

To study about an industry, the following things need to be looked upon:-

- Background check about industry
 - What is the industry's economic perspective?
 - What is the economic impact of industry in India and on the world?
- Location of the industry
 - Is it located close to the market?
 - Is it located close to raw material site.
- Look at the various departments present in the industry.
 - Administrative Department
 - Finance Department
 - Inspection Department
 - Materials Department
 - Machine Management Department
 - Production Department
 - Safety, Health and Environment (SHE) Department
 - Power and Utilities Group.
- Identify the boundary and see what crosses the boundary and why?
 - Possible things entering: Raw material, Power, Utilities, Chemicals etc.
 - Possible things leaving: Products, By products, Wastes, Effluents etc.
- Identify the different process plants present and identify their functionality including
 - Every process plant has raw material and product storage unit, pre processing unit and main processing unit.
 - Every unit has the following:
 - Safety related element
 - Effluent and discharging element
 - Power input element

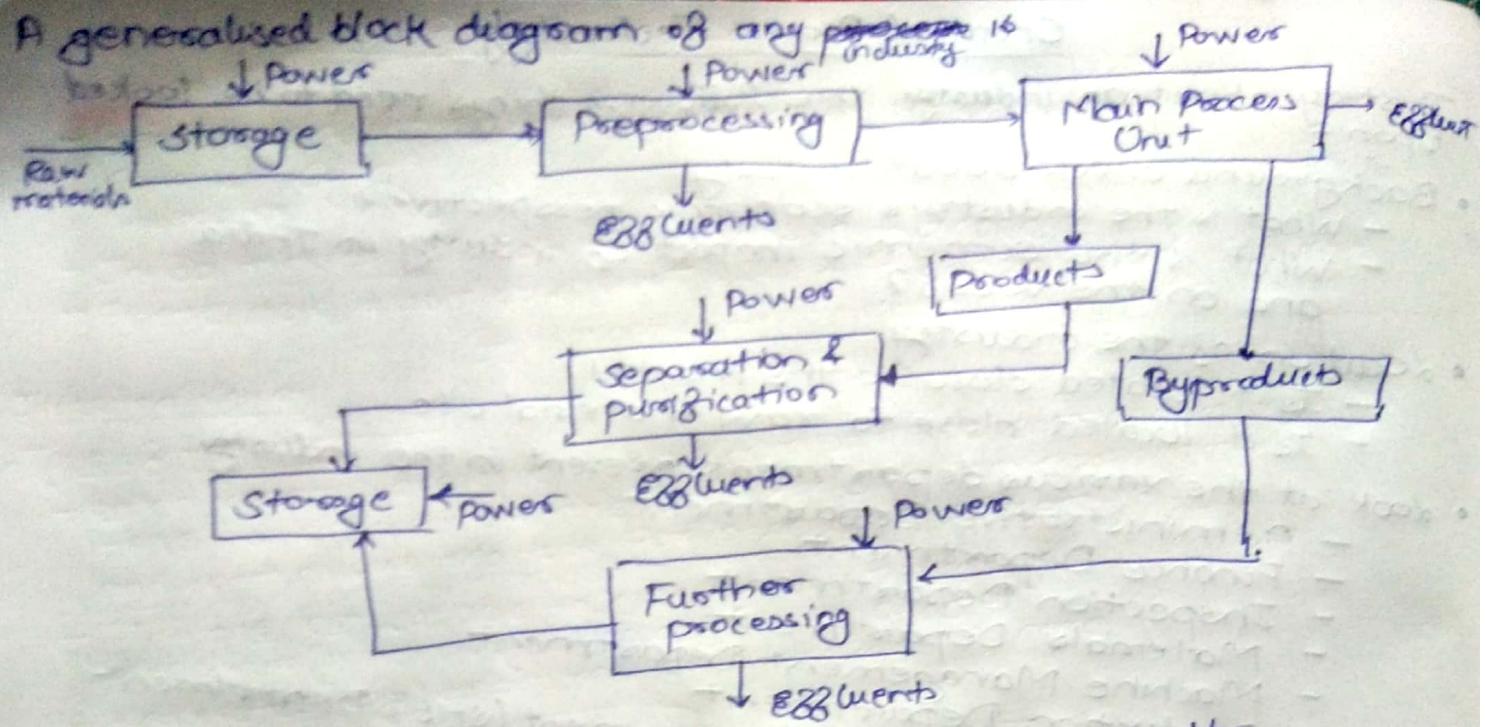
Block Diagram: A diagram showing in schematic form the general arrangement of the parts or components of a complex system or process.

Purpose of Block Diagram:

- Its structure provides a high level overview of major system components, key process participants and important working relationships.
- It does not provide every level of detail required for comprehensive planning or implementation.
- It is mainly focussed about input and output of system and not what goes in between.
- Block diagrams use basic geometric shapes. The blocks are connected by ~~cross~~ lines with arrows representing direction of material / energy flow.



NOTES



Process Flow Diagrams - A process flow diagram tells the different functionalities inside a process. It tells the interrelation between different components of a process plant.

- A PFD displays the relationship between major equipment of a plant facility and does not show minor details such as piping details and designations.
- A PFD is also termed as a flowsheet

A typical PFD will include the following:-

- Process piping
- Major equipment items
- Principal process control functions
- Connections with other systems
- Major bypass and recirculation streams
- Operational data
- Process stream names

Piping and Instrumentation Diagram (P&ID)

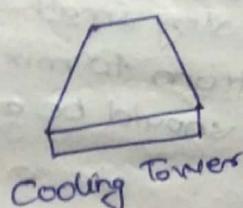
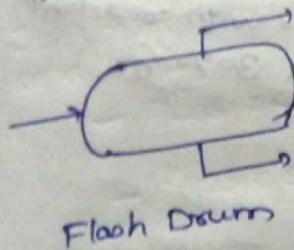
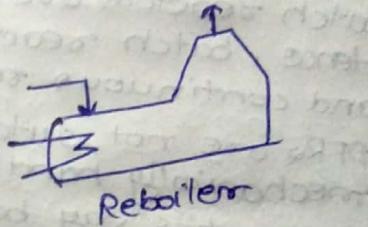
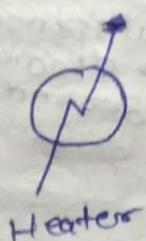
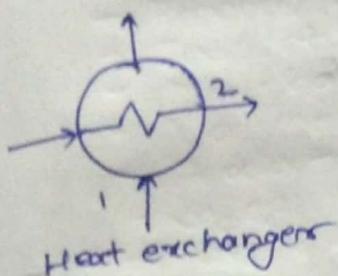
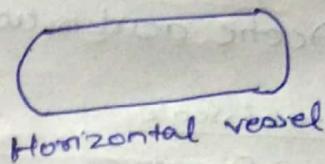
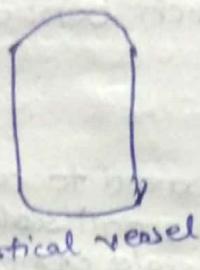
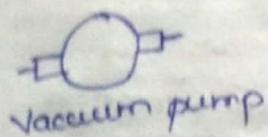
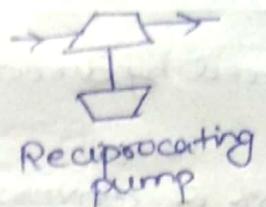
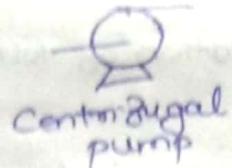
A P&ID diagram is a detailed diagram in process industry which shows piping and vessels in process flow together with the instrumentation and control devices.

A P&ID usually consists of:-

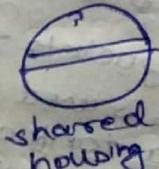
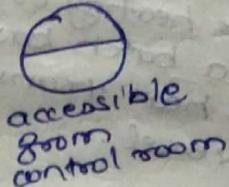
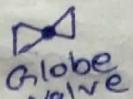
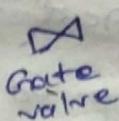
- Mechanical Equipment
- Process piping, sizes and identification
 - Pipe classes and piping line numbers
 - Flow directions
 - ~~Yard~~ Pipelines, flowlines, permanent startup, flush and bypass lines
- Process control instrumentation and designation

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Process Flow Symbols



Major pipeline
+ + +
Pneumatic line
- - - -
Electrical line



Instrumentation Symbols



First letters

F - Flow

L - level

P - pressure

T - Temperature

Second letter

C - Controller

I - Indicator

R - Recorder

E - Sensor

T - Transmitter

Y - Converter

A - Alarm

Yours

NOTES

Toluene to Benzoic Acid Conversion

Laboratory Scale:

- Benzoic acid is prepared by direct oxidation of toluene.
- Catalyst: Co Ac
- Promoter: Mn Ac
- In 30 minutes, 86-90% of conversion is reached.
- Acetic acid is used as solvent, in which benzoic acid is soluble.

