Chemical Processes:

Every industrial process is designed to produce a desired product from a variety of starting raw materials using energy through a succession of treatment steps integrated in a rational fashion. The treatments steps are either physical or chemical in nature.

A chemical process consists of a combination of chemical reactions such as synthesis, calcination, ion exchange, electrolysis, oxidation, hydration and operations based on physical phenomena such as evaporation, crystallization, distillation and extraction.

Unit processes:

Unit processes are the chemical transformations or conversions that are performed in a process.

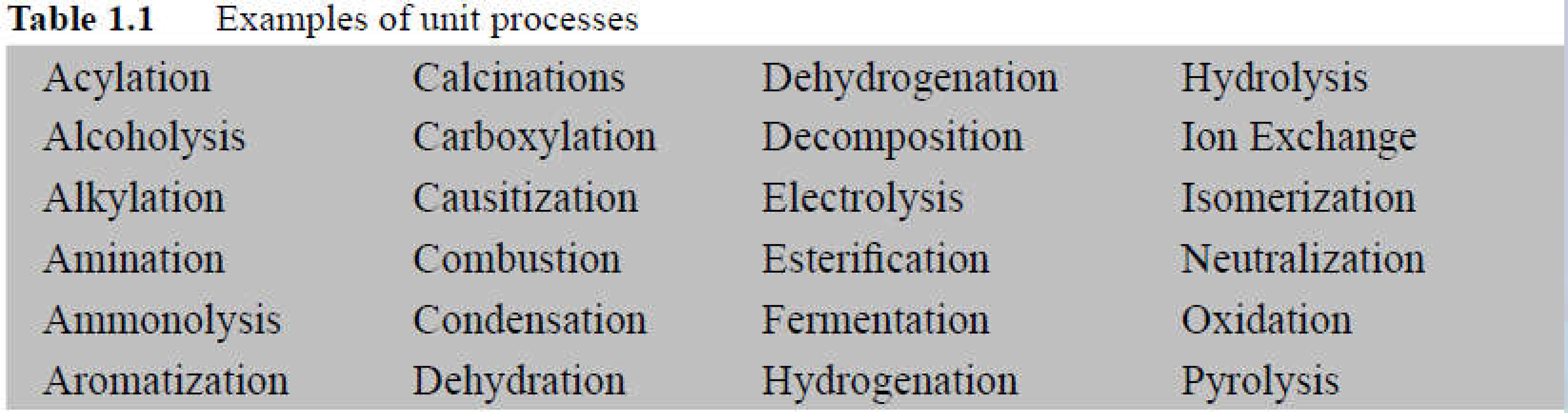
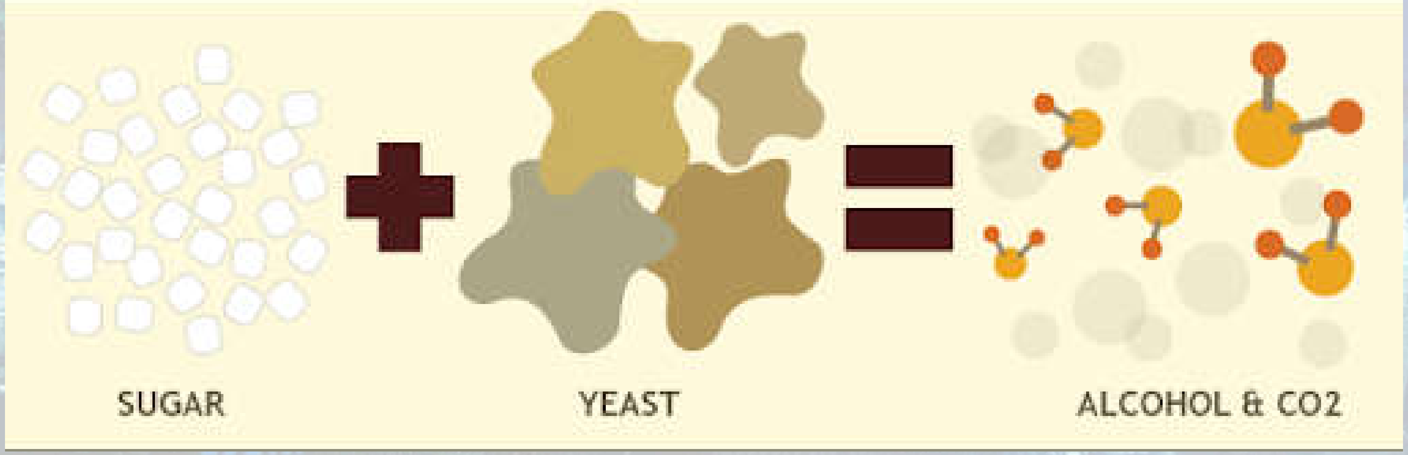


Table 1.1 Examples of unit processes

Acylation
Alcoholysis
Alkylation
Amination
Ammonolysis
Aromatization
Calcinations
Carboxylation
Causitization
Combustion
Condensation
Dehydration
Dehydrogenation
Decomposition
Electrolysis
Esterification
Fermentation
Hydrogenation
Hydrolysis
Ion Exchange
Isomerization
Neutralization
Oxidation
Pyrolysis

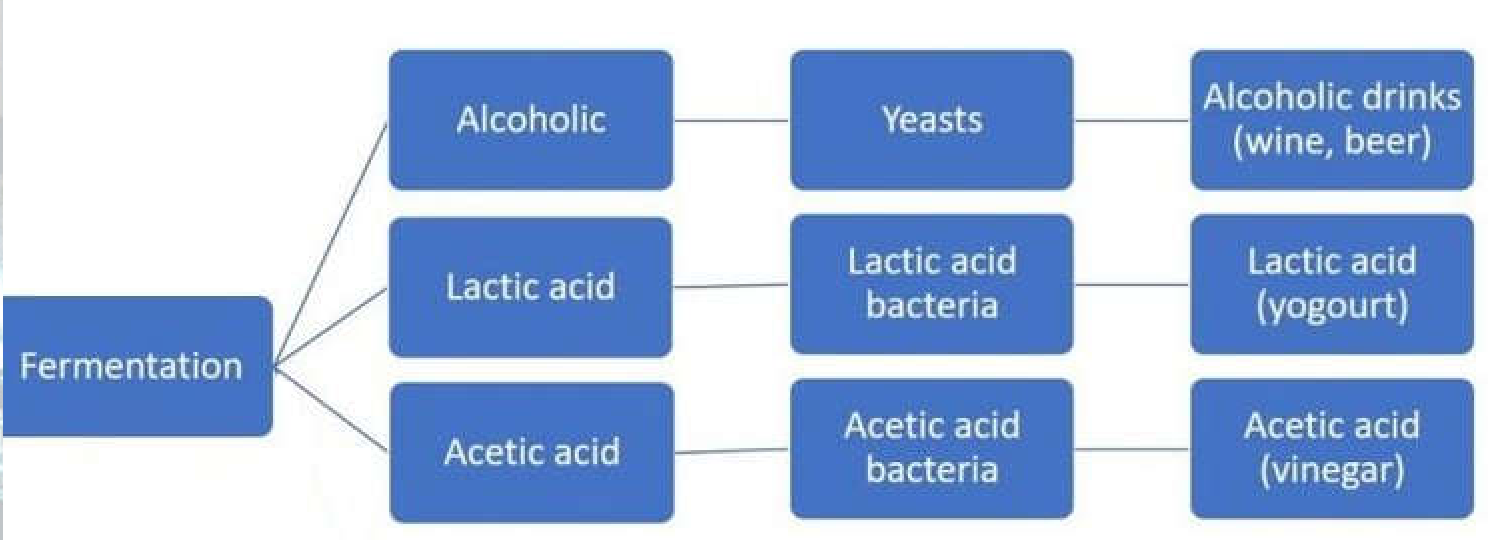
Fermentation:

Fermentation is a reaction wherein a raw material is converted into a product by the action of micro-organisms or by means of enzymes. When micro-organisms are used, they produce enzymes in-situ which then catalyze fermentation reactions.



1- Microbial fermentations promoted by micro-organisms:

Micro-organisms include bacteria, viruses, fungi and protozoa. During microbial fermentation, a raw organic feed is converted into a product by the action of micro-organisms.



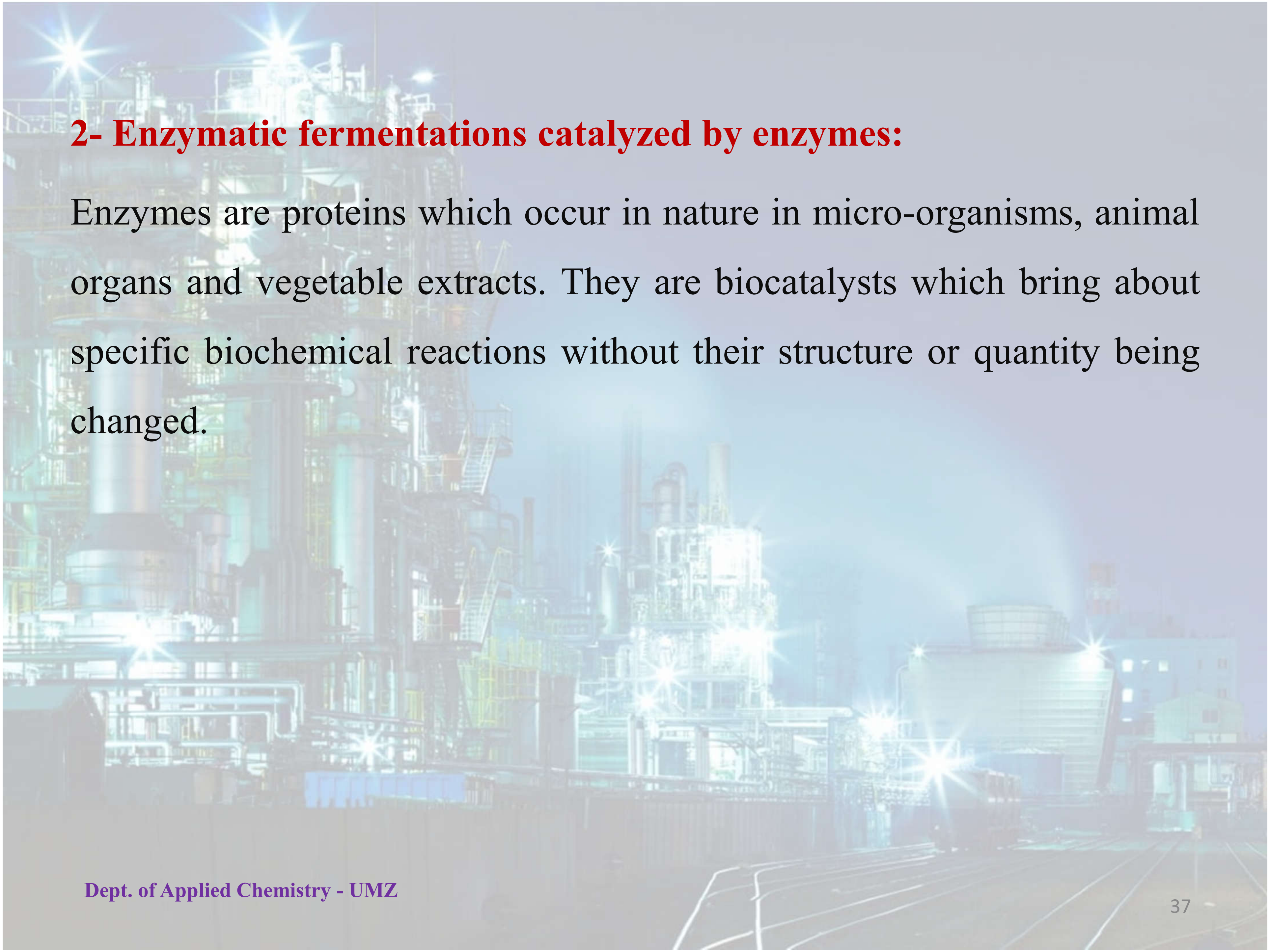
Fermentation

Alcoholic — Yeasts — Alcoholic drinks (wine, beer)

Lactic acid — Lactic acid bacteria — Lactic acid (yogourt)

Acetic acid — Acetic acid bacteria — Acetic acid (vinegar)

- At first the rate of conversion of raw materials to products is low because the micro-organisms are few i.e. the catalytic agent is small.
- As more micro-organisms are formed, the rate starts to rise. The rate then reaches a maximum when there is optimum ratio of unconverted material and the micro-organisms.
- The rate then drops as the raw material becomes depleted. Finally the rate stops when the raw material is finished.

