (x - y)} = \frac{2.2}{100}$$

$$\therefore x - y = 2.12 \text{ kg moles.}$$

Moles of gas after first converter
 = $100 + 0.5 (x - y) = 101.06$.

$$SO_2 \text{ present} = 101.06 \times \frac{2.2}{100} \\ = 2.22 \text{ kg moles.}$$

Oxygen balance :

After first converter,

O_2 with SO_2 = 2.22 kg mole.

O_2 with SO_3 = 1.5 y kg mole.

Free O_2 = $9.3 + 0.5 (x - y) = 10.36$ kg mole.

Total O_2 = $10.36 + 2.22 + 1.5y$
 = $12.58 + 1.5y$ kg. mole.

After second converter,

O_2 with SO_2 = 0.1 kg mole

O_2 with SO_3 = 1.5 x kg. mole

$$\begin{aligned}\text{Free O}_2 &= 9.3 \text{ kg mole} \\ \text{Total O}_2 \text{ after second converter} &= 9.3 + 0.1 + 1.5x \\ &= (9.4 + 1.5x) \text{ kg mole}\end{aligned}$$

$$\begin{aligned}\text{N}_2 \text{ after second converter} &= \frac{79}{21} (9.4 + 1.5x)\end{aligned}$$

$$\text{So, } \frac{79}{21} (9.4 + 1.5x) = 90.6 - x$$

$$\text{or, } x = 8.32 \text{ kg. moles.}$$

$$(a) \text{ SO}_3 \text{ formed} = 8.32 \text{ kg moles.}$$

$$\text{SO}_2 \text{ unconverted} = 0.1 \text{ kg mole.}$$

$$\begin{aligned}\% \text{ conversion of SO}_2 \text{ to SO}_3 \text{ in the two converters} &= \frac{8.32}{8.42} \times 100 = 98.8.\end{aligned}$$

$$(b) \text{ Total moles of SO}_2 = 8.42$$

$$\begin{aligned}\text{Theoretical oxygen required for sulphur to be converted to SO}_3 &= 8.42 \times 1.5 = 12.63 \text{ kg mole}\end{aligned}$$

$$\text{O}_2 \text{ required for 0.1 kg mole SO}_2 = 0.05$$

$$\begin{aligned}\text{Actual excess oxygen} &= 9.3 - 0.05 = 9.25 \text{ kg mole}\end{aligned}$$

$$\% \text{ excess oxygen} = \frac{9.25}{12.63} \times 100 = 73.24.$$

Ex. 43. Two engineers are calculating the average molecular weight of a gaseous mixture containing oxygen and other gases. One of them using the correct molecular weight of 32 for oxygen, determines the average molecular weight correctly as 39.2. The other using an incorrect value of 16, determines the average molecular weight as 32.8. This is the only error in his calculations. What is the mole per cent of oxygen in the mixture ?

(A.M.I.E. Exam., 1984 Summer)

Solution :

$$\text{Let } x_{O_2} = \text{mole fraction of O}_2 \text{ in the mixture.}$$

$$\Sigma x_i = \text{mole fractions of other gases in the mixture excluding O}_2.$$

$$\Sigma M_i = \text{Molecular weights of other gases except O}_2.$$

Average molecular weight of the gaseous mixture as calculated by the first engineer

$$= M_{av} = 32 x_{O_2} + \Sigma x_i M_i$$

$$\text{So,} \quad 39.2 = 32 x_{O_2} + \sum x_i M_i$$

$$\therefore \quad \sum x_i M_i = 39.2 - 32 x_{O_2}$$

With molecular weight of 16 for O_2 , the average molecular weight of the mixture = $16 x_{O_2} + \sum x_i M_i$

$$\therefore \quad 32.8 = 16 x_2 + \sum x_i M_i$$

$$\therefore \quad 32.8 = 16 x_{O_2} + (39.2 - 32 x_{O_2})$$

$$(\because \sum x_i M_i = 39.2 - 32 x_{O_2})$$

$$\text{or} \quad x_{O_2} = 0.40$$

Therefore, mole percent of Oxygen in the mixture = 40.

Ex. 44. Methane containing 4% O_2 is flowing through a pipe. It is required to calculate the volumetric flow rate of the gas flowing. For this purpose, $10 \text{ m}^3/\text{min.}$ of air at 27°C and 760 mm Hg are introduced into the pipe and several metres further down the pipe, a sample is drawn which is found to contain 11% of $(O_2 + N_2)$. How many cubic metres of the initial gas were flowing per minute at 27°C and 740 mm Hg through the pipe? (A.M.I.E. Exam., 1984 Winter)

Solution :

Let $x \text{ m}^3/\text{min.}$ of methane— O_2 mixture flows through the pipe at 27°C and 760 mm Hg .

To this $10 \text{ m}^3/\text{min.}$ of air is added at the same conditions.

Total volume of gas mixture in the down stream

$$= (10 + x) \text{ m}^3$$

O_2 in CH_4 — O_2 mixture = $0.04x$

O_2 in air = 2.1 m^3

N_2 in air = 7.9 m^3

$(O_2 + N_2)$ is 11% in the down stream gas mixture.

So, $(O_2 + N_2)$ in the down stream

$$= (0.04 x + 2.1) + 7.9 = (10 + 0.04 x) \text{ m}^3$$

$$\therefore \quad \frac{10 + 0.04x}{10 + x} = \frac{11}{100}$$

$$\text{or,} \quad x = 127.14 \text{ m}^3/\text{min.}$$

Let $V =$ volume of initial gas mixture at 27°C and 740 mm Hg .

$$\text{So,} \quad \frac{V \times 740}{(273 + 27)} = \frac{127.14 \times 760}{(273 + 27)}$$

$$\text{or,} \quad V = 130.58 \text{ m}^3/\text{min.}$$

Gas flowing through the pipe at 27°C and 740 mm

$$\text{Hg.} = 130.58 \frac{\text{m}^3}{\text{min.}}$$

Ex. 45. Air at 60°C and 745 mm Hg having a per cent humidity of 10 is supplied to a drier at the rate of $1000 \text{ m}^3/\text{hour}$. Water to evaporated in the drier at a rate of 20 kg/hr . The air leaves the drier at 35°C and 742 mm Hg. Calculate :

(a) Per cent humidity of the air while leaving the drier.

(b) Volumetric flow rate of wet air leaving the drier.

Given : Vapour pressure of water

at $60^{\circ}\text{C} = 150 \text{ mm Hg}$.

at $35^{\circ}\text{C} = 42 \text{ mm Hg}$. (A.M.I.E. Exam., 1984 Winter)

Solution :

Basis : 1 hour operation.

Vapour pressure = 150 mm Hg.

Let p = partial pressure

$$\text{So,} \quad 0.1 = \frac{p}{150}$$

$$\text{i.e.,} \quad p = 15 \text{ mm Hg.}$$

$$\text{Initial humidity} = H_1 = \frac{p}{P_T - p} \quad (\text{where } P_T = \text{total pressure})$$

$$\begin{aligned} H_1 &= \frac{\text{kg. mole water vapour}}{\text{kg. mole dry air}} \\ &= \frac{15}{745 - 15} = 0.0205 \\ &= \frac{0.0205 \times 18}{28.84} = 0.0128 \frac{\text{kg water}}{\text{kg dry air}} \end{aligned}$$

Let us assume that air-water vapour mixture behaves ideally.