Industrial Scale:

- Type of Reactors
 - Batch reactors are huge in size compared to continuous reactors. Hence, batch reactors are used for small scale operations and continuous reactors for large scale operations.
 - PFRs are not suitable in case of multiphase flow because mechanically handling such a flow is difficult.
 - Hence, usually batch reactors are preferred here.
- Size of reactors

Typically,

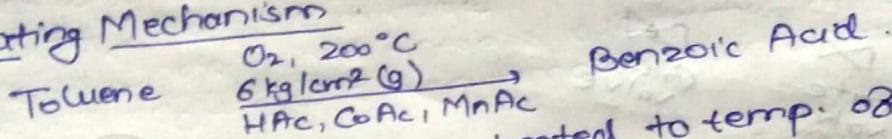
Volume of reactant = 200 L

Volume of solvent = 200 L

Catalyst and promoters - Very small

Airs spargers are present at bottom for mixing air with reactant. The vapours space above liquid should be around 30% of liquid volume (120 L).

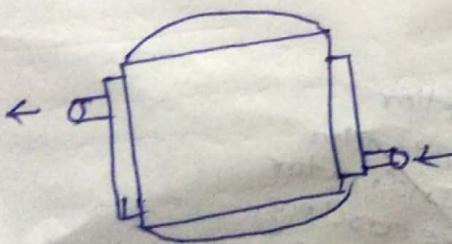
• Heating Mechanism



The liquid needs to be heated to temp. of 200°C

Various heating jackets that can be used are:-

- Dimplet Coil: This is used for heating or cooling of a liquid contained in a tank on a batch basis. In a dimplet coil, the jacket through which heat transfer medium flows fits onto the outside of vessel.



- Benefits:
 - Uniform fluid velocity through channel benefits in heat transfer
 - There is good distribution of heat transfer medium around vessel periphery.

When there is agitation inside tank, the heat transfer is substantially improved. If tank is not agitated, heat transfer depends on natural convection of liquid within tank, which is not efficient.

Yours

NOTES

- Dimple Jacket: A thin external shell is affixed ~~with~~ to shell with spot welds located in a regular fashion. These so-called dimples impart turbulence to heating or cooling media as it flows through the jacket.

- Simple annulus: This is not generally used because it is not very strong and requires a high thickness.

The liquid is heated with steam as heating medium.

Desirable qualities of steam:-

- low pressure: steam at lower pressure has higher latent heat and hence less quantity of steam will be needed.
- lower degree of superheat (closer to saturation): In steam heat transfer takes place through gas phase. But if it condenses, heat transfer takes place through condensation, which has a much higher heat transfer coefficient.

The reactor contains an air sparger that supplies excess air. This excess air comes out of liquid and maintains $5 \text{ kg/cm}^2(\text{g})$ pressure over liquid.

- Solvent and Reactant last on Excess Air:

- The excess air above liquid level has
 - very less amount of oxygen
 - good quantity of toluene vapour
 - good amount of acetic acid vapour

Because benzoic acid is not very volatile, its quantity in vapour phase is very less.

To prevent loss of reactant and solvent, there is a heat exchanger at top of reactor. This condenses toluene and acetic acid which is sent back down. Water is used as the cooling liquid. The air coming out is mixed with more air and throttled back into the reactor from bottom.

- Cooling of mixture after reaction:

After reaction is completed, the mixture is cooled using cooling using the same steam jacket to a temperature of $30-35^\circ\text{C}$. If it is not cooled, on depressurising, the mixture will vapourise.

The contents toluene, acetic acid and benzoic acid are drained out.

- Separation:

The contents are drained out in a vessel containing iced water.

Upper layers - Toluene

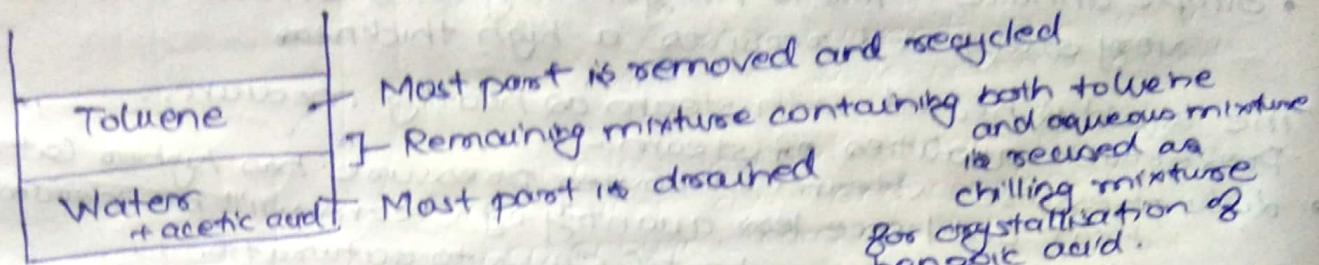
Middle layers - Water + Acetic acid

Bottom layers - Benzoic acid crystals

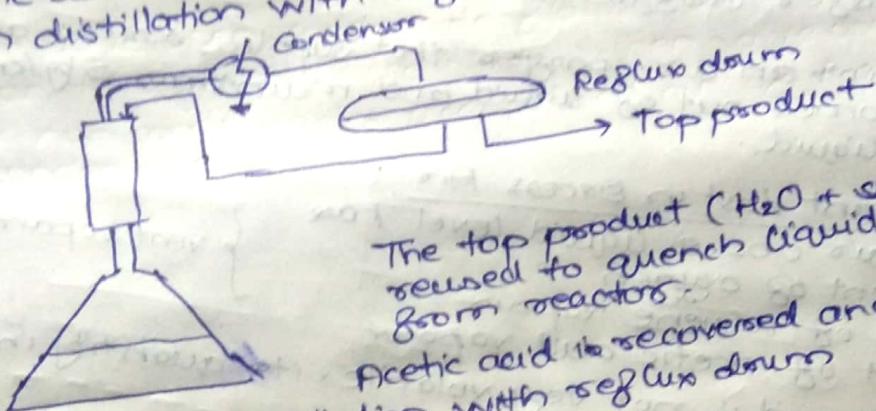
The benzoic acid crystals are scooped, washed with water, filtered in plate and frame filters present and dried in compartment tray drier.

• Recovery of solvent

The remaining mixture containing toluene and aqueous mixture is decanted.



Acetic acid and waters solution is distilled and separated.
Batch distillation with reflux drum is used



The top product ($H_2O + \text{small HAc}$) is reused to quench liquid mixture from reactors.

Acetic acid is recovered and used as solvent.

- To operate batch distillation with reflux drum
- Initially heat the mixture
- Reflux starts when there is substantial amount of accumulation
- Adjust reflux rate with time to maintain top product purity

Plot plan: A plot plan is an architectural drawing of a plant layout which shows the position of every equipment in an industry. It is basically a top-down orientation.

- Used to know the locations of various equipments in a industry.

Isometric view: It is used for visually representing three dimensional objects in order to know about their elevations along with other dimensions.

All diagrams needed to completely know about an industry! -

- Block diagram
- Process Flow Diagram
- Piping and Instrumentation Diagram
- Plot plan
- Isometric view

Unit process and Unit Operations

Anything that involves only a physical change is termed as unit operation.

Ex. Drying, Evaporation, Mixing, Size Reduction etc.

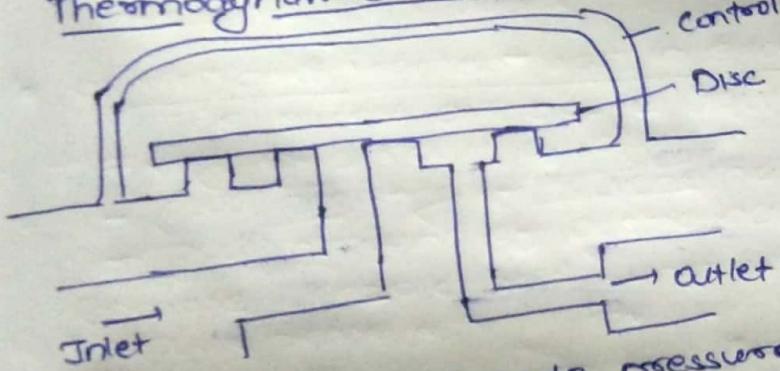
On the other hand, unit processes involve conversion of raw materials into products chemically (by a chemical reaction)

Eg - Oxidation, Reduction etc.

