CHNG 1103 INTRODUCTION OF MATERIAL AND ENERGY TRANSFORMATIONS

COURSE NOTES

PART A: MATERIAL BALANCE

GENERAL INFORMATION

LECTURERS

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TEXTBOOK

R.M. Felder and R.W. Rousseau " Elementary Principles of Chemical Processes", John Wiley & Sons, 3rd Edition (1999).

COURSE SCHEDULE

Lectures: Monday, 10:00-11:00, Civil LR1
Friday, 10:00-11:00, PNR LT

Tutorials: Thursday, 2:00-5:00, PNR DO1

(Tutorials will start on week 1)

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COURSE OBJECTIVES

To develop:

- An understanding of units and dimensions
- An appreciation of material quantities and how they are obtained and measured.
- An appreciation of various processing operations
- The methodology for accounting for the materials entering and exiting units in a process.
- Problem solving skills through tutorials and projects.
- Written and communication skills.

SUMMARY OF COURSE CONTENT

This is the first course in chemical engineering calculations. It aims to teach students how they should formulate and solve material balances in various processing systems. Essentially, the materials which goes into the process will be converted by physical (e.g., drying) and chemical processes, whilst some may remain unconverted. The task for the chemical engineer is to create a process statement which identifies and quantifies all the materials entering, remaining and leaving the system.

HOW IS THIS DONE?

According to Felder and Rousseau, *"the engineering approach to solving process related problems: breaking a process down into its components, establishing the relations between known and unknown process variables, assembling the information needed to solve for the unknowns.. and finally putting the pieces together to obtain the desired problem solution"*

So this is a course about approaches and procedures. These are concepts which cannot be taught just in lectures, but must be learned by practice. The tutorials should expose you to a series of process problems and the projects to more realistic and complex applications.

ORGANISATION AND ASSESSMENT

Assessment for this course will consist of tutorial, assignment and a final examination

Exam: 3 hours open-book examination at the end of semester 2. This examination accounts for 5**0%** of the final course marks.

Assignments: The assignments consist of 8 tutorials and 2 projects. There will be 4 tutorials in material balance and 4 tutorials for energy balance. (Tutorials: 10%; Projects: 30%)

Quiz: **One** open book quiz will be provided. This will be worth **10% of the course mark**.

GENERAL NOTES:

Working in Groups

You will working in pre-assigned groups of 4-6 students. (See the first year notice board for your group number). However you must still submit individual tutorials.

Assessment and Attendance of Tutorials

- You will be required to attend all designated tutorial sessions and to participate in the group discussions.
- Tutorial solutions must be **submitted 1 week after your tutorial session (Thursday 5:00 p.m.)**. Late assignments will **NOT** be accepted.
- Students who miss more than 2 tutorial sessions without adequate and properly documented reasons will be ineligible for assignment marks. **This means you will lose 30% of the total course mark.**

Where should I hand in my tutorial solutions and assignments?

All assignments must be submitted in the **General Office pigeon hole**. A box marked **CHNG 1103 Material and Energy Transformations** will be allocated there for this purpose.

Where can I pick up my marked tutorials and assignment?

All the marked assignments will be brought back to the tutorial. Assignments which have not been picked up will be placed in the "Marked Assignment" Box, located in a box outside Dr. Valix or Dr. Gomes's office.

Can I win a prize for doing well in this subject?

McGraw-Hill Prize:

A copy of "Perry's Chemical Engineer's Handbook", (authors: R.H. Perry and Don Green), will be awarded to the Engineering student with best performance in this course. The prize will be presented during the graduation dinner in second year.

COURSE CONTENT AND SEMESTER 2 CALENDAR (2008) PART A

The following provides a guideline on the course topics that will be covered and the timetable.

Uni. Week	Week Beginning	Lecture Topics	Assessment Tasks Due Date
1	28-July	• Units and Dimensions, • Process and Process Variables, Process Flowsheeting	
2	4-August	• Introduction to Material Balance • Balances on Multiple-Unit Processes	Tutorial 1
3	11-August	• Mass Balance with Chemical Reactions • Introduction on Mass Balance with Reactive Systems	Tutorial 2
4	18-August	• Combustion Systems • Recycle Bypass and Purge	Tutorial 3
5	25-August	• Quiz 1 • Project -1	Quiz 1
6	1 - September	• Project-1	Tutorial 4 Project Assignment

CHNG 1101 CHEMICAL ENGINEERING 1A

LECTURE SERIES 1: UNITS AND DIMENSIONS

Text Reference

Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 2, Series 2.1, 2.2 and 2.3.

Aims:

At the end of this lecture, the students should be able to perform the following tasks:

1. Add, subtract, multiply, and divide variables (both the value and units)
2. Convert the units of a variable from one system to another if the required conversion factors are provided.
3. Explain the difference between weight and mass.
4. Convert between units of force and units of mass, length, and time (for example, convert lbf to units of lbm, ft and s or vice versa).
5. Determine if an equation is dimensionally homogeneous and consistent in units.
6. Change the units of variables in a dimensionally homogeneous equation with consistent units.
7. Determine if a quantity is dimensionless.
8. Determine the correct number of significant figures in an arithmetic operation.

1.1 SYSTEMS OF UNITS

Dimensions are concepts of measurements such as:

Length [L]
Time [t]
Mass [M]
Temperature [T]

The units which define these dimensions are called **Base Units.**

There are several unit systems today which define base units. As chemical engineers you have to be familiar with the equivalent values of the base units and be able to convert from one to another.

Table 1. Common System of Units and Corresponding Base Units

Systems of Units	**Length**	**Time**	**Mass**	**Temperature**
SI (Systeme Internationale) d'Unites	meter (m)	second (s)	kilogram (kg)	kelvin (K)
CGS (centimeter, gram, second)	Centimeter (cm)	second	gram (g)	kelvin
English Absolute	Foot (ft)	second	pound (lb)	rankin (°R)
British Engineering	foot	second	slug	rankin
American Engineering	foot	second	pound mass (lb_m)	rankin

Derived units are compounded units consisting of more than one base unit.

For example:

$$Force = m.a = [M]\frac{v}{[t]} = [M]\frac{[L]}{[t]^2}$$

in SI units, the base units will be:

$$kg\frac{m}{s^2} = N(Newton)$$

So in this case the unit for Force can be expressed in terms of the ***derived unit*** **(newton)** or in ***base units*** **(kg.m/s^2).**

Table 2. Derived SI Units

Physical Quantity	Name of Unit	Definition of Unit
Energy	joule	$Kg.m^2.s^{-2}$
Power	watt	$Kg.m.s^{-2}$
Frequency	hertz	Cycle/s
Pressure	pascal	$N.m^{-2}$, Pa
Velocity	Meters per second	$m.s^{-1}$

Multiple Units- Units used to express multiples of the base unit.

For example time, the base unit is second. The ***multiple units of time*** include:

minutes = 60 seconds
hour = 3600 seconds
day = 86400 second.

These units are used for convenience when dealing with either large or very small fractional multiples of the basic units. It easier for example to quote 1 day rather than 86400 seconds.

Other Multi Unit Prefixes include:

mega (M)	=	10^6
kilo (k)	=	10^3
centi (c)	=	10^{-2}
milli(m)	=	10^{-3}
micro(μ)	=	10^{-6}
nano (n)	=	10^{-9}

1.2 CONVERSION OF UNITS

To convert units from one system to another, we simply multiply the old unit with a ***conversion factor***. This is defined as follow:

$$\textit{conversion factor} = \frac{\textit{new units}}{\textit{old units}}$$

EXAMPLE 1. ***Convert 10 m/s to ft/s.***

SOLUTION

1 m is equal to 3.28 ft.

The conversion factor is $\frac{3.28\,ft}{1\,m}$

The result is:

$$\frac{10\,\not{m}}{s} x \frac{3.28\,ft}{1\,\not{m}} = \frac{32.8\,ft}{s}$$

EXAMPLE 2. ***Convert 10 m^2/s to ft^2/s.***

SOLUTION

The conversion factor is $\frac{(3.28\,ft)^2}{(1\,m)^2} = \frac{10.7\,ft^2}{1\,m^2}$

The result is:

$$\frac{10\ m^2}{s} x \frac{10.7\ ft^2}{1 m^2} = \frac{107\ ft^2}{s}$$

EXAMPLE 3. ***Convert 10 kg.m/s² to lb.ft/min²***

SOLUTION

1 kg = 2.2 lb
1m = 3.28 ft
60 s = 1 min

The result is:

$$\frac{10 kg.m}{s^2} x \frac{2.2 lb}{1 kg} x \frac{3.28 ft}{1 m} x \frac{(60 s)^2}{(1 \min)^2} = 2.6 x 10^5 \frac{lb.ft}{\min^2}$$

1.3 DIMENSIONAL HOMOGENEITY

When adding or subtracting values, the units of each value must be similar to be valid.

EXAMPLE

A (m) =2 B(s)+5

What should the units for constants 2 and 5 have to be for the equation to be valid?

2 (m/s) and 5 (m).

1.4 WEIGHT AND MASS

Weight is the **force of gravity** on an object with a certain mass m.

For example, the **mass** of a steel ball is **10 kg.** The **weight** of this ball on the earth's surface is:

W = m.g

where g is the acceleration due to gravity. W = 10x 9.81 = 98.1 N

1. 5 SIGNIFICANT FIGURES

The significant figures quoted when expressing a value provides an indication of the accuracy of the measurement.

EXAMPLE

The measured **length** of the pipe is quoted as **2.3 m**.

This means that the accuracy of the measurement is about 2.3 ±0.05 m

If the length was quoted as 2 m, the accuracy of this measurement is 2 ± 0.5 m.

The significant figures are the first non-0 digits from the left to:
1) the last digit to the right if there is a decimal point.
2) the last nonzero digit of the number if there is no decimal point.

0.03500

non zero digit

Last digit, since there is a decimal point

4 significant figures

2500

Non zero digit, no decimal point

2 significant figures

1. 6 DIMENSIONLESS QUANTITIES

Dimensionless numbers are often used by chemical engineers, because these numbers are independent of the size or quantity of the system being considered. Thus the values can be applied to any sized system and is useful for scaling up the operation.

An example of a dimensionless quantity is Reynold's number N_{Re}.

$$N_{\mathrm{Re}} = \frac{\rho D u}{\mu}$$

where
D = characteristic length usually the diameter (m)
u = mean velocity (m/s)
ρ = fluid density (kg/m^3)
μ = viscosity

With the given units, what should the units for viscosity, if the Reynold number is to be dimensionless?

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LECTURE SERIES 2: PROCESS AND PROCESS VARIABLES

Text Reference

Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 3.

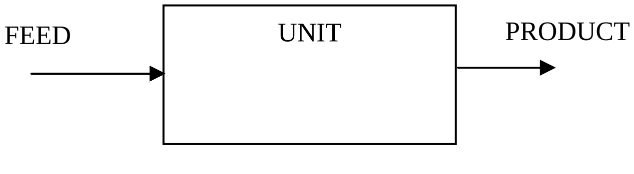
Aims:

At the end of this lecture, the students should be able to perform the following tasks:

1. State the definition of a *process* and identify its components.
2. State the definition of a *process unit* and identify its components.
3. Define density and specific volume.
4. Use density to convert a mass to a volume and vice versa.
5. Calculate density given specific gravity and the value of the reference density.
6. Use density to convert a mass flow rate to a volume flow rate and vice versa.
7. Define molecular weight.
8. Use molecular weight to convert mass (mass flow rate) to moles (mole flow rate) and vice versa.
9. Define mass and mole fraction.
10. Convert between mass and mole fractions.
11. Define mass and molar concentration.
12. Convert between mass, molar, and volumetric flow rates.
13. Define pressure and give typically units.
14. Define hydrostatic pressure and pressure head
15. State the difference between absolute pressure and gauge pressure.
16. Convert between degrees Centigrade, Fahrenheit, Kelvin and Rankin.

2.1 WHAT IS A PROCESS?

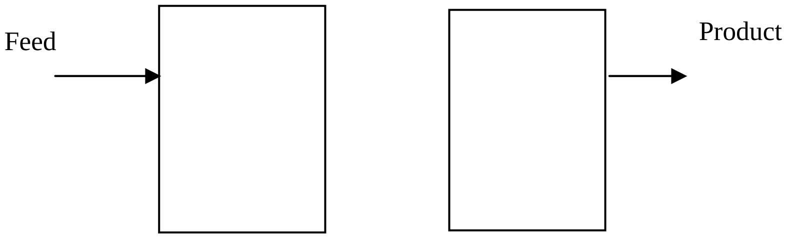
<u>Process</u> is an operation which could cause physical or chemical change in the material being processed.



The process is carried out in a **<u>unit</u>**. The material which enters the unit is the **<u>feed</u>** and the material leaving the unit is the **<u>product.</u>**

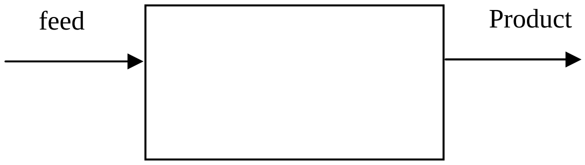
The process can be carried out in a **batch** or **continuous unit**.

