

①

Materials Balance

Material Balances :- are nothing more than the application of the conservation law for mass.

(Matter is neither created nor destroyed).

Why study material balances as a separate topic?

The aim will be to help you acquire a generalized approach to problem solving so that you may avoid looking upon each new problem,

The process can be defined as a series of operations or treatments in which physical and chemical.

Changes are carried out on specified quantities of materials, with the result of specified products.

Examples of the major chemical engineering processes are Chemical reactions:-

Filtration, Mixing, Distillation, Absorption, Drying, etc'

(2)

Materials balance is of great importance in
the following fields:-

- ① Process and equipment Design.
- ② Economic evaluation and optimization
between different process.
- ③ Process control.

Process Classification

Chemical process may be classified as batch,
continuous, and semibatch. On the other hand such
process are either steady state or transient
(unsteady state).

Batch Process

In such process, certain of several materials
are placed in according the reaction (mixer,

(3)

(filter). Change is allowed to occur.

The products are removed all from the container at once sometime later.

Materials balance for physical batch process in which there is no chemical reaction, can be written as

$$\text{Initial Quantities} = \text{Final Quantities}$$

(input) (out+put)

This equation can be applied for every substance or for total materials.

Continuous Process
~~Continuous~~

In such process different materials are continuously fed to each equipment in which the physical changes or chemical reactions take place during the flow of materials through out the

(4)

equipments. The products of such process are also continuously removed from one or many points.

This means that the materials will have to be held in each equipment for a period of time which is called "Residence Time".

In order to make material balance on any continuous process that period of time such as, min, hr, day chosen as a basis of such calculations. other hand if the values of all the operating variables in the process (like, temperature, pressure, composition, flow rates, etc.) don't change with time the process is called "a Steady State". The equations of materials balance for physical continuous steady state process in which there is no chemical reaction can be written as :- Input = Output

(5)

If any of the process variables change with time, the process is called "unsteady state".

The equation of material balance for physical unsteady state process can be written as:-

$$\text{In put} = \text{Out put} + \text{Accumulation}$$

In general, continuous process are usually run as close to steady state as possible by using the suitable control units. Unsteady state conditions exist only during the start up of the process.

(b)

Materials Balance without Reaction

Example 1-

A slurry containing 25 percent by weight of solids is fed into a filter. The filter cake contains 90 percent solids and the filtrate contains 1 percent solids. Make a materials balance around the filter for a slurry feed rate of 2000 kg/hr (4400 lb/hr). For that feed rate, what are the corresponding flow rates for the cake and the filtrate?

Calculation Procedure :-

1. Sketch the system, showing the available data, indicating the unknowns, defining the system boundary, and establishing the basis for the calculations.

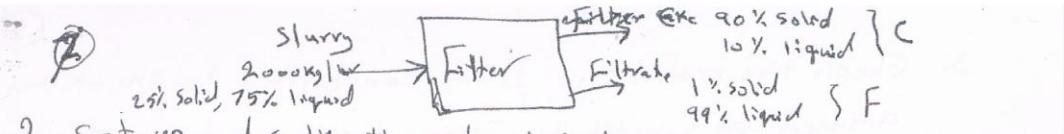
A convenient unit of mass is selected, usually the Kilogram or Pound and all components are expressed in that unit.

As ^{the} basis for ~~an~~ a continuous process, always choose a unit of time or consistent set of flow rates per unit of time.

For batch processes, the appropriate basis is 1 batch. In the present (Continuous) Process let the basis be 1 hr, let

C be the mass flow rate of filter cake and F the mass flowrate of filtrate, in kilograms ~~per hour~~.

Figure 1 is the sketch of the system.



2. Set up and solve the material-balance equations. This is steady state operation, so accumulation equals (zero) and the amount of (mass in) equals the amount of (mass out) per unit of time.

Since there are two unknowns, C and F, two independent independent equations must be written. One will be an overall balance; the other can be either a liquid balance (the option chosen in this example) or a solids balance.