Steam Trap : A steam trap is a device used to discharge condensate and non-condensable gases with negligible consumption or loss of live steam. The three important functions of steam traps are :-

- Discharge condensate as soon as it is formed
- Have negligible steam consumption
- Have capacity of discharging air and other non-condensable gases.

Thermodynamic Steam Trap



The trap operates by means of dynamic effect of flash steam as it passes through the trap.

The only moving part is disc inside control chamber.

On startup, inlet condensate pressure raises the disc and the condensate is discharged from the outlet. When hot condensate flows, the pressure below the disc drops and it releases flash steam moving at high velocity. This creates high pressure above disc and low pressure below disc, drawing it towards its seat. This holds the trap shut.

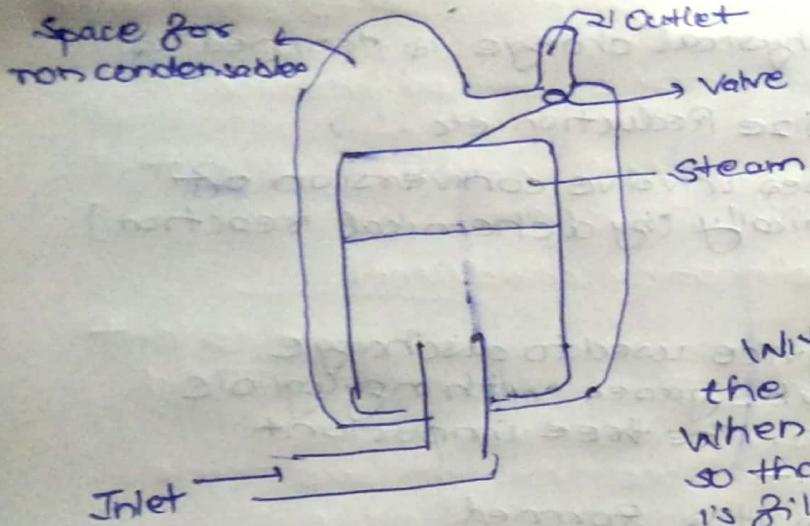
The pressure above the disc equals the pressure applied from below, but greater area above ensures that force on top surface of disc is greater.

Eventually due to heat loss, the steam trapped above the disc condenses, the pressure falls and next cycle begins. Non-condensables are removed through a bleed passage between control chamber and outlet.

Inverted Bucket Steam Trap

This is a type of mechanical trap. It responds directly to the density difference between steam and condensate.

The main component is an inverted bucket that acts as an open float. Small orifice is present at top to ensure that non-condensable gases cannot be trapped.

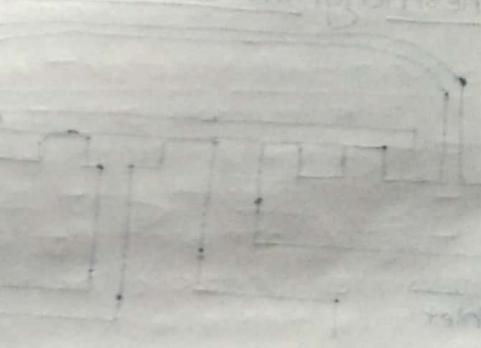


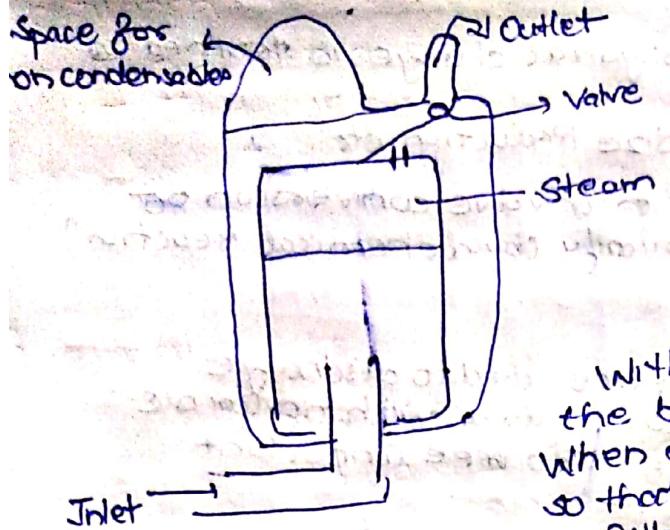
Steam is trapped between top of bucket and water seal below

When a good portion of bucket is filled with steam, bucket becomes buoyant, it floats up and the valve becomes closed

With loss of heat, steam inside the bucket cools and condenses. When enough steam has been condensed so that large amount inside bucket is filled with water, the valve opens as bucket loses buoyancy.

With valve open, condensate flows round bottom of bucket and out through discharge port. When valve opens, air and other non condensables are pushed out of trap ahead of the condensate.





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In a thermodynamic steam trap, only non-condensables can not be removed. If there are non condensables moving with the condensate, they are removed.

Petroleum Refinery - Petroleum crude oil is a mixture of hydrocarbons, formed as natural deposits over a long period of time. The volumetric consumption of crude oil in India is around 650 million liters per day.

Quality of crude oil - Anything is considered to be of good quality if impurities are less. The various impurities present in crude oil are:

- Sulphur - A good crude oil should have low sulphur content
- BS&W (Basic Sediment and Water) : BS&W includes all the aqueous components that contaminate crude. This includes dirt, water, silt and dissolved salts. Crude oil with BS&W content of less than 0.7% by volume is acceptable.

Heavy metals : Generally metals having density above 8 g/cc are termed as heavy metals. They are the inorganic component present in crude and contaminate the crude. Generally, higher concentration of heavy metals is found in higher hydrocarbons. Ash content of a sample determines which sample has a heavier proportion of heavy metals. More the ash content, more is the proportion of heavy metals in sample.

Product from petroleum refining

A product is anything sellable either to an industry or an individual user. The various products of petroleum refining with their density are:-

- Liquified Petroleum Gas (0.55 g/cc)
- Naphtha] 0.74 g/cc
- Gasoline / Petrol and ATF (0.77 g/cc)
- Kerosene (0.81 g/cc)
- High Speed Diesel (0.88 g/cc)
- Light Diesel Oil (0.95 g/cc)
- Furnace Oil (Fuel oil) (1.006 g/cc)
- Bitumen

The density of products is defined at a standard temperature. This temperature used by refineries is 15°C.

In general, lighter the product, higher is the price of product in Rs./ton.

Density of crude oil is specified in API - 131.5

$$\text{API} = \frac{141.5}{\text{specific gravity } (60^{\circ}\text{F})} - 131.5$$

~34° API corresponds to specific gravity of 0.855.

Higher the API, higher is the price of crude.

User of various products

Liquified Petroleum Gas (LPG)

- LPG mainly contains C₃, C₄ and small amounts of C₁, C₂, C₅.
- It is mainly used as a domestic fuel.
- It is used as a fuel for internal combustion engines.
- It is used as fuel in glass industry. Glass industry requires a clean fuel and LPG is one of the cleanest fuel.
- It is used primarily as lamp oil.
- It is also used as a solvent.

Kerosene:

- It is used primarily as a solvent.
- It is also used as a fuel for internal combustion engines.

Aviation Turbine Fuel (ATF):

- It is used in running of jet planes.

Gasoline / Petrol / Motor Spirit:

- It is used in spark type internal combustion engine.

Diesel:

- It is used in compression ignition internal combustion engine.

Furnace oil:

- It is used in furnaces and boilers.

Light Diesel Oil (LDO):

- It is used in furnaces. The first lightup is done using LDO and then furnace oil is used.

- Used in irrigation pumps and heating machines.

• Bitumen:

- Bitumen and asphalt are similar.
- It is used for
 - road making
 - road surfacing
 - corrosion protection of underground pipe
 - water proofing

• Petroleum Coke:

- It is used in making electrodes for metallurgical industries. [Al, Ag, Cu]

- For doing so sulphur content has to be very low.

- Indian crude has very low amount of sulphur

→ Bombay High

→ Ankleshwar (Gujarat)

→ Digboi and Nafarkatiya (Assam)

- Middle East Crude has higher sulphur content

→ can be converted to gasoline.

- Heavy naphtha can be converted to petrochemicals.

- Naphtha is used as raw material for petrochemicals.

These are two types of petrochemicals.

- Naphtha based petrochemicals.

- Natural gas based petrochemicals.

- Fertilizer industry uses naphtha as a source of H₂ for producing urea. They prefer naphtha with more H₂ content. Lighter naphtha has more % H by weight, hence fertilizer industry prefers lighter naphtha.

- Heavy naphtha is used as petrochemical feed stock.

- It is easy to crack.