<u>Batch processing</u> means the material is fed into the unit at once, processing is allowed to occur. When this is complete all products and any un-reacted reagents are withdrawn.



This processing is referred to as an **unsteady state process**. This means that the concentration of the material being processed, at a specific point in the unit, will change with time.

Continuous processing- the feed enters and the product exits the unit continuously.



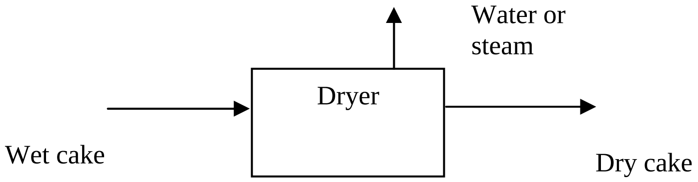
At the start up, this process will be an unsteady state process. As equilibrium is reached the system will perform as a **steady state process**. This means if we pick any point in the reactor, the concentration of the material being processed at that point will be constant. A combination of a batch and continuous process is called a **semi-batch process.**

2.2 WHAT ARE PHYSICAL AND CHEMICAL PROCESSES?

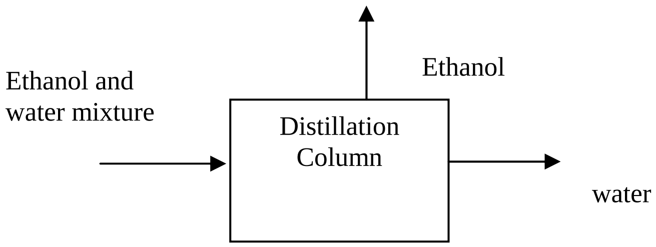
Physical Processing – are any operations which cause change in the physical properties but has no effect on the molecular structure or composition of the material being processed. In other word, processing does not involve chemical reactions.

Examples of such processing include:

1. **Drying –** separation of volatile solvent or water from a wet solid. A flowchart for this process is shown below. There are three **process streams** in and out of the unit called a **dryer.** These include feed wet cake and products which consist of the water evaporated from the wet cake and the final dry cake.

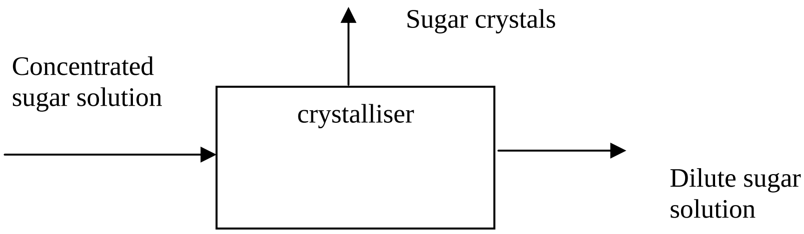


2. **Distillation**- separation of two fluids of different volatilities and boiling points.



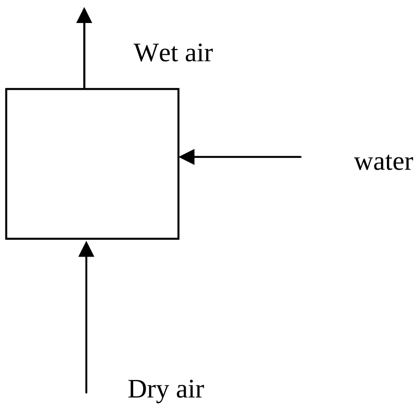
The flowsheet shows three process streams and the unit is a **distillation column**.

3. **Crystallisation** – separation of solute from liquid. For example separation of water from a sugar solution results in the formation of a supersaturated solution. The aim here is to increase the concentration of sugar in solution such that it exceeds the solubility limit for sugar. The excess sugar will therefore form solid crystals.



The unit is this process is called a **crystalliser.**

4. **Humidification** – the process whereby water is transferred into gas, eg, air.



Chemical Processing – will result in a molecular change as well as physical change in the material being processed. For example when we burn coal and convert it to gaseous products, CO_2 and CO.

2.3 EXPRESSING QUANTITIES

If you are to be able to account for materials entering and leaving the system, then the amounts of the materials must be expressed as measured values. As you will see these values will depend on the type of processing, physical or chemical, if the process is batch or continuous, and the size of the process.

Mass and Moles

Chemical formulae provide us with an indication of what reacts together and the products produced. Most importantly it provides us with the proportion by which reagents reacts and is produced. For example, the combustion of coal can be described by the following equation:

$$C + \frac{1}{2}O_2 = CO$$

From this equation, if the reaction proceeds to completion, it can be stated that 1 mole of carbon will react with 0.5 mole of oxygen to produce 1 mole of CO. These ratios are also called **stoichiometry**.

Chemical Engineering mole

$$mole\ (gmole\ ) = \frac{mass\ (g)}{molecular\ \ weight\ (g\ /\ mol\ )}$$

Chemical Engineers usually deal with very large quantities and in various units. For convenience an alternative definition to the conventional mole is used. Generally it is defined as follows:

$$mole(unit\ of\ \ mass - mole) = \frac{mass(unit)}{molecular\ weight(g / mol)}$$

We can also define it as follow:

$$mole(tonmole) = \frac{mass(tons)}{molecular\ weight(g / mol)}$$

$$mole(kgmole) = \frac{mole(kg)}{molecular\ weight(g / mol)}$$

$$mole(lbmole) = \frac{mass(lb)}{molecular\ weight(g / mol)}$$

So instead of quoting 1 000 000 gram moles we can use 1 ton-mole. The ton-mole, kg- mole and lb-mole can still be used in a similar manner to g-mole in determining the quantities of reactants used in the reaction and the quantities of products produced. One must note however that the corresponding mass associated with these molar quantities are tone, kg and lb.

2.4 DEFINITION OF CONCENTRATION

Mass Concentration: $C_M\,(g/L) = \dfrac{mass(g)}{volume(L)}$

Molar Concentration: $C_m\,(M) = \dfrac{moles}{volume}$

Note that concentration values can be used as conversion factors to convert mass or moles to volume and visa versa.

EXAMPLE C*alculate the weight of NaOH in 1 litre of 2 M NaOH solution.*

SOLUTION

Moles of NaOH = 1 ~~litre~~ x 2 $\dfrac{mole}{\cancel{litre}}$ = 2 moles.

Mass of NaOH = 2 moles x 40 g/mol = 80 grams

2.5 COMPOSITIONS

When a stream is consists of more than one compound, the values of these compounds are expressed as **fractions of the total quantity** in that stream. The value of doing this will become apparent when we start formulating mass balance equations. These values are called **compositions**. There are several ways of expressing compositions, but the most common ways are as follows:

(i) Mass Fraction

$$Mass\ \ fraction = \frac{mass(i)}{total\ mass}\,x100$$

mass(i) is the mass of individual components.

EXAMPLE ***Calculate the composition of a stream which is composed of 20 kg of CO_2, 25 kg CO and 30 kg N_2.***

SOLUTION

Components	**Mass (kg)**	**Composition wt%**
CO_2	20	26.7
CO	25	33.3
N_2	30	40.0
total	75	100

(ii) Mole Fraction

$$Mole\ \ fraction = \frac{moles(i)}{total\ moles}\ x100$$

EXAMPLE ***Calculate the compositions of a stream which is composed on 20 moles of CO_2, 25 moles CO and 30 moles N_2.***

SOLUTION

Components	**Number of moles**	**Composition Mole%**
CO_2	20	26.7
CO	25	33.3
N_2	30	40.0
total	75	100

2.6 MOLAR AND MASS FLOWRATE

In a **batch system**, the feed and product exiting from the process are expressed as **absolute mass**. For example **1 tonne of syrup** is fed into a crystallizer to produce **500 kg of sugar crystals**.

In a **continuous system**, the quantities of the materials being processed are usually measured as **mass being transferred per unit time** or **mass or mole flow**.

The following conversions are useful when dealing with a continuous system.

(i) Conversion of Mass Flow to Mole Flow

$$Mole\ Flow = \frac{mass\ \ flow}{molecular\ \ weight}$$

rearranging this equation will allow the reverse conversion.

(ii) Conversion of Mass or Mole Flow to Volume Flow

The conversion factor which is used to convert mass flow to volumetric flowrate is density of the solution of the molar concentration.

Density is defined as the mass per unit volume of a substance or alternatively.

$$Density(\rho) = \frac{mass}{volume}$$

The specific gravity of a substance is the ratio of density (ρ) of the substance to the density (ρ_{ref}) of a reference substance at a specific condition”

$$SG = \frac{\rho}{\rho_{ref}}.$$

The most common reference used for solids and liquid is water at 4°C which has the following density:

$$\rho_{H2O,l}(4°C) = 1.000\frac{g}{cm^3} = 1000\frac{kg}{m^3}$$

The mass flowrate (m, kg/s) of a liquid can be converted to its volumetric flowrate using the density of that liquid:

$$Volumetric\ \ flowrate = \dot{V} = \frac{\dot{m}}{\rho} \quad \text{or}$$

$$Volumetric\ \ Flowrate = \frac{mass}{time}\ x\ \frac{1(volume)}{density(mass)}$$

The conversion factor for **mole to volume flow** is **molar concentration**

2.7 CONVERTING MOLE% TO MASS %.

As in the above problem, the mole composition is as given.

Assume a **basis**; Total moles = 100

Components	**(1) Composition Mole%**	**(2) Number of moles**	**Mol. Wt. g/mol**	**(3) Mass g**	**(4) Composition Mass%**
CO_2	26.7	26.7	44	1174.8	36.4
CO	33.3	33.3	28	932.4	28.9
N_2	40.0	40.0	28	1120	34.7
total	100	100		3227.2	100

(1) Calculate these values based on the assumed basis

(2) Calculate the corresponding weights and add to get the total weight. Obtain the compositions by dividing each weight by the total.

(1) The mole composition is given.
(2) Calculate the absolute mole quantities by multiplying the mole% with the total number of moles (100 moles).
(3) Calculate the corresponding mass of each component by multiplying the number of moles with the molecular weight. Add the total mass.
(4) Calculate the mass % by taking each mass and dividing it by the total mass (32227.2) and multiply by 100. Check the composition adds to 100%.

This table can be used in reverse to convert mass % to mole %.

2.8 STREAM CONDITIONS

Other stream conditions which are of interest apart from the quantities are **temperature** and **pressure.**

Pressure values are expressed as follow:

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

Pressure measured from any pressure measuring device gives the **pressure gauge**. This must be corrected with the atmospheric pressure, as above, to give the absolute pressure. The atmospheric pressure is often taken as 1 atm. Note in units such as psi**a** and psi**g** the "a" term indicates absolute and the "g" term indicates gauge pressures. Negative pressure indicates vacuum pressure.

Temperature

There are several temperature scales which could be used, the table below shows the conversion between each scale:

$T(K) = T(°C) + 273.15$
$T(°R) = T(°F) + 459.67$
$T(°R) = 1.8\, T(K)$
$T(°F) = 1.8T(°C) + 32$

Temperature Differences

$T_1(K) = T_1(°C) + 273.15$
$T_2(K) = T_2(°C) + 273.15$

$\Delta T(K) = \Delta T(°C)$

That is $\Delta T(20K) = \Delta T(20°C)$

$T_1(°R) = T_1(°F) + 459.67$
$T_2(°R) = T_2(°F) + 459.67$

$\Delta T(°R) = \Delta T(°F)$

$T_1(°R) = 1.8\, T_1(K)$
$T_2(°R) = 1.8\, T_2(K)$

$\Delta T(°R) = 1.8\Delta T(K)$

That is in ΔT, 1 K = 1.8°R

$T_1(°F) = 1.8T_1(°C) + 32$
$T_2(°F) = 1.8T_2(°C) + 32$

$\Delta T(°F) = 1.8\Delta T(°C)$

That is in ΔT, 1°C = 1.8°F

CHNG 1101 CHEMICAL ENGINEERING 1A

LECTURE SERIES 3: PROCESS FLOW SHEETING

Aims

At the end of this lecture, the students should be able to perform the following tasks:

1. Given a process description, assess whether the process is batch, continuous or semi-batch
2. State the definitions of a transient and steady state process.
3. Given a process description determine whether the process is transient or steady state.
4. Given a process description: draw a process flow chart, assign values and units to known flows and compositions, and assign variable names to unknown flows and compositions.