Overall balance :-

$$\cancel{\text{Slurry in} = \text{Filtrate out} + \text{Cake out}}$$

$$\text{Slurry in} = \text{Filtrate} + \text{Cake out}$$

Liquid balance :-

~~$$\text{Liquid in Filtrate} + \text{Liquid in Cake} = \text{Liquid in Slurry}$$~~

~~$$\text{OR } \text{Liquid in Slurry} = \text{Liquid in Cake} + \text{Liquid in Slurry}$$~~

(wt fraction liquid in filtrate)(mass of ^{slurry} filtrate) ≠ (wt fraction liquid in cake)(mass of cake) ≠ (wt fraction liquid in ^{slurry} filtrate)(mass of ^{slurry} filtrate).

~~$$\text{OR } (1 - 0.25)(2000) = (1 - 0.1)F + (1 - 0.9)C$$~~

$$1500 = 0.9F + 0.1C \quad \dots \dots \quad (1)$$

$$2000 = F + C \quad \dots \dots \quad (2)$$

$$\therefore F = 1460.7 \text{ kg/hr}$$

$$C = 539.3 \text{ kg/hr}$$

(3)

3. Check the results :- It is convenient to check the answers by substituting them into the equation not used above, namely, the solids balance. Thus

~~Solid infiltrate \rightarrow solid in filter + solid in slurry,~~

~~or~~ Solid in slurry = Solid infiltrate + Solid in soil

$$(0.25)(2000) = (0.01)(1480.7) + (0.9)(539.3)$$

Example-2

It is required to prepare 1250 kg of a solution composed of 12 wt% ethanol and 88 wt% water. Two solutions are available, the first contains 25 wt% ethanol. How much of each solution are required to prepare the desired solution.

Answer

Basis 1 Batch;

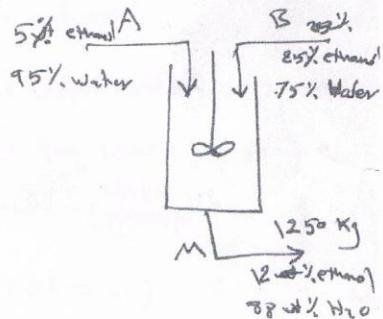
$$= 1250 \text{ kg of M}$$

Material

1. Ethanol balance

2. Water material balance

3. Total material balance



Ethanol balance

$$\text{Ethanol Input} = \text{Ethanol Output}$$

$$A\left(\frac{5}{100}\right) + B\left(\frac{25}{100}\right) = M\left(\frac{12}{100}\right)$$

(1)

$$0.05A + 0.25B = 1250 \text{ (0.12)}$$

$$A = \frac{150 - 0.25B}{0.05} \quad \dots \dots \quad (1)$$

Water balance

$$A\left(\frac{95}{100}\right) + B\left(\frac{75}{100}\right) = 1250 \text{ (0.88)} \quad \dots \dots \quad (2)$$

Substitute equation (1) in to equation (2) gives

$$B = 437.5 \text{ kg}$$

$$A = 812.5 \text{ kg}$$

Checking in Total material balance (T.M.B)

$$\text{Total input} = A + B = 812.5 + 437.5 = 1250$$

$$\text{Total output} = M = 1250 \text{ kg}$$

$$\therefore \text{Total input} = \text{Total output}$$

\therefore Calculation is correct.

Example - 3 -

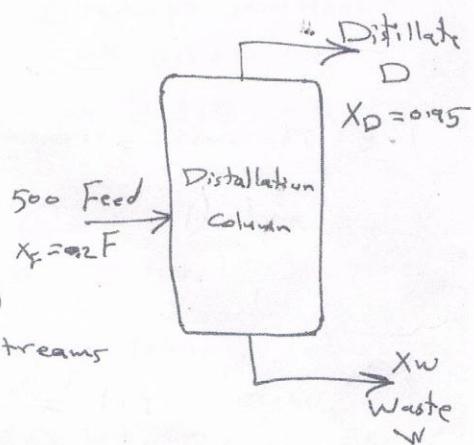
(10)

500 $\frac{\text{kg}}{\text{hr}}$ of binary mixture composed of 20% acetone and 80% water are continuously fed to the distillation column. It is found that 5 $\frac{\text{kg}}{\text{hr}}$ of acetone are out with the waste per hour. The distillate contains 95 mole % acetone.

Calculate the flow rates of the distillate and waste and the composition of the waste.