- Petrochemical industry requires BTX (Benzene Toluene Xylene) to make aromatic products. These basic

aromatics are present in heavy naphtha.

BTX aromatics are present in heavy naphtha.

• Narmal fertilizers industry uses electrolysis for H generation as hydro electricity is available at cheaper price.

Indian crude:

- cannot produce bitumen

- provides low quality lubricating oil base stock

- Ankleshwar crude provides high quality ATF

- Bombay high crude has high wax content and is a good

petrochemical base stock.

- has less sulphur content.

Middle East Crude:

- has moderate kinematic viscosity

- has low pour point

- has 2 - 2.5% sulphur content

- has 2 - 2.5% sulphur content

Properties of products

The specifications for most of the products are decided on the basis of end use of product.

LPG:

- **Copper Strip Corrosion Test:** This limits the presence of sulphur in LPG. At elevated temperatures, a copper strip that has been polished is immersed in a sample. The strip is then removed and tested for corrosion.
 - LPG should not contain any free H₂S or sulphur compounds.
- **Odour level Test:**
 - LPG has a very faint smell and hence, it is necessary to add some odourant so that any escaping gas can be easily detected.
 - Ethyl mercaptan is added as an stenching agent.
 - The amount to be added should be sufficient to allow detection in atmosphere $1/5^{\text{th}}$ of total flammability level.
 - The amount to be added is $1/5^{\text{th}}$ of total flammability level.
- **Vapour pressure limit:**
 - The vapour pressure must be $8 \text{ kg/cm}^2(\text{g})$ at 65°C .
 - This is the upper limit.
 - The temperature 65°C is chosen as it is the maximum temperature which the cylinder will attain when left in the sun on a very hot day.
- There are no composition specifications.
- **95% evaporation temperature test (Weathering test):**
 - LPG is chilled to a very low temperature and allowed to evaporate. When 95% of liquid has been evaporated, the temperature is noted.
 - The temperature must lie in the range of -2°C to 2°C .
 - If temperature is less than -2°C , it indicates excess presence of lighter hydrocarbons (C₁, C₂).
 - If temperature is greater than 2°C , it indicates excess presence of heavier hydrocarbon (C₃).

• Motor Spirit / Gasoline:

- Octane Number:

- The quality of gasoline is determined on the basis of its performance in standard spark ignition engine.
- The octane numbers of a denotes that the fuel has the same combustion characteristics as $\pi\%$ by volume of isoctane and $(100 - \pi)\%$ normal heptane in standard spark ignition engine.
- Octane numbers of isoctane is 100 and normal heptane is 0.
- A higher octane number indicates that fuel can withstand more compression before igniting. Gasoline engines rely on ignition of air and fuel compressed together as mixture, hence high compressibility and higher octane numbers matters for gasoline.
- Use of low octane number fuels leads to engine knocking.

- Knocking is checked by vibration and pressure inside chamber. These qualities are checked in quality of combustion.
- Kerosene:
 - Smoke point:
 - Minimum height of flame must be 21 mm
- ATF:
 - Freezing point must be below -50°C .
 - Flash point must be above a lower limit so that fuel doesn't catch fire during storage.
 - Aromatic content
- Diesel:
 - Cetane Numbers:
 - A cetane number of α denotes that the fuel has the same combustion characteristics as $\alpha\%$ by volume of cetane and $(100-\alpha)\%$ by volume of α -methyl naphthalene in a compression ignition engine.
 - Cetane numbers for cetane is 100 and α -methyl naphthalene is 0.
 - High speed diesel engines operate more effectively with higher cetane numbers fuels. Fuels with lower cetane number will have longer ignition delay and require more time for fuel combustion process to be completed.
 - Pour point:
 - There is an upper limit on pour point to prevent freezing of diesel.
 - The pour point specification is variable at variable places.
 - 90% recovery test for diesel
 - The maximum temperature when 90% of sample is distilled in standard setup is 360°C for diesel.
 - The ignition inside a diesel engine is caused only by air and temperature inside the engine. Lower value of temperature indicates a decrease in efficiency and higher maintenance requirement. However, higher value of temperature leads to root going out from emissions which is not acceptable.
 - * For same carbon numbers, paraffins have the highest cetane numbers whereas aromatic and branched paraffins have highest octane numbers.
 - Fuel Oil:
 - Fuel oil is converted into spray droplets in order to burn. It's done by a spray nozzle where steam is used at the tip of the burner at some pressure.
 - Most industrial burners are designed to operate with a fuel of kinematic viscosity 10-15 centistokes at burner tip.

- Kinematic Viscosity

If decided how easily the fuel oil can be atomised down the kinematic viscosity, easier it is to atomise the fuel oil.

The desired kinematic viscosity can be achieved in two ways:-

- Stock is of desired quality

- Add a preheater to bring down viscosity.

Kinematic Viscosity is a strong function of temperature.

It is specified at 50°C for two grades

- Summer Grade [Higher is can be afforded]

- Winter Grade

(Upper limit)

- Pour point (Upper limit)

- Bitumen: Bitumen should not turn sticky during hot weather.

- Penetration Number:

A sample of bitumen is taken at 25°C . A standardised needle is taken above which a standard weight is kept.

The needle is released into sample.

Penetration Number = $10 \times [\text{Distance it penetrates in mm}]$.

Higher the penetration number, $\text{so } +\infty$ is the material.

Higher the penetration number, lower penetration number is.

A bitumen grade with lower areas is progressed in hotter areas.

A bitumen emulsion: It is used in areas where it may not be wise

to melt bitumen. Bitumen is mixed with a solvent,

Bitumen emulsion: It is used in areas where it may not be wise to melt bitumen. Bitumen is mixed with a solvent, that evaporates and leaves behind bitumen.

- Spark Ignition Engine:

Spark Ignition Engine is an internal combustion engine in which the ignition of air-fuel mixture takes place by spark. The spark is generated with the help of spark plug. It works on the principle of Otto cycle or constant volume heat addition cycle. A four stroke spark ignition engine has following strokes:-

• Suction Stroke: Air-fuel mixture enters the cylinder.

• Compression Stroke: The air-fuel mixture is compressed by a piston.

• Power Stroke: A spark is produced by spark plug. The spark ignites the air-fuel mixture and combustion takes place in combustion chamber. This produces a very high thrust force which pushes the piston downward and causes

the shaft connected to it to rotate.

• Exhaust Stroke: The piston moves upward and combustion gases are released.

In spark ignition engines, petrol is used as working fuel. The engine consists of carburetor for mixing air and fuel before suction stroke. The compression ratio of fuel is determined by anti-knock properties of fuel. They are lighter in weight and are used in light duty vehicles like motorcycles.

Compression Ignition Engine

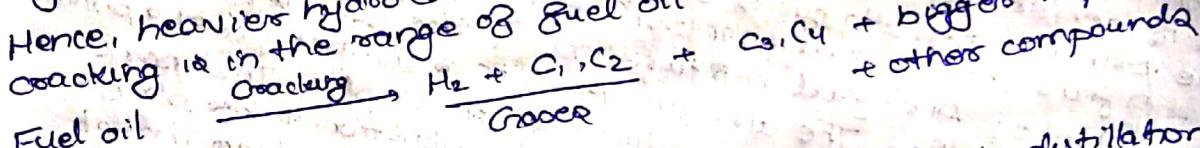
Compression ignition engine is an internal combustion engine in which ignition of fuel takes place with the help of hot compressed air. As air is compressed, it gets hot and its heat is used for ignition and burning of fuel. It works on the basis of diesel cycle or constant pressure heat addition cycle. A four-stroke compression ignition engine has the following strokes:-

- Suction Stroke: The piston moves downward and the suction of air takes place.
 - Compression Stroke: Air is compressed and its temperature increases. It reaches upto that level where combustion of diesel takes place.
 - Power Stroke: The injector injects the fuel into the cylinder. Due to heat of air, ignition of fuel begins and combustion takes place. Due to combustion, hot exhaust gases produced exert a very high thrust force on piston and it moves downwards, which causes shaft connected to it to rotate.
 - Exhaust Stroke: The piston moves upward and pushes burnt gases out of engine cylinder through exhaust valve.
- Diesel is used as the working fuel because of its low self-ignition temperature. They are heavy weight engines and are used in heavy duty vehicles.

Processes in a Refinery

Distillation is based on the difference in volatilities of components. Every crude oil is different, i.e. it has a different proportion of components. The proportion of crude composition and product demand might not be the same always. Usually heavier the hydrocarbon, lesser is the demand. Hence, to meet the demand heavier hydrocarbons are converted into lighter hydrocarbons.