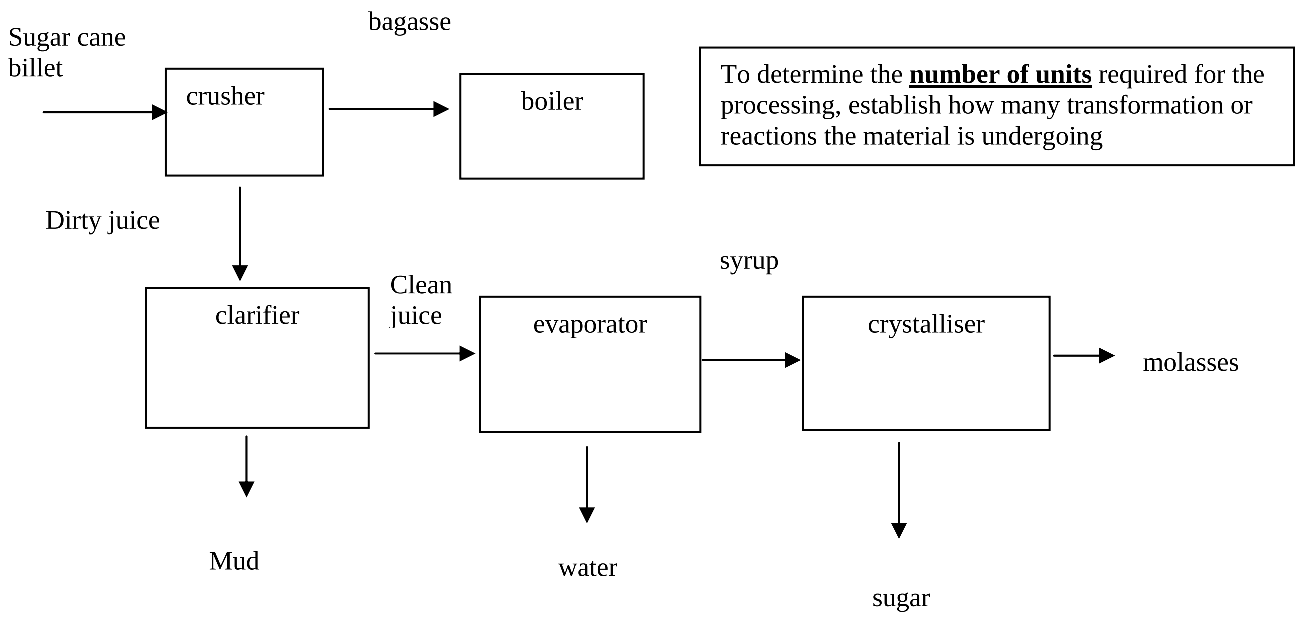
3.1 INTERPRETING PROCESS DESCRIPTION INTO A FLOWSHEET

Steps in drawing flow sheets.

1. Identify the units
2. Identify the feed, products and streams.

Process Description: Sugar Production.

Sugar cane billets, which are about 10 cm in size, are fed into the cane crusher. The juice extracted from the crusher are fed into the clarifier, whilst the remaining fibre, bagasse is sent into the boiler where it is used as fuel. In the clarifier, mud and other impurities are flocculated and settle to the bottom of the unit and the clarified juice is fed into the evaporator. The juice is concentrated in the evaporator. The syrup produced is sent to the crystalliser to separate the sugar crystals from the molasses.



To determine the **number of units** required for the processing, establish how many transformation or reactions the material is undergoing

Process: Engine

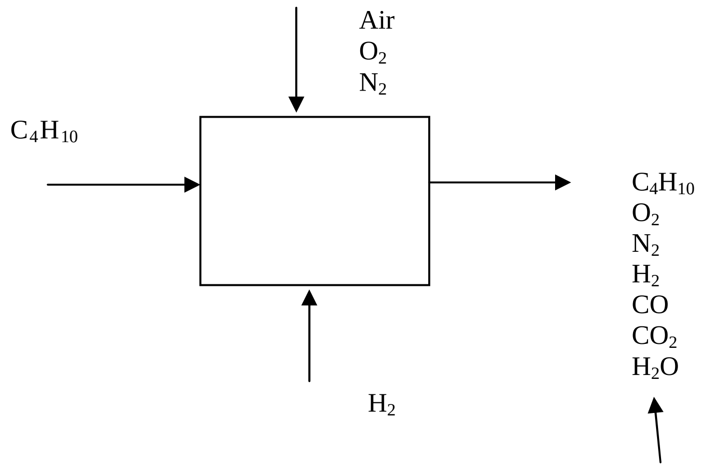
A mixture of butane and hydrogen is burnt with air. Air is made up of nitrogen and oxygen. Oxygen reacts with butane to form carbon dioxide and carbon monoxide.

Note that in this process reactions take place. If chemical reaction equations are not provided, then you must formulate them to determine all the type of products which will be produced.

$$\boldsymbol{C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O}$$

$$\boldsymbol{C_4H_{10} + \frac{9}{2}O_2 \rightarrow 4CO_2 + 5H_2O}$$

$$\boldsymbol{H_2 + \frac{1}{2}O_2 \rightarrow H_2O}$$



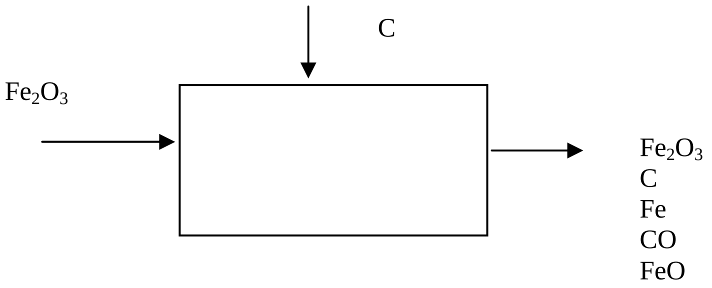
Note that the product stream must have all the products and un-reacted raw feed. Unless specified, always put the un-reacted raw feed in the product stream. If they have all reacted, you will simply get zero composition

Process: Blast Furnace

One can view the blast furnace from a simple viewpoint as a process in which the principle reaction is:

$$Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$$

In the blast furnace, coke (carbon) is mixed with pure iron oxide, Fe_2O_3, the process produces pure iron, FeO and Fe_2O_3.



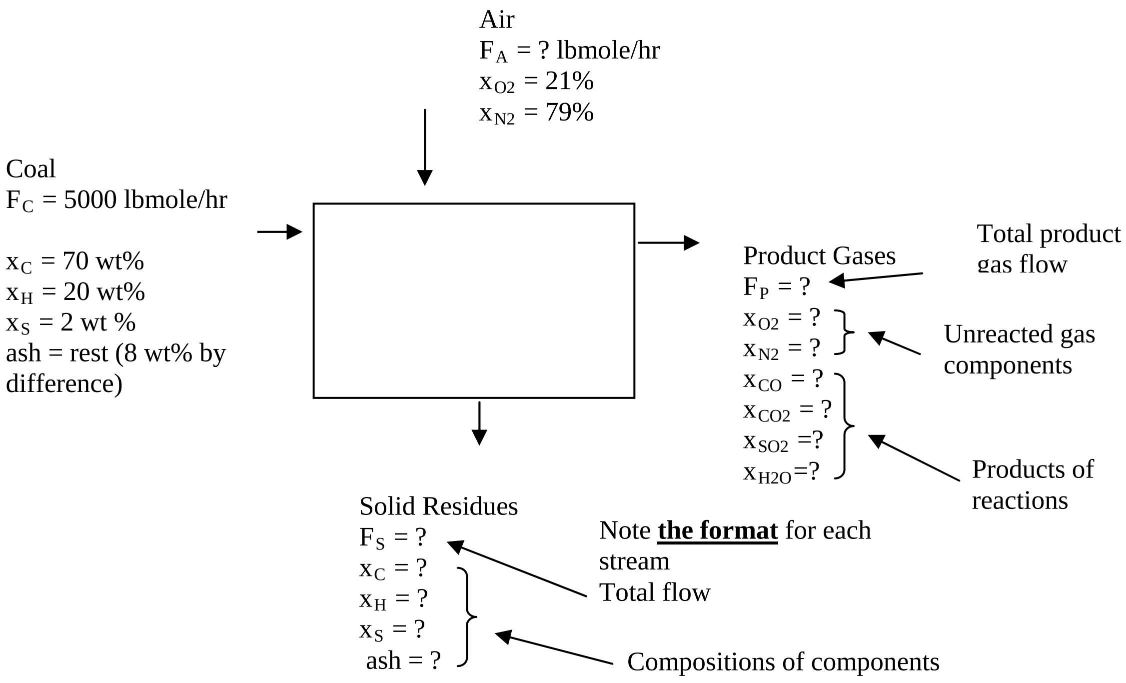
Process: Coal Combustion

Coal consists of 70wt% C, 20wt% H and 2 wt % S and the balance non combustible ash. The coal is burned at the rate of 5000 lbmoles/hr and the feed rate of air to the furnace is 50 lbmoles/min. All the ash and 4% of the carbon in the fuel leave the furnace as a solid slag; the remainder of the carbon leaves in the stable gas as CO and CO_2. The hydrogen in the coal is oxidised to water and the sulfur emerges as SO_2.

Note here you are provided with data for the process stream. Remember that process stream quantities are expressed as 1) Total mass or flow and 2) composition of that stream.

Reactions:

$$C + \frac{1}{2}O_2 \rightarrow CO$$
$$C + O_2 \rightarrow CO_2$$
$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$
$$S + O_2 \rightarrow SO_2$$


Air
F_A = ? lbmole/hr
x_{O2} = 21%
x_{N2} = 79%
Coal
F_C = 5000 lbmole/hr
x_C = 70 wt%
x_H = 20 wt%
x_S = 2 wt %
ash = rest (8 wt% by difference)
Product Gases
F_P = ?
x_{O2} = ?
x_{N2} = ?
x_{CO} = ?
x_{CO2} = ?
x_{SO2} =?
x_{H2O}=?
Total product gas flow
Unreacted gas components
Products of reactions
Solid Residues
F_S = ?
x_C = ?
x_H = ?
x_S = ?
ash = ?
Note **the format** for each stream
Total flow
Compositions of components

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LECTURE SERIES 4: INTRODUCTION TO MATERIAL BALANCE

Text Reference

Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 4, Series 4.1, 4.2 and 4.3.

Aims

At the end of this lecture, the students should be able to perform the following task:

1. State the general balance equation.
2. State the two types of balances that one may write using the general balance equation and give typical units for the terms in the balance.
3. Scale up or down the results of a material balance problem.
4. State the steps involved in solving material balance problems.

4.1 GENERATING MASS BALANCE EQUATION

Material balance are based on the **law of conservation of mass**, that is

TOTAL MASS INPUT = TOTAL MASS OUTPUT (1)

This is the basic form of a material balance equation.

The more **general form**:

$$INPUT + GENERATION - OUTPUT - CONSUMPTION = ACCUMULATION \quad (2)$$

Enters through the system boundary	+	Produced within the system (chemical reaction)	-	Material leaving the system	-	Consumed within the system (chemical reaction)	=	Build up within the system (material not leaving the system)

We use this general equation to formulate the mass balance equation for the system to solve for unknowns.

Under a **steady state** condition, that is when the concentration profile along the reactor becomes constant, then it can be assumed that the **accumulation term = 0.**

As a result, the mass balance equation can be simplified to:

$$INPUT + GENERATION = OUTPUT + CONSUMPTION \quad (3)$$

Under a condition where there is **no chemical reaction**, the material balance is simplified to:

$$INPUT = OUTPUT \quad (4)$$

4.2 PROCEDURE FOR MATERIAL BALANCE CALCULATION

1. Draw a **<u>FLOWCHART</u>** and include all the stream components (eg. total flowrate, compositions, temperature, pressure). Fill in the given values and identify and label the unknowns.

2. Choose a control volume by drawing a box around it. The **<u>control volume</u>** is the system on which the mass balance will be conducted.

3. Choose a **<u>basis</u>** for the calculation. Usually it is best to choose an amount or the flowrate of one of the streams. If no amount is given, then assume the amount or flowrate of one of the stream.

4. If the units provided are mixed, then convert all to one system of unit.

5. Write the mass balance equations for the unknowns and solve.

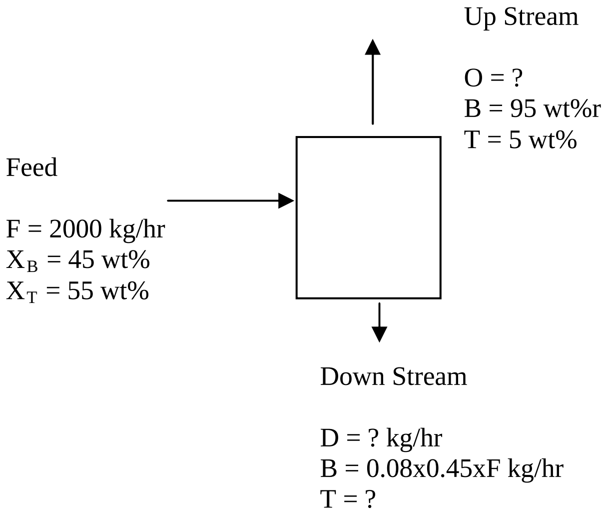
There are **<u>two types of mass balance</u>** equations which can be written for the streams:

1. **TOTAL quantity** balance (for each stream) and
2. **COMPONENT** quantity balance for each stream

Note that **TOTAL mole balance** is only feasible if **<u>no chemical reaction</u>** is involved.