Solution

X_F, X_D, X_W = weight fraction of more volatile component (acetone) in the feed, distillate, & waste streams respectively



Basis of Calculations 1 hr

- Acetone balance
- Water balance
- T.M.B

T.M.B

$$500 = D + W \quad \dots \quad (1)$$

Acetone balance

$$X_F \cdot F \cdot X_F = X_D \cdot D \cdot X_D + W \cdot X_W$$

$$\text{Acetone in waste} = W \cdot X_W = 5$$

-4

$$500(0.2) = D(0.95) + 5 \quad \text{---} \textcircled{2}$$

$$100 = 0.95D + 5$$

$$D = \frac{95}{0.95} = 100 \text{ mole}$$

From equation number ①

$$500 = 100 + w$$

$$\therefore w = 400 \text{ mole}$$

$$X_w = \frac{5}{w} \Rightarrow X_w = \frac{5}{400} = 0.0125$$

i.e. the waste stream composed of 1.25 wt% acetone
and $(1 - 0.0125) = 98.75$ wt% water

Checking in water balance

$$\begin{aligned} \text{water input} &= F(1 - X_f) \\ &= 500(1 - 0.12) \\ &= 500(0.8) \\ &= 400 \text{ mol} \end{aligned}$$

$$\begin{aligned} \text{water out put} &= D(1 - X_D) + w(1 - X_w) \\ &= 100(1 - 0.95) + 400(1 - 0.0125) \\ &= 100(0.05) + 400(0.9875) \\ &= 5 + 395 \\ &= 400 \end{aligned}$$

∴ Total water input = Total water out put

Example - 3-

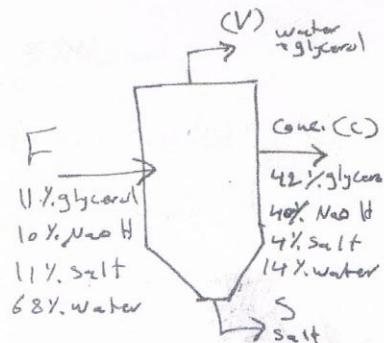
12

1000 lb/hr of a solution F composed of 11 wt% glycerol, 10 wt% NaOH, 11 wt% salt and 68 wt% water are continuously fed to the evaporator. Part of the salt (S) are crystallized in the salt box at the bottom of the evaporator. Part of the glycerol are lost with the evaporator the vapour (V) which composed of glycerol and water. The concentrated solution (C) out from the evaporator contains 42 wt% glycerol, 40 wt% NaOH, 4 wt% salt and 14 wt% water.

Calculate \rightarrow S, V & the composition of the vapour.

Basis of Calculations = 1 hr

- 1 - Glycerol balance
- 2 - NaOH balance
- 3 - Salt balance
- 4 - Water balance
- 5 - Total material balance



1 - Glycerol balance

$$F \left(\frac{11}{100} \right) = V \times 6 + C \left(\frac{42}{100} \right) \quad \text{(1)} \quad \text{--- (3 Unknowns)}$$

2 - NaOH balance

$$F \left(\frac{10}{100} \right) = C \left(\frac{40}{100} \right) \quad \text{--- (one Unknown)}$$

$$① 1000 \left(\frac{12}{100} \right) = C \left(\frac{40}{100} \right) \quad (13)$$

$$\therefore C = 250 \text{ lb}$$

3 - Salt balance

$$F \left(\frac{11}{100} \right) = C \left(\frac{4}{100} \right) + S$$

$$1000 (0.11) = 250 (0.04) + S$$

$$\therefore S = 100 \text{ lb}$$

4 - Total Material Balance

$$F = V + C + S$$

$$1000 = V + 250 + 100$$

$$V = 650 \text{ lb}$$

From Glycerol balance equation No. ①

$$F \left(\frac{11}{100} \right) = V * X_V + C \left(\frac{42}{100} \right)$$

$$1000 (0.11) = 650 * X_V + 250 (0.42)$$

$$\therefore X_V = \frac{0.008}{650}$$

\therefore The vapour composed of 0.8 wt% glycerol
 \therefore 99.2 wt% Water

Checking in Water balance

$$\text{Water input} = F * \left(\frac{68}{100} \right) = 1000 * \left(\frac{68}{100} \right) = 680 \text{ lb}$$

$$\text{Water output} = V * X_W + C \left(\frac{14}{100} \right) = 650 * 0.992 + 250 * \frac{0.14}{0.14}$$

$$= 680 \text{ lb}$$

Example + 80 lb of nitric acid solution (N) containing 40 wt% HNO_3 and 60 wt% water are mixed with sulfuric acid solution (S). 25% of total water input are evaporated (V). The final mixture (M) contains 16 wt% HNO_3 , 24 wt% H_2SO_4 and 60 wt% water.