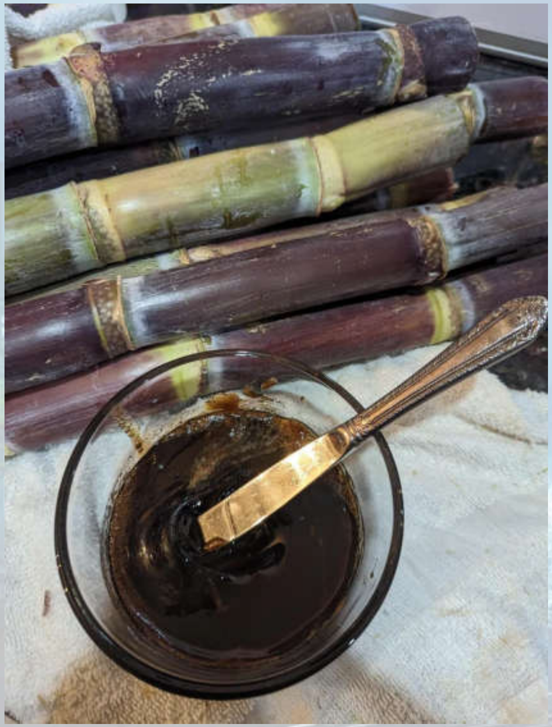


2- Enzymatic fermentations catalyzed by enzymes:

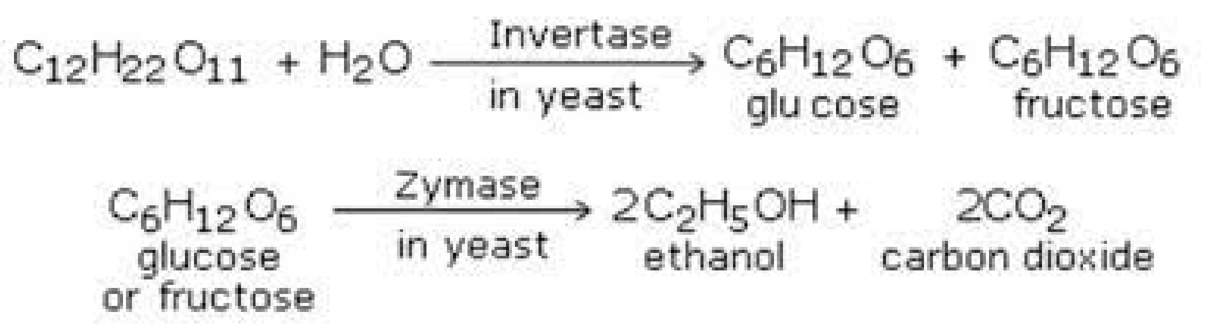
Enzymes are proteins which occur in nature in micro-organisms, animal organs and vegetable extracts. They are biocatalysts which bring about specific biochemical reactions without their structure or quantity being changed.

What Is Molasses?

Molasses is a thick, dark syrup made during the sugar-making process. First, the sugar cane is crushed and the juice is extracted. The juice is then boiled to form sugar crystals and removed from the liquid. The thick, brown syrup left after removing the sugar from the juice is molasses.



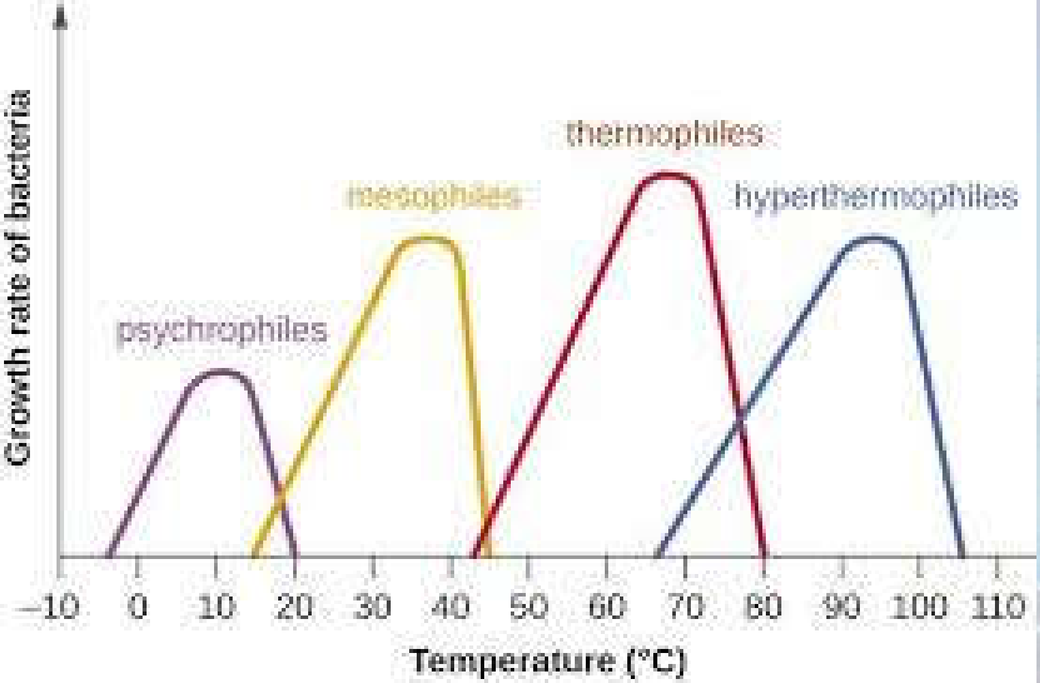
Saccharomyces cerevisiae contains two main enzymes Invertase and Zymase. Invertase converts sucrose present in the sample to glucose and fructose, while zymase converts it finally to ethanol and CO_2. A fixed volume of fruit extracts were fermented anaerobically by Saccharomyces cerevisiae.



$$\underset{}{C_{12}H_{22}O_{11}} + H_2O \xrightarrow[\text{in yeast}]{\text{Invertase}} \underset{\text{glu cose}}{C_6H_{12}O_6} + \underset{\text{fructose}}{C_6H_{12}O_6}$$

$$\underset{\substack{\text{glucose}\\ \text{or fructose}}}{C_6H_{12}O_6} \xrightarrow[\text{in yeast}]{\text{Zymase}} \underset{\text{ethanol}}{2C_2H_5OH} + \underset{\text{carbon dioxide}}{2CO_2}$$

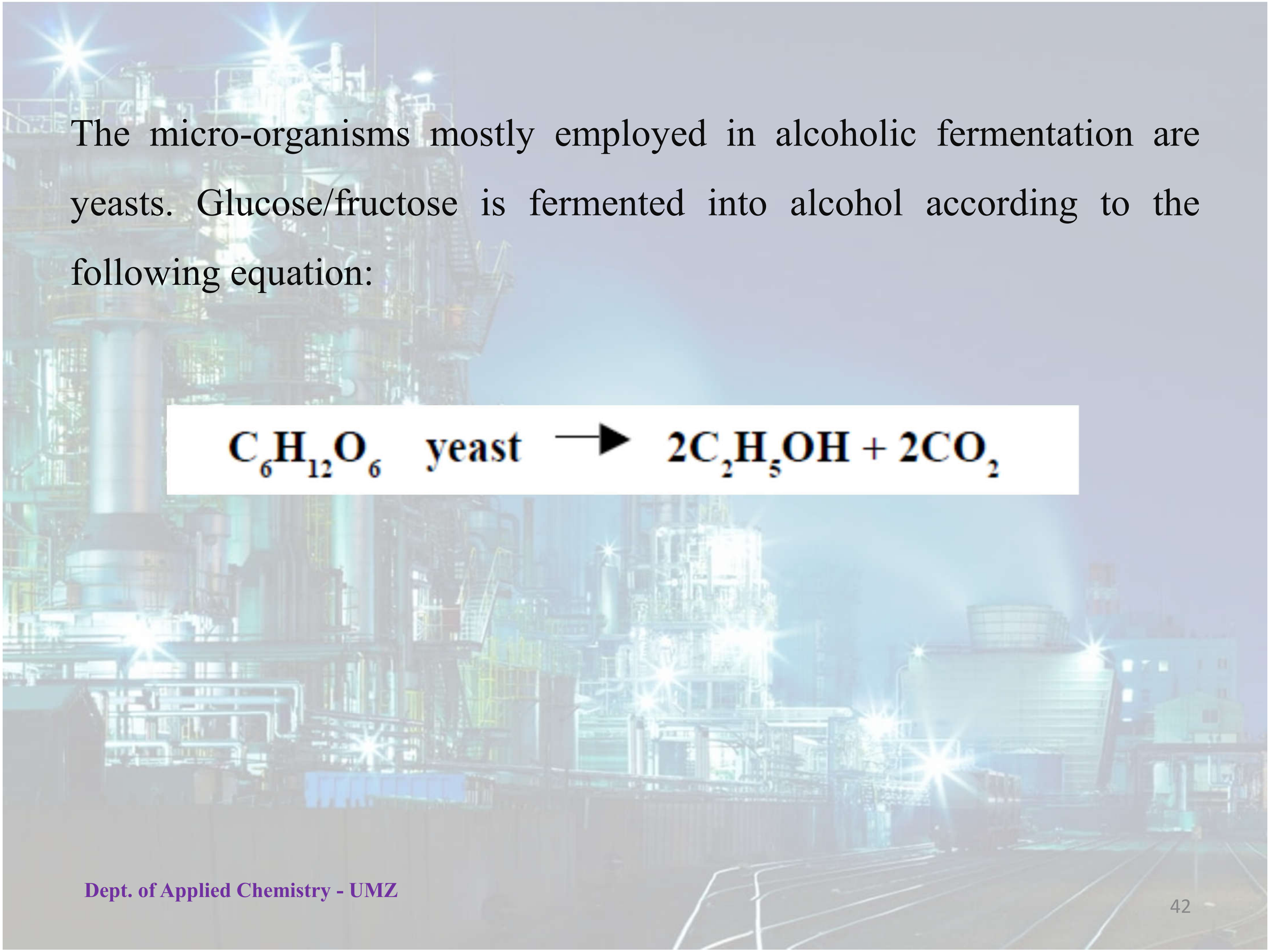
Micro-organisms whose growth is favored by low temperatures are referred to as mesophilic. Those that grow better at higher temperatures (thermophilic) offer a technical advantage in that the growth of contaminants is inhibited.



Manufacture of Fermentation Ethanol:

Biomass raw materials include those containing sugar, starch and cellulose. The sugar-containing raw materials include sugar cane, sweet sorghum, sweet potatoes, sugar beet and molasses. These materials contain disaccharides which are easily hydrolyzed by water to reducing sugar (glucose and fructose) in equations similar to the following:

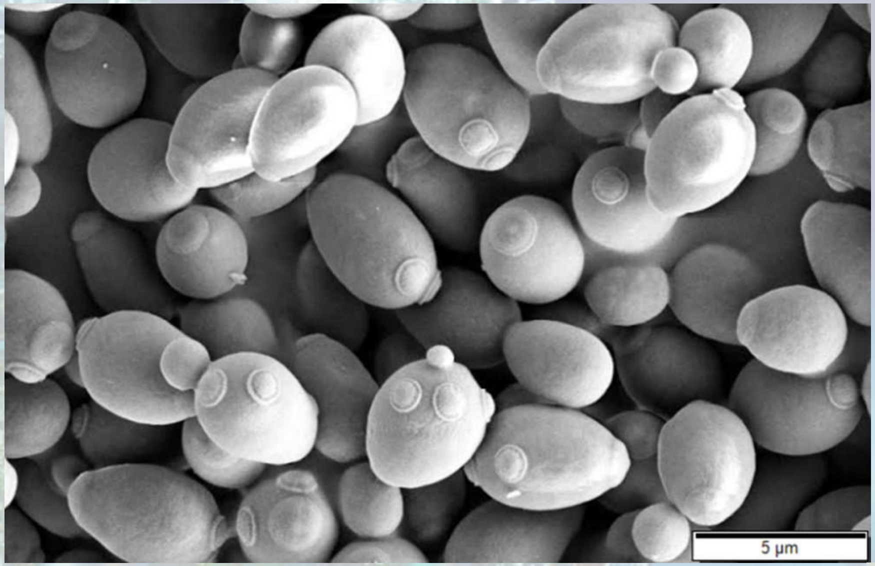
$$\underset{\text{Sucrose}}{C_{12}H_{22}O_{11}} + H_2O \rightarrow \underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{fructose}}{C_6H_{12}O_6}$$



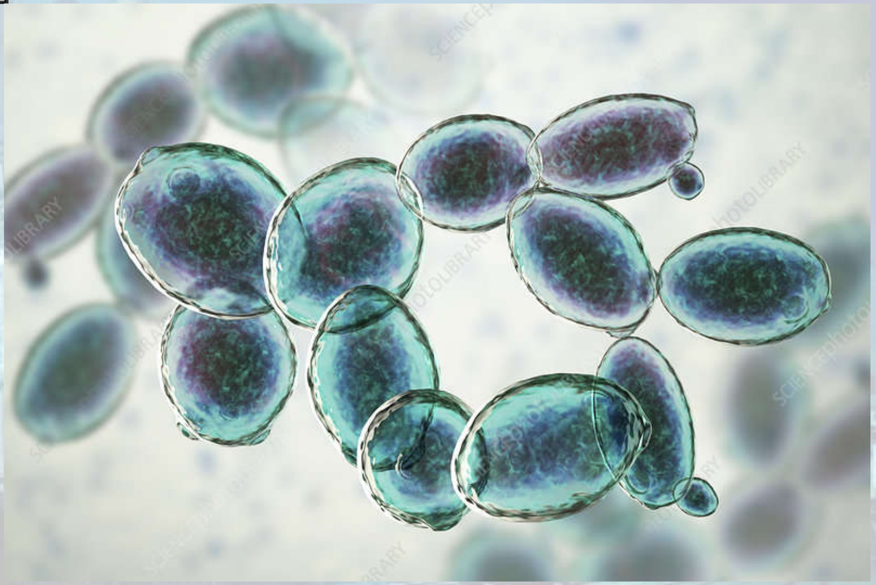
The micro-organisms mostly employed in alcoholic fermentation are yeasts. Glucose/fructose is fermented into alcohol according to the following equation:

$$C_6H_{12}O_6 \quad \text{yeast} \longrightarrow 2C_2H_5OH + 2CO_2$$

Several viable yeast strains exist but the most commonly used strain is *saccharomyces cerevesie*. These yeasts produce enzymes that catalyze the reaction that converts substrate into energy for the yeast and ethanol. During reproduction, the fermentation yeast produces enough enzymes needed for the alcoholic fermentation. These enzymes will continue fermenting far beyond the yeasts’ need for energy and even long after reproduction has stopped. This is the fact that is exploited industrially.