Hence, heavier hydrocarbons are cracked. The feed stock for cracking is in the range of fuel oil



Fuel oil

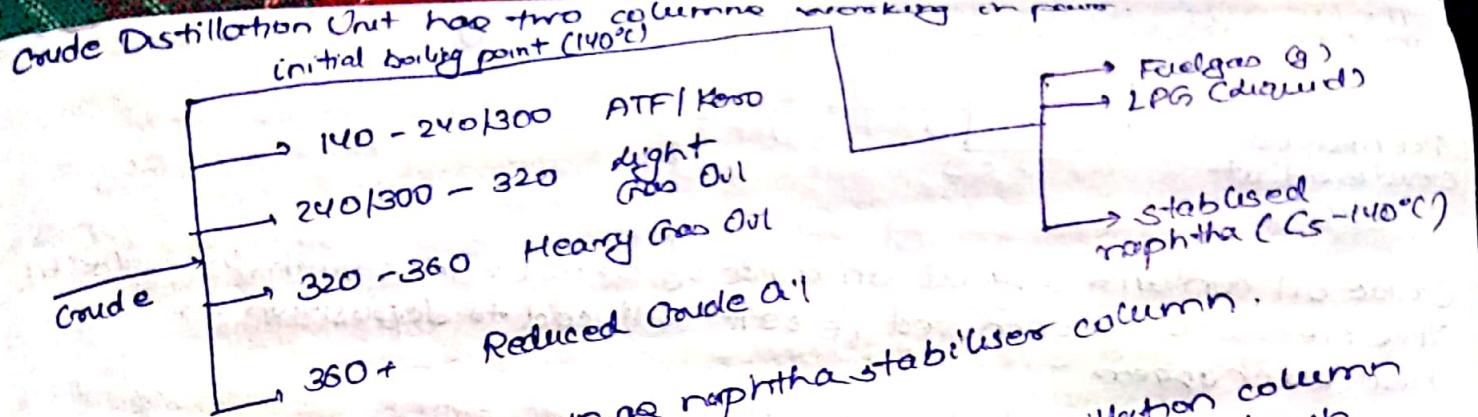
Crude Distillation Unit

Crude distillation is performed in an atmospheric distillation column. The column is a continuous fractionator with side stream draws.

The various components are

- C₁, C₂ - non condensable
- C₃, C₄ - LPG
- C₅ - Naphtha
- C₆ (140-240) or Kero (140-300)
- ATF (140-240) or Upto 320
- light Gas Oil (Upto 360)
- Heavy Gas Oil (Upto 360)
- Reduced Crude Oil (360°C +)

} First cut, around 140°C temp



The second column is known as naphtha stabilizer column.

Distillation Column Operating Pressure:
 The boiling point of top product decides the distillation column operating pressure. The top product to be refluxed should be in liquid state. It is condensed using cooling waters which has an inlet temperature of $30-33^{\circ}\text{C}$. For effective heat transfer to occur, LPG should leave with $\Delta T = 20^{\circ}\text{C}$ i.e. temperature of $50-55^{\circ}\text{C}$. Hence, LPG must be a liquid at this temperature.

Thus, the bubble pressure of top product at a temperature close to $55-60^{\circ}\text{C}$ is the operating pressure of distillation column. For naphtha, this pressure is around $1.2-1.8 \text{ kg/cm}^2(\text{g})$. For LPG, this is around $10-12 \text{ kg/cm}^2(\text{g})$. The first column operates at a pressure of $1.2 \text{ kg/cm}^2(\text{g})$.

The second one around $12 \text{ kg/cm}^2(\text{g})$.
 Need for two columns:
 If both columns were combined into a single column with another side draw, the whole column with such high capacity at high pressure would be too expensive. Hence, two columns are used.

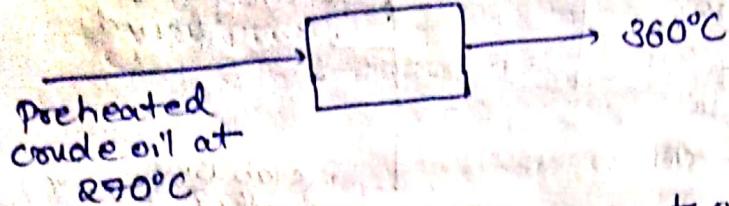
Reboiler is used to maintain bottom product composition. Instead of reboiler, the feed will reduce reboiler duty but this is not a proper alternative for a reboiler.

The temperature of bottom of CDU is 360°C . Hence, reboiler surface must be atleast at 400°C to provide required heat. However, all hydrocarbons start cracking at 400°C . Hence, reboiler will get coked up immediately. Thus a reboiler is not used in a crude distillation unit.

Instead of reboiler, live stripping steam is used at bottom. This reduces the partial pressure and causes lighter products to vapourise.

The bottom product coming out at 360°C has to be stored at 40°C . This extra heat is used in heat exchanger to preheat the feed. In a refinery, there are plenty of heat exchangers.

The last stage of crude heating before entering into CDU is done in pipe steam heater.



Crude oil contains a good amount of boron compounds with dissolved salts. This needs to be removed, else it will lead to deposition in heat exchangers. This is removed in electric desalting unit.

Brine →
H₂O will start oscillating and colliding with other particles. It will become bigger and eventually settle.

Removal of sulphur impurities: Sulphur is present in various forms in crude oil:

- Dissolved H₂S
- Mercaptans
- Thiophenes and benzo thiophenes
- More complex sulphur compounds present in heavier hydrocarbons.

RCO: 3-4% S

LPG: ppm content of S.

To remove sulphur:-

- H₂S can be stripped out
- Those present as organosulphur compounds can be catalytically hydrogenated to H₂S, which can be stripped out.
- Those are various hydrodesulphurisation processes.

Streams which cannot be sold outside are used to meet the supplemental fuel requirements.

Fuel gas refinery = Fuel gas + Fuel oil

Fuel gas (C₁, C₂) comes from direct distillation and cracking.

Motor spirit Production: Motor spirit must have a high octane number. Hence, it must have a high proportion of aromatics.

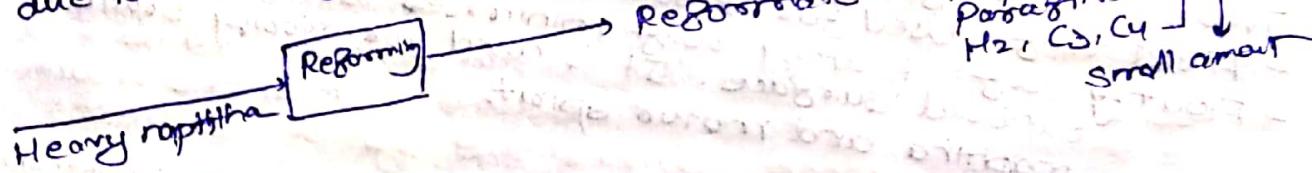
On distillation of naphtha, heavy naphtha and light naphtha are obtained. Heavy naphtha has more of C₆+ content. Hence, it is preferred to be used for conversion into aromatics.

Catalytic Reforming of Naphtha

Naphtha mainly consists of paraffins and naphthenes. Olefins are present in minor quantities in crude oil. These are converted to aromatics by reforming process known as catalytic reforming of naphtha. Platinum is used as catalyst for the reaction.

Various reactions involved in catalytic reboiling of naphtha are -

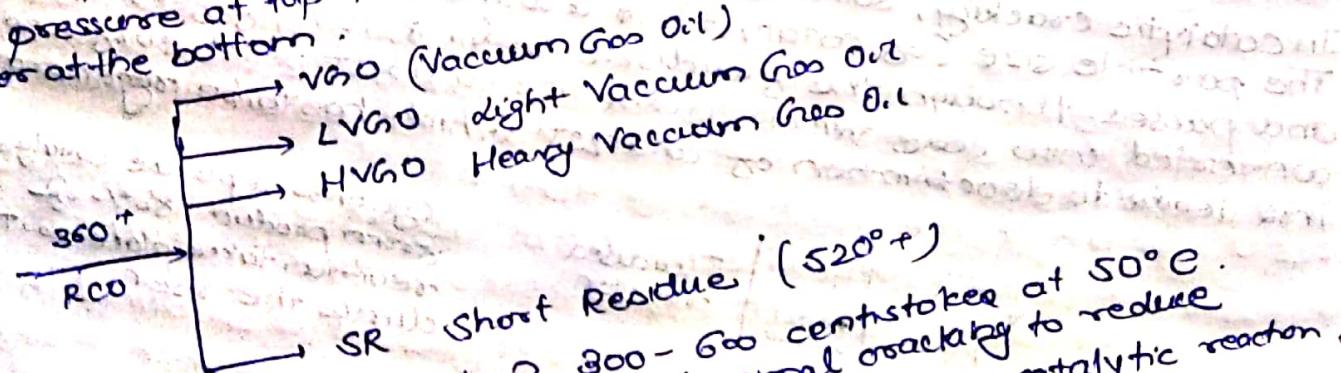
- Catalytic dehydrogenation of naphthenes to aromatics:
This is a very fast reaction and adds maximum value to octane numbers.
- Catalytic dehydrogenation of paraffins to naphthenes:
This is a slow reaction. As the naphthenes formed are very reactive in this condition, they are immediately converted into aromatics.
- Hydrocracking:
The above two reactions produce H₂ as well. Hydrocracking is the cracking of hydrocarbons in presence of high partial pressure of H₂. This leads to production of H₂, C₃ and C₄ in some amounts.
 - Hydrocracking is desirable in small amounts. High hydrocracking will lead to coke deposition on catalyst.
 - Hence, controlled burning of catalyst needs to be done to remove coke, else catalyst may degrade due to sintering.