(14)

Calculate: M; V; S and the composition of S.

Solutions

Basis 1 batch \equiv 80 lb of N

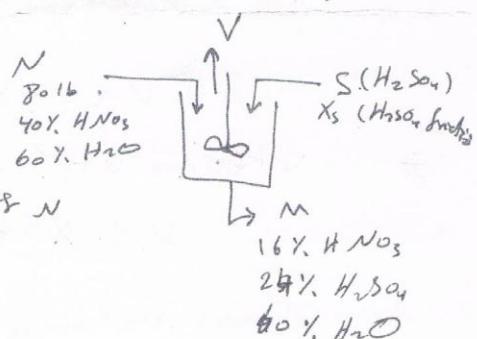
- HNO_3 balance

$$80 \left(\frac{40}{100} \right) = M \left(\frac{16}{100} \right)$$

$$\therefore M = 200 \text{ lb}$$

- Water balance

$$\begin{aligned} \text{Water output w.r.t. } M &= M \left(\frac{60}{100} \right) = 200 \left(0.6 \right) \\ &= 120 \text{ lb} = \left(\frac{120}{100} \right) 75\% \text{ of water input} \end{aligned}$$



Water in M

75

120

= 160 lb total water

Water input

100

X

$$X = \frac{100 \times 120}{75}$$

$$\text{water in } N = 80 \left(\frac{60}{100} \right) = 48 \text{ lb}$$

(15)

$$\text{water in } S = 160 - 48 = 112 \text{ lb}$$

$$V = \text{water input} \times \frac{25}{100} = 160 (0.25) = 40 \text{ lb}$$

H_2SO_4 balance

$$V = 40 \text{ lb}$$

$$H_2SO_4 \text{ Input (ins)} = H_2SO_4 \text{ output (mm)}$$

$$H_2SO_4 = m \left(\frac{24}{100} \right) = 200 (0.24) = 48 \text{ lb}$$

$$\therefore S = 48 + 112 = 160 \text{ lb}$$

$$\text{wt\% water} = \frac{112}{160} \times 100 = 70\%$$

$$\text{wt\% } H_2SO_4 = \frac{48}{160} \times 100 = 30$$

Checking in T.M.B

$$\text{Total input} = N + S = 80 + 160 = 240$$

$$\text{Total output} = M + V = 200 + 40 = 240$$

$$\therefore \text{Total input} = \text{Total output}$$

Example (10) 1000 lb/hr (F) of gaseous mixture composed of 16wt% CS_2 and 84wt% air are continuously fed to the absorption column most of CS_2 input are absorbed by liquid benzene (L) which is fed to the top of the column. 1% benzene input are evaporated and out with the exit gas (Stream G) which is composed of 96wt% air, 2wt% CS_2 .

Calculate:

(a) G, L, P and composition P.

(b) The percentage of CS_2 absorbed in process.

Solution

Air balance

$$F \left(\frac{84}{100} \right) = G \left(\frac{96}{100} \right)$$

$$1000 \times 0.84 = G \times 0.96 \Rightarrow G = \frac{1000 \times 0.84}{0.96} = 875 \text{ lb}$$