saccharomyces cerevesie

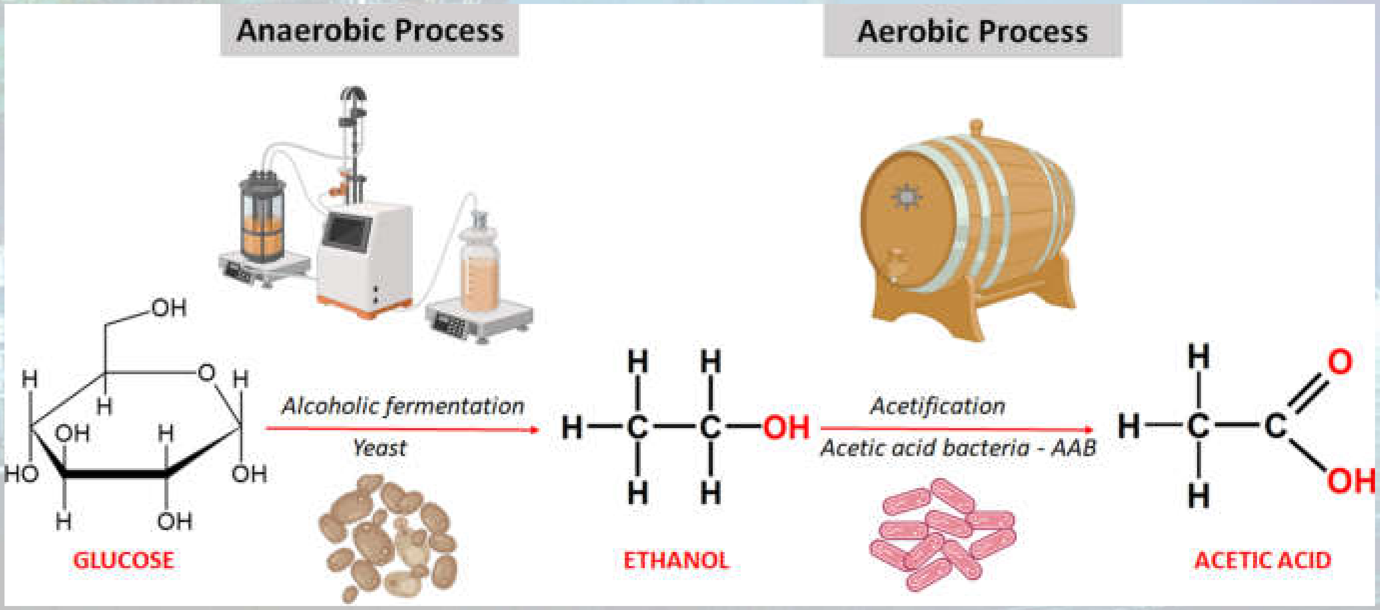


Vinegar production by fermentation:

Vinegar is produced through a two-stage fermentation process, the first being the conversion of fermentable sugars into ethanol by yeasts, generally Saccharomyces species, and the second being the oxidation of ethanol by bacteria, generally Acetobacter species.

Vinegar is 5% aqueous solution of acetic acid. It is formed by fermentation of sugars and starch. Ethanol is the intermediate product.

The main species responsible for the production of vinegar belong to the genera Acetobacter, Gluconacetobacter, Gluconobacter and Komagataeibacter because of their high capacity to oxidize ethanol to acetic acid and high resistance to acetic acid released into the fermentative medium.



Yogurt:

Contains bacteria that are “thermophilic” = heat loving.

Two main types of Lactic Acid Bacteria:

Lactobacillus:

- meaning “milk” and “rod”
- over 50 different species
- found on plants and in the digestive system of animals such as cows and humans.

Lactococcus:

- meaning “milk” and “sphere” because of its shape
- found primarily on plants
- less common than lactobacillus

$$\text{Lactose} \xrightarrow{\text{Lactic acid Bacteria}} \text{Lactic Acid}$$

(Milk sugar)

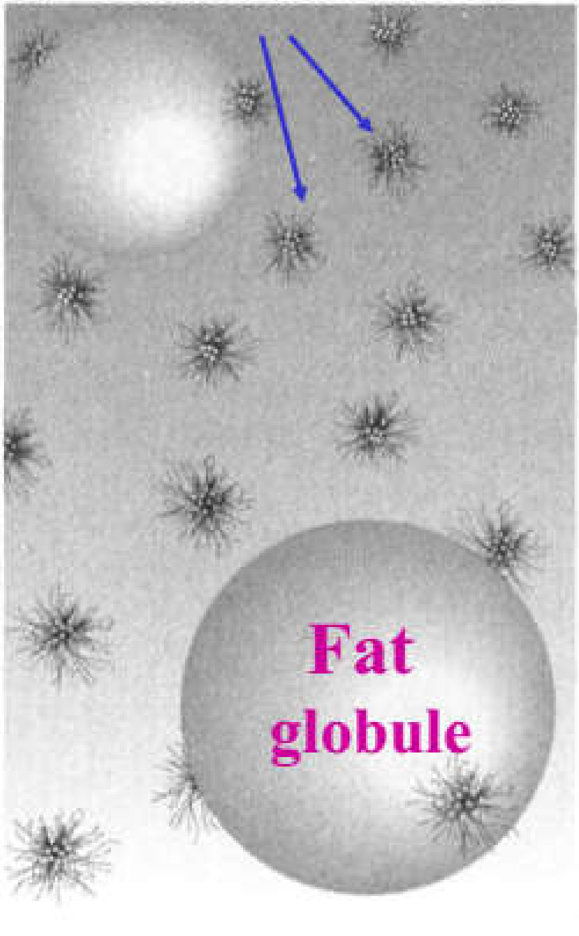
↓

Acid causes casein (milk protein) to ***denature*** and hold water into a semi-solid gel = yogurt

Milk

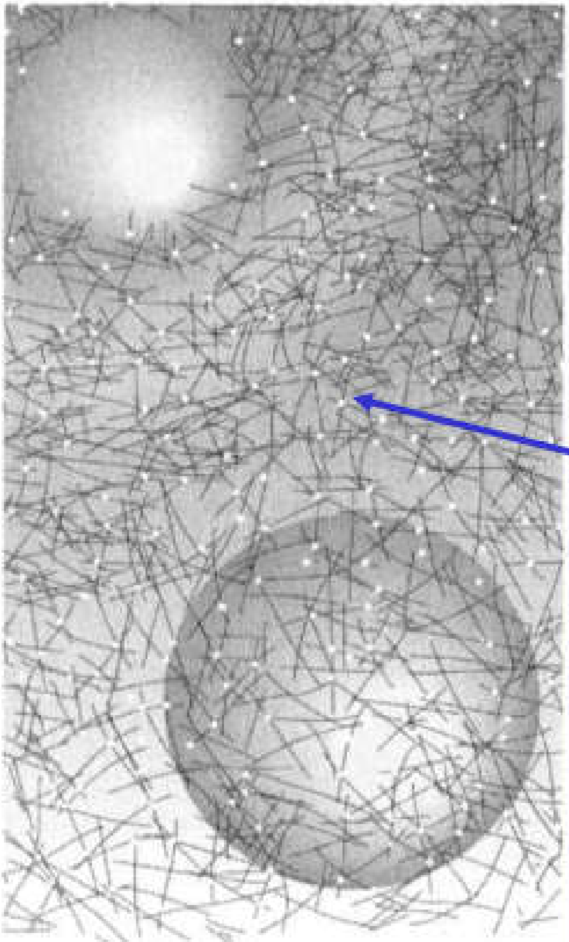
Casein protein micelles (bundles)

10^{-7} meters in diameter



Yogurt

Bacteria produce acid



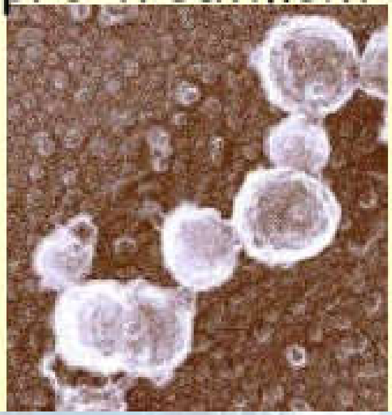
Acid causes Casein bundles to fall apart into separate casein molecules.

These rebind to each other in a network that traps water.

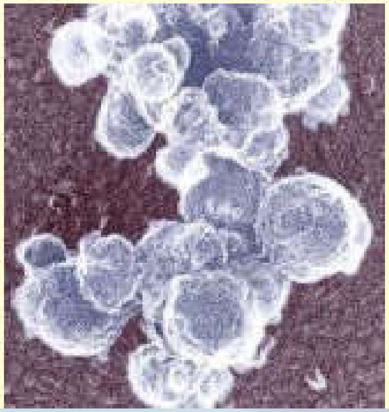
=> makes a gel

Casein before heat pre-treatment:

Casein after heat pre-treatment:



Casein after acid:



Unit Operations:

There are many types of chemical processes that make up the global chemical industry. However, each may be broken down into a series of steps called unit operations.

These are the physical treatment steps, which are required to:

- put the raw materials in a form in which they can be reacted chemically
- put the product in a form which is suitable for the market

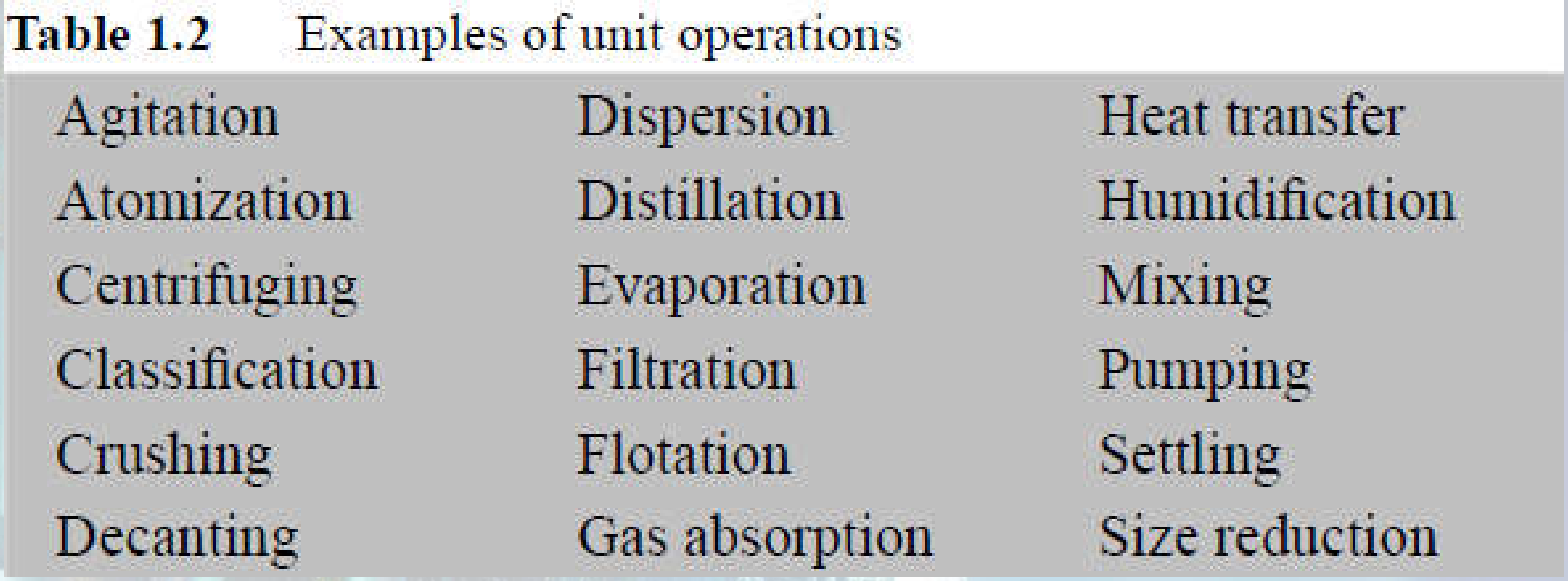


Table 1.2 Examples of unit operations

- Agitation
- Atomization
- Centrifuging
- Classification
- Crushing
- Decanting
- Dispersion
- Distillation
- Evaporation
- Filtration
- Flotation
- Gas absorption
- Heat transfer
- Humidification
- Mixing
- Pumping
- Settling
- Size reduction

Atomization:

Atomization refers to the disintegration of a liquid into droplets in a surrounding gas. The characteristics of the spray are highly dependent on the spray nozzle type.

Flow Diagrams:

A picture says more than a thousand words.