Bitumens Production

Bitumens can be formed from RCO by vacuum distillation. Due to high temperature required for distillation, normal distillation is not possible.

The pressure at top is 40 mm Hg absolute. The pressure is higher at the bottom.



RCO has a kinematic viscosity of 300-600 centistokes at 50°C. RCO is converted into fuel oil by mild thermal cracking to reduce viscosity. This is known as vis-breaking. This is non-catalytic reaction. Temperature requirement (lower temperature than thermal cracking). Catalytic cracking

Severity of cracking is decided by temperature, low pressure and higher temperature (leads to severe cracking).

This cracking is liquid phase cracking.

- Heaters is the main component
- Vis breaking fractionator is used for separating products

The largest operating cost of refinery is crude oil cost followed by energy cost.

Naphtha and Kerosene contains small amount of H₂S. These are removed by amine treatment.

For good amount of H₂S to be removed, the products are washed with mono/diethyl amine. Because amine is expensive, the amine has to be regenerated.

When H₂S content is very low (in ppm), caustic wash is used i.e. it is washed with caustic soda. This cannot be regenerated, hence caustic spent has to be discarded. This process is economic and simple to handle.

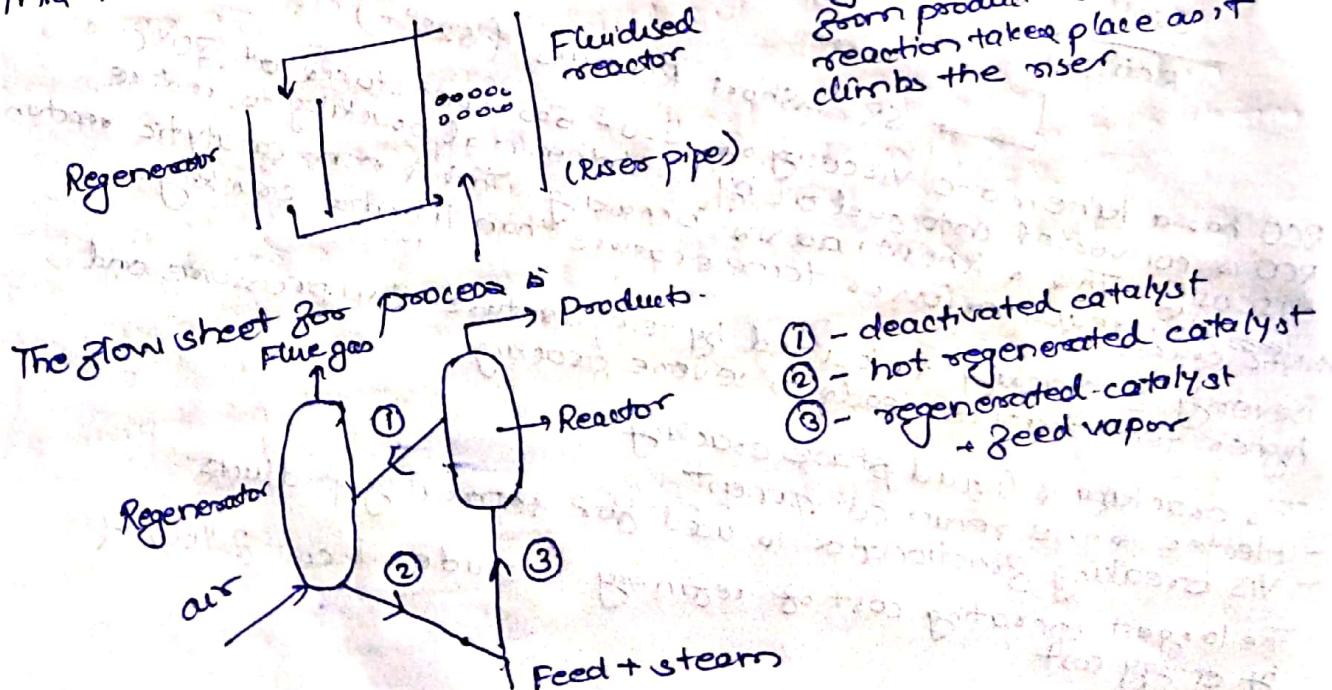
Caustic wash has to be followed by dinner ethane dehydrogenated water wash to remove caustic soda bound with hydrocarbons. In all storage tanks with fixed roofs, some amount of water is always present at bottom. This comes from atmosphere.

Two types of roofs are used in refineries:

- Fixed roof: Used for kerosene
- Floating roof: Floating roof minimizes losses due to heat exposure surface. It is used for storing crude, naphtha and motor spirit.

Catalytic Dehydrogenation Reactions:
Reaction takes place in the presence of catalyst. Reaction takes place in around 10-15°. The reaction is a vapour phase reaction after which products deposit. The heavier products (solids) sit on the catalyst.

In catalytic cracking, solid catalyst is used in the form of fluidised bed. The particle size (of catalyst) is around 100 μm. Feed is vapoured and passed through the fluidised bed. 8-10% of feed is converted into coke which covers the catalyst pellet surfaces. This leads to deactivation of catalyst which has to be regenerated.



- The steps in a complete cycle are:
 - Gravity conveying of deactivated catalyst from reactors to regenerator.
 - Gravity conveying of regenerated catalyst to bottom of reactors.
 - Mixture of steam and feed vapors in the contact of hot tube pipe.
 - Mixture of steam and feed vapors in the contact of hot regenerates catalyst and carries the catalyst to the reactor.
 - No reverse flow in the process is allowed by ensuring minimum pressure drop by using a special type of valve.

Coke from catalyst is burnt in the presence of air. The heating controlled else it may lead to sintering of catalyst. The products released after burning of coke contain CO_2 , CO , N_2 , O_2 and SO_2 which are at high temperature. The heat from products is used.

Coke is formed primarily by polymerisation of unsaturated compounds formed due to cracking. Polymerisation is exothermic, hence lower temperature known as coking. The unit where catalytic cracking occurs is known as fluidised bed catalytic cracking unit (FCCU).

Cracking temp: 505°C .

This cracking gives gas which is heavy naphtha.

Cracking Catalyst: Alumina (carrier) Zeolites (present)

The catalyst is granular catalyst of size around $100\ \mu\text{m}$. It has a large surface area.

Cracking produces the following

- H_2
- $\text{C}_1\text{C}_2 \rightarrow \text{LPG}$
- $\text{C}_3\text{C}_4 \rightarrow \text{Light Cycle Oil (LCO)}$
- C_5
- Kerosene / light cycle oil
- Heavy cycle oil
- heavier than feed
- heavier than feed

An FCC unit consists of reaction unit followed by separation unit + distillation.

Reaction unit \rightarrow Separation \rightarrow Distillation

The unconverted feed is in the range of heavy cycle oil.

Heavy product comes out of fractionator has low viscosity, but it contains fines of catalyst (around 10%). This containing small particles of catalyst is known as clarified oil. This has to go to a settler.

After distillation, various products are

- non-condensable gases. (Used as fuel)
- LPG - treated and sent to product storage
- LCO - hydodesulfurised
- H₂O
- clarified oil

The clarified oil is sent (after settling and removal of catalyst) to vis-breakers feed. The clarified oil has less viscosity but a higher pour point. Hence, it is sent to mild thermal cracking unit.

Hydrocracking is the cracking along with simultaneous hydrogenation. It happens in a hydrocracker. For hydrogenation, the operating pressure has to be substantial. It also requires a good source of H₂. This generally occurs during catalytic reforming of naphtha.

Hydrocracking can happen by reaction of any hydrocarbons with steam. When done with naphtha, this is known as steam reforming of naphtha.