EXAMPLE 1 ***A mixture containing 45% benzene(B) and 55% toluene (T) by mass is fed into a distillation column. An overhead stream of 95wt % B is produced and 8% of the benzene fed to the column leaves in the bottom stream. The feed rate is 2000 kg/hr. Determine the overhead flowrate and the mass flowrate of benzene and toluene in the bottom stream.***

SOLUTION



Basis: Feed F = 2000 kg/hr, assume steady state conditions

Note that we formulate mass balance equations to determine the unknown quantities in the system.

Since no chemical reaction is involved in this process and if we assume a steady state process, then the general mass balance equation we can use in this system is:

INPUT = OUTPUT

***Total Balance*:** F = O + D or 2000 = O + D

Component Balance

There are two components involved in this process, benzene and toluene. If we inspect the known and unknown, benzene components has the least number of unknown, therefore we will start with this component.

$$X_{B.}F = X_{B.}O + B$$
$$0.45x2000 = 0.95xO + 0.08x0.45x2000$$

Benzene balance: $O = 871.5\frac{kg}{hr}$

from (1)

$$D = 1128.4\frac{kg}{hr}$$

$$X_T F = X_T O + T$$

Toluene Balance: $0.55x2000 = 0.05*O + T$

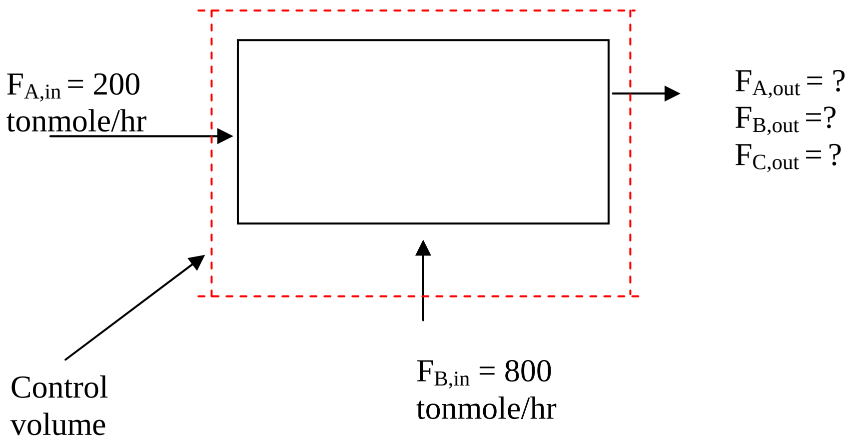
$$T = 1056.4\frac{kg}{hr}$$

EXAMPLE 2. ***Let's consider a process of producing methanol (CH_3OH) from 200 tonmole/hr methyl acetate (CH_3COOCH_3) and 800 tonmole/hr of water. Assume the reaction goes to completion. That is all the methyl acetate reacts. Calculate the composition of the product stream.***

SOLUTION

For simplification let's label the components as follow:

CH_3COOCH_3 = A
water = B
methanol = C



Basis: 200 tonmole/hr of CH_3COOCH_3 feed.

The material involved with the chemical reaction will be:

$CH_3COOCH_3 + H_2O \quad = \quad 2CH_3OH + CO$

200 tonmole 200 tonmole 400 tonmole 200 tonmole

We can now **develop a mass balance** for each of the input and output components.

Methanol Balance: *a*ssuming **steady state process**

Methanol In + Methanol Generated = Methanol Out

$$F_{C,in} + F_{C,rxn} = F_{C,out}$$

No methanol enters with the feed, $F_{C,in} = 0$

$$F_{C,out} = F_{C,rxn} = 400 \text{ tonmole}$$

(according to the reaction equation)

Water Balance: $F_{B,in} - F_{B,rxn} = F_{B,out.}$

$800 - 200 = 600$ tonmole /hr $= F_{B,out}$

Since all the methyl acetate is consumed, $F_{A,out} = 0$.

Product Composition

Components	Flow Quantities (tonmole/hr)	Composition (wt%)
A	0	0
B	600	60%
C	400	40%
Total	1000	

4.3 FORMS OF MASS BALANCE EQUATIONS

Form of balance equations:

(i) Differential Balance – balances which indicate what is happening in a system at an instant of time. Each term are quantities expressed with respect to time or a **RATE** e.g. 1000 kg/hr, 100 moles/min**.**

So far the mass balance we have been carrying out are called **Differential Balances.**

(ii) Integral Balance – describes what happens between two instants of time. Each term of the equation is an **AMOUNT** e.g. 1000 kg, 100 moles.

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LECTURE SERIES 5: BALANCES ON MULTIPLE UNIT PROCESSES

Text Reference

Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 4, Section 4.4.

Aims

At the end of this lecture, the students should be able to perform the following tasks:

1. Identify and isolate control volumes or systems
2. Set up overall and unit balances
3. Solve balances in multiple systems

5.1 SETTING UP MASS BALANCE EQUATION FOR MULTIPLE SYSTEMS

You should now be able to set up mass balance equations to determine the unknown components for a single unit. In this lecture we are going to establish the procedures for determining the unknowns for multiple systems or units. The **key** to solving multiple unit system is to **isolate a unit or group of units** and **solve** the unknowns around these systems as if they are a single unit.

The procedure:

1. Draw a **FLOWSHEET** and label the streams. Fill in the total and compositions of each component in each stream. Note any given values and other information and identify the unknown quantities.

2. **Separate each of the system** or control volume by drawing a box around each one. Note that it is also possible to consider the whole system as a control volume. The idea here is to isolate the units, then to set up the mass balance equations for each separate unit as if they are independent of each other. Once you have drawn a control volume around a single or group of units, you will only consider materials going in and out of the control volume. That is the control volume is considered as a single unit and flow streams in between the units within the control volume can be ignored.

DIVIDE, SOLVE EACH CONTROL VOLUME, THEN CONQUER!

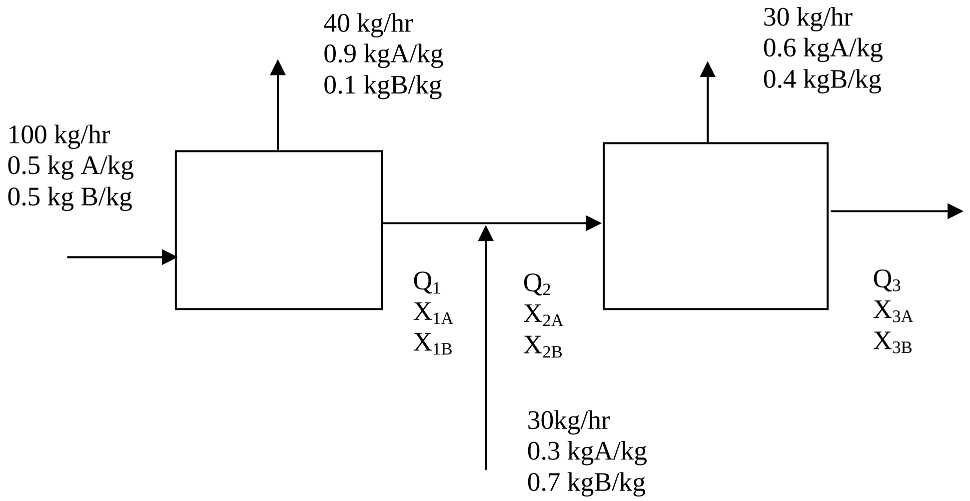
How can we recognize a control volume?

3. Each of the control volume will have feed and also exit streams.

4. Identify which control volume which has **the least number of unknowns** and set up mass balance equations for this part of the system.

5. **Solve** the mass balance for this single unit system first.

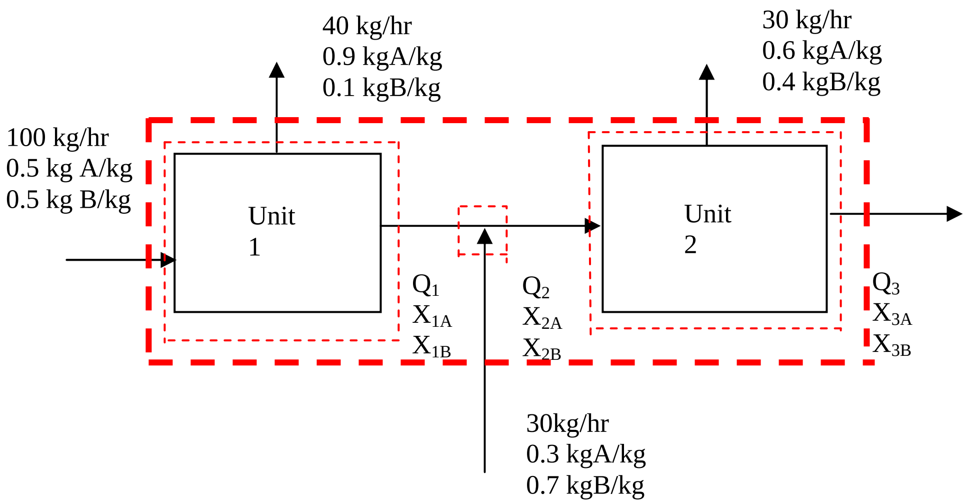
EXAMPLE



SOLUTION

Solve for unknowns.

1. Isolate control volumes.

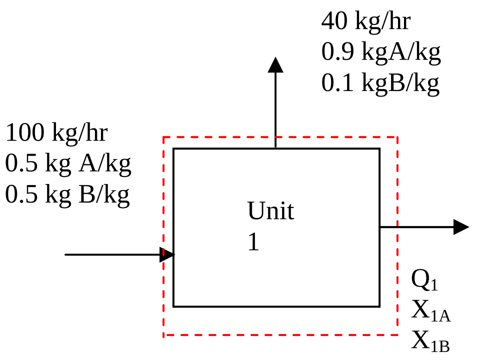


Note that we have isolated **4 control volumes**.

2. We can now conduct a mass balance on each of these control volumes and consider them as if they are individual systems.

3. Mass balance around Unit 1

<u>Basis:</u> 100 kg of Feed into Unit 1



Total Mass Balance: $100 \text{ (kg/hr)} = 40 \text{ (kg/hr)} + Q_1 \text{ (kg/hr)}$

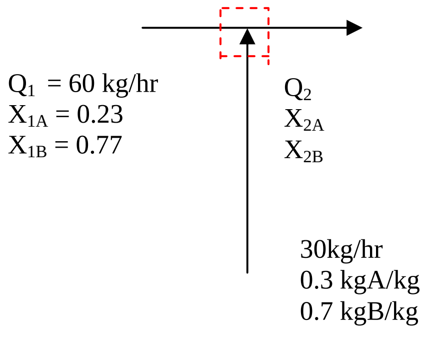
$Q_1 = 60$ kg/hr

Component (A) Balance: $0.5x100 = 0.9x40 + X_{1A}x60$

$X_{1A} = 0.23$

There fore $X_{1B} = 0.77$

Mass Balance Around the Mixing Unit.