Block Diagrams:

This is a schematic diagram, which shows:

- what is to be done rather than how it is to be done. Details of unit operations/processes are not given
- flow by means of lines and arrows
- unit operations and processes by figures such as rectangles and circles
- raw materials, intermediate and final products

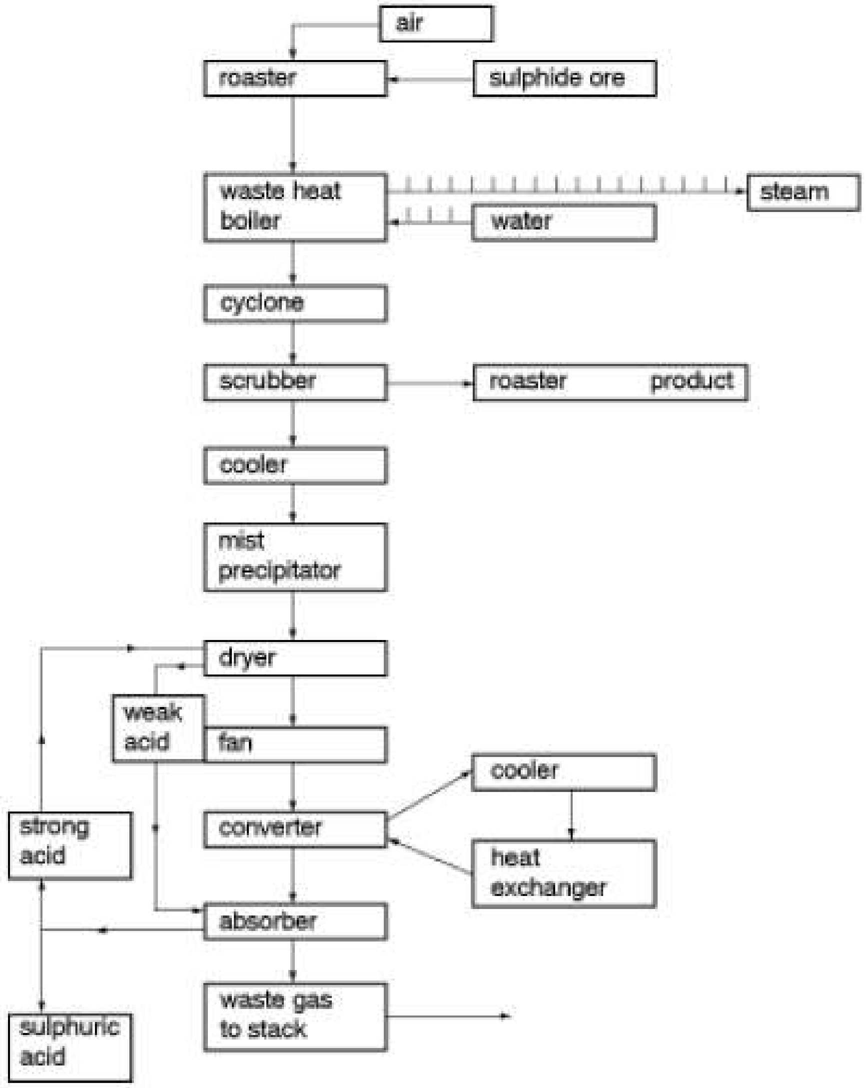


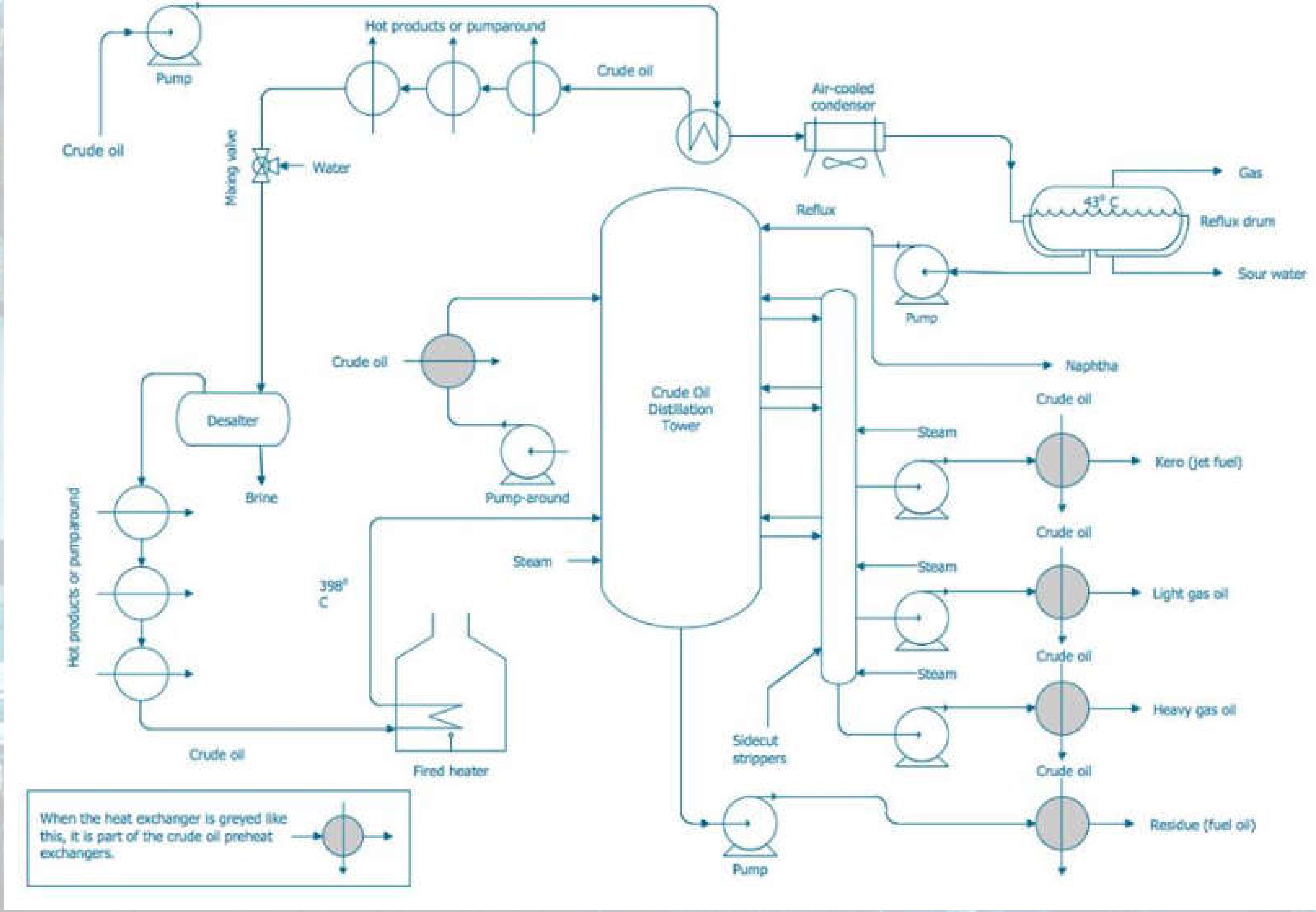
Fig 1.1 A block diagram for a sulphuric acid plant

Process flow diagram (PFD):

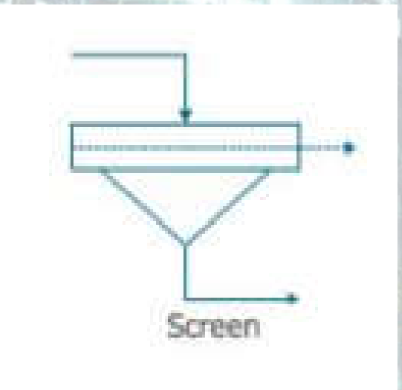
Communication is improved if accepted symbols are used. The advantages of correct use of symbols include:

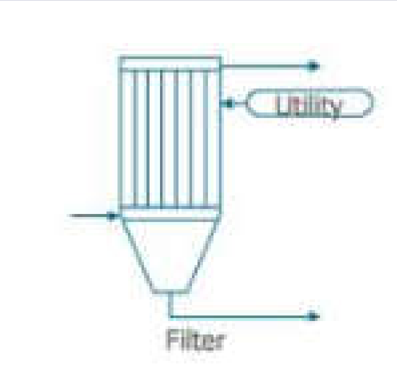
- the function being performed is emphasized by eliminating distractions caused by detail
- possibility of error that is likely to occur when detail is repeated many times is virtually done away with

Flow sheet symbols are pictorial quick-to-draw, easy-to-understand symbols that transcend language barriers.

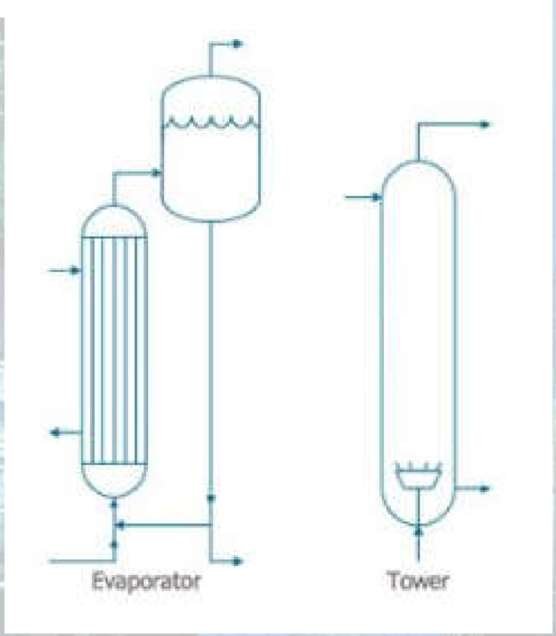


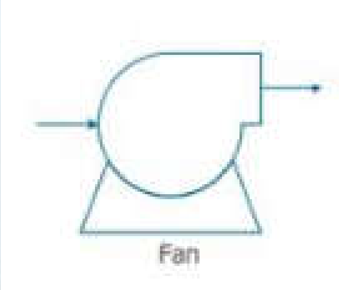
When the heat exchanger is greyed like this, it is part of the crude oil preheat exchangers.


Screen

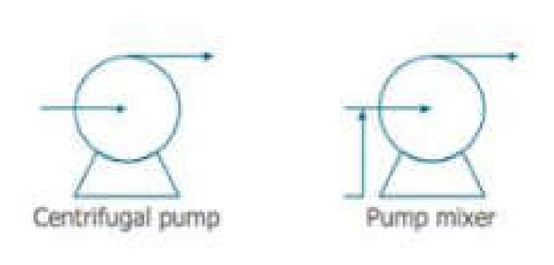

Utility
Filter

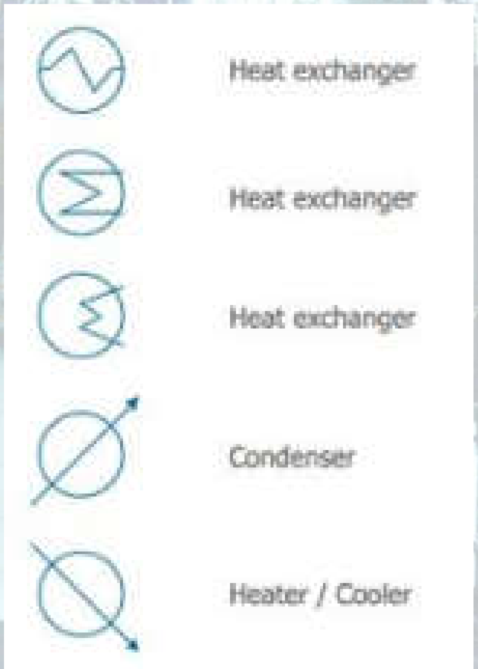

Agitator

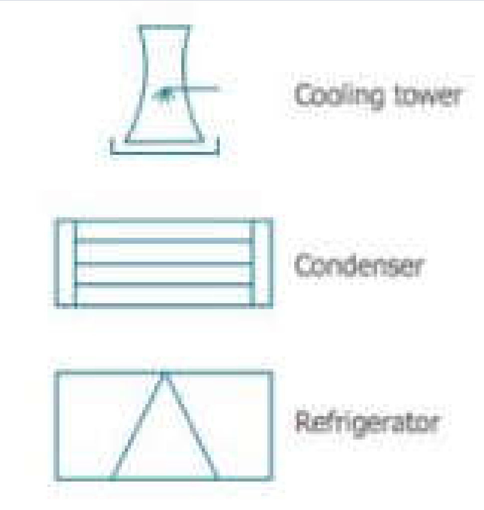

Evaporator
Tower

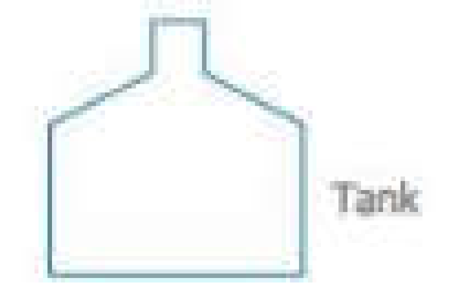

Fan


Propeller


Centrifugal pump
Pump mixer


Heat exchanger
Heat exchanger
Heat exchanger
Condenser
Heater / Cooler


Cooling tower
Condenser
Refrigerator


Tank


Open tank with lip
Covered tank floating roof

Mass balance:

Mass balance calculations serve the following purposes:

1. They help us know the amount and composition of each stream in the process.

2. The calculations obtained in 1 form the basis for energy balances through the application of *the law of conservation of energy*.

3. We are able to make technical and economic evaluation of the process and process units from the knowledge of material and energy consumption and product yield obtained.