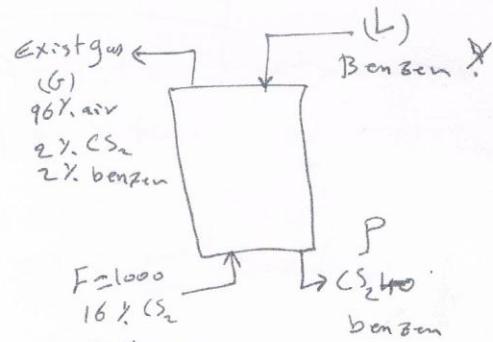
Benzene Balance

$$\text{Benzene out in } G = G \times \frac{1}{100} = 875 \times 0.02$$

$$= 17.5 = L \left(\frac{1}{100} \right)$$

$$\therefore L = 1750 \text{ lb}$$

$$\therefore \text{Benzene in } P = L \left(\frac{99}{100} \right) = 1750(0.99) = 1732.5 \text{ lb}$$



T.M.B

(17)

$$F + L = G + P$$

$$1000 + 175\% = 875 + P$$

$$P = 1875$$

Checking

CS_2 Balance

$$CS_2 \text{ input} = 1000 * \frac{16}{100} = 160 \text{ lb}$$

$$CS_2 \text{ output} = CS_2 \text{ in } G + CS_2 \text{ in } P$$

$$= 875 \left(\frac{2}{100} \right) + (1875 - 1732.5)$$

$$= 17.5 + 142.5 = 160 \text{ lb}$$

$$\therefore CS_2 \text{ input} = CS_2 \text{ output}$$

(b) % CS_2 absorbed = $\frac{CS_2 \text{ in } P}{CS_2 \text{ input}} * 100$

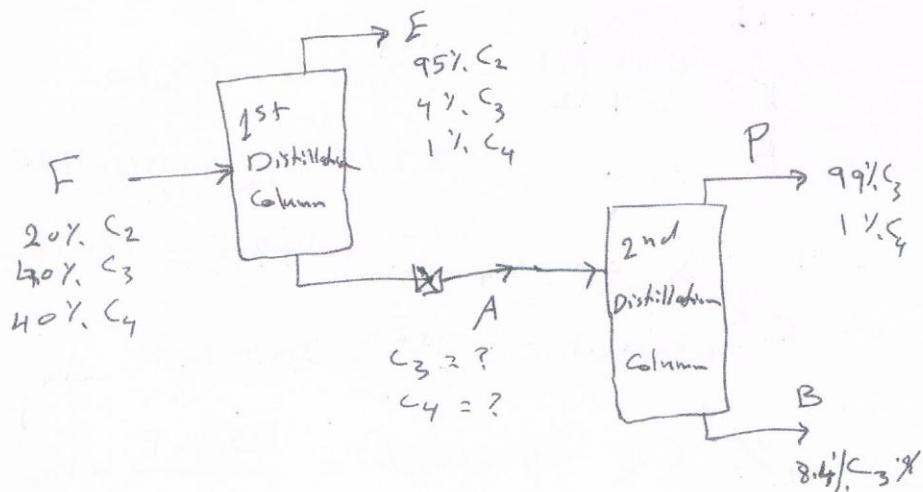
$$= \frac{142.5}{160} * 100 = 89\%$$

(16) Material Balance on Multiple-Unit Process without Chem. Reaction

Example:-

1000 lb/hr of mixture composed of 20 wt% ethane, 40 wt% propane and 40 wt% butane are continuously fed to a multidistillation process.

Calculate the flowrate of each stream in such process and the composition of stream A as shown in the flowing figure.



Basis 1 hr \equiv 1000 lb of F.

① Material Balance on overall process

② C₂ M.B

$$F\left(\frac{20}{100}\right) = E\left(\frac{95}{100}\right)$$

$$1000(0.2) = E(0.95) \Rightarrow E = \frac{200}{0.95} = 210.5 \text{ lb}$$

(i) C₃ balance

(19)

$$F\left(\frac{40}{100}\right) = E\left(\frac{4}{100}\right) + P\left(\frac{99}{100}\right) + B\left(\frac{8.4}{100}\right)$$

$$1000(0.4) = 210.5(0.04) + 0.99P + 0.084B$$

(ii) T.M.B

--- (1)

$$F = E + P + B$$

$$1000 = 210.5 + P + B$$

$$P + B = 789.5 \quad \text{--- (2)}$$

Sub. eq. (2) in eq. (1) gives

$$P = 359 \text{ lb}$$

$$B = 430.5 \text{ lb}$$

Checking on C₄ M.B --- H.W

(2) Material Balance on 1st Distillation column

(i) T.M.B

$$F = E + A \Rightarrow 1000 = 210.5 + A$$

$$\therefore A = 789.5 \text{ lb}$$

C₃ balance

$$F\left(\frac{40}{100}\right) = E\left(\frac{4}{100}\right) + A \cdot X_{C_3}$$

$$1000(0.4) = 210.5(0.04) + 789.5 \cdot X_{C_3}$$

$$\therefore X_r = 0.014$$

(20)