Total Balance: $60 \text{ (kg/hr)} +30 \text{ (kg/hr)} = Q_2$

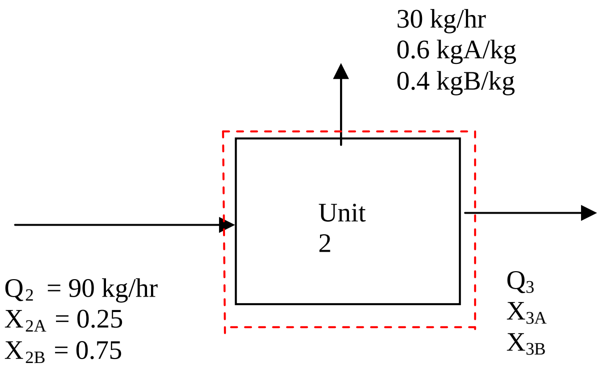
$Q_2 = 90$ kg/hr

Component (A) Balance: $0.23x60 +0.3x30 = X_{2A}x90$ kg/hr

$X_{2A} = 0.25$

Therefore $X_{2B} = 0.75$

Mass Balance Around Unit 2



Total Balance: $90\ (kg/hr) = 30\ (kg/hr) + Q_3$

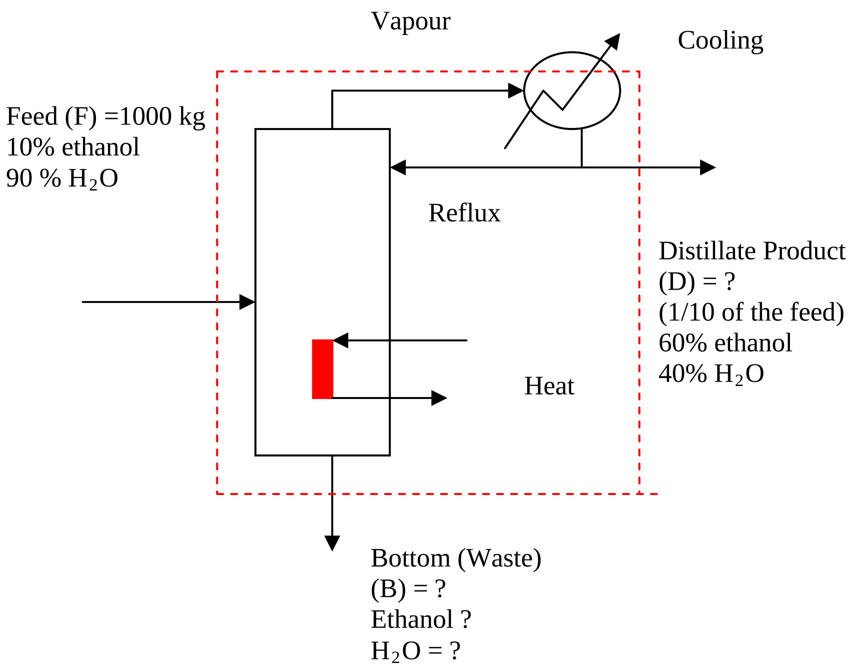
$Q_3 = 60\ kg/hr$

Component (A) Balance: $0.25x90 = 0.6 \times 30 + X_{3A} \times 60\ (kg/hr)$

$X_{3A} = 0.075$

Thus $X_{3B} = 0.925$

EXAMPLE ***A moonshiner is having a bit of difficulty with his still (shown below). He finds he is loosing too much alcohol in the bottom (waste). Calculate the composition of the bottom for him and the weight of the alcohol lost in the bottom.***



SOLUTION

The solution to this problem is easily obtained by conducting an overall mass balance.

Basis : 1000 kg of feed

Overall Balance:

Total Balance: $F = D + B$

$= 1/10(1000) + B$

$B = 1000-100 = 900$ kg

Ethanol Balance: $0.1x1000 = 0.6x100 + X_B x900$

$X_B = 0.044$

$X_E = 0.9556$

Weight of ethanol lost = 0.044 x 900 = 39.6 kg.

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LECTURE SERIES 6: BALANCES ON REACTIVE SYSTEMS

Text Reference

Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 4, Sections 4.6-4.9.

Aims

At the end of this lecture, the students should be able to perform the following tasks:

1. Determine the stoichiometric equation for a chemical reaction (i.e. determine the proper stoichiometric coefficients).
2. Determine which reactant is the limiting reactant for a chemical reaction.
3. Determine the percentage excess of a reactant.
4. Determine the fractional conversion of a reactant.
5. Determine yield and selectivity for reactors which involve multiple reactions.
6. Calculate overall conversion and single-pass conversion.
7. Write the material balance equations for a reactor using: extents of reactions, atomic balances, and molecular balances.
8. Define partial combustion and complete combustion.
9. Calculate compositions using both a wet and dry basis.
10. Calculate theoretical oxygen, theoretical air, and percent excess air.

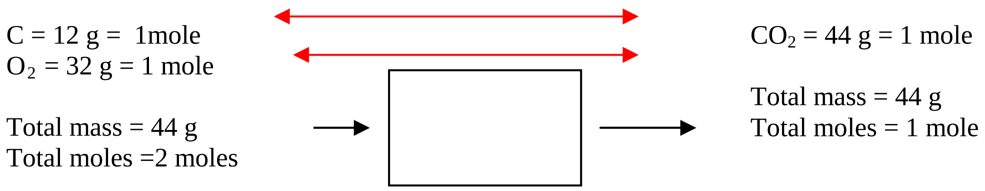
6.1 SETTING UP MASS BALANCE WITH A CHEMICAL REACTION

Mass balances involving chemical reactions

1) Total mass balance - Yes (conservation of mass must be preserved). This is hardly used to solve a mass balance problem because it is complicated to use. Most of the time this is used to check the mass balance conducted is correct.

$C + O_2 = CO_2$ CO_2 = 44 g = 1 mole

Total mass = 44 g
Total moles = 1 mole



2) Total mole balance - **No** (mole balance often is not preserved)

INPUT TOTAL MOLES ≠ OUTPUT TOTAL MOLES

the TOTAL MOLE BALANCE cannot be used to solve the mass balance problem.

However it is also possible to get total mole balanced, for example

$$CH_4 + 2\,O_2 = CO_2 + 2H_2O$$
3 moles in = 3 moles out

This does not hold in general, thus we do not use a TOTAL balance (in moles) when a chemical reaction is involved in the process.

3) Component balances = **Yes** , BUT **the reaction must be known** with the amount consumed and generated from the chemical reaction.

If only ONE or TWO reactions are involved, then this type of mass balance is straightforward. However, in the real system, several reactions can be involved, and often the actual reactions involved may not be known.

4) Elemental Balance – Yes Since the elements eg. C, H, O are conserved, in terms of both MASS and MOLE, elemental balances could be used WITHOUT HAVING TO KNOW ANYTHING ABOUT THE REACTIONS INVOLVED.

That is the following mass balance, for carbon say, could be used:

TOTAL MASS of carbon IN = TOTAL MASS of carbon OUT

TOTAL MOLES of carbon IN = TOTAL MOLES of carbon OUT

What kind of Mass Balance Equations Can I Develop?

At this stage you should now recognise that you can write the following mass balance equations:

No reactions are involved:

- Total mass balance
- Component mass balances

Chemical Reactions (but quantities reacting are unknown):

- Total mass balance (Yes)
- Total Mole Balance (No)
- Component Balance (No)
- **Elemental Balance (Yes)**
- **Tie Component (Yes)**

Chemical Reactions (quantities reacting are known):

- Total mass balance (Yes)
- Total Mole Balance (No)
- Component Balance (Yes)

- **Elemental Balance (Yes)**
- **Tie Component (Yes)**

These are the rough rules of thumb and will work for most cases.

DEFINING CHEMICAL REACTIONS

In this section we will define a few terms which are used to describe the engineering aspects of chemical reactions. These parameters are required to enable mass balance to be conducted in systems where the reactions are occurring.

STOICHIOMETRY

Stoichiometry is the theory of the **proportion** in which chemical species combine with one another.

Stoichiometry limits the reaction

e.g. $2SO_2 + O_2 \rightarrow 2SO_3$ ← Balanced equation

Stoichiometric numbers

6.4 LIMITING AND EXCESS REACTANTS

In a process, some reactants will tend to be more expensive that the rest. It would be more economical if these reactants are used in excess and as such the more expensive reactants are totally consumed in the reaction. For example, in combustion reaction air is cheaper than coal. Thus we can use air in excess.

We will define two terms that will be used to identify the extent to which reactants are supplied to the system.

Limiting Reactants = present in less than its stoichiometric proportion.

Thus the other reactants must be supplied in **Excess**.

EXAMPLE ***100 kgmole of ethylene (C_2H_4) and 100 kgmole of oxygen is fed into a burner. Determine which reactant is limiting and which is in excess***.

SOLUTION

The balanced chemical reaction for this system is:

$$2C_2H_4 + O_2 \rightarrow 2C_2H_4O$$

The easiest way to determine the limiting and excess reactants is to **compare the stoichiometric and real ratio.**

$$\begin{array}{cc} \textit{stoichiometry} & \textit{real} \\ \frac{C_2H_4}{O_2} = \frac{2}{1} & \frac{100kgmole}{100kgmole} = \frac{1}{1} \end{array}$$

Always bring the ratio such that the denominator is equal to 1

The **test is always conducted on the numerator first**, that is:

For $\mathbf{C_2H_4}$ Stoichiometry = 2 > real = 1, this is the **limiting reactant**. That is the material actually supplied is less than what is required by stoichiometry.

Oxygen must be in excess.

Let say 300 kgmoles of C_2H_4 and 100 kgmole of oxygen are supplied.

$$\mathrm{Re}\,al$$

$$\frac{C_2H_2}{O_2} = \frac{300kgmoles}{100kgmoles} = \frac{3}{1}$$

$C_2H_{4,}$ stoichiometry = 2 < Real = 3, C_2H_4 is in excess, oxygen is limiting.

What happens in a real situation?

Chemical reactions do not take place instantaneously; often the reactions could be slow. It may also be uneconomical and impractical to proceed to full conversion of the limiting reactants. Thus there will be un-reacted reactants leaving with the material exiting the system. Depending on the economics of the system, this material may be separated and recycled.

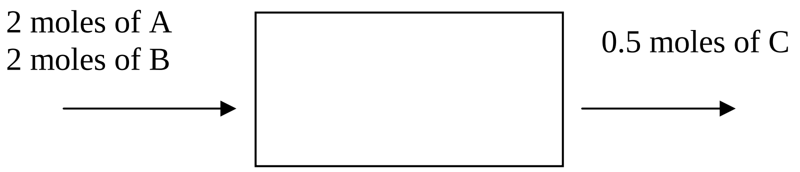
6.5 FRACTIONAL CONVERSION

Now we will define a term called **fractional conversion**, which is used to give an indication of the extent by which the reaction proceeded.

$$\textit{fractional conversion} = \frac{\textit{moles reacted (limiting reactant)}}{\textit{moles fed (limiting reactant)}}$$

EXAMPLE *Consider the following reaction being carried out in the reactor shown below:*

2A + B = C



What is the fractional conversion of this system?

SOLUTION

limiting reactant:

Stoichiometry	Real
$\frac{A}{B} = \frac{2}{1}$	$\frac{2moles}{2moles} = \frac{1}{1}$

For A (Stoichiometry = 2) > Real = 1, therefore A is the limiting reactant and B is in excess.

fractional conversion: $$\frac{\textit{moles of limiting reactant which reacted}}{\textit{moles of limiting reactant fed}} = \frac{1}{2} = 0.5$$

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LECTURE SERIES 7: BALANCES ON COMBUSTION SYSTEMS

Text Reference Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 4, Section 4.8.

Aims

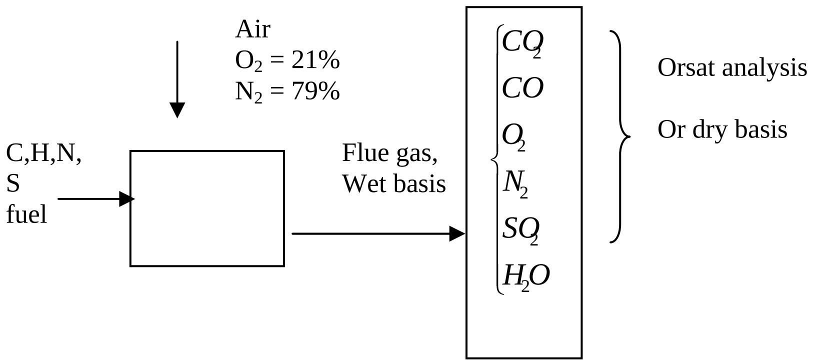
At the end of this lecture, the students should be able to perform the following task:

1. Define fluestack gas (wet basis), Orsat analysis (dry basis), theoretical air (oxygen), required air (oxygen), and excess air (oxygen).
2. Define complete and partial combustion
3. Conduct material balance involving combustion reactions
4. Use elemental balances to solve mass balance problems

7.1 Defining the Gas Composition

The combustion reactions involve the reaction of a carbonaceous material with oxygen (or air). The carbonaceous material of fuel could include elements such as C, H, O, S and N. The source of oxygen generally used for combustion of fuel is air, since it is cheap and readily available.

The combustion reaction of fuel will produce the following product gases:



Flue stack gas

All gases produced from the combustion reaction including water (**wet basis**)

Orsat analysis

All gases excluding water (**dry basis**)

7.2 Combustion Reactions

a) Complete combustion

All the carbon is converted to CO_2

$$C + O_2 = CO_2$$

b) Partial combustion
The carbon is partially converted to CO.

$$C + 1/2O_2 = CO$$

c) Theoretical Oxygen
The moles of oxygen required for complete combustion of all fuel fed into the reactor. That is all C is converted to CO_2 and all H to H_2O.

d) Theoretical Air
Moles of air which contains theoretical oxygen

$$theoretical\ air = \frac{theoretical\ oxygen}{0.21}$$

e) Excess oxygen
Amount by which the air fed to the reactor exceeds the theoretical air.

$$\%Excess\ O_2 = \frac{O_{2\,fed} - O_{2theoretical}}{O_{2theoretical}} \text{x}100$$

Note the percent excess oxygen is equal to percent excess air.

$$\%Excess\ air = \frac{O_{2(fed)}/0.21 - O_{2theoretical}/0.21}{O_{2theoretical}/0.21} x100 = \%Excess\ O_2$$

EXAMPLE 1

100 moles/hr of C_4H_{10} and 5000 moles/hr of air are fed into a combustion reactor. Calculate the percent excess air.