4. We can quantitatively know the environmental emissions of the process.

In mass balance calculations, we begin with two assumptions:

- There is no transfer of mass to energy
- Mass is conserved for each element or compound on either molar or weight basis

Process Classification:

Three type of process:

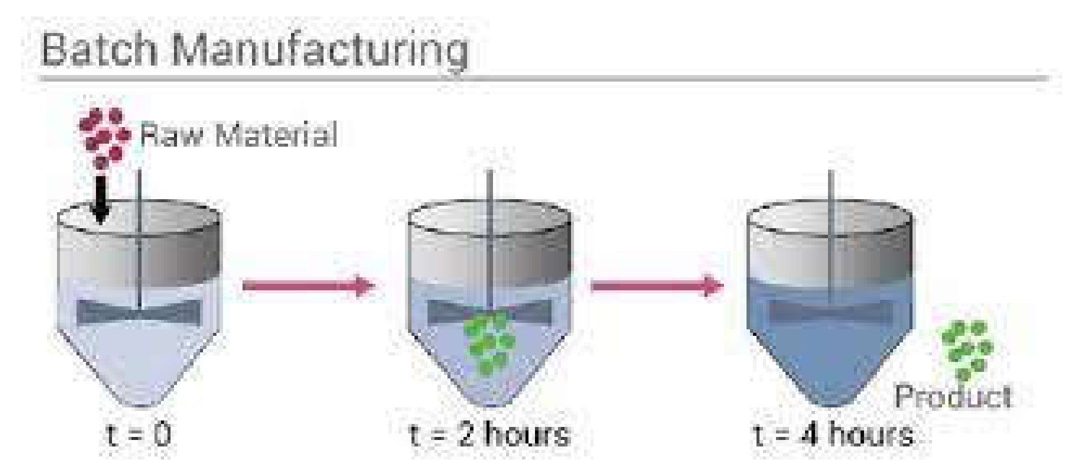
1- Batch process

Feed is charged to the process and product is removed when the process is completed

No mass is fed or removed from the process during the operation

Used for small scale production

Operate in unsteady state



Process Classification:

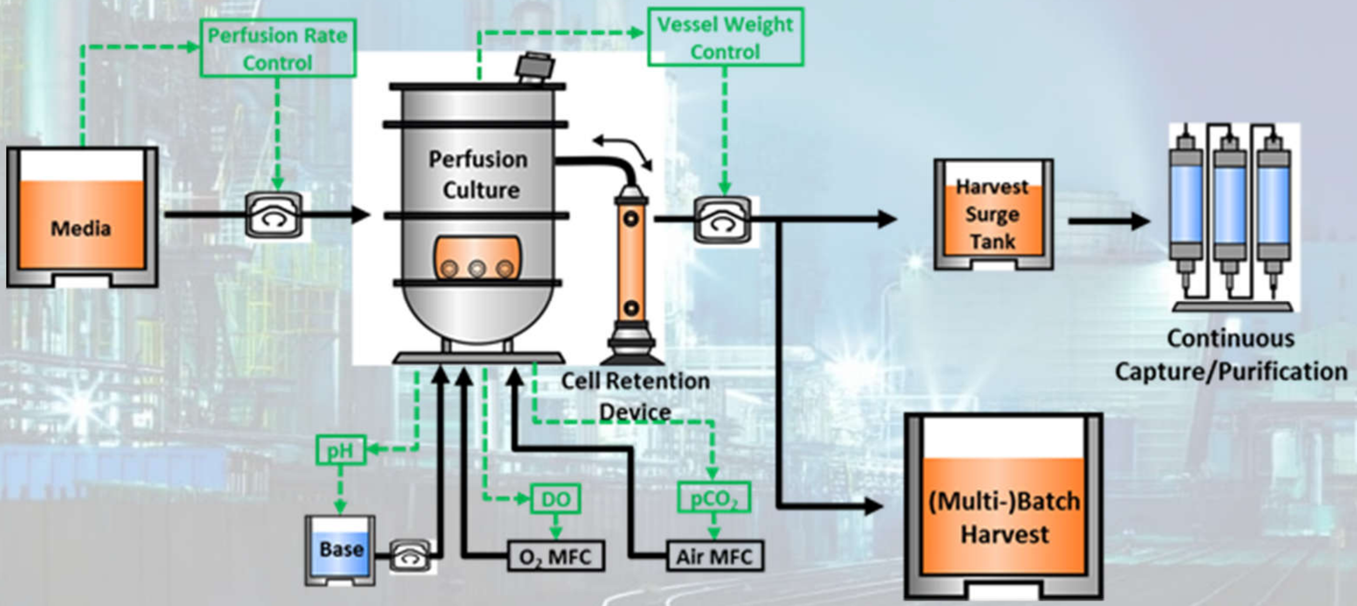
Three type of process:

2- Continuous process

Input and output is continuously fed and remove from the process

Operate in steady state

Used for large scale production



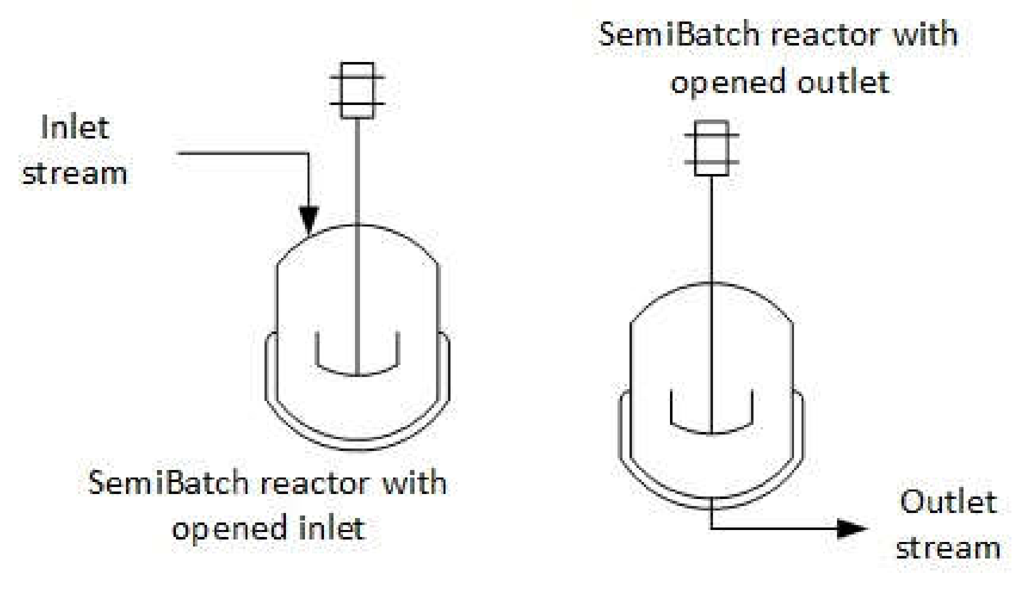
Process Classification:

Three type of process:

3- Semibatch process

Neither batch nor continuous

During the process a part of reactant can be fed or a part of product can be removed.



Operation of Continuous Process:

1- Steady state

All the variables (i.e. temperatures, pressure, volume, flow rate, etc) do not change with time.

Minor fluctuation can be acceptable.

2- Unsteady state or transient

Process variable change with time, in particular mass flow rate.

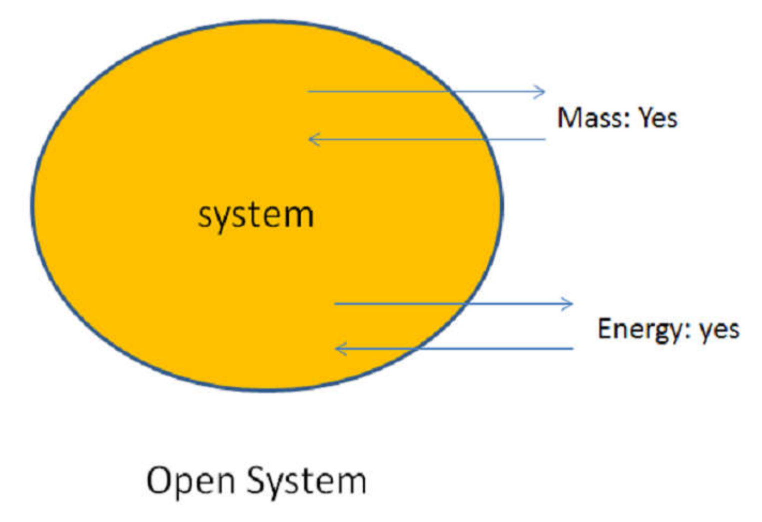
Balances:

General Balance:

A balance on a conserved quantity (total mass, mass of a particular species, energy, momentum) in a system (a single process unit, a collection of units, or an entire process) may be written in the following way:

INPUT + GENERATION – OUTPUT – CONSUMPTION = ACCUMULATION

The system is any process or portion of a process chosen for analysis. A system is said to be “open” if material flows across the system boundary during the interval of time being studied; “closed” if there are no flows in or out.



Simplified Rule for Mass Balance:

If the balanced quantity is TOTAL MASS, set generation = 0 and consumption = 0. Mass can neither be created nor destroyed.

If the balanced substances is a NONREACTIVE SPECIES (neither a reactant nor a product), set generation = 0 and consumption = 0.

If a system is at STEADY STATE, set accumulation = 0, regardless of what is being balanced.

Balances on Continuous Steady State Process:

Steady state: accumulation = 0

INPUT + GENERATION – OUTPUT – CONSUMPTION = 0

If balance on nonreactive species or total mass; balance equation become

INPUT = OUTPUT

Balances on Batch Process:

From GMBE: (input=0; output=0):

Generation – Consumption = Accumulation

For batch reactor:

Accumulation = Final output – Initial Input

Final GMBE for batch process:

Initial input + Generation = Final output + Consumption

Mass balance calculation procedure:

The general procedure for carrying out mass balance calculations is as follows:

1. Make a block diagram (flow sheet) over the process
2. Put numbers on all the streams
3. List down all the components that participate in the process.
4. Find the components that are in each stream and list them adjacent to the stream in the block diagram
5. Decide on an appropriate basis for the calculations e.g. 100kg raw material A, 100kg/hr A, 1 ton of product, 100 moles reactant B etc.

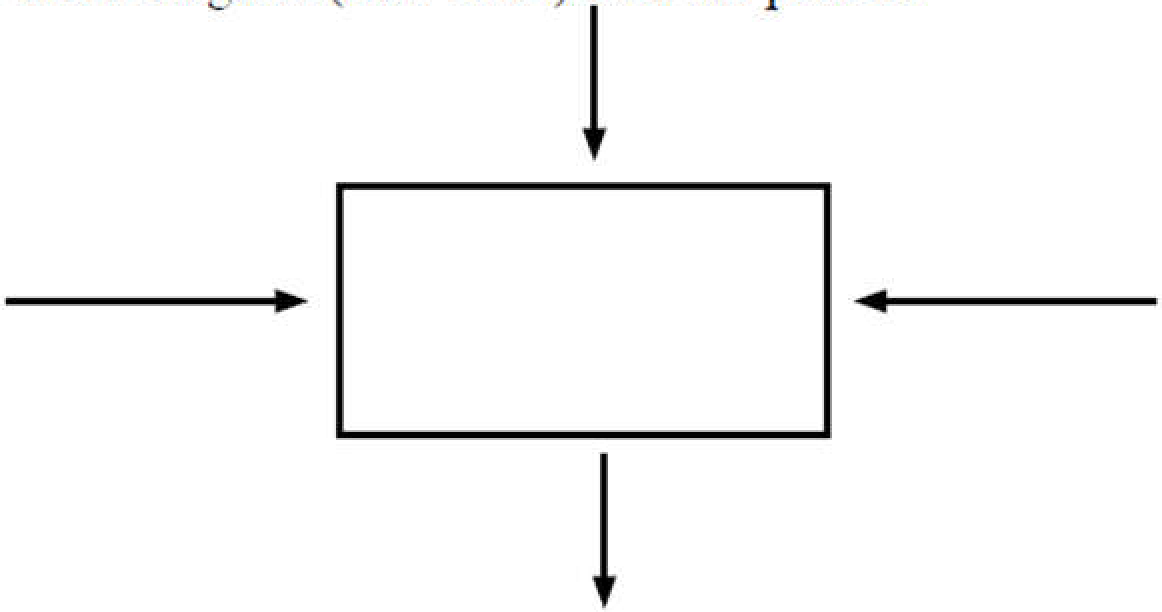
6. Find out the total number of independent relations. This is equivalent to the total number of stream components.

7. Put up different relations between stream components and independent relations to calculate concentrations

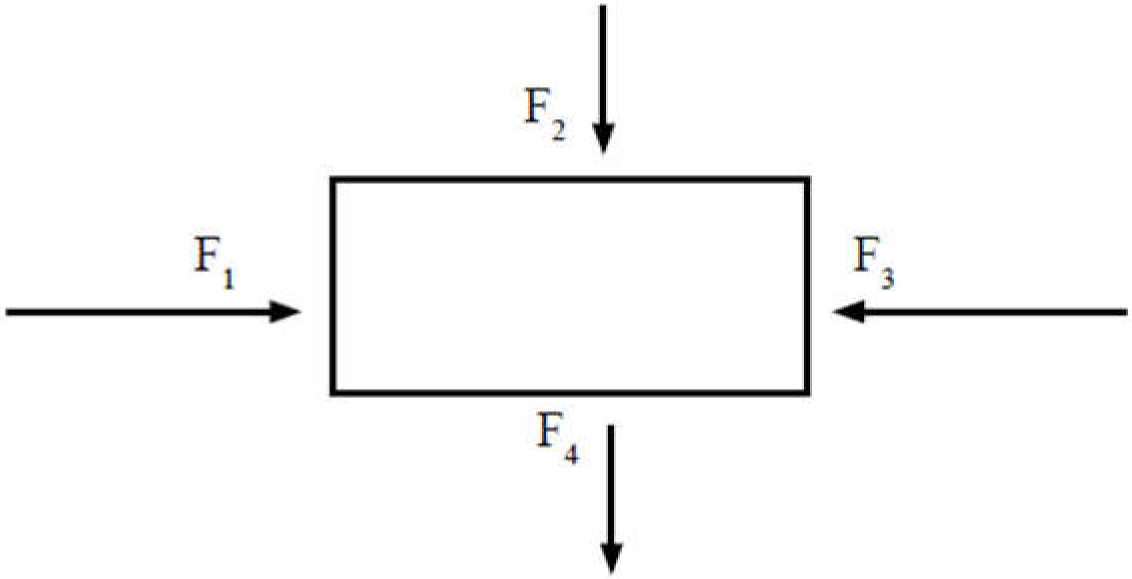
Example:

Three raw materials are mixed in a tank to make a final product in the ratio of 1:0.4:1.5 respectively. The first raw material contain A and B with 50% A. The second raw material contain C while the third raw material contain A and C with 75% A. Assuming a continuous process at steady state, find the flow and composition of the product.