If n = kg. moles of air-water vapour mixture,

$$\begin{aligned} n &= \frac{PV}{RT} = \frac{(745/760) \times 1000}{0.082 \times (273 + 60)} \\ &= 35.9 \text{ kg moles.} \end{aligned}$$

$$\frac{\text{kg. mole wet air}}{\text{kg mole dry air}} = 1 + .0205 = 1.0205$$

$$\text{kg mole dry air} = \frac{35.9}{1.0205} = 35.18$$

Water with entering air,

$$= 35.9 - 35.18 = 0.72 \text{ kg mole} = 12.96 \text{ kg}$$

Water evaporated in the drier and added to air = 20 kg

Water in the exit air = 20 + 12.96 = 32.96 kg

$$= 1.83 \text{ kg mole}$$

In the exit air,

$$\frac{\text{kg mole water}}{\text{kg mole dry air}} = \frac{1.83}{35.18} = 0.052$$

Let p' = partial pressure of water vapour in exit air

$$\therefore 0.052 = \frac{p'}{742 - p'}$$

So, $p' = 40.7 \text{ mm Hg.}$

(i) Per cent humidity of exit air

$$= \frac{p'}{p_s} \times 100 = \frac{40.7}{42.0} \times 100 = 96.9$$

(ii) Moles of wet air leaving the drier

$$= 35.18 + 1.83 = 37.01$$

Volumetric flow rate of wet air

$$= V = \frac{nRT}{P}$$

$$= \frac{37.01 \times 0.082 \times (273 + 35)}{742/760} = 957.4 \text{ m}^3.$$

Ex. 46. A mixture of NaCl and KCl was treated with H_2SO_4 and 1.2 kg of mixed sulphate (K_2SO_4 and Na_2SO_4) was obtained. If the original sample weighed 1 kg, determine the percentage of chlorine in the sample.

(Na = 23, K = 39 and S = 32).

(A.M.I.E. Exam., 1985 Summer)

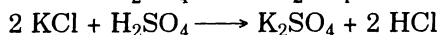
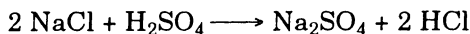
Solution :

Basis : 1 kg of mixed chloride

Let x kg of NaCl is present

So, KCl = $(1 - x)$ kg.

Reactions :



$$\text{Na}_2\text{SO}_4 \text{ formed} = \frac{142}{117} x = 1.214 x \text{ kg}$$

$$\text{K}_2\text{SO}_4 \text{ formed} = \frac{174}{149} (1 - x) = 1.168 (1 - x)$$

$$\text{So, } 1.214 x + 1.168 (1 - x) = 1.2$$

$$\therefore x = 0.696 \text{ kg.}$$

$$\text{Amount of NaCl} = 0.696 \text{ kg}$$

$$\text{Amount of KCl} = 1 - 0.696 = 0.304$$

$$\text{Chlorine in NaCl} = 0.696 \times \frac{35.5}{58.5} = 0.422 \text{ kg}$$

$$\text{Chlorine in KCl} = 0.304 \times \frac{35.5}{74.5} = 0.145 \text{ kg}$$

$$\begin{aligned}\text{Total chlorine in the same sample} \\ &= 0.422 + 0.145 = 0.567 \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Per cent chlorine in the sample} \\ &= \frac{0.567}{1.0} \times 100 = 56.7.\end{aligned}$$

Ex. 47. A liquid hydrocarbon feed is passed into a flash vaporizer where it is heated and separated into vapour and liquid streams. The analysis of the various streams in weight percentage is given below.

Stream \longrightarrow Feed Component \downarrow		Vapour product	Liquid product
C_4H_{10}	20	71.4	?
C_5H_{12}	30	23.8	31.6
C_6H_{14}	50	4.8	?
Total	100.0	100.0	100.0

Calculate,

(a) Weight of vapour product per unit weight of feed.

(b) Full composition of liquid product.

(c) Average molecular weight of vapour product.

(A.M.I.E. Exam., 1985 Summer and 1990 Winter)

Solution :

Basis : 1 kg of liquid hydrocarbon feed to vaporizer.

Let V = Vapour product, kg

L = Liquid product, kg

F = Feed, kg

$$F = V + L = 1$$

C_5H_{12} balance gives,

$$0.3 F = 0.238 V + 0.316 L$$

$$\text{or,} \quad 0.3 = 0.238 V + 0.316 (1 - V)$$

$$\text{Solving,} \quad V = 0.205 \text{ kg}$$

$$\therefore L = 1 - 0.205 = 0.795 \text{ kg}$$

$$(i) \frac{\text{Wt. of vapour}}{\text{Wt. of feed}} = 0.205$$

(ii) Let x = Wt. per cent butane in liquid product.

Butane (C_4H_{10}) balance gives,

$$F \times 0.2 = V \times 0.714 + Lx$$

$$\text{or} \quad 1 \times 0.2 = 0.205 \times 0.714 + 0.795 x$$

Solving, $x = 0.0679$ or 6.79%

So, C_6H_{14} in liquid product

$$= 100 - (6.79 + 31.6) = 61.61\%$$

Analysis of liquid product :

Constituents	Weight %
C_4H_{10}	6.79
C_5H_{12}	31.60
C_6H_{14}	61.61
Total	100.00

(iii) Weight of vapour = 0.205 kg.

Vapour analysis :

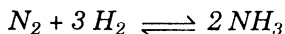
Constituents	Wt. %	Wt.	Mol. Wt.	kg mole
C_4H_{10}	71.4	0.146	58	0.00251
C_5H_{12}	23.8	0.049	72	0.00068
C_6H_{14}	4.8	0.010	86	0.00012
Total	100.0	0.205		0.00331

Average molecular weight of vapour

$$= \frac{\text{Weight in kg.}}{\text{kg mole}}$$

$$= \frac{0.205}{0.00331} = 61.93.$$

Ex. 48. Nitrogen and hydrogen react under certain conditions to form ammonia, according to the following equation :



If 280 kg of nitrogen and 64.5 kg of hydrogen are brought together and allowed to react at 515°C and 300 atm. pressure and it is found that there are 38 kg mole of gases present at equilibrium :

(a) How many kg moles of nitrogen, hydrogen and ammonia are present at equilibrium ?

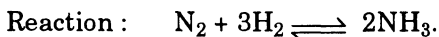
(b) Which is the limiting reactant and which is the excess reactant ?

(c) What is the amount of theoretically required hydrogen and what is the per cent excess hydrogen ?

(d) What is the degree of the completion of the reaction ?

(e) *What is the percentage conversion of hydrogen to ammonia.*
(Ravishankar Uni. 1983)

Solution :



Amount of $\text{N}_2 = 280 \text{ kg} = 10 \text{ kg mole}$

Amount of $\text{H}_2 = 64.5 \text{ kg} = 32 \text{ kg mole}$

At equilibrium 38 kg moles of gases are present.

Let $x \text{ kg. mole}$ of N_2 is converted to NH_3 .

H_2 used = $3x \text{ kg. mole}$.

(a) Equilibrium mixture contains.

$$\text{N}_2 = (10 - x) \text{ kg mole}$$

$$\text{H}_2 = (32 - 3x) \text{ kg mole}$$

$$\text{NH}_3 = 2x \text{ kg mole}$$

$$\text{So, } (10 - x) + (32 - 3x) + 2x = 38$$

$$\therefore x = 2.$$

At equilibrium,

$$\text{Nitrogen} = 10 - x = 8 \text{ kg mole}$$

$$\text{Hydrogen} = 32 - 3x = 26 \text{ kg mole}$$

$$\text{Ammonia} = 2x = 4 \text{ kg mole}$$

$$\text{Total} \quad \quad \quad \underline{38 \text{ kg mole.}}$$

(b) Since 10 kg. mole of N_2 require 30 kg mole of H_2 for complete conversion, hence hydrogen present is excess.

So, nitrogen is the limiting reactant and hydrogen is the excess reactant.