SOLUTION

$$C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$

100 650 400 500 (moles/hr)

theoretical O_2 = 650 moles/hr

theoretical air = 650/0.21 =3094 moles/hr

$$\%Excess\ air = \frac{5000 - 3094}{3094} x100 = 61.6\%$$

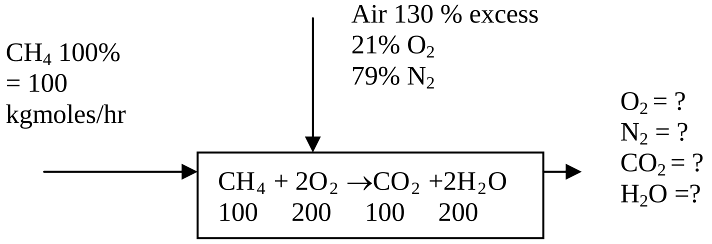
EXAMPLE 2

100 % methane is fed into a burner with 130% excess air. Assuming complete combustion occurs; give the composition of the product gas both as stack (wet basis) and orsat analysis (dry basis).

SOLUTION

Since complete combustion occurs, we know the product will include CO_2. The quantities in the product stream are unknown. We will assume a feed basis to enable the estimation of the compositions of the product stream.

Basis**:** 100 kgmole/hr of CH_4 feed



O_2 Balance: from the reaction,

O_2 required to react completely with CH_4 = 200 kgmoles/hr.= $O_{2theoretical}$

Estimating O_2 in from % excess air (130%):

$$\%Excess = 1.30 = \frac{O_2(IN) - O_{2theoretical}}{O_{2theoretical}}$$

rearranging the equation,

O_2 (In) = 460 kgmoles/hr

Air balance: Air (In) = 460/0.21 = 2190.47 kgmoles/hr

Nitrogen balance: N_2(In) = 1730.5 kgmoles/hr = N_2(out)

O_2 Balance: O_2 (out) = 460-200 = 260 kgmoles/hr

Product Composition

Components	Flowrate kgmoles/hr	Flue gas composition %moles	Flowrate kgmoles/hr	Orsat Analysis %moles
O_2	260	11.4	260	12.4
N_2	1730.5	75.5	1730.5	82.8
H_2O	200	8.7		
CO_2	100	4.4	100	4.8
Total	2290.5	100	2090.5	100

7.3 ELEMENTAL BALANCE

Elemental balance is useful when we do not know the chemical reactions involved in the process. Since elements are conserved we can use the following mass balance:

Element In = Element Out

EXAMPLE

An unknown carbonaceous fuel is burnt with 100 % excess air. The product gas has the following analysis:

1.3 mole % CO
5.2 mole % CO_2
7.1 mole % O_2
73.4 mole % N_2 and 15 mole % H_2O

Determine the ratio of H/C in the fuel fed into the combustion rig.

SOLUTION

***Basis**:* 100 moles of product gas

***C balance*:** C(In) = 1.3+5.2 = 6.5 moles

***H Balance*:** H(In) = 2x15 =30 moles

H/C = 30/6.5 = 4.6

CHNG 1101 CHEMICAL ENGINEERING 1A

LECTURE SERIES 8: RECYCLE, BYPASS AND PURGE

Text Reference

Felder R.M. and Rousseau R.W. "Elementary Principles of Chemical Processes, Chapter 4, Section 4.5.

Aims

At the end of this lecture, the students should be able to perform the following tasks:

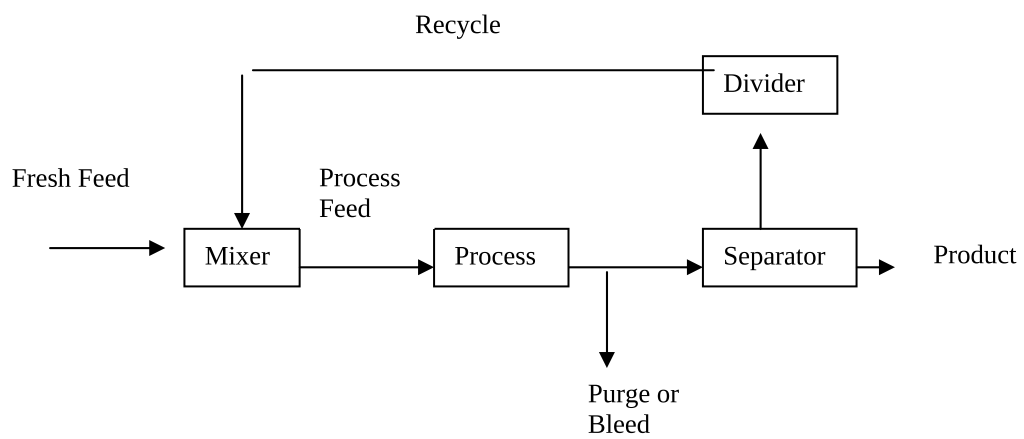
1. Define recycle, bypass, purge, and bleed stream.
2. Formulate mass balance on reactive systems with recycle and bypass.
3. Define overall conversion and single pass conversion.

8.1 RECYCLE STREAM

Recycle = feed back un-reacted material into the system

Purge = bleeding off a stream. The purpose of this is to remove an accumulation of inerts or unwanted material that might otherwise build up in the recycle stream.

A flow sheet representing this step is as follows:



In the recycle stream note that:

(i) The process is in **STEADY STATE** that is no build up or accumulation takes place in the process or in the recycle stream.

(ii) Fresh feed = feed to the system

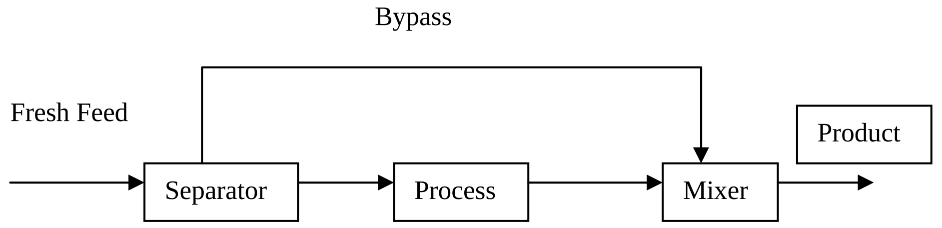
(iii) Process feed = feed to the reactor = fresh feed + recycle stream

(iv) Stoichiometry of reaction must be taken into account in the mass balance if reaction occurs.

8.2 BYPASS STREAM

Bypass = one that skips one or more stages of the process and goes directly to another stage.

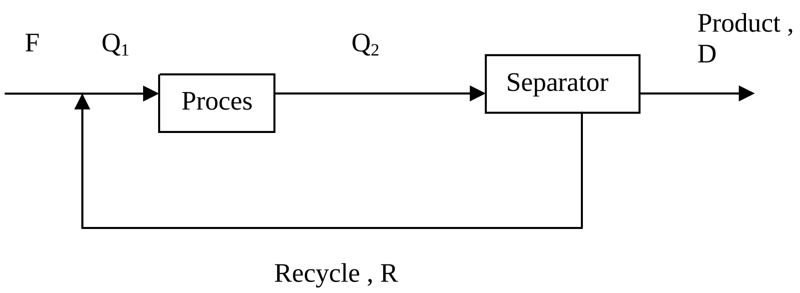
A flow sheet representing this process is as follows:



Note: The separator can split the fresh feed into 2 streams with the same composition or a pure component and a mixed component.

8.3 BALANCES ON REACTIVE SYSTEMS WITH RECYCLE AND BY-PASS

The extent of reaction in a system with recycle and bypass can be measured using overall conversion or single pass conversion.



$$\boldsymbol{O.C.} = \frac{\textit{reactant input to process} - \textit{reactant output from process}}{\textit{reactant input into the process}}$$

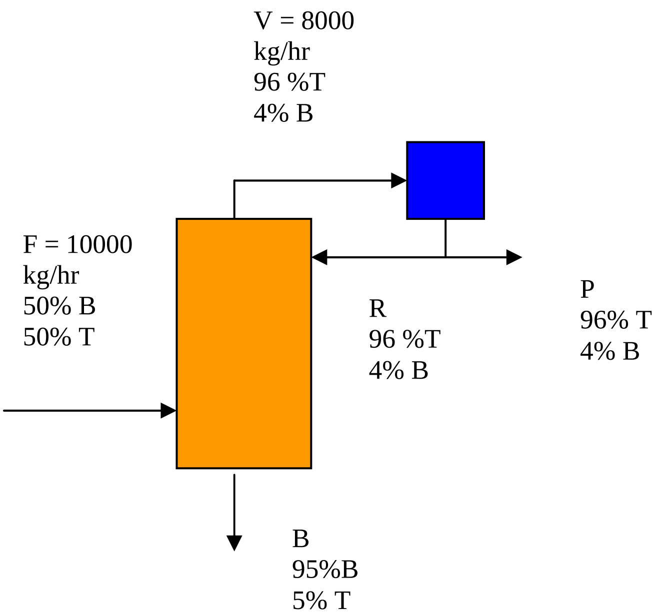
Overall conversion: $= \dfrac{F - D}{F}$

Single pass conversion: $\boldsymbol{S.C.} = \dfrac{\textit{reactant input to reactor} - \textit{reactant output from reactor}}{\textit{reactant input to reactor}} = \dfrac{Q_1 - Q_2}{Q_1}$

EXAMPLE** **A distillation column separates 10 000 kg/hr of 50% benzene (B) and 50% toluene (T) mixture. The product recovered from the condenser at the top of the column contains 96% toluene. The vapour stream entering the condenser from the top of the column is 8000 kg/hr. A portion of the product is returned to the column a reflux, and the rest is withdrawn for use elsewhere. Assume that the composition of the stream at the top of the column (V), the product withdrawn (D), and the reflux (R) are identical. The bottom stream has 95 % benzene. Find the ratio of the amount refluxed to the product withdrawn.

SOLUTION

Basis : Feed = 10000 kg/hr



Overall Balance

Total Balance:	10 000 = P + B	(1)
Benzene Balance:	5000 = 0.04 P + 0.95 B	(2)

Solve (1) and (2) simultaneously

P = 4945 kg/hr
B = 5054.9 kg/hr

Condenser Balance

Total Balance: 8000 = R + 4945

R = 3055 kg/hr

R/P = 3055/4945 = 0.61

8.4 RECYCLE WITH CHEMICAL REACTION

EXAMPLE ***1.56 kgmoles/hr of HI is reacted with CH_3OH to produce CH_3I according to the following reaction:***

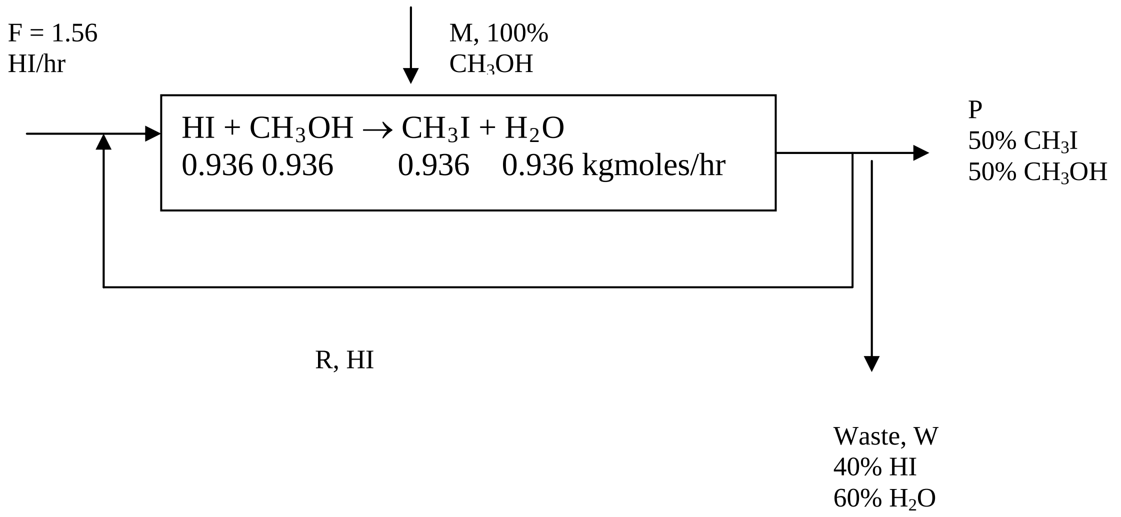
$HI + CH_3OH \rightarrow CH_3I + H_2O$

HI is separated from the product stream and recycled back into the reactor. The product contains 50 mole% CH_3I and 50mole % CH_3OH and the waste stream contains 40 mole% HI and 60% H_2O. The single pass fractional conversion of the process is 40%.

Calculate:

(i) methanol added
(ii) amount of HI recycled.

SOLUTION



Overall Balance

HI Balance: Let the amount of HI which have reacted = x

input – consumption = output

$- x = 0.4 W \qquad (1)$

H_2O balance: Input + generation = output

$0 + x = 0.6 W \qquad (2)$

solving (1) and (2) simultaneously gives:
W = 1.56 kgmole/hr
X = 0.936 kgmoles/hr.