1. Make a block diagram (flow sheet) over the process



2. Put numbers on all the streams

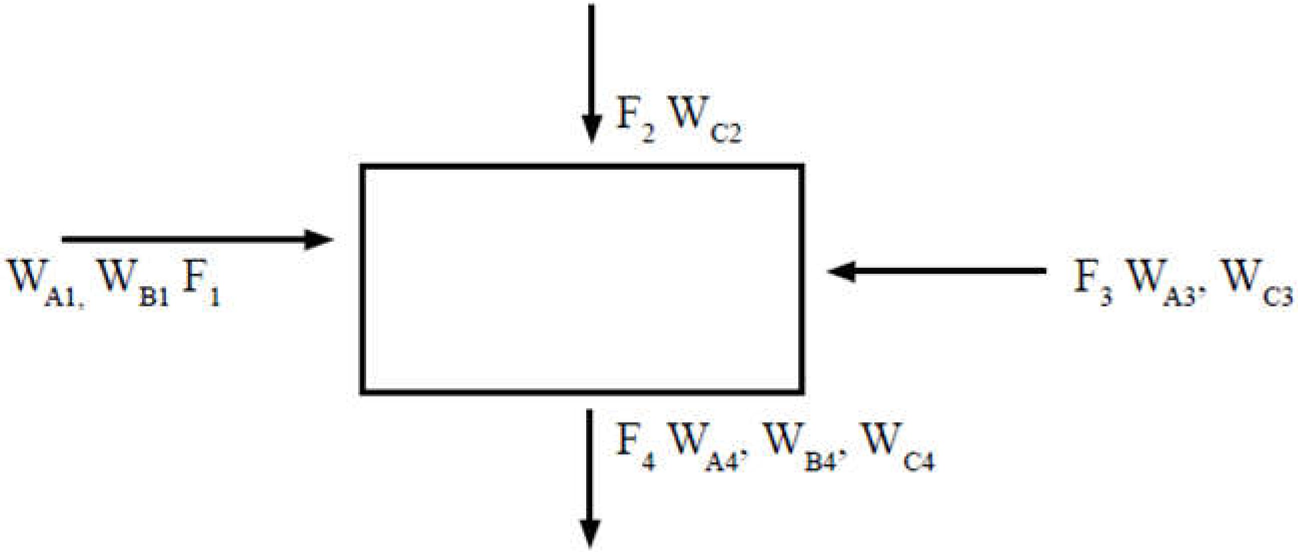


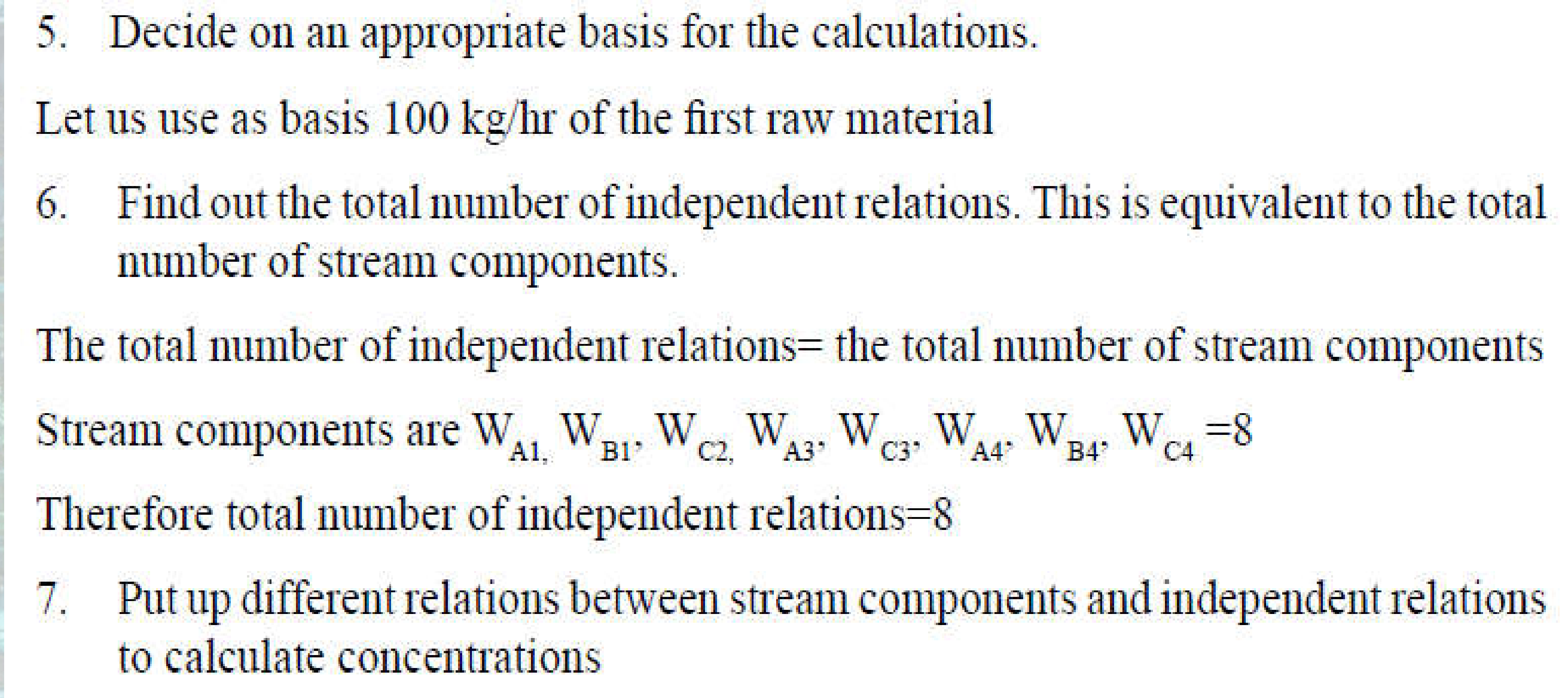
3. List down all the components that participate in the process.

   The components are A, B and C.

4. Find the components that are in each stream and list them adjacent to the stream in the block diagram.

   Let W represent composition by weight.





5. Decide on an appropriate basis for the calculations.

Let us use as basis 100 kg/hr of the first raw material

6. Find out the total number of independent relations. This is equivalent to the total number of stream components.

The total number of independent relations= the total number of stream components

Stream components are W_{A1}, W_{B1}, W_{C2}, W_{A3}, W_{C3}, W_{A4}, W_{B4}, W_{C4} $=8$

Therefore total number of independent relations=8

7. Put up different relations between stream components and independent relations to calculate concentrations

We need at least 8 independent mathematical relations to enable us solve the problem. These are:

- Basis: Stream F_1 is 100kg
- The ratio of the three raw materials
- W_{A1} is 50%
- W_{C2} is 100%
- W_{C3} is 25%
- Material balance for A
- Material balance for B
- Material balance for C

We have the required number of independent relations and we can proceed to do the calculations.

We start with the general balance equation:

Accumulation = Flow in – Flow out + Production – Consumption

For a mixing reaction, production and consumption are zero. Therefore:

$$\textbf{Accumulation} = (F_1 + F_2 + F_3) - F_4$$

where the flow rates are in kg per hour.

Because the system is at steady state, accumulation is zero, and:

$$F_4 = F_1 + F_2 + F_3$$

From the ratio of input flows, $F_2 = 0.4X(100/1) = 40kg$

$F_3 = 1.5X(100/1) = 150kg$

Therefore $F_4 = 100 + 40 + 150$

$= 290kg$

The next step is to find the quantities of A, B and C in F_4. To do this, we shall write the mass balance equation for each of these three components assuming no accumulation. For A:

$$\text{Accumulation}_A = \text{Flow in}_A - \text{Flow out}_A + \text{Production}_A - \text{Consumption}_A$$

$$\begin{aligned}
\text{Accumulation}_A = \quad 0 &= (F_1 W_{A1} + F_2 W_{A2} + F_3 W_{A3}) - F_4 W_{A4} \\
0 &= 100(0.5) + 40(0) + 150(0.75) - 290W_{A4} \\
&= 162.5 - 290W_{A4} \\
W_{A4} &= 162.5/290 \\
&= 0.56
\end{aligned}$$

Similar balances are done for B and C:

$$\text{Accumulation}_B = 0 = (F_1 W_{B1} + F_2 W_{B2} + F_3 W_{B3}) - F_4 W_{B4}$$

$$0 = 100(0.5) + 40(0) + 150(0) - 290W_{B4}$$

$$= 50 - 290W_{B4}$$

$$W_{B4} = 50/290$$

$$= 0.17$$

$$\text{Accumulation}_C = 0 = (F_1 W_{C1} + F_2 W_{C2} + F_3 W_{C3}) - F_4 W_{C4}$$

$$0 = 100(0) + 40(1) + 150(0.25) - 290W_{C4}$$

$$= 77.5 - 290W_{C4}$$

$$W_{C4} = 77.5/290$$

$$= 0.27$$

It is always good to check answers for consistency. We do this by summing the weight fractions:

$$W_{A4} + W_{B4+} W_{C4} = 0.56 + 0.17 + 0.27 = 1.0$$

This proves that the solution is right.

8. Tabulate results.

Stream	Components	Kg/hr	ΣKg	%	Σ%
1	A	50		50	
	B	50	100	50	100
2	C	40	100	100	100
3	A	112.5		75	
	C	37.5	150	25	100
4	A	162.5		56	
	B	50		17	
	C	77.5	290	27	100

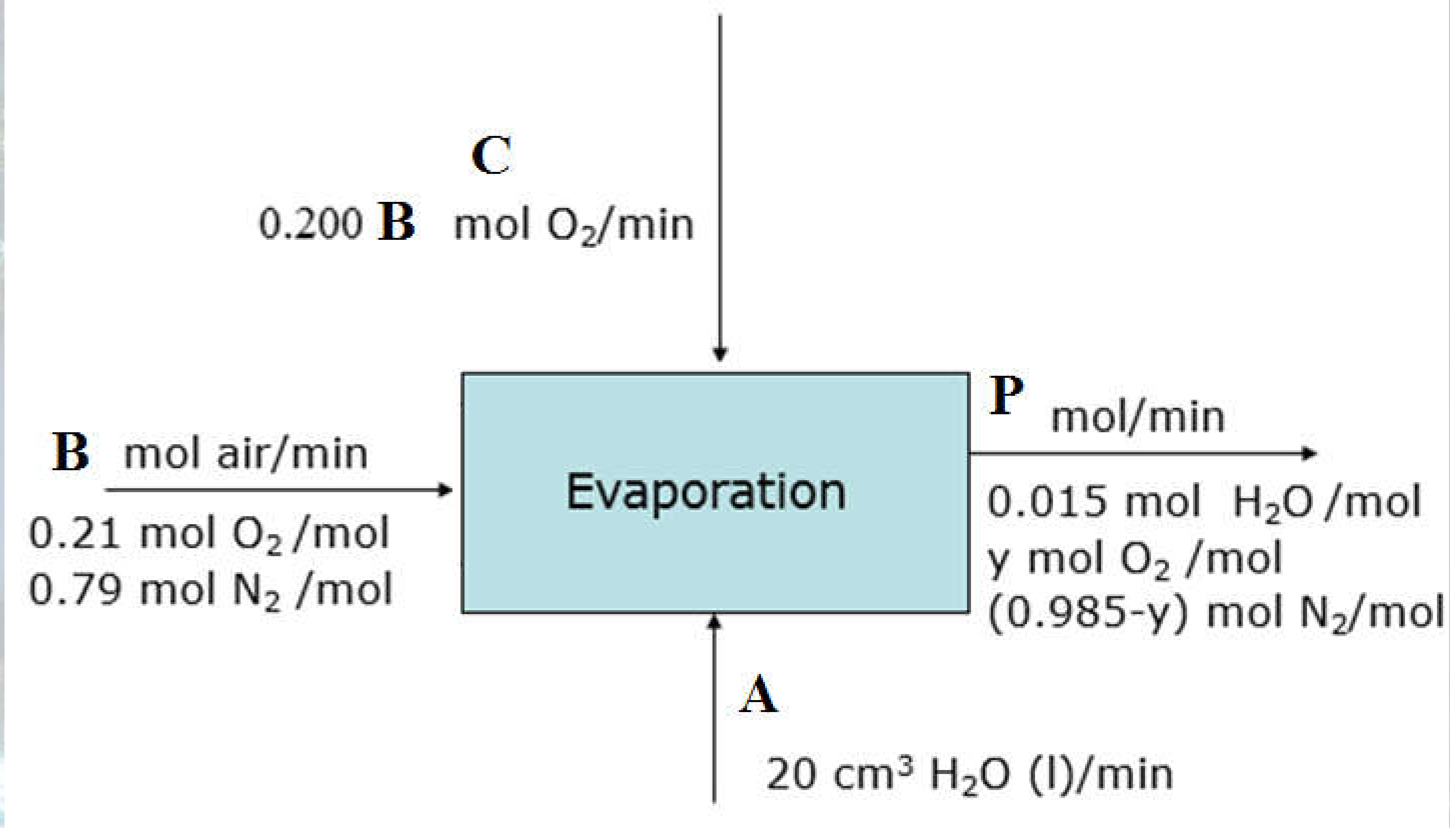
An experiment on the growth rate of certain organism requires an environment of humid air enriched in oxygen. Three input streams are fed into an evaporation chamber to produce an output stream with the desired composition.

A: Liquid water fed at rate of 20 cm^3/min

B: Air (21% O_2 and 79% N_2)

C: Pure O_2 with a molar flow rate one-fifth of the molar flow rate of stream B

The output gas is analyzed and is found to contain 1.5 mole% water. Draw and label the flowchart of the process, and calculate all unknown stream variables.