Composition of stream A

49.6 wt% C₃

50.4 wt% C₄

Checking Material Balance on 2nd distillation

T.M.B

$$\text{Total input} = A = 789.5 \text{ lb}$$

$$\text{Total output} = P + B = 359 + 430.5 = 789.5 \text{ lb}$$

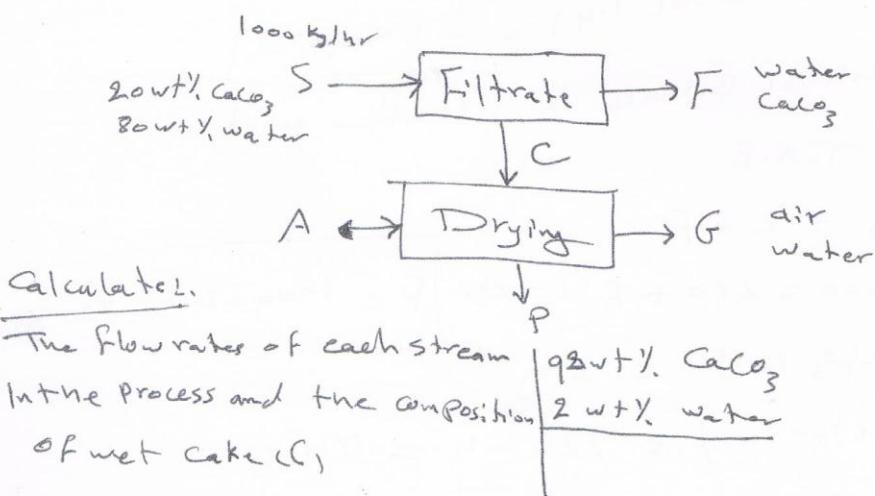
$$\therefore \text{Total input} = \text{Total output}$$

Example:-

(21)

1000 kg/hr of ~~residuary~~ ^{slurry} (S) containing 20 wt% CaCO_3 and 80 wt% water are continuously feed to the filtration unit in which only 2% of CaCO_3 input are passed through the filter cloth and out with the filtrate (F). The wet cake (C) are discharged in a continuous manner and fed to the drying unit in which hot dry air (A) are processed over it producing product (P) contains 98 wt% CaCO_3 and 2 wt% water. The mass ratio between C and P = 1.4 : 1

The air leaving the dryer (G) contains continuous 0.05 kg water / 1 kg dry air. The process can be represented according the following block diagram



Solution

Basis 1 hr \equiv 1000 kg of S

(22)

i) Material Balance of the all of process,

ii) CaCO_3 Balance.

$$\begin{aligned} \text{CaCO}_3 \text{ input} &= \text{CaCO}_3 \text{ output} \\ 1000 \left(\frac{20}{100}\right) &= 200 \text{ kg} \\ \text{CaCO}_3 \text{ in } F &= \left(\frac{2}{100}\right)(200) = 4 \text{ kg} \\ \text{CaCO}_3 \text{ in } P &= 200 - 4 = 196 \text{ kg} \end{aligned}$$

```

graph TD
    S --> Filtrate
    Filtrate --> Drying
    Drying --> G
    Filtrate -- "water" --> F
    Filtrate -- "CaCO3" --> F
    Drying -- "Air" --> G
    Drying -- "Water" --> G
  