CH_3I Balance: Generation = Output

0.936 = 0.5 P
P =1.872 kgmole/hr

Methanol Balance: Input –Consumption = Output

M – 0.936 = 0.5x1.872
M = 1.872 kgmole/hr

We have been told that the **fractional conversion = 40%**

Fractional conversion: $\mathbf{f} = \dfrac{HI_{rxn}}{HI_{reactor\ fed}}$

HI fed to the reactor = 1.56 + R

HI reaction = 0.936 = 0.4(1.56+R)

R = 0.78 kgmole/hr.

CHNG 1103 INTRODUCTION TO MATERIAL AND ENERGY TRANSFORMATIONS

TUTORIAL 1

Basic Skills: Unit Conversion

References:

(i) Felder R.M. and Rousseau R.W., Elementary Principles of Chemical Processes, Chapters 2 and 3.
(ii) Lectures 1-3.

Tutorial Due Date*: Thursday, Week 2*

OVERVIEW

This tutorial trains you to avoid the most common "unforced error" found in engineering – failure to account for units. In most cases unit conversion is a trivial matter, with many conversion values known to all engineers (eg. 12 inches = 1 ft, 25.4 mm = 1 inch, 14.7 psi = 1 atm, 2.205 lbm = 1 kg) however, conversion of compound units such as BTU/lb °F into J/kg °C, requires a rigorous method to avoid mistakes. As a professional engineer you will be expected to be able to handle quantities given in any units.

QUESTION 1

Using the table of conversion at the front of F&R to convert the following.

I. 1 day to microseconds
II. 1 mi^3 to m^3
III. 10 kW.hr to N.m
IV. 1 ft^3/s to gal/min
V. 20 g/m.s to lbf. hr/ft^2

QUESTION 2

Convert the densities of the following to kg/m^3 (see F&R Section 3.1)

I. A liquid with a density of 60 oz/gallon
II. A solid with a specific gravity of 7.8

The specific gravity (SG) of a substance is the ratio of density of the substance (ρ) to the density of the reference substance (ρref). That is:

$$SG = \frac{\rho}{\rho_{ref}}$$

The most common reference material is water at 4 °C (ρ_{ref} = 1000 kg/m^3)

QUESTION 3

Convert the following temperatures (see F&R Section 3.5)

I. T=100°C to °F, K and °R
II. T=100°F to °C, K and °R

and temperature intervals

III. ΔT=100°C to °F, K and °R

IV. ΔT=100°F to °C, K and °R

QUESTION 4

Convert the following pressures (see F&R Section 4)

I. 100 atm to Pa
II. 35mmHg to mmH_2O @4°C
III. 200 kPa to cmH_2O
IV. 10 psig to kPa(gauge)
V. 10 psig to kPa (abs)

QUESTION 5

Give the sum of the following in SI units (i.e. make the quantities dimensionally homogeneous before adding their values)

I. 0.5 W +0.5cal/s
II. 2.5 quartz +10 ft^3

QUESTION 6

Perry's Chemical Engineering Handbook lists the following properties for acetone:

heat capacity: Cp = 0.514 BTU/(lb °F)
thermal conductivity: λ = 0.102 (BTU.ft)/(hr ft^2.°F)

Note that Cp is used to calculate the sensible heat of a substance (E) using the equation:

$$E = mc_p \Delta T$$

and thermal conductivity (λ) is used in calculating the rate of energy transfer (Q) from the equation:

$$Q = \frac{\lambda}{x} A \Delta T$$

Convert this data into SI units (i.e. Cp to J/kg K and λ to W/m K)
Give a common use for this chemical

QUESTION 7

The Colburn equation for heat transfer is:

$$\left(\frac{h}{CG}\right)\left(\frac{C\mu}{k}\right)^{2/3} = \frac{0.023}{(DG/\mu)^{0.2}}$$

where C = heat capacity , Btu/(lb_{fluid}.°F)
μ = viscosity, lb/(hr.ft)
k = thermal conductivity , (Btu.ft)/(hr.ft^2.°F)
D = pipe diameter, ft
G = mass velocity, lb/(hr.ft^2).

What are the units of the heat transfer coefficient h?

CHNG 1103 INTRODUCTION TO MATERIAL AND ENERGY TRANSFORMATIONS

TUTORIAL 2

Basic Skills: Introduction to Material Balance

References:

(i) Felder R.M. and Rousseau R.W., Elementary Principles of Chemical Processes, Chapter 4, Sections 4.0-4.3.

(ii) Lecture 4.

Tutorial Due Date: Thursday Week 3

QUESTION 1

I) Convert the following composition from mole % to mass % by assuming a basis.

SO_2 20mole%
NO_2 35 mole%
H_2O 45 mole%

II) What would be the weight of each component if the total weight of the gas is 2350 g ?

QUESTION 2

Convert the following composition from mass % to mole %

C_4H_8=10 wt%
O_2=15 wt%
CO_2 =35 wt%
H_2O =40 wt%

QUESTION 3

Water enters a 2 litre tank at the rate of 100 g/min and is withdrawn at a rate of 2.5 g/s. The tank in initially half full.

I. Draw a flowsheet to represent this process.
II. Is this process continuous, batch or semi batch? Is it transient or steady state?
III. Write a mass balance for this process (Note that the mass balance must be dimensionally homogeneous.
IV. How long will it take the tank to drain completely.

(Assume the density of water is 1 g/ml)

QUESTION 4

One hundred pounds per minute of a mixture containing 60% oil and 40% water by mass are fed into a settling tank that operates at a steady state. Two products streams emerge from the settler, the top one contains pure oil, and the bottom one is 90 % water by mass.

I. Draw a flow sheet to represent this process.

II. Write a differential mass balance on water and total mass to calculate the flowrates of the two product streams.

QUESTION 5

To prepare a solution of 50 wt% H_2SO_4, a dilute waste acid containing 28 wt% H_2SO_4 is fortified with a purchased acid containing 96 wt% H_2SO_4.

I. Draw a flow sheet to represent this process.
II. Write a differential mass balance on the total and sulfuric acid balance and calculate how many kilograms of the purchased acid must be bought for each 100 kg of dilute acid.

CHNG 1103 INTRODUCTION TO MATERIAL AND ENERGY TRANSFORMATIONS

TUTORIAL 3

Basic Skills: Mass Balances Calculations in Multiple Units

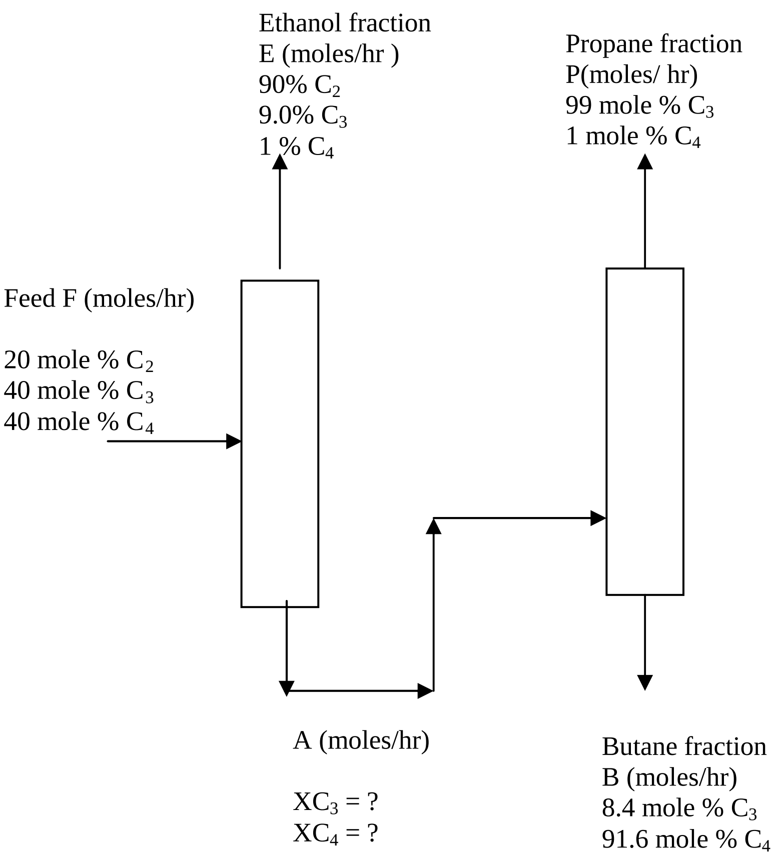
References:

(i) Felder R.M. and Rousseau R.W., Elementary Principles of Chemical Processes, Chapter 4, Section 4.4.
(ii) Lectures 5

Tutorial Due Date: Thursday, Week 4

QUESTION 1

In a distillation train a liquid hydrocarbon containing 20 mole% ethane (C2), 40 mole % propane (C3) and 40 mole % butane (C4) is to be fractionated into essentially pure components as shown in the diagram below.



a) Isolate each control volume and:

I. Identify the unknowns,
II. Determine the number of mass balance equations which can be written for each control volume,

III. Establish if the mass balance equations in each control volume is solvable (i.e. number of unknowns≤ number of equations)

b) On the basis of F = 100 moles/hr, what is P and B(in moles/hr) and the composition of stream A?

QUESTION 2

Coffee beans contain components that are soluble in water and others that are not. Instant coffee is produced by dissolving the soluble portion in boiling water (i.e. by making coffee) in large percolators, then feeding the coffee to a spray drier in which the water is evaporated, leaving the soluble coffee as dry powder. The insoluble portion of the coffee beans (the spent grounds) passes through several drying operations, and dried grounds are either burned or used as landfill. The solution removed from the grounds in the first stage of the drying operation is fed to the spray drier to join the effluent from the percolator. A flow chart of this process is shown below. The symbol S and I denote the soluble and insoluble components of the coffee beans, W is water and C is a solution containing 35% S and 65 % W by mass.

a) Isolate each control volume and identify:

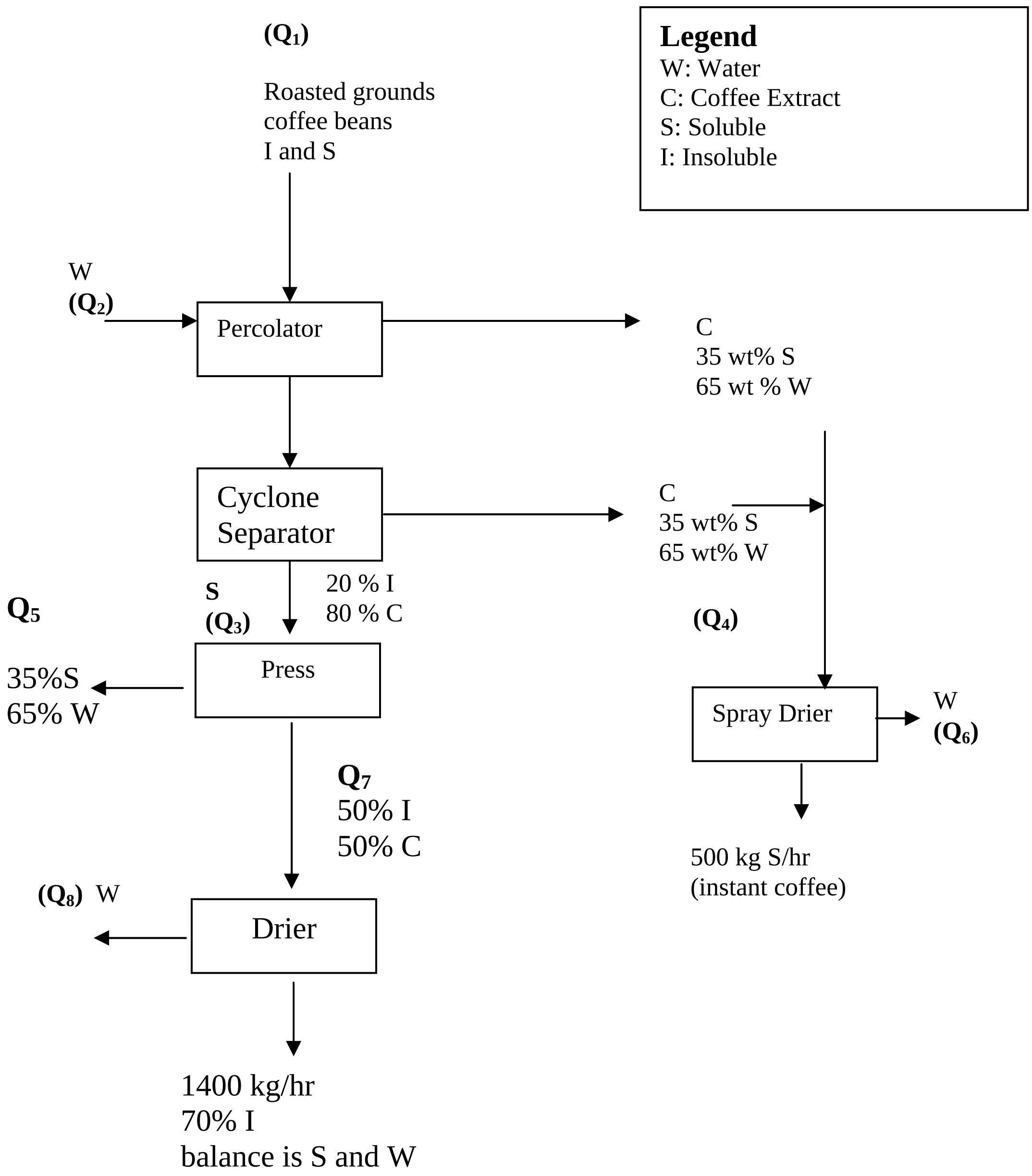
I. The unknowns

II. The number of mass balance equations which can be written for each control volume.

III. Establish if the mass balance equations in each control volume is solvable (number of unknowns≤ number of equations)

IV. Calculate the flowrates (kg/hr) of each stream Q_1 to Q_8.

b) If the liquid effluent from the press (Q_5) could be fed to the spray drier without affecting the taste of the product, by what percentage could the production rate of instant coffee be increased?