C

0.200 **B** mol O_2/min

B mol air/min

0.21 mol O_2 /mol

0.79 mol N_2 /mol

Evaporation

P mol/min

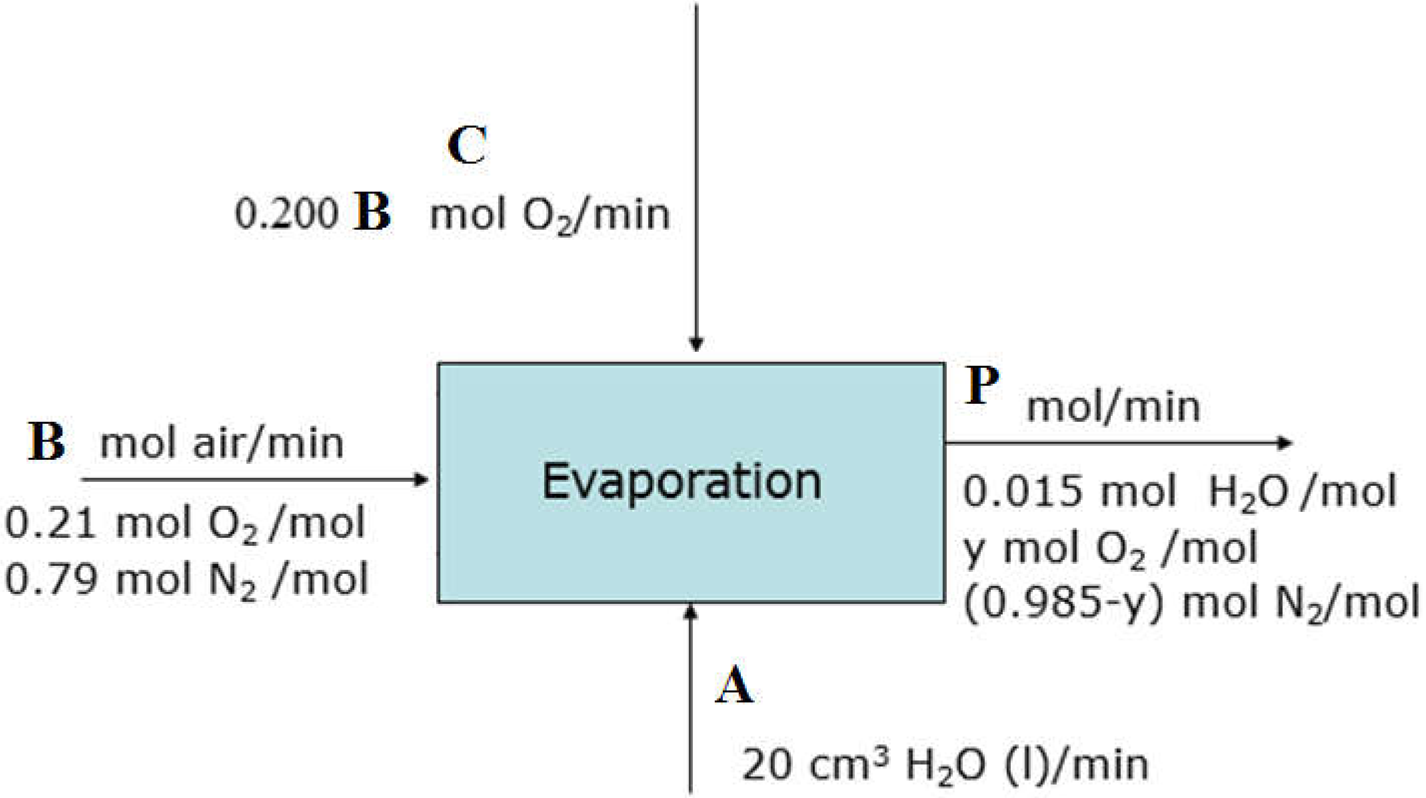
0.015 mol H_2O /mol

y mol O_2 /mol

(0.985-y) mol N_2/mol

A

20 cm^3 H_2O (l)/min



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Evaporation

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0.015 mol H_2O/mol

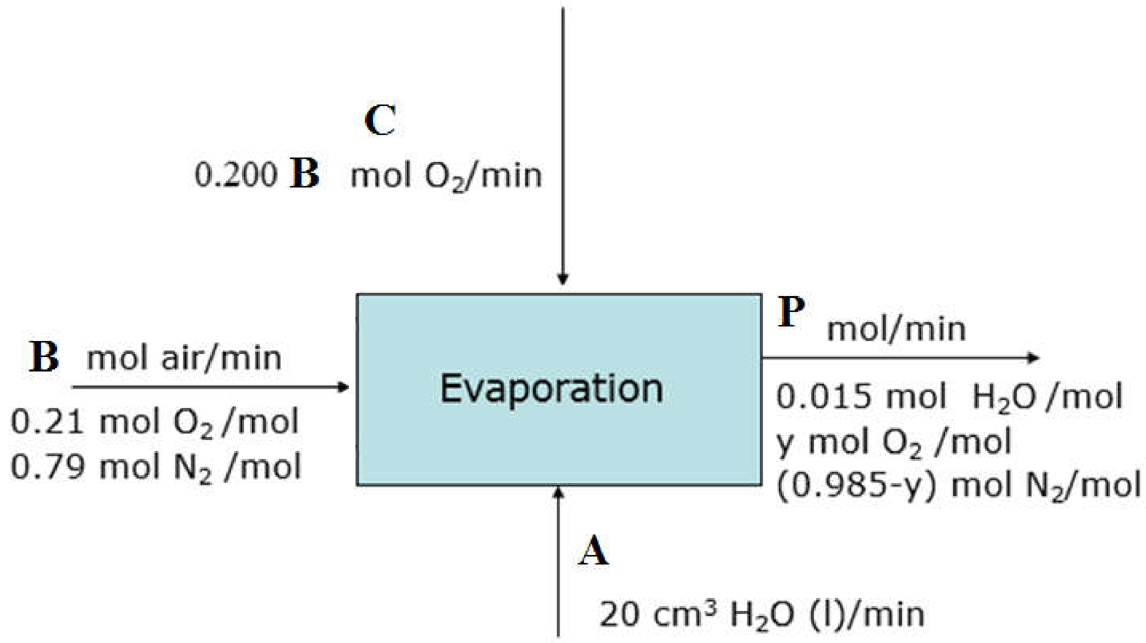
y mol O_2/mol

(0.985-y) mol N_2/mol

A

20 cm^3 H_2O (l)/min

$$\mathbf{A} = \frac{20.0\ \text{cm}^3\ \text{H}_2\text{O}}{\text{min}} \left| \frac{1.00\ \text{g H}_2\text{O}}{\text{cm}^3} \right| \frac{1\ \text{mol}}{18.02\ \text{g}} \Longrightarrow \boxed{\mathbf{A} = 1.11\ \frac{\text{mol H}_2\text{O}}{\text{min}}}$$



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A

20 cm^3 H_2O (l)/min

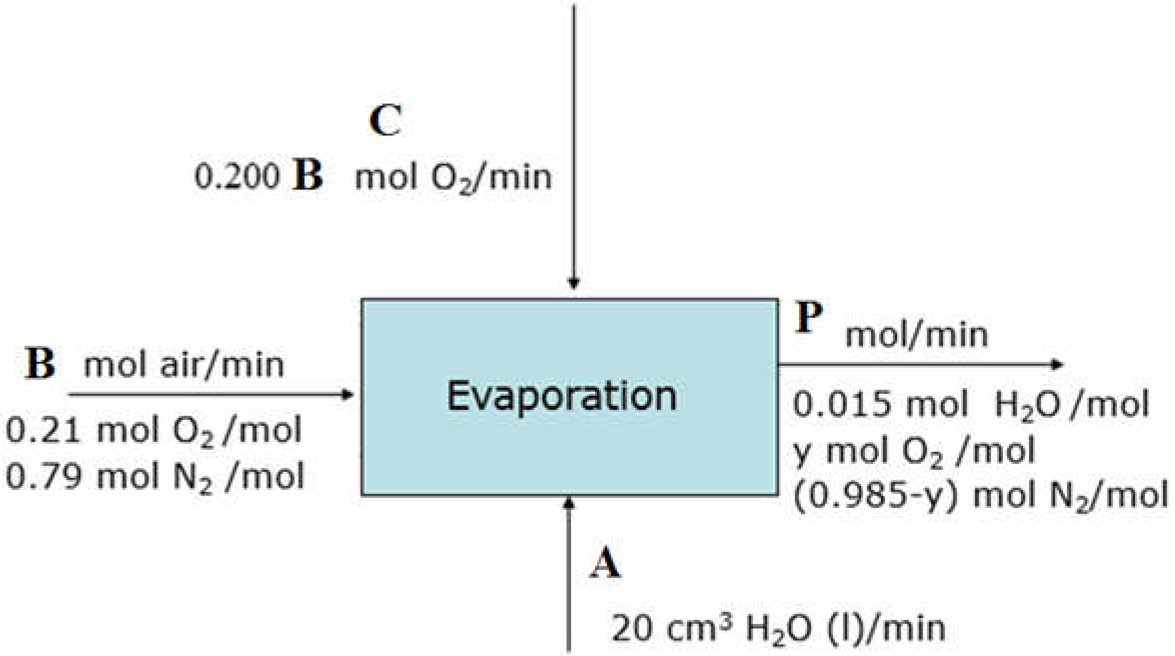
$$\mathbf{A} = \frac{20.0\ cm^3\ H_2O}{min}\left|\frac{1.00\ g\ H_2O}{cm^3}\right|\frac{1\ mol}{18.02\ g} \Longrightarrow \boxed{\mathbf{A} = 1.11\ \frac{mol\ H_2O}{min}}$$

H_2O Balance

$$\mathbf{A}\left(\frac{mol\ H_2O}{min}\right) = \mathbf{P}\ \frac{(mol)}{(min)}\left|\frac{0.015\ mol\ H_2O}{mol}\right.$$

$$\Downarrow\ \mathbf{A} = 1.11\ mol/min$$

$$\boxed{\mathbf{P} = 74\ \frac{mol}{min}}$$



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0.21 mol O_2 /mol

0.79 mol N_2 /mol

Evaporation

P mol/min

0.015 mol H_2O /mol

y mol O_2 /mol

(0.985-y) mol N_2/mol

A

20 cm^3 H_2O (l)/min

Total mol balance

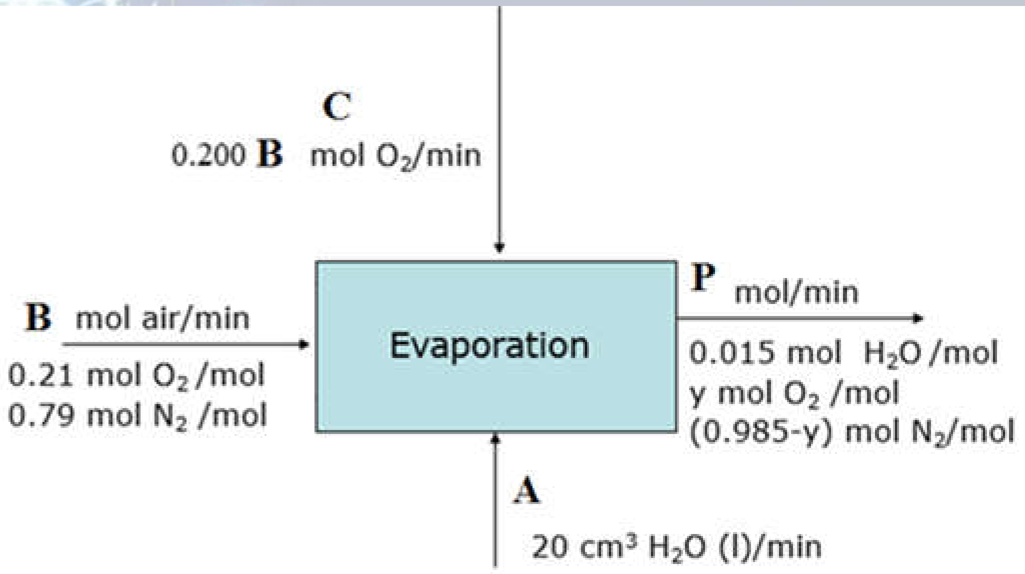
$$A + B + C = P$$

$$A + B + 0.2B = P$$

$$A + 1.2B = P$$

$$1.11 \text{ (mol/min)} + 1.2B = 74 \text{ (mol/min)}$$

$$\Rightarrow B = 60.8 \text{ (mol/min)}$$



C

0.200 **B** mol O_2/min

B mol air/min

0.21 mol O_2 /mol

0.79 mol N_2 /mol

Evaporation

P mol/min

0.015 mol H_2O /mol

y mol O_2 /mol

(0.985-y) mol N_2/mol

A

20 cm^3 H_2O (l)/min

N_2 balance

$$\frac{\mathbf{B}\,(\text{mol})}{(\text{min})}\left|\frac{0.79\ \text{mol}\ N_2}{\text{mol}}\right. = \frac{\mathbf{P}\,(\text{mol})}{(\text{min})}\left|\frac{(0.985-y)(\text{mol}\ N_2)}{(\text{mol})}\right.$$

$$\Downarrow$$

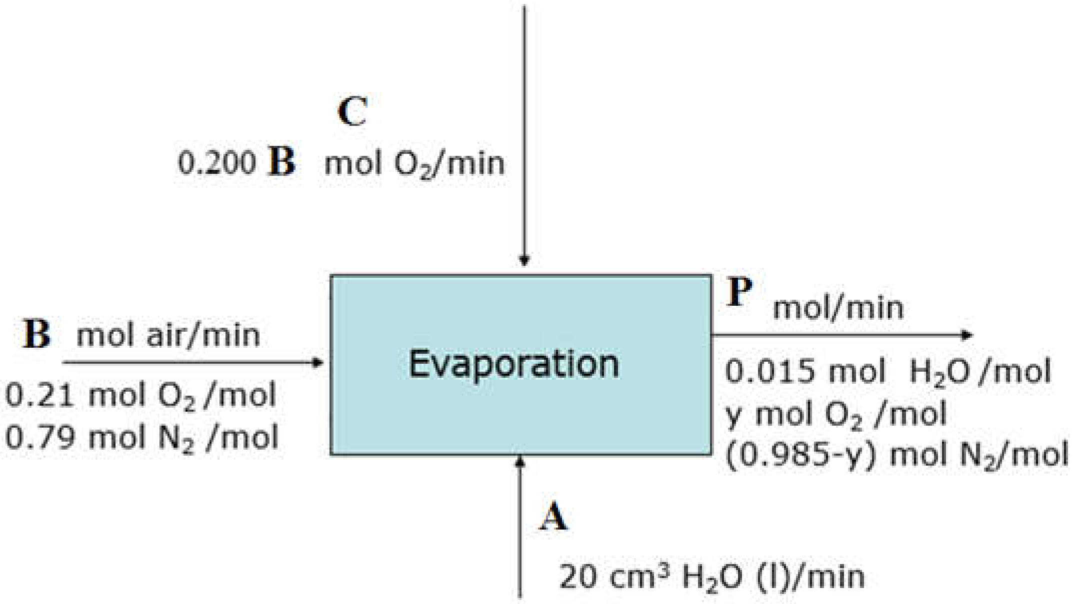
$$0.79\mathbf{B} = \mathbf{P}\,(0.985-y)$$