Quench Column

The gases from the cracking unit are sent to quench column for separation. Distillation requires two phases in contact with each other. The feed for quench column is generally gaseous. Hence, for effective separation, a good amount of reflux is needed.

An FCC unit is used when demand for lighter products is to be made at the cost of heavier products. Hence, the main products out of quench column are lighter products.

Along with thermal cracking, coking also takes place. This coke is used in metallurgical electrodes. However, there is a limit on S content in coke as raw material. The sulphur content depends on origin of crude oil. Hence, cracking is preferred only when it is ensured that low S coke can be produced.

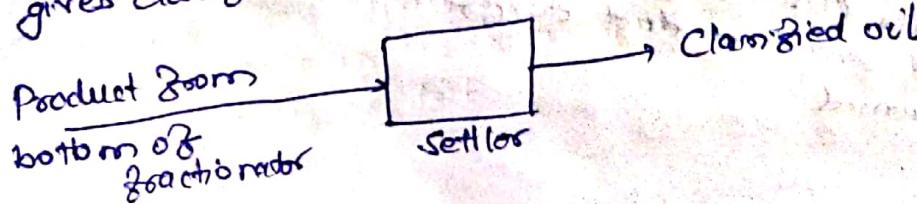
The quality of products obtained from cracking in an FCCU differs significantly from those obtained from crude distillation on the basis of olefin content. The naphtha obtained from FCCU has an octane number of 90+.

FCCU type of products should not be prepared from FCCU. Kerosene type of products should not be prepared from FCCU.

Because the olefin content is high, smoke point is reduced. Similarly, light cycle Oil (LCO) i.e. diesel/gas oil is produced in large quantity but quality is not that good, as it is rich in olefins. This diesel has a very low cetane number (30 - 35).

Heavy Cycle Oil is unconverted and it is sent back to bottom of fractionator and mixed with feed.

The product from bottom of column is sent to settler which gives clarified oil.

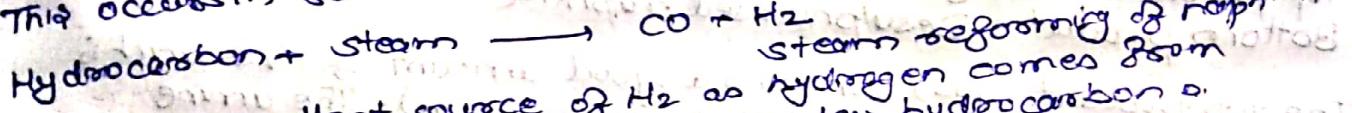


- The products out from quench column are:-
- non-condensable gases: Used as fuel
 - LPG: treated and sent to storage
 - LCO: Hydrodesulphurised - High Speed Diesel (HSD)
 - HCO: recycled
 - Distilled oil: Sent with feed to vis breakers unit to reduce viscosity of feed.

Hydrocracking is also used for conversion of higher hydrocarbons to lighter hydrocarbons. This process removes the unsaturation and leads to production of very less amount of debris.

$$\text{Hydrocracking} = \text{Cracking} + \text{Hydrogenation}$$

This occurs in substantial partial pressure of H_2 via nitrogen.



This is an excellent source of H_2 as hydrogen comes from steam as well as hydrocarbon. Hence, less hydrocarbon is required for production of H_2 .

Bitumen:

- Test:
- Penetration Number (Ring ball test): becomes when warmed.
 - Softening Point: (Ring ball test) This test tells how soft bitumen is.

Asphaltenes (polycyclic aromatic) are tough. However, the presence of wax makes them soft.

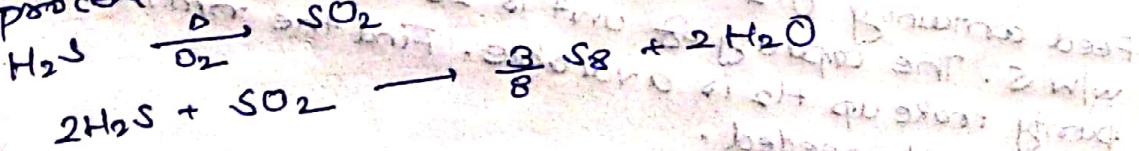
India cannot stop importing crude because of the following technical reasons:-

- Indian crude oil (and hence bitumen) has a higher wax content. Hence, it doesn't give good quality bitumen.
- It also doesn't have good amount of ATF. If has good amount of aromatics.

To produce bitumen, short residue is blown with air. This leads to formation of asphaltenes. They are produced in bitumen producing towers.

- In a refinery, none of the products are byproducts. All are co-products. One can always be increased at the cost of other.

Sulphur is a byproduct in refinery when washed with diethyl amine. All streams containing H_2S when washed with sulphur by produce H_2S . This H_2S is converted into sulphur by Claus process.



Naphtha desulphurisation

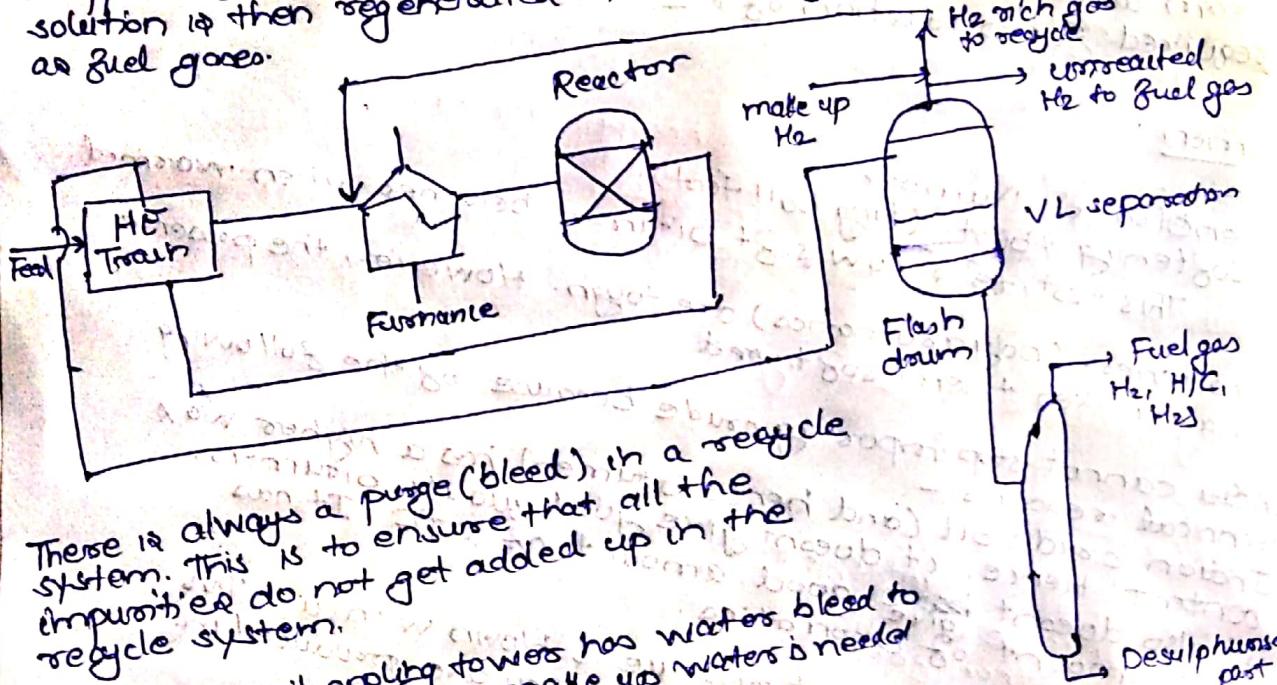
- This is a vapours phase reaction.
- The vapours phase is ensured by preheating the feed to a particular temperature and pressure.
- Before that, naphtha is mixed with H₂. This reduces the partial pressure of naphtha, and it vapourises more readily.

After reaction, the products are condensed in a flash drum where the lighter components get recycled. This is sent to a distillation column. This distillation column is equivalent to a naphtha stabilisers column.

Top product: Fuel gases, H₂, LPG, H₂S

Bottom product: Desulphurised naphtha

The top product (gas) contains a good amount of H₂S which is stripped by amine wash (10% amine solution). The amine solution is then regenerated. The rest hydrocarbons are used as fuel gases.



There is always a purge (bleed) in a recycle system. This is to ensure that all the impurities do not get added up in the recycle system.

e.g. Closed circuit cooling towers has water bleed to drain out solids. Hence make up water is needed.

Hydrodesulphurisation is an exothermic reaction. Most reactions where H₂, O₂ are involved as reactants are exothermic reaction.