(c) Theoretically required hydrogen is 30 kg. mole.

$$\text{H}_2 \text{ in excess} = 32 - 30 = 2 \text{ kg mole}$$

$$\% \text{ excess} = \frac{2}{30} \times 100 = 6.67.$$

(d) Degree of completion of the reaction

$$= \frac{2}{10} \times 100 = 20\%.$$

(e) Per cent conversion of H_2 to NH_3

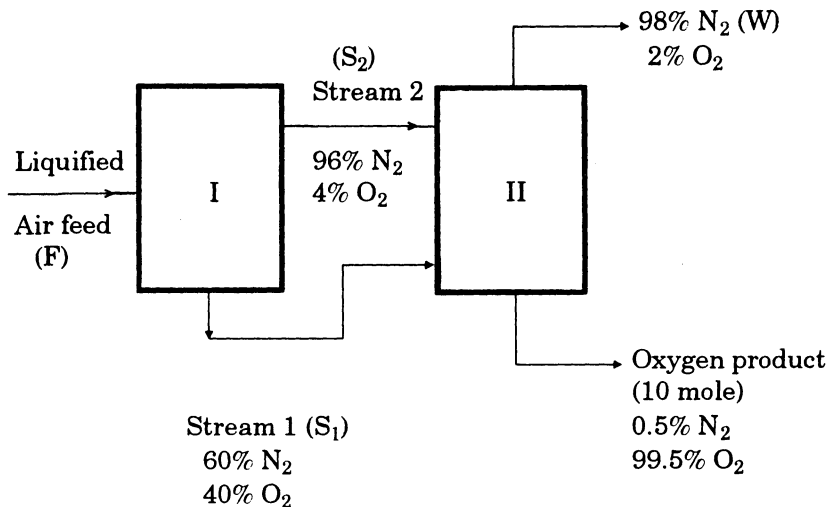
$$= \frac{6}{32} \times 100 = 18.75.$$

Ex. 49. *Oxygen is produced by liquifying air and distilling it at low temperature. In a particular installation two distillation columns are used as shown in the figure below. All the compositions are reported in mole per cent. Calculate :*

(a) *the per cent recovery of oxygen in the oxygen rich product stream.*

(b) the flow rate of stream 1 for 10 mole/s of the product oxygen stream.
(Ravishankar Uni., 1984)

Solution :



Basis : 10 mole/s of oxygen product.

Let, F = liquified air feed, mole/s

S_1 = amount of stream 1, mole/s

S_2 = amount of stream 2, mole/s

W = waste stream from second column, mole/s.

$$\text{Overall balance, } F = S_1 + S_2 = 10 + W \quad \dots(1)$$

Oxygen balance around the first column,

$$\begin{aligned} F \times 0.21 &= S_2 \times 0.04 + S_1 \times 0.4 \\ 0.21 F &= 0.04 S_2 + 0.4 S_1 \quad \dots(2) \end{aligned}$$

Overall oxygen balance gives,

$$F \times 0.21 = 10 \times 0.995 + W \times 0.02 \quad \dots(3)$$

or, $0.21 F = 9.95 + (F - 10)0.02$

Solving, $F = 51.32$ mole/s.

From, equation (1),

$$S_2 = F - S_1 = (51.32 - S_1) \quad \dots(4)$$

Putting the value of F and equation (4) in (2),

$$51.32 \times 0.21 = 0.4 S_1 + (51.32 - S_1)0.04$$

Solving, $S_1 = 24.23$ mole/s.

(a) Percentage recovery of oxygen in the oxygen-rich product stream

$$= \frac{10 \times 0.995}{51.32 \times 0.21} \times 100 = 92.84.$$

(b) Flow rate of stream 1 = 24.23 mole/s.

Ex. 50. An absorption tower packed with rasching rings is used to absorb CO_2 in an aqueous solution of MEA. The volumetric flow rate of incoming gas mixture is $1000 \text{ m}^3/\text{hr}$ at 45°C and 755 mm Hg . The CO_2 content of the gas is $10.4 \text{ mole } \%$ while the outgoing gas mixture contains $4.5 \text{ mole } \%$ CO_2 . A 3.2 m MEA solution is introduced at the top of the tower at the rate of 37.5 litres/min . Dissolved CO_2 concentration of the entering MEA solution is $0.166 \text{ mole per mole of MEA}$. Find the concentration of dissolved CO_2 in the solution leaving the tower.

Data : Chemical formula of MEA is : $\text{CH}_2\text{OH CH}_2 \text{NH}_2$.
Molecular weight of MEA : 61. (Ravishankar Uni., 1984)

Solution :

Basis : 1 hour operation.

Entry condition : $T = 45^\circ\text{C}$

$P = 755 \text{ mm Hg}$.

$V = 1000 \text{ m}^3/\text{hr}$.

Assuming ideal gas to hold good for the gas mixture,

$$n = \frac{PV}{RT} = \left(\frac{755}{760} \right) \times \frac{1000}{0.082 \times 3.18}$$

$$= 38.1 \text{ kg. moles.}$$

CO_2 in inlet stream = $38.1 \times 0.104 = 3.96 \text{ kg mole}$

CO_2 in exit stream = $4.5 \text{ mole } \%$

Inert with the stream = $38.1 - 3.96 = 34.14$

$$\frac{\text{CO}_2 \text{ in exit}}{(\text{inert} + \text{CO}_2) \text{ in exit}} = 0.045$$

$$\frac{\text{CO}_2}{\text{CO}_2 + 34.14} = 0.045$$

CO_2 in exit stream = 1.61 kg. mole

CO_2 absorbed = $3.96 - 1.61 = 2.35 \text{ kg mole}$.

Absorption is by 3.2 m MEA solution. i.e. $3.2 \text{ gm moles of MFA}$ in 1000 kg of water .

\therefore Amount of MEA = $3.2 \times 61 = 195.2 \text{ gm}$.

CO₂ in entering MEA solution

$$= \frac{0.166 \text{ gm mole}}{\text{mole M.E.A.}}$$

$$= 0.166 \times 3.2 = 0.53 \text{ gm. mole.}$$

Let us assume that the aq. MEA solution entering the absorber has a density equal to that of water.

Flow rate of MEA solution = 37.5 lit/min

$$= 2250 \text{ lit/hr.} = 2250 \text{ kg/hr.}$$

CO₂ with entering MEA solution

$$= \frac{0.530}{1000 + 0.195} \times 2250 = 1.19 \text{ gm moles}$$

CO₂ with exit MEA solution

$$= 2.35 \text{ kg mole} + 1.19 \text{ gm mole}$$

$$= 2.3512 \text{ kg mole.}$$

Exit solution :

$$\text{Water and MEA} = \frac{2250}{18}$$

$$= 125 \text{ kg mole.}$$

$$\text{CO}_2 = \frac{2.3512 \text{ mole.}}{127.3512 \text{ mole.}}$$

$$\text{Total}$$

CO₂ content of exit solution

$$= \frac{2.3512}{127.3512} \times 100 = 1.85$$

So, concentration of CO₂ in the solution leaving the tower is 1.85 mole %.

Ex. 51. 1000 m³, of a mixture of H₂, N₂ and CO₂ at 150°C was found to have the following ratio of the partial pressures of the gases :

$$P_{H_2} : P_{N_2} : P_{CO_2} = 1 : 4 : 3$$

If the total pressure is 2 atm. absolute, find

(a) mole fraction of each of these gases

(b) Weight percent of these gases

(c) Average molecular weight

(d) Weight of CO₂ in kilograms.

(Sambalpur Univ. 1991 ; A.M.I.E. Exam., 1994 Summer)

Solution. Basis : 1000 m³ of a mixture of H₂, N₂ and CO₂ at 150°C.

$$P_{H_2} : P_{N_2} : P_{CO_2} = 1 : 4 : 3.$$

$$\Sigma P = P_T \text{ where } P_T \text{ is total pressure.}$$

Calculation of moles of gases :

Since $P_T = 2 \text{ atm}$

$$P_{H_2} = 2 \times \frac{1}{8} = 0.25 \text{ atm}$$

$$P_{N_2} = 2 \times \frac{4}{8} = 1.0 \text{ atm}$$

$$P_{CO_2} = 2 \times \frac{3}{8} = 0.75 \text{ atm}$$

(a) Mole fraction of the gases :

$$H_2 = \frac{0.25}{2.0} = 0.125$$

$$N_2 = \frac{1.0}{2.0} = 0.500$$

$$CO_2 = \frac{0.75}{2.0} = 0.375$$

$$\text{Total} = 1.00$$

(b) Calculation of amount of moles

$$PV = nRT$$

$$P_{H_2} \times 1000 = n_{H_2} \times 0.08205 \times (273 + 150)$$

with $P_{H_2} = 0.25$

$$n_{H_2} = 7.203 \text{ kg moles}$$

Similarly, $n_{N_2} = 28.813 \text{ kg moles}$

$$n_{CO_2} = 21.609 \text{ kg moles}$$

Calculation of weight per cent :

Constituent	kg moles	mol. wt.	kg	%W
H ₂	7.203	2.0	14.406	0.81
N ₂	28.813	28.0	806.764	45.53
CO ₂	21.609	44.0	950.796	53.66
Total	57.625		1771.966	100.0

(c) Average molecular weight

$$\begin{aligned} \text{Av. mol. wt.} &= 0.125 \times 2 + 0.50 \times 28 + 0.375 \times 44 \\ &= 30.75 \end{aligned}$$

(d) Weight of CO₂ in kilograms

$$= 950.796.$$

Ex. 52. Limestone containing 95% (wt.) CaCO₃ and 5% SiO₂ is being calcined as shown in the flow sheet below. Heat for reaction

is supplied from a furnace burning powdered coke which is essentially pure carbon.