(Q1)
Roasted grounds coffee beans I and S
Legend
W: Water
C: Coffee Extract
S: Soluble
I: Insoluble
W (Q2)
Percolator
C 35 wt% S 65 wt % W
Cyclone Separator
C 35 wt% S 65 wt% W
S (Q3)
20 % I 80 % C
Q5
35%S 65% W
Press
(Q4)
Spray Drier
W (Q6)
Q7 50% I 50% C
500 kg S/hr (instant coffee)
(Q8) W
Drier
1400 kg/hr 70% I balance is S and W

CHNG 1103 INTRODUCTION TO MATERIAL AND ENERGY TRANSFORMATIONS

TUTORIAL 4

Basic Skills: Balances on Reactive Systems

References:

(i) Felder R.M. and Rousseau R.W., Elementary Principles of Chemical Processes, Chapter 4, Sections 4.5-4.9.
(ii) Lecture 6, 7 and 8.

Tutorial Due Date: *Thursday, Week 6*

QUESTION 1

Acrylonitrile (C_3H_3N) is produced by the reaction of propylene (C_3H_6), ammonia (NH_3) and oxygen (O_2):

$$C_3H_6 + NH_3 + \frac{3}{2}O_2 \rightarrow C_3H_3N + 3H_2O$$

The feed contains 10 mole % propylene, 12 moles % NH_3 and 78% air.

I. Which reactant is limiting? By what percentage is each of the others in excess?
II. Calculate the kg mole of C_3H_3N produced per kgmole of NH_3 feed for a 30% conversion of the limiting reactant.

QUESTION 2

The reactions:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$
$$C_2H_6 + H_2 \rightarrow 2CH_4$$

take place in a continuous reactor at steady state. The molar flow rate of the feed stream is 100 kgmole/hr, and that of the product stream is 140 kgmole/hr. The composition of these gases is given below:

Mole %			
Feed		Product	
C_2H_6	85%	C_2H_6	30.3%
Inert	15%	C_2H_4	28.6%
		H_2	26.8%
		CH_4	3.6%
		Inert	10.7%
total	100%	total	100%

Calculate the fractional conversion of ethane, the yield of ethylene based on feed and reactant consumption, and the selectivity of ethylene relative to methane.

QUESTION 3

One hundred moles/hr of butane (C_4H_{10}) and 5000 moles/hr of air are fed into a combustion reaction. Calculate the percent excess air.

$$C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$

QUESTION 4

The analysis of coal indicates 70 wt% C, 20 wt% H and 2 wt % S and the balance non-combustible ash. The coal is burnt at a rate of 5000 lb/hr and the feed rate of air to the furnace is 500 lbmoles/min. All of the ash and 4% of the carbon in the fuel leaves the furnace as a solid slag; the remainder of the carbon leaves in the stable gas as CO and CO_2. The hydrogen in the coal is oxidised to water, and the sulfur emerges as SO_2. The selectivity of CO_2 to CO production is 10:1. Calculate the mole fraction of the gaseous pollutant CO and CO_2 –in starch gas, and the emission rate of these substances in lbm/hr.

QUESTION 5

A distillation column separates 10 000 kg/hr of a 50% benzene (B) and 50% toluene (T) mixture. The product recovered from the condenser at the top of the column contains 95% benzene, and the bottom of the column contains 96% toluene. The vapour stream entering the condenser from the top of the column is 8000 kg/hr. A portion of the product is returned to the column as reflux, and the rest is withdrawn for use elsewhere. Assume that the composition of the stream at the top of the column (V), the product withdrawn (D) and the reflux (R) are identical.

I. Draw a flowsheet to represent this process.
II. Identify the unknowns and the equations for each control volume. Use this information to identify if the mass balance calculations in each control volume are solvable.
III. Find the ratio of the amount refluxed to the product withdrawn (R/D).

QUESTION 6

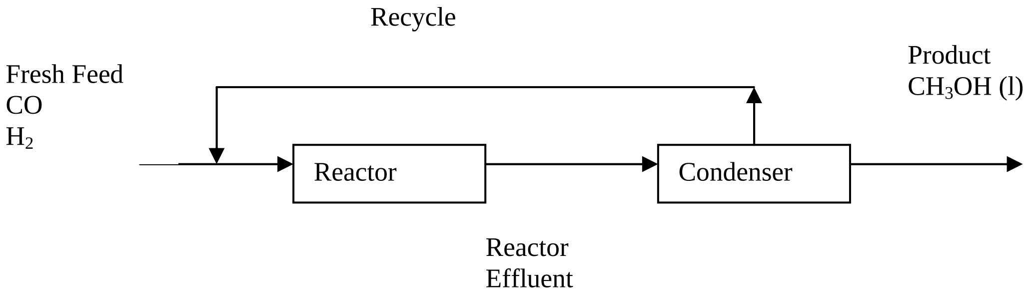
Methanol is produced by reaction carbon monoxide (CO) and hydrogen (H_2) according to the following reaction:

$$CO + 2H_2 \rightarrow CH_3OH$$

A portion of the methanol leaving the reactor is condensed, and the unconsumed CO and H_2 and the uncondensed CH_3OH are recycled back to the reactor. The reactor effluent flows at a rate of 275 mols/min and contains 10.6 wt% H_2, 64wt% CO and 25.4 wt% CH_3OH. The mole fraction of methanol in the recycle stream is 0.004.

I. Identify the unknowns and the equations for each control volume in this system. Use this information to determine is the mass balance calculations in each control volume are solvable.

II. Calculate the molar flowrates of CO and H_2 in the fresh feed, and the production rate of methanol.



CHNG 1103 Group-Assignment

Due Date: Thursday, Week 6

There are two parts to this assignment; parts A and B. Each group must complete part A and in part B you must select only one question. Submit only one report per group.

PART A – Chemical Processes

The objective of this assignment is to give students some familiarisation with the various processing operation used in the chemical, mineral, and food and associated industries. The students should be able to relate fundamental techniques used in Chemical Engineering 1A to their particular application in these processing operations. Furthermore, the students should be able to put the industry within the context of global factors which affect processing. Issues such as marketing, competition and environmental issues will be addressed in this assignment. Furthermore the students should get some familiarisation in conducting a literature search.

Task:

Each student group should select only one of the chemicals or products provided below:

Alumina	Gold
Copper	Sugar
Caustic Soda	ethylene
Styrene-butadiene rubber	ethylene dichloride
Polyvinyl chloride	Nickel
Ethanol	Chocolates
Beer	Sulfuric Acid
Uranium	Fragrances(or aromatic oils)

Write a report which addresses the following points.

1) Nature of the chemical or product
2) Identify the Raw Materials used in the production of the product
3) Identify the processing steps required to manufacture this chemicals or products.
4) Draw a flowsheet to represent the units identified in 2).
5) Determine the process streams and if possible obtain qualitative values of these streams (total and composition).
6) Superimposed the process streams on the flowsheet developed in 3).
7) Identify industries (in Australian only) involved in the processing of such materials.
8) Identify environmental or potential problems and how are these addressed.
9) How important is this product to the Australian economy and is it likely to lead to growth in the future.

In your report, note all the references used.

References:

1. Kirk – Othmer, ***Encyclopedia of Chemical Technology***, John Wiley, New York. 2. 2. Kompass

PART B- Mass Balance (Choose only one question from this part).

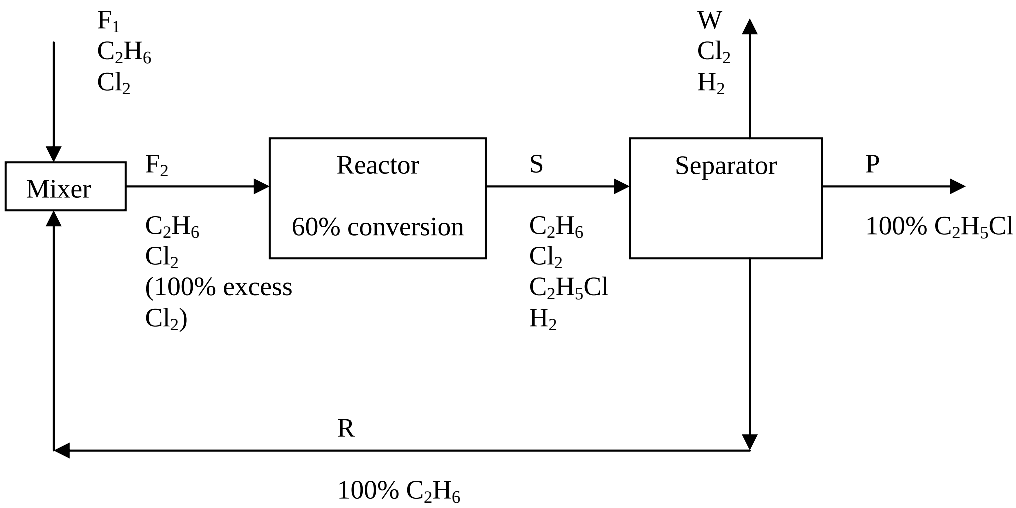
Question 1

Alkyl halides are used as an alkylating agent in various chemical transformations. The alkyl halide ethyl chloride can be prepared from the following chemical reactions:

$2\ C_2H_6 + Cl_2 \rightarrow 2C_2H_5Cl + H_2$

In the reaction process shown, fresh ethane and chlorine gas and recycled ethane are combined and fed into the reactor. A test shows that if 100% excess chlorine is mixed with ethane, a single pass optimal conversion of 60% results and of the ethane that reacts all is converted to products and none goes into undesired products. Calculate:

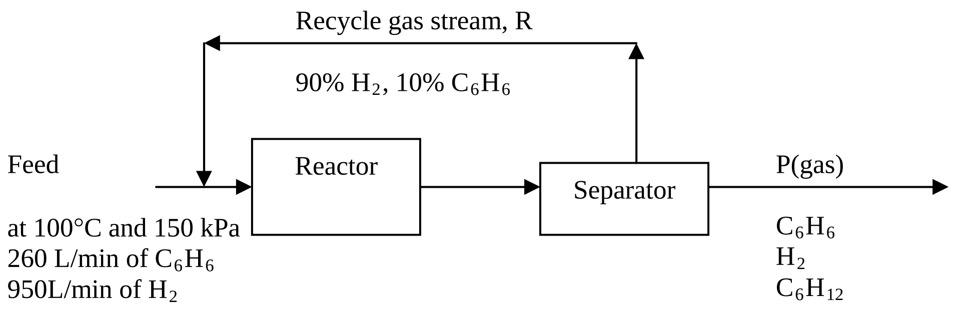
(a) The fresh feed concentrations required for the operations
(b) The moles of C_2H_5Cl produced in P per mole of C_2H_6 in the fresh feed F_1.



Question 2

Benzene (C_6H_6) is converted to cyclohexane (C_6H_{12}) by direct reaction with H_2. The fresh feed to the process is 260 L/min of C_6H_6 plus 950 L/min of H_2 at 100°C and 100 kPa. The single pass conversion of H_2 in the reactor is 48% while the overall conversion of H_2 in the process is 75%. The recycle stream contains 90% H_2 and the remainder benzene (no cyclohexane).

(a) Determine the molar flowrates of H_2, C_6H_6 and C_6H_{12} in the exiting product.
(b) Determine the volumetric flowrates of the product stream if it exits at 100 kPa and 200°C.
(c) Determine the molar flowrate of the recycle stream, and the volumetric flowrate if the recycle stream is at 100°C and 100 kPa.


Recycle gas stream, R
90% H_2, 10% C_6H_6
Feed
Reactor
Separator
P(gas)
at 100°C and 150 kPa
260 L/min of C_6H_6
950L/min of H_2
C_6H_6
H_2
C_6H_{12}