$$\mathbf{B} = 60.8\ \text{mol/min}$$

$$\mathbf{P} = 74\ \text{mol/min}$$

$$\boxed{y = 0.336\ \text{mol}\ O_2/\text{mol}}$$

=> N_2 = 0.649



C

0.200 **B** mol O_2/min

B mol air/min

0.21 mol O_2/mol
0.79 mol N_2/mol

Evaporation

P mol/min

0.015 mol H_2O/mol
y mol O_2/mol
(0.985-y) mol N_2/mol

A

20 cm^3 H_2O (l)/min

O_2 balance

$$0.21\,B + C = y\,P$$

$$0.21\,B + 0.2\,B = y\,P$$

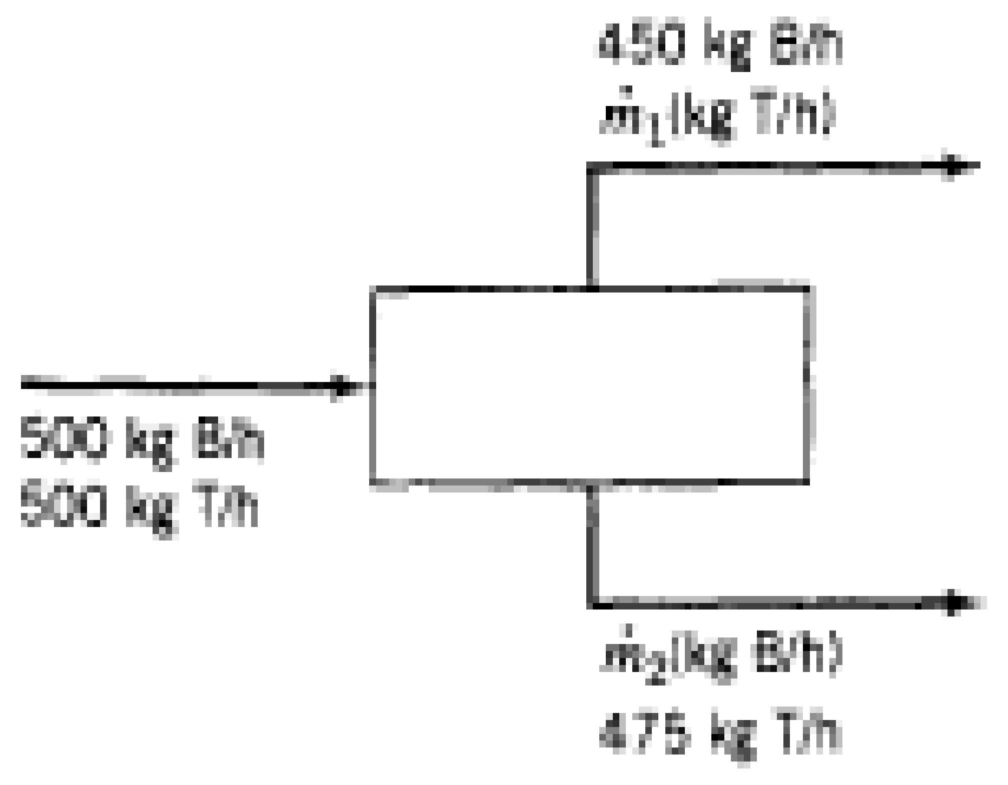
B = 60.8 mol/min
P = 74 mol/min

$$\boxed{y = 0.336 \text{ mol } O_2/\text{mol}}$$

One thousand kilograms per hour of a mixture of benzene (B) and toluene (T) containing 50% benzene by mass is separated by distillation into two fractions. The mass flow rate of benzene in the top stream is 450 kg B/h and that of toluene in the bottom stream is 475 kg T/h. The operation is at steady state.

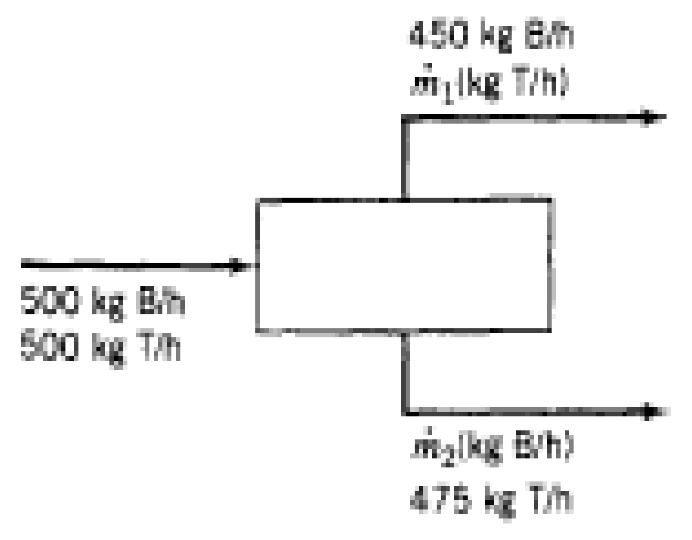
Write balances on benzene and toluene to calculate the unknown component flow rates in the output streams.

The process can be depicted schematically as follows:



Since the process is at steady state there can be no buildup of anything in the system, so the accumulation term equals zero in all material balances. In addition, since no chemical reactions occur, there can be no nonzero generation or consumption terms.

For all balances, input = output.



Benzene Balance

500 kg *B/h* = *450 kg B/h* + m_2

m_2 = 50 kg B/h

Toluene Balance

500 kg *B/h* = *475 kg B/h* + m_1

m_1 = 25 kg T/h

Check the calculation:

Total Mass Balance

1000 kg */h* = *450* + m_1+m_2+*475*

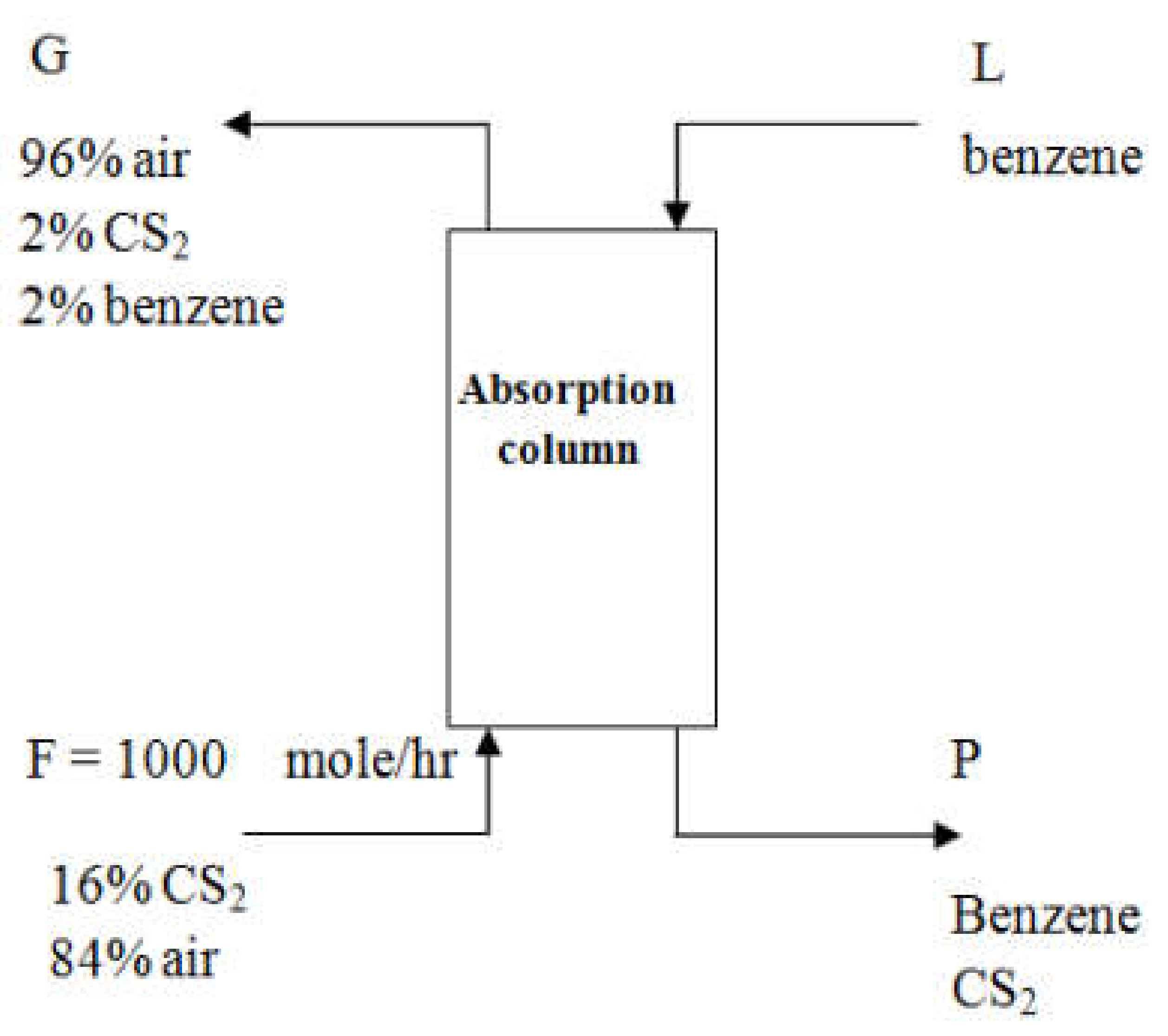
(all in kg/h)

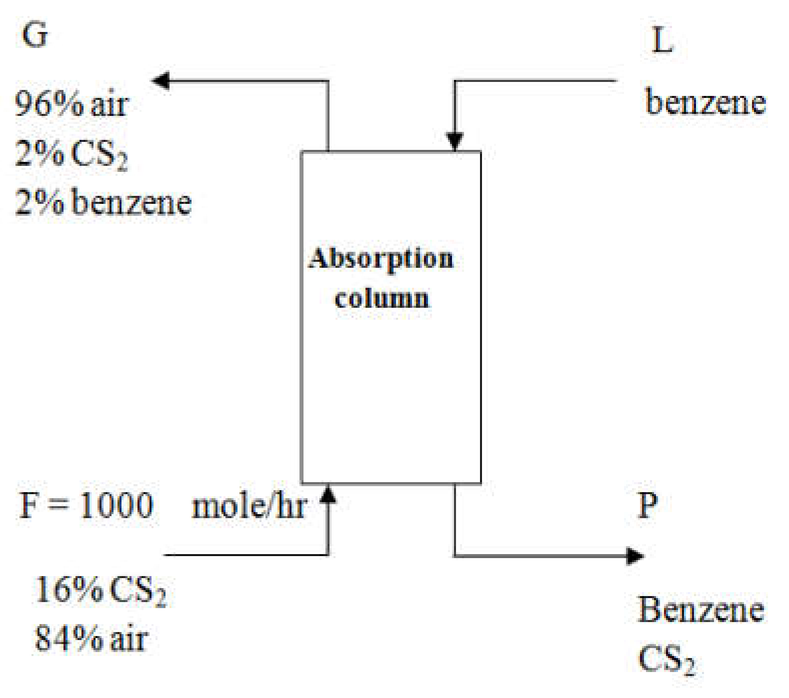
m_l = 25 kg T/h

m_2= 50kg B/h

1000 kg/h = 1000 kg/h

A gaseous mixture (F) consists of 16 mol% CS_2 and 84 mol% air are fed to the absorption column at a rate of 1000 mole/hr. Most of the CS_2 input are absorbed by liquid benzene (L) which is fed to the top of the column. 1 % of benzene input are evaporated and out with the exit gas stream which consists of 96 mol% air, 2 mol% CS_2 and 2 mol% benzene. The product liquid stream (P) consists of benzene and CS_2. Calculate the mole flow rates of (G), (L) and (P) and the compositions.


G
96% air
2% CS_2
2% benzene
L
benzene
Absorption column
F = 1000 mole/hr
16% CS_2
84% air
P
Benzene
CS_2



Basis = 1 hr
F = 1000 mole

Air material balance:

$(0.84) (F) = (0.96) (G)$

$(0.84)(1000) = (0.96) (G)$

$G = 840/0.96 = 875$ mole

Benzene material balance:

Benzene in (G) = (875) (0.02) = 17.5 mole

17.5 = 1% of benzene input

$17.5 = (0.01) (L)$ ⇨ $L = 1750$ mole

Benzene in (P) = 99% of benzene input = (0.99) (L) =(0.99) (1750) = 1732.5 mole

Let x = mole fraction of benzene in (P) ⇨ $P x = 1732.5$ ……………...(1)

CS_2 material balance:

$(0.16)\,(F) = (0.02)\,(G) + P\,(1\text{-}x)$

$(0.16)\,(1000) = (0.02)\,(875) + P - P\,x$

$160 = 17.5 + P - 1732.5 \quad \Longrightarrow \quad P = 1875$ mole

Sub. (P) in equation (1):

$x = (1732.5) / (1875) = 0.924$ mole fraction of benzene in (P)

mole fraction of CS_2 in (P) = $1 - 0.924 = 0.076$