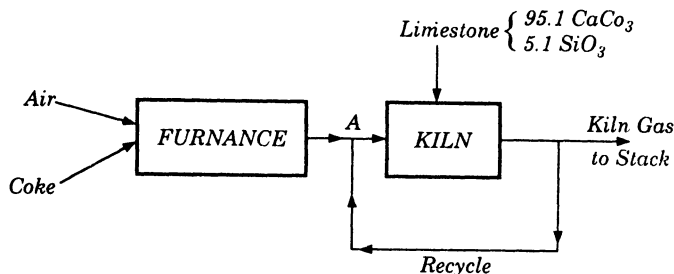
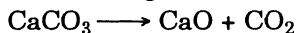


Fig. 1.11

The hot flue gas analyses 5 mole % CO_2 . The kiln gas is found to contain 8.65% CO_2 . In order to conserve some of the sensible heat a portion of the kiln gas is continuously recycled and mixed with fresh hot flue gases. After mixing, the gas entering the kiln analyses 7 mole % CO_2 .

- (a) Calculate kg of crude CaO produced per kg of coke burnt.
 (b) Calculate the recycle ratio. (Sambalpur Univ. 1992)

Solution. Basis : 100 kg of limestone



CaCO_3 in limestone is 95 kg.

100 kg CaCO_3 produces 56 kg CaO

95 kg CaCO_3 will produce $\frac{56}{100} \times 95 = 53.2$ kg

100 kg CaCO_3 produces 44 kg CO_2

95 kg CaCO_3 will produce $\frac{44}{100} \times 95 = 41.8$ kg = 0.95 kg mole

Let the amount of various streams be as under :

Flue gas = x kg moles (fresh)

Kiln gas = y kg

Recycle gas = z kg

Hot flue gas to kiln = $(x + z)$

$y - z$ = kiln gas out to stack

Carbondioxide balance around kiln

$$0.05x + 0.95 = 0.0865 y \quad \dots(1)$$

Carbondioxide balance at point A :

$$0.05x + 0.0865z = 0.07(x + z) \quad \dots(2)$$

From (2), $z = 1.212x$... (3)

Complete combustion with theoretical amount of air is assumed.

From nitrogen balance,

$$0.95x = 0.9135y \quad \dots (3)$$

$$\therefore y = 1.04x$$

Putting value of 'y' in (1)

$$x = 23.77 \text{ kg mole}$$

$$\therefore z = 28.81 \text{ kg mole}$$

(a) CO_2 in flue gas of furnace

$$= 23.77 \times 0.05 = 1.1865$$

Amount of carbon (which is also coke)

$$= 1.1865 \times 12 = 14.26 \text{ kg}$$

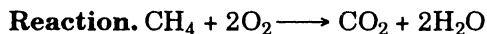
$$\frac{\text{kg of CaO produced}}{\text{kg of coke}} = 3.73$$

(b) Recycle ratio $= \frac{z}{x} = 1.212$.

Ex. 53. An inspector files a report against a factory owner charging him that the CO_2 content of the gases leaving the chimney rises above 15% being dangerous to health and against city code. The factory owner burns natural gas containing 100% CH_4 and the air supply adjusted to provide 130% excess air. Is the inspector's charge correct? (Nagpur 1987)

Solution. Assume complete combustion of the fuel gas.

Basis. 1 kg mole of natural gas.



Oxygen required = 2 kg mole

Oxygen supplied = 130% excess

$$= 2 \times 2.3 = 4.6 \text{ kg mole}$$

$$\text{Nitrogen supplied} = 4.6 \times \frac{79}{21}$$

$$= 17.3 \text{ kg mole}$$

$$\text{Air supplied} = 17.3 + 4.6 = 21.9 \text{ kg mole}$$

$$\text{CO}_2 \text{ formed} = 1 \text{ kg mole}$$

$$\text{H}_2\text{O formed} = 2 \text{ kg mole}$$

$$\text{O}_2 \text{ unreacted} = 4.6 - 2.0 = 2.6 \text{ kg mole}$$

Flue gas analysis : (Wet)

<i>Constituents</i>	<i>Amount kg mole</i>	<i>Percentage</i>
CO ₂	1.0	4.37
H ₂ O	2.0	8.74
O ₂	2.6	11.35
N ₂	17.3	75.54
	22.9	100.00

Considering dry flue gas, CO₂ percentage

$$= \frac{1.0}{20.9} \times 100 = 4.78.$$

The percentage of CO₂ in the flue gas is much lower than the specified limit (i.e. 15%).

The charge of the inspector against the factory is not correct.

Ex. 54. Compounds A, B and C form a liquid mixture containing 10 kg of A, 25%W B and 1.5 moles of C for each mole of B. The molecular weights of A, B and C are 56, 58 and 72 respectively. The specific gravities of A, B and C are 0.58, 0.60 and 0.67 respectively. Calculate the analysis of the mixture in weight and mole percent, the molecular weight and density of the mixture and the total number of moles in the mixture.

Solution. Let M = total weight of mixture.

$$\text{Amount of B} = 0.25 M$$

$$\text{Mole of B} = \frac{0.25 M}{58}$$

$$\begin{aligned} \text{So, Amount of C} &= 1.5 \times \frac{0.25}{58} M \text{ mole} \\ &= 1.5 \times \frac{0.25}{58} M (72) = 0.4655 M \text{ kg.} \end{aligned}$$

$$\text{So, } M = 10 + 0.25 M + 0.4655 M$$

$$\text{or, } \frac{0.25 M}{10 + 0.25 M + 0.4655 M} = 0.25$$

$$\text{or, } M = 35.16 \text{ kg.}$$

$$\text{Amount of C} = 0.4655 M = 16.37 \text{ kg.}$$

$$\text{Amount of B} = 0.25 M = 8.79 \text{ kg.}$$

Analysis of the mixture :

Constituents	Weight kg	Mol. wt.	Mol.	Mol%
A	10.00	56	0.1786	32.03
B	8.79	58	0.1516	27.19
C	16.37	72	0.2274	40.78
Total	35.16		0.5576	100.00

Analysis in weight percent and volume :

	wt., kg	$\rho \cdot \frac{\text{kg}}{\text{m}^3}$	wt. %	Vol. m^3
A	10.00	580	28.44	0.0172
B	8.79	600	25.00	0.0147
C	16.37	670	46.56	0.0244
				0.0563

Density of the mixture :

$$\begin{aligned}\text{Mixture density} &= \frac{\text{Weight}}{\text{Volume}} = \frac{35.16}{0.0563} \\ &= 624.5 \text{ kg/m}^3.\end{aligned}$$

Molecular weight of the mixture :

$$\begin{aligned}\text{Mol. wt.} &= \sum x_i M_i \\ &= 0.3203 \times 56 + 0.2719 \times 58 + 0.4078 \times 72 \\ &= 63.07\end{aligned}$$

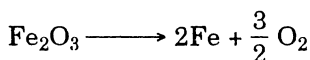
Total number of moles = 0.5576.

Ex. 55. A blast furnace uses iron ore which contains Fe_2O_3 —90% and SiO_2 —10%. The coke fed to the furnace has 90% Carbon and 10% Silica (as SiO_2). Limestone used as flux contains 95% CaCO_3 , 3% MgCO_3 and 2% SiO_2 . The rate of coke is 1 kg per kg of pig iron produced. The pig iron contains 95% Fe, 4% C and 1% Si. The slag contains 45% of MgO and CaO taken together. Assume slag to be Feo-free. Find the amount of flux required for 2000 kg of pig iron produced.

Solution.

Basis : 1000 kg of pig iron produced.