```

$$\text{CaCO}_3 \text{ in } P = p \left(\frac{98}{100}\right) \rightarrow 196 = p(0.98)$$

$$\therefore P = \frac{196}{0.98} = 200 \text{ kg}$$

$$\text{water in } P = 200 \left(\frac{2}{100}\right) = 4 \text{ kg}$$

$$\frac{C}{P} = \frac{1.4}{1} \Rightarrow C = P(1.4)$$

$$\therefore C = 200(1.4) = 280 \text{ kg} = C$$

ii) Material Balance on filtration unit

iii) T.M.B

$$S = C + F$$

$$1000 = 280 + F \rightarrow F = 1000 - 280 = 720 \text{ kg}$$

$$\text{CaCO}_3 \text{ in } F = 4 \text{ kg}$$

$$\therefore \text{water in } F = 720 - 4 = 716 \text{ kg}$$

Composition of F

(23)

$$\text{CaCO}_3 = \frac{4}{720} \times 100 = 0.5\%$$

$$\text{Water} = \frac{716}{720} \times 100 = 99.5\% \text{ water}$$

(ii) CaCO₃ balance

$$\begin{aligned}\text{Ca CO}_3 \text{ in C} &= \text{CaCO}_3 \text{ (in)} - \text{CaCO}_3 \text{ in F} \\ &= 1000 \left(\frac{20}{100} \right) - 4 = 196 \text{ kg}\end{aligned}$$

$$\text{water in C} = 280 - 196 = 84 \text{ kg}$$

Composition of C

$$\text{CaCO}_3 = \frac{196}{280} \times 100 = 70 \text{ wt \%}$$

$$\text{water} = \frac{84}{280} \times 100 = 30 \text{ wt \%}$$

Ans

Basis: 1 kg of Air

water = 0.05 kg

Total = 1 + 0.05 = 1.05 kg

wt % air = $\frac{1}{1.05} \times 100 = ?$

OR

Water removed by ~~air~~ drying = Water in C - Water in air

$$= 84 - 4 = 80 \text{ kg}$$

QH

Kg dry air required (A)	water removed per
1	0.05
X	80
$X = \frac{80}{0.05} = 1600 \text{ kg}$	

$$G = A + \text{water removed}$$
$$= 80 + 1600 = 1680 \text{ kg}$$

Checking in T.M. B

$$\begin{aligned}\text{Total input} &= S + A = 1000 + 1600 \\ &= 2600 \text{ kg}\end{aligned}$$

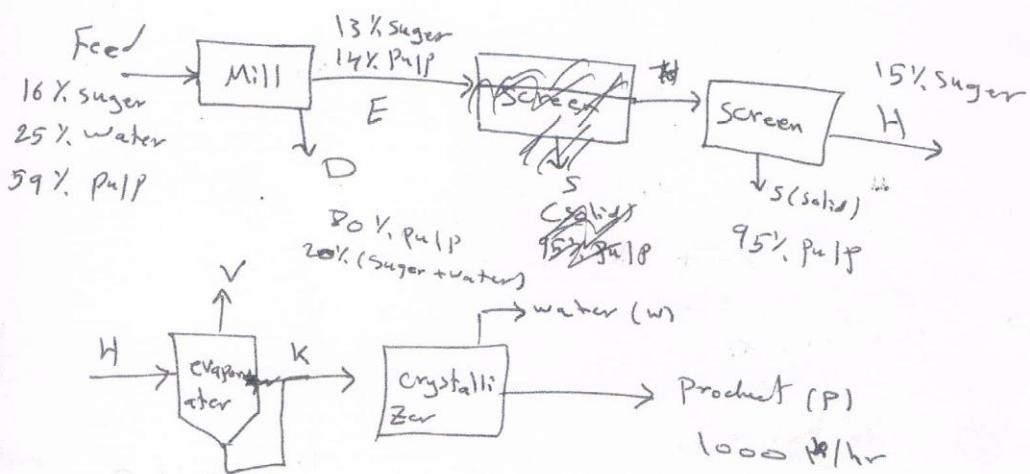
$$\begin{aligned}\text{Total output} &= G + F + p \\ &= 1680 + 720 + 200 \\ &= 2600 \text{ kg}\end{aligned}$$

$$\therefore \text{Total input} = \text{Total output}$$

(25)

H.W

The manufacture of sugar from concentrated sugar can be represented by the following simplified block diagram

Answers

$$K = 2500 ; V = 4167 ; S = 1152$$

$$W = 1500 ; F = 1457 ; H = 6667$$

$$E = 7819 ; D = 16753$$

$$F = 24572 , \downarrow$$