Fe in pig iron = $1000 \times 0.95 = 950 \text{ kg}$.



$$\text{Equivalent Fe}_2\text{O}_3 \text{ from ore} = 950 + \frac{112}{160} = 1357 \text{ kg.}$$

$$\text{SiO}_2 \text{ from ore} = \frac{1357}{90} \times 10 = 150.78 \text{ kg.}$$

Let y = kg of slag produced.

x = kg of limestone (flux) used.

Slag contains : $\text{MgO} + \text{CaO} + \text{SiO}_2$

$$\text{MgO} + \text{CaO} = 45\%$$

$$\therefore \text{SiO}_2 = 55\%$$

$$\text{Coke used} = 1000 \text{ kg}$$

SiO_2 balance :

$$\text{SiO}_2 \text{ from coke} = 1000 \times 0.1 = 100 \text{ kg}$$

$$\text{SiO}_2 \text{ from limestone} = 0.02x \text{ kg}$$

$$\text{SiO}_2 \text{ from ore} = 150.78 \text{ kg.}$$

$$\text{Si in pig iron} = 10 \text{ kg}$$

$$\text{Equivalent SiO}_2 = 10 \times \frac{60}{28} = 21.43 \text{ kg.}$$

$$\text{SiO}_2 \text{ found in slag} = 0.55y.$$

$$\text{So, } 150.78 + 100 + 0.02x = 21.43 + 0.55y \quad \dots(1)$$

($\text{MgO} + \text{CaO}$) balance :

$$\text{From flux} = 0.95x \times \frac{56}{100} + 0.03x \frac{40}{84} = 0.546x$$

$$\text{Amount in slag} = 0.45y$$

$$\text{So, } 0.45y = 0.546x$$

$$\text{or, } y = 1.213x \quad \dots(2)$$

Putting the value of y from (2) in (1),

$$0.02x + 229.35 = 0.55(1.213x) = 0.667x$$

$$\text{Solving, } x = 354.5 \text{ kg.}$$

$$\text{Flux required for 2000 kg} = 354.5 \times 2 = 709 \text{ kg.}$$

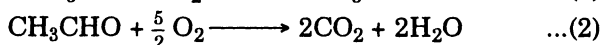
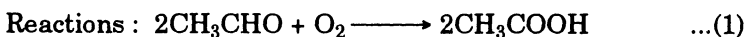
Ex. 56. *Acetaldehyde is oxidized over silica gel with the help of air. The mixture is passed over catalyst at 115°C . The outgoing dry gas is found to contain 4.85% CO_2 , 8.65% acetaldehyde, 14.9% acetic acid, 2.55% O_2 and 69.05% N_2 by volume on dry basis. For the purpose of dry analysis, water was first removed from the mixture and some acetic acid was also removed along with it. Calculate :*

- (i) *the percentage conversion of acetaldehyde*
- (ii) *the percentage yield of acetic acid*
- (iii) *the ratio of air to acetaldehyde in the feed*

(iv) the percentage removal of acetic acid during the removal of water

(v) the actual analysis of the gases leaving the reactor.

Solution.



Oxygen balance : (based on 100 kg moles of dry gas)

$$\text{Oxygen supplied} = 69.05 \times \frac{21}{79} = 18.355 \text{ kg mol}$$

Oxygen used for acetic acid (reported)

$$= 14.9 \times \frac{1}{2} = 7.45 \text{ kg mol.}$$

Oxygen used for CO_2 produced

$$= 4.85 \times \frac{2.5}{2} = 6.06 \text{ kg mol.}$$

Oxygen in exit gas = 2.55 kg mol.

Total oxygen reported in dry gas (as O_2 and products of oxygen)

$$= 7.45 + 6.06 + 2.55 = 16.06 \text{ kg mol}$$

Oxygen unreported = $18.355 - 16.06$

$$= 2.295 \text{ kg mol.}$$

This oxygen is used for the production of additional acetic acid which has condensed and accompanied the water stream.

Additional acid formed (reaction-1)

$$= 2.295 \times 2 = 4.59 \text{ kg mol.}$$

Acetaldehyde balance :

Acetaldehyde used for acetic acid

$$= 14.9 + 4.59 = 19.49 \text{ kg. mol.}$$

Acetaldehyde used for $\text{CO}_2 = 4.85 \times \frac{1}{2} = 2.425 \text{ kg. mol.}$

Total acetaldehyde used = $19.49 + 2.425 = 21.915 \text{ kg. mol.}$

Acetaldehyde unused = 8.65 kg. mol.

(i) Percentage conversion of acetaldehyde

$$= \frac{21.915}{(21.915 + 8.65)} \times 100 = 71.7$$

(ii) Percentage yield of acetic acid

$$= \frac{19.49}{21.915} \times 100 = 88.93$$

$$(iii) \text{ Air used} = 69.05 \times \frac{100}{79} = 87.405 \text{ kg mol}$$

$$\text{Air/Acetaldehyde} = \frac{87.405}{(21.915 + 8.65)} = 2.86$$

$$(iv) \text{ Percentage removal of acetic acid with water} \\ = \frac{4.59}{19.49} \times 100 = 23.55$$

(v) Actual analysis of reactor gases :

From reaction (2), amount of water formed = 4.85 kg mol.

Analysis of the gases from reactor.

Constituents	Amount kg mole	Percentage
CO ₂	4.85	4.432
CH ₃ CHO	8.65	7.904
CH ₃ COOH	19.49	17.809
N ₂	69.05	63.094
O ₂	2.55	2.330
Water	4.85	4.432
Total	109.44	100.001

Ex. 57. Nicotine is to be extracted with kerosene from a water solution containing 1.5% nicotine at 22°C. Water and kerosene are essentially immiscible. The equilibrium distribution of nicotine between water and kerosene layer is given by a term called distribution coefficient (*K*) which is expressed as under

$$K = \frac{Y}{x} = \frac{\text{kg nicotine/kg kerosene}}{\text{kg nicotine/kg. water}} = 0.91$$

where, y = concentration in extract phase

x = equilibrium concentration in raffinate phase.

Calculate :

(i) the percentage extraction of nicotine if 100 kg of feed solution is extracted once with 180 kg of kerosene.

(ii) the percentage extraction using three extraction stages with 60 kg of kerosene for each stage.

Solution.

Basis : 100 kg of feed solution.

Nicotine in feed = $100 \times 0.015 = 1.5$ kg.

Water in feed = $100 - 1.5 = 98.5$ kg.

Since water and kerosene are not miscible, there are 98.5 kg water in the raffinate and 180 kg kerosene in the extract.

(i) Let E_N = kg. of nicotine extracted

So, nicotine in raffinate = $1.5 - E_N$

y = concentration of nicotine in kerosene

$$= \frac{E_N}{180}$$

x = concentration of nicotine in water

$$= \frac{1.5 - E_N}{98.5}$$

As per equilibrium,

$$\frac{E_N}{180} = 0.91 \left(\frac{1.5 - E_N}{98.5} \right)$$

$$E_N = 0.9367 \text{ kg.}$$

$$\% \text{ nicotine extracted} = \frac{0.9367}{1.5} \times 100 = 62.45.$$

(ii) For the first stage,

$$y_1 = \frac{E_{N_1}}{60}; x_1 = \frac{1.5 - E_{N_1}}{98.5}$$

$$\text{So, } \frac{E_{N_1}}{60} = 0.91 \left(\frac{1.5 - E_{N_1}}{98.5} \right)$$

$$E_{N_1} = 0.5349 \text{ kg.}$$

For the second stage,

$$\begin{aligned} y_2 &= \frac{E_{N_2}}{60}; x_2 = \frac{1.5 - E_{N_1} - E_{N_2}}{98.5} \\ &= \frac{0.9651 - E_{N_2}}{98.5} \end{aligned}$$

As per equilibrium,

$$\frac{E_{N_2}}{60} = 0.91 \left(\frac{0.9651 - E_{N_2}}{98.5} \right)$$

Solving, $E_{N_2} = 0.3442 \text{ kg.}$

For the third stage,

$$\begin{aligned} y_3 &= \frac{E_{N_3}}{60} \\ x_3 &= \frac{1.5 - E_{N_1} - E_{N_2} - E_{N_3}}{98.5} \\ &= \frac{1.5 - 0.5349 - 0.3442 - E_{N_3}}{98.5} = \frac{0.6209 - E_{N_3}}{98.5} \end{aligned}$$

As per equilibrium,

$$\frac{E_{N_3}}{60} = 0.91 \left(\frac{0.6209 - E_{N_3}}{98.5} \right)$$

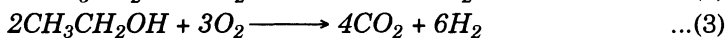
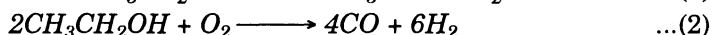
Solving, $E_{N_3} = 0.2215$ kg.

In the above, E_{N_1} , E_{N_2} and E_{N_3} are the amounts of nicotine extracted in the first, second and third stages respectively.

$$\begin{aligned} \text{Total nicotine extracted} &= E_{N_1} + E_{N_2} + E_{N_3} \\ &= 1.1006 \text{ kg.} \end{aligned}$$

$$\% \text{ nicotine extracted} = \frac{1.1006}{1.5} \times 100 = 73.37.$$

Ex. 58. Dehydrogenation of ethanol is a commercial process for the manufacture of acetaldehyde. Ethyl alcohol vapour (preheated) with air enters the reactor packed with silver catalyst. The reaction temperature is maintained at 450°C . Various reaction taking place are

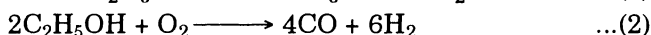
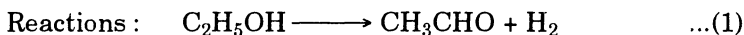


The exit gases from the converter are passed through a scrubber where cold dilute alcohol cools the gases and dissolves both alcohol and aldehyde. The stripped gas is scrubbed in a second scrubber with water. The dilute acetaldehyde alcohol solution from the bottom of the first scrubber is sent to a distillation column to produce 99% acetaldehyde as overhead. The gases leaving the second scrubber contains 0.7% CO_2 , 2.2% O_2 , 2.2% CO , 7.1% H_2 , 2.6% CH_4 and 85.2% N_2 on dry basis (by volume). Find

(i) the yield of acetaldehyde.

(ii) for 98% absorption of acetaldehyde and alcohol in scrubber-I and for the production of 1000 kg/hr of 99% acetaldehyde, find the composition of the reaction mixture if the overall conversion with respect to alcohol is 30%.

Solution.



The flow diagram for the process is as under :

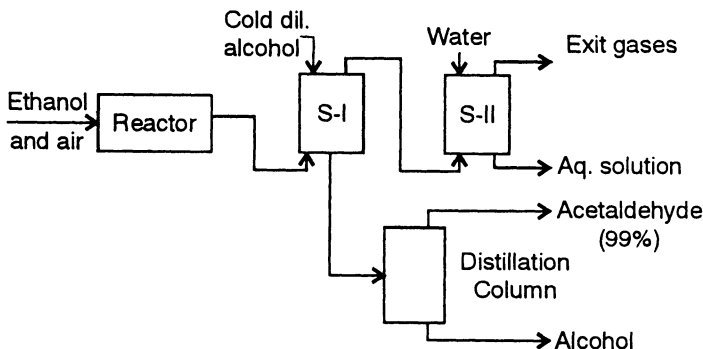


Fig. 1.12

Basis : 100 kg moles of outgoing gases from second scrubber.

N_2 present = 85.2 kg moles

O_2 supplied = $85.2 \times \frac{21}{79} = 22.65$ kg moles.

O_2 in exit gases = 2.2 kg moles.

O_2 reacted = $22.65 - 2.2 = 20.45$ kg moles.

Let x, y and z kg moles of ethanol reacted by reactions, (2), (3) and (4) respectively and H = kg moles of hydrogen reacted by reaction (5). Oxygen balance gives,

$$\frac{x}{2} + \frac{3}{2}y + \frac{H}{2} - \frac{Z}{2} = 20.45$$

$\left(\frac{Z}{2} \right.$ is moles of oxygen produced by reaction (4) $\left. \right)$

or, $x + 3y + H - Z = 40.9$... (6)

From (2), CO produced = $2x$

So, $2x = 2.2$ i.e. $x = 1.1$ kg mole.

From (3), CO_2 produced = $2y$

So, $2y = 0.7$ i.e. $y = 0.35$ kg mol

From (4), CH_4 produced = $2Z$

So, $2Z = 2.6$ i.e. $Z = 1.3$ kg mol

From (6), $H = 40.9 + Z - (x + 3y)$

$$= 40.9 + 1.3 - (1.1 + 3 \times 0.35)$$

$$= 40.05 \text{ kg mols.}$$

Hydrogen balance :

H_2 produced by (2) and (3) = $3x + 3y$

H_2 produced by (1) = A (say)

$$\text{H}_2 \text{ reacted by (4)} = Z$$

$$\text{H}_2 \text{ reacted by (5)} = H$$

$$\text{H}_2 \text{ in final exit gas} = 7.1$$

$$\text{So, } (3x + 3y + A) - (Z + H) = 7.1$$

$$\text{or, } (3 \times 1.1 + 3 \times 0.35 + A) - (1.3 + 40.05) = 7.1$$

$$\text{Solving, } A = 44.1.$$

(i) Yield of acetaldehyde :

$$\begin{aligned} \text{Yield} &= \frac{\text{Alcohol converted to acetaldehyde}}{\text{Alcohol converted by reactions (1), (2), (3) and (4)}} \\ &= \frac{44.1}{44.1 + 1.1 + 0.35 + 1.3} \times 100 = 94.13\%. \end{aligned}$$

(ii) Acetaldehyde formed = 44.1 kg moles

$$\begin{aligned} \text{Acetaldehyde absorbed} &= 44.1 \times 0.98 \\ &= 43.218 \text{ kg mole,} \end{aligned}$$

$$\begin{aligned} 99\% \text{ acetaldehyde formed} &= \frac{43.218}{0.99} \\ &= 43.654 \text{ kg mols.} \end{aligned}$$

1% alcohol is as impurity.

$$\text{Alcohol present} = 43.654 - 43.218 = 0.436 \text{ kg mole.}$$

Analysis of acetaldehyde product :

	kg mols	kg
Acetaldehyde	43.218	= 1901.590
Alcohol	0.436	= 20.056
		<hr/> 1921.646

For 1921.646 kg aldehyde, ethanol reacted

$$\begin{aligned} &= 44.1 + 1.1 + 0.35 + 1.3 \\ &= 46.85 \text{ kg mols} = 2155 \text{ kg.} \end{aligned}$$

For 1000 kg aldehyde, ethanol reacted

$$= \frac{2155}{1921.646} \times 100 = 1121.43 \text{ kg}$$

For 30% conversion, alcohol used

$$= \frac{1121.43}{0.30} = 3738.1 \text{ kg.}$$

Air used :

$$\text{N}_2 - 85.20 \text{ kg mols} = 2385.6 \text{ kg}$$

$$\text{O}_2 - 22.65 \text{ kg mols} = 724.8 \text{ kg}$$

$$\hline 3110.4 \text{ kg.}$$

For 1921.65 kg aldehyde, air used is 3110.4 kg

For 1000 kg aldehyde, air used is

$$\frac{3110.4}{1921.65} \times 1000 = 1618.61 \text{ kg}$$

Reaction mixture composition :

	weight, kg	%W
Alcohol	3738.10	69.78
Air	1618.61	30.22
Total =	<u>5356.71</u>	<u>100.00</u>

Ex. 59. Sucrose can be converted to glucose and fructose by the inversion process and the combined quantity is called inversion sugar. If 90% conversion of sugar occurs on one pass through the reactor, find the recycle stream flow per 100 kg of 30% sucrose solution entering the process. What is the concentration of inversion sugar in the recycle and product streams ? The concentration of components in the above two streams may be taken as equal. The concentration of inversion sugar in the reactor feed is 5%. Also calculate the amount of recycle stream.

Solution.

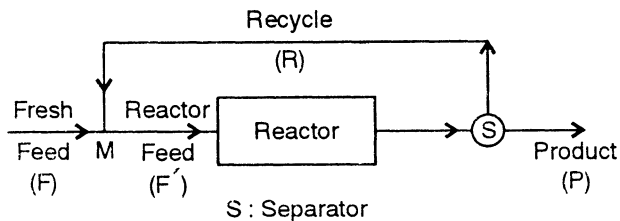


Fig. 1.13

Basis : 100 kg of 30% sugar solution.

x_S = mass fraction of sucrose

x_I = mass fraction of inversion sugar

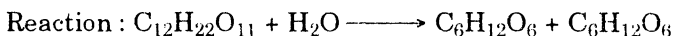
F = fresh feed and F' = Reactor feed

P = product and R = Recycle

Thus, x_{SF} = mass fraction sucrose in feed

$x_{SF'}$ = mass fraction sucrose in reactor feed

x_{IR} = mass fraction inversion sugar in recycle stream
and so on.



Also, $x_{SF} + x_{WF} = 1.0$

$$x_{SF'} + x_{WF'} + x_{IF'} = 1.0$$

$$x_{SP} + x_{IP} + x_{WP} = 1.0 = x_{SR} + x_{IR} + x_{WR}$$

$$x_{SP} = x_{SR}, x_{IP} = x_{IR}, x_{WP} = x_{WR}$$

$$x_{IF'} = 0.05$$

Overall balance gives, $P = 100$

At point M, $100 + R = F'$

Sucrose balance at M gives,

$$0.30 \times 100 + x_{SR} \cdot R = x_{SF'} \cdot F' \quad \dots(1)$$

Inversion sugar balance at M gives,

$$O + x_{IR} \cdot R = x_{IF'} \cdot F' \quad \dots(2)$$

$$\frac{\text{kg. water}}{\text{kg sucrose}} = \frac{18}{342} = 0.0526$$

Sucrose in feed = 30 kg.

Water used for 90% inversion

$$= 0.0526 \times 30 \times \frac{90}{100} = 1.42 \text{ kg.}$$

Water balance around reactor,

$$\begin{aligned} \text{Water entering} &= (100 + R)(1 - x_{SF'} - x_{IF'}) \\ &= (100 + R)(1 - x_{SF'} - 0.05) \end{aligned}$$

$$\begin{aligned} \text{Water leaving} &= (100 + R)(1 - x_{SR} - x_{IR}) \\ &= (100 + R)(1 - x_{SP} - x_{IP}) \end{aligned}$$

$$\text{Water consumed} = (100 + R)(0.90)(0.0526) x_{SF'}$$

Water balance gives,

$$(1 - x_{SF'} - 0.05) - (1 - x_{SR} - x_{IR}) - 0.047 x_{SF'} = 0 \quad \dots(3)$$

Sucrose balance around reactor,

$$\text{Sucrose entering} = (100 + R) x_{SF'}$$

$$\text{Sucrose leaving} = (100 + R) x_{SR}$$

$$\text{Sucrose consumed} = (100 + R) x_{SF'} (0.9)$$

From sucrose balance,

$$x_{SF'} - x_{SR} - 0.9 x_{SF'} = 0 \quad \dots(4)$$

$$\text{or,} \quad 0.1 x_{SF'} = x_{SR} \quad \dots(5)$$

$$\text{From (3),} \quad 1.047 x_{SF'} = x_{SR} + x_{IR} - 0.05$$

Substituting for x_{SR} from (5),

$$0.947 x_{SF'} = x_{IR} - 0.05$$

$$\text{or,} \quad x_{IR} = 0.947 x_{SF'} + 0.05 \quad \dots(6)$$

$$\text{From (2)} \quad \frac{F'}{R} = \frac{(100 + R)}{R} = \frac{x_{IR}}{0.05}$$

Substituting for x_{IR} from (5),

$$1 + \frac{100}{R} = \frac{0.947 x_{SF'} + 0.05}{0.05}$$

$$\text{or, } (18.94 x_{SF'} + 1) = 1 + \frac{100}{R} \quad \dots(7)$$

Substituting for x_{SR} from (5) in sucrose balance (1),

$$30 + (0.1 x_{SF'})R = (100 + R) x_{SF'}$$

$$\text{or, } (100 + 0.9R) x_{SF'} = 30 \quad \dots(8)$$

$$\text{From (7), } R = \frac{100}{18.94 x_{SF'}} \quad \dots(9)$$

Putting the expression for 'R' from (9) in (8) gives,

$$\left[100 + 0.9 \left(\frac{100}{18.94 x_{SF'}} \right) \right] x_{SF'} = 30$$

$$\text{or, } (1894 x_{SF'} + 90) x_{SF'} = 30 \times 18.94 x_{SF'}$$

$$\text{or, } 1894 x_{SF'}^2 = 478.2 x_{SF'}$$

$$x_{SF'} = 0.252$$

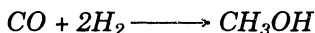
$$\text{From (6), } x_{IR} = 0.947 x_{SF'} + 0.05 = 0.2886$$

$$\text{From (9), } R = \frac{100}{18.94 x_{SF'}} = 20.95 \text{ kg.}$$

Concentration of inversion sugar in the recycle and product stream is 28.86%.

Amount of recycle stream = 20.95 kg.

Ex. 60. Methanol is produced from carbon monoxide and hydrogen as per the reaction



The reactants obtained from coal combustion in presence of steam also contain small quantity of methane, which does not participate in the reaction. The reaction products pass through a separator, where the unreacted reactants are separated from the product and recycled. A purge stream is used to maintain the methane concentration in the exit to the separator at no more than 3.1% mol. The once-through conversion of the carbon monoxide in the reactor is 20%. Reactor receives recycle and fresh feed (H_2 —67.4%, CO —32.4%, CH_4 —0.2% mole). For a fresh reactor feed of 100 kg. mols, calculate

(i) Moles of methanol produced

(ii) Moles of recycle

(iii) Moles of purge and purge gas composition.

Solution.

The flow diagram for the process is given below :

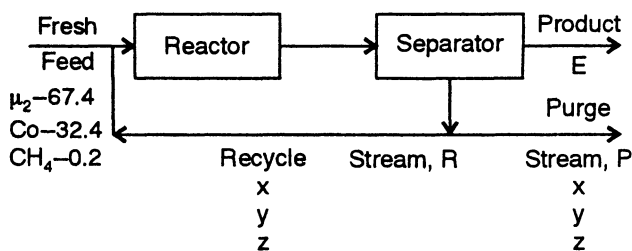


Fig. 1.14

Basis : 100 kg moles of fresh feed.

Let x, y and z are mole fractions of hydrogen, carbon monoxide and methane respectively in purge and recycle streams,

$$x + y + z = 1.0$$

Let us consider overall balance with respect to the constituents.

Hydrogen balance,

$$67.4 + 2(0.2) = P(x + 2Z) + E(2)$$

$$\text{or, } P(x + 2Z) + 2E = 67.8 \quad \dots(1)$$

Carbon balance,

$$32.4 + 0.2 = P(Y + Z) + E(1)$$

$$\text{or, } P(Y + Z) + E = 32.6 \quad \dots(2)$$

Oxygen balance,

$$32.4 = E(1) + P(y)$$

$$\text{or, } E + Py = 32.4 \quad \dots(3)$$

$$Z = 0.031 \text{ (given)}$$

From (2) and (3), $PZ = 0.2$

$$\text{So, } P = \frac{0.2}{Z} = \frac{0.2}{0.031} = 6.45 \text{ kg moles}$$

Multiplying (2) by 2.0 and subtracting from (1) gives,

$$Px - 2Py = 2.6$$

$$\text{or, } x - 2y = \frac{2.6}{P} = 0.403 \quad \dots(4)$$

$$x + y = 1 - Z = 1 - 0.031 = 0.969 \quad \dots(5)$$

$$(5) - (4) \text{ gives, } 3y = 0.566$$

$$\text{or, } y = 0.189$$

$$\text{So, } x = 1 - y - z = 1 - 0.189 - 0.031 = 0.78$$

$$\begin{aligned} \text{From (3), } E &= 32.4 - Py \\ &= 32.4 - 6.45 \times 0.189 = 31.18 \text{ kg moles.} \end{aligned}$$

Carbon monoxide balance is made with combined reactor and separator.

$$(\text{Co-entering}) - (\text{Co-outgoing}) = \text{Co-consumed}$$

$$\text{or, } (32.4 + R_y) - (R + P)y = (32.4 + R_y) \times 0.20$$

$$\text{or, } 32.4 - P_y = (32.4 + R_y) 0.2$$

$$\text{or, } 32.4 - 6.45 \times 0.189 = (32.4 + 0.189R) \times 0.2$$

$$\text{Solving, } R = 653.46 \text{ kg moles.}$$

$$\text{Moles of methanol produced} = 31.18 \text{ kg mols}$$

$$\text{Moles of recycle} = 653.46 \text{ kg moles}$$

$$\text{Moles of purge} = 6.45 \text{ kg moles.}$$

Composition of purge gas : (in mole %)

$$\text{H}_2\text{—}78.0$$

$$\text{CO—}18.9$$

$$\text{CH}_4\text{—}3.1.$$

PRACTICE EXERCISES WITH ANSWERS

1. A solution of potassium hydroxide (KOH) in water contains 250 gm of KOH per litre of solution at 27°C. The density of the solution and that of water at 27°C are 1.2 and 1.0 gm/cc respectively. Calculate :
(i) Composition in weight per cent.
(ii) Composition in volume per cent.

(A.M.I.E. Exam. 1983 Summer)

[Ans. (i) KOH—20.83% water 79.17%

(ii) KOH—5.0% water 95.0%]

2. Liquid effluent from a process contains 37% A and 63% B by weight. This has to be mixed with a fresh charge containing 89% A and 11% B by weight to produce a mixture containing 45% A and 55% B by weight. Find out the amounts of effluent and fresh charge required to produce 1000 kg of the final mixture.

(A.M.I.E. Exam. 1983 Summer)

[Ans. Effluent = 846.2 kg ; Fresh charge = 153.8 kg.]

3. City gas has composition by volume expressed as :

$$\text{CH}_4\text{—}78\%$$

$$\text{C}_2\text{H}_6\text{—}12\%$$

$$\text{and } \text{C}_3\text{H}_8\text{—}10\%$$

Calculate the gas density in kg/m^3 under 585 psig and 37°C.

(A.M.I.E. Exam. 1983 Winter)

[Ans. Gas density = 32.85 kg/m^3 .]

4. An astronaut who drinks 2 litres of water per day discharges 2.4 litres of liquid water each day. The additional amount is produced by metabolism of food. The use of Li_2O in a space ship to absorb this discharged water has been suggested. What minimum amount of

Li_2O must be carried on board for this purpose for a 10-day voyage by one astronaut ? In the process lithium hydroxide is formed. (Atomic weight of Li = 7.0). (A.M.I.E. Exam. 1984 Winter)

[Ans. 40 kg.]

5. A pan contains 6420 kg of an aqueous solution at 104°C , 29.6% of which is anhydrous sodium sulphate. The whole solution is cooled without evaporation to 20°C at which temperature crystals of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ separate out. The remaining mother liquor is found to contain 16.1% anhydrous Na_2SO_4 . What is the weight of the mother liquor ? (A.M.I.E. Exam. 1984 Winter)

[Ans. 3324.6 kg.]

6. Two process streams are mixed to form a single stream. A soluble salt is added to one of the original streams at a steady rate. Samples taken of this stream show it to be 4.76% salt by weight. Another original stream does not contain any salt. Samples from the mixed stream show 0.62% salt by weight. What is the ratio of flows in the two streams ? (A.M.I.E. Exam. 1985 Summer)

$$\left[\text{Ans. } \frac{\text{Stream with salt}}{\text{Stream free of salt}} = 0.15 \right]$$

7. 1000 kg of limestone analysing 90% CaCO_3 and 10% inerts are reacted with a sulphuric acid solution containing 60% sulphuric acid and 40% water. The mass is heated to remove some water vapour and CO_2 . The analysis of the final cake is 45% CaSO_4 , 20% water, 4% inerts and rest unreacted acid and calcium carbonate. Calculate :

(a) degree of completion of the reaction.

(b) water vapour removed during heating.

(Sambalpur Uni. 1985 May)

[Ans. (a) 91.91% ; (b) 657.47 kg.]

8. 1000 kg of sodium carbonate solution containing 25% Na_2CO_3 is subjected to evaporative cooling during which process 15% of water present in the solution is evaporated. From the concentrated solution $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$ crystallizes out. Calculate how much crystals will be produced if the solubility of Na_2CO_3 is 21.5 gm per 100 gm. water. (A.M.I.E. Exam. 1990 Winter) [Ans. 513.95 kg]

9. A natural gas having 90% CH_4 , 5% C_2H_6 and 5% N_2 is piped from a well at 25°C and 3 atm. pressure. Assuming ideal gas behaviour, find the following :

(i) partial pressure of N_2

(ii) volume of N_2 per 100 m^3 of gas

(iii) density of the gas.

(A.M.I.E. Exam. 1990 Winter)

[Ans. (i) 0.15 atm., (ii) 5 m^3 , (iii) 2.123 kg/m^3 .]

10. If 10 kg of PbS and 3 kg of oxygen react to yield 6 kg Pb . and 1 kg PbO_2 and the only other product of the reaction is SO_2 . What is

(i) the amount of PbS that does not react ?

- (ii) the amount of SO_2 formed ?
 (iii) the percent conversion of PbS into Pb ?

Reaction : $2\text{PbS} + 3\text{O}_2 \longrightarrow \text{Pb} + 2\text{SO}_2 + \text{PbO}_2$. (Nagpur Uni. 1987)

[Ans. (i) 2.073 kg, (ii) 2.123 kg, (iii) 87.38]

11. An ammonia synthesis plant is to produce 2000 moles of NH_3 per hour from a mixture of nitrogen and hydrogen (1 : 3). The mixture of unreacted N_2 and H_2 is separated in a separator and fed back with the main stream of N_2 and H_2 and only 15% conversion occurs in the converter. Calculate the quantity and composition of the streams entering and leaving

- (i) the converter
 (ii) the separator and
 (iii) the recycle ratio.

Assume 100% separation in the separator. (Nagpur Uni. 1987)

[Ans. (i) entering—26666.7 moles, N_2 —25%, H_2 —75%
 leaving—24666.7 moles (NH_3 —8.11,
 N_2 —22.97, H_2 —68.92%)

(ii) entering (same as converter leaving)
 leaving : 22666.7 moles (N_2 —25%, H_2 —75%)
 (iii) 5.667]

12. A solid material with 15% w water is dried to 7% w water under the following conditions. Fresh air is mixed with recycled air, which is part of the air leaving the drier containing 0.1 kg water per kg dry air. The proportions of fresh and recycled air are adjusted so that the mixture entering the drier contains 0.03 kg water per kg dry air.

- (a) How many kg of water are removed from 100 kg of wet material fed to the drier ?
 (b) How many kg of dry air are in the fresh air fed per 100 kg of wet material ?
 (c) How many kg of dry air are recycled per 100 kg of wet material ?
 (d) Draw a diagram of the process indicating the amounts of material in each stream per 100 kg of wet material.

The fresh air contains 0.005 kg water per kg dry air.

(Sambalpur Uni. 1991)

[Ans. (a) 8.602 kg, (b) 90.55 kg, (c) 32.34 kg.]

13. A salt solution containing 25% NaCl by weight is prepared as given below :

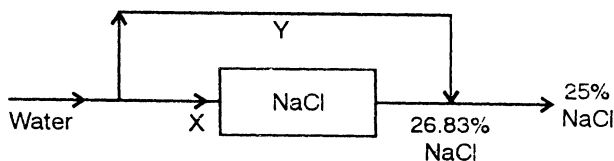


Fig. 1.15

A part of the incoming water stream is introduced into a vessel containing sodium chloride, where it becomes saturated with a salt concentration of 26.83%. This solution is mixed with by-pass water to give the final salt solution of 25% concentration. Find the ratio of the two streams. **[Ans. $x/y = 9.997$]**

14. A gas mixture consists of three components : argon, B and C. The following analysis of the mixture is given :

40 mol % argon

18.75 mass % B

20 mol % C

The molecular weight of argon is 40 and of C is 50. Calculate

(i) The molecular weight of B.

(ii) The average molecular weight of the mixture.

[Ans. (i) 15, (ii) 32]