Generally there are two types of compressors used in a refinery:

- Reciprocating compressors: Used by smaller units
- Centrifugal compressors: Used by larger units

- Q - Feed containing 0.2% w/w S is to be converted into 5 ppm w/w S. The capacity of unit is 20 tonnes per hour. g³/s purity make up H₂ is available. Find the nm³/hr of make up H₂ needed.

$$\text{Sulphur content in feed} = \frac{0.2}{100} \times 20 \text{ ton/hr}$$

$$= 0.04 \text{ ton/hr.}$$

$$\text{Sulphur content in product} = 5 \times 10^{-6} \times 20 \text{ ton/hr}$$

$$= 10^{-4} \text{ ton/hr.}$$

$$\text{Amount of sulphur reacted} = 0.04 - 0.0001 \text{ ton/hr}$$

$$= 0.0399 \text{ ton/hr.}$$

$$= 39.9 \text{ kg/hr.}$$

$$\text{No. of moles of sulphur reacted} = \text{no. of moles of H}_2 \text{ needed}$$

$$= \frac{39.9 \text{ kg}}{32 \text{ kg/mol}}$$

$$= \frac{39.9}{32} \text{ mol}$$

$$= 1246.875 \text{ mol/hr. of H}_2.$$

$$\text{nm}^3/\text{hr. of H}_2 = \frac{1246.875 \times 8.314 \times 273}{1.01325 \times 10^5}$$

$$= 27.93 \text{ nm}^3/\text{hr. of pure H}_2.$$

$$\text{Amount of H}_2 \text{ needed} = \frac{27.93}{0.93} \text{ nm}^3/\text{hr.}$$

$$= 30.032 \text{ nm}^3/\text{hr.}$$

Dangliens Index: The Dangliens Index is an approximate indicator of degree of saturation of CaCO_3 in water. It is calculated using pH, alkalinity, Ca concentration, total dissolved solids and water temperature of water sample. If Dangliens Index is:-

- negative, water is undersaturated by CaCO_3 and will tend to be corrosive in distribution system.
- positive, water is oversaturated by CaCO_3 and will tend to form scales in distribution system.
- close to zero, water is just saturated with CaCO_3 and will neither be strongly corrosive nor scale forming.

Dangliens Index is used by water operators for stabilizing water to control both internal corrosion and deposition of scales. It can help determine leakage potential due to corrosion as well.

Sulphur content in feed = $\frac{0.2}{100} \times 20 \text{ ton/hr}$
 $= 0.04 \text{ ton/hr}$

Sulphur content in product = $5 \times 10^{-6} \times 20 \text{ ton/hr}$
 $= 10^{-4} \text{ ton/hr}$

Amount of sulphur reacted = $0.04 - 0.0001 \text{ ton/hr}$
 $= 0.0399 \text{ ton/hr}$
 $= 39.9 \text{ kg/hr}$
 $= 0.08 \text{ mole}/\text{hr}$ H₂ needed

No. of moles of sulphur reacted = $39.9 \frac{\text{kg}}{\text{mole}} \times \frac{1}{2} \text{ a}$
 $= 32 \frac{\text{kg}}{\text{mole}}$

mm³/hr of H₂ = $1246.875 \text{ mol/hr} \times 0.08 \text{ H}_2$
 $= 1246.875 \times 8.314 \times 273$
 $= 27.93 \text{ mm}^3/\text{hr}$ of pure H₂
 $= 27.93 \text{ mm}^3/\text{hr}$
 $\text{Amount of H}_2 \text{ needed} = \frac{27.93}{0.03} \text{ mm}^3/\text{hr}$
 $= 90.032 \text{ mm}^3/\text{hr}$

Dongliers Index: The Dongliers Index is an approximate indicator of degree of saturation of CaCO₃ in waters. It is calculated using pH, alkalinity, Ca concentration, total dissolved solids and water temperature of water sample. If Dongliers Index is:-

- negative, water is undersaturated by CaCO₃ and will tend to form corrosive in distribution system.
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- close to zero, water is just saturated with CaCO₃ and will neither be strongly corrosive nor scale forming.

Dongliers Index is used by water operators to stabilise water to control both internal corrosion and deposition of scales. It can help determine leakage potential due to corrosion as well.

Reformation:

Reformation reactions and cracking are endothermic reaction. The fastest reformation reaction is conversion of naphthenes into aromatics. This reaction is highly endothermic.

Because reformation produces aromatics, feed must contain carbon compounds C₆, C₇, C₈ +. Depending on final requirement feed has to be selected

- For BTX preparation, lighter feed is needed
- For motor spirit production, heavier feed is needed

The feed must be hydrosulphurised before reforming reaction takes place. This is because the catalyst for reforming can not tolerate any sulphur. Sulphur acts as poison for catalyst.

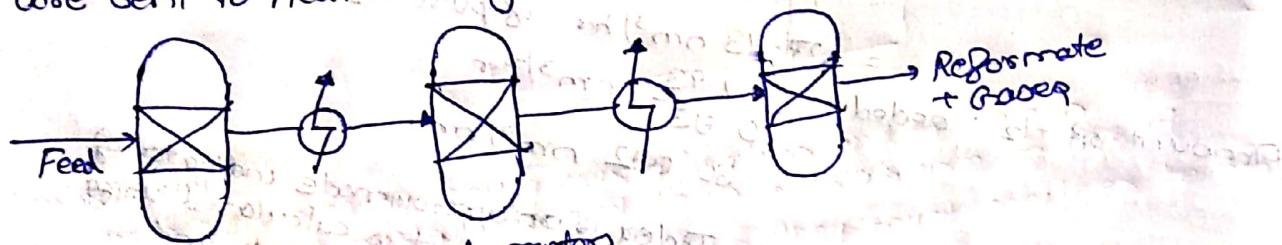
Hence, hydrotreatment unit precedes a reformer unit.

- Vapour phase reaction
- Characterised by increase in number of moles
- Type of reactor used: Packed Bed Reactor

Inlet temperature to reformer: 490°C
Outlet temperature: $< 490^{\circ}\text{C}$ [Endothermic]

This leads to substantial decrease in reaction rate.

Hence, a large number of packed bed reactors in series are used. After every reactor, the feed is preheated to the desired temperature in a furnace. After all reactors, the products are sent to heat exchangers and vapour liquid condenser.



Equipment:
Packed bed reactors
Heat exchangers

Furnaces
Vapour Liquid Condensers

If dehydrogenation is very fast, coke formation may start. Hence, we need to continuously supply H₂ to control rate of dehydrogenation.

Lubricating Oil Base Stock: Refineries do not produce lubricating oil, but they produce the base (raw material) needed to produce lubricating oil. Properties:

- It must have adequate viscosity grade. If viscosity is too low, then oil will flow out of moving parts. If viscosity is too high, the moving parts will stick.
- Viscosity Index: It is the sensitivity of η (kinematic viscosity) with temperature variation. Higher the viscosity index, lower is the variation of kinematic viscosity with temperature. As a lubricating fluid, the temperature of oil rises as energy is lost between moving parts. This reduces the kinematic viscosity of oil. The lubricating oil must be such that there is no considerable change in kinematic viscosity with increase in temperature. Thus, viscosity index must be high.
- It must have a low pour point.

The pour point has to be low because the parts where liquid has to placed to lubricate are not directly accessible. The liquid has to flow to be the pour. Hence, to ensure flowability, the lubricating oil must have low pour point.

Hydrocarbon Kinematic viscosity Viscosity index Pour point

Paraffins High High

Olefins Moderate Moderate

Naphthalene Low Low

Aromatics Lowest Lowest

The kinematic viscosity of lubricating oil is always specified with temperature.

Grease is a mixture of lubricating oil and soap. Increase is caused when-

- Lubricant is desired to stick to surface.
- There is direct access to the surface.

Lubricating Oil Base Stock is prepared from Reduced Crude Oil (RCO).

Vacuum distillation is used to separate RCO into different distillates, each with different kinematic viscosity.

RCO → Vacuum Gas Oil
→ Spindle Oil
→ Light Oil
→ Heavy Oil
→ Shot residue

Spindle oil is thin oil and is the least viscous. It is used for lubricating spindles.

Deasphalted oil

Wax → Demixing → Hydrofinishing
Demixed oil → Lubricating oil base stock (SO, LO, HO)

RCO → SO
→ LO
→ HO
→ SR

To improve pour point, wax must be removed.
Paraffins are present in oil as wax. To improve kinematic viscosity, aromatics must be removed.

To improve kinematic viscosity, aromatics must be removed. Crude oil contains small amount of N_2 which reacts with oxygen present in air to form oxides of nitrogen. They are dark in colour and turn the oil dark. However, this doesn't deteriorate the quality of product. But still, these nitrogen products need to be removed. This is done by hydro treatment that converts N_2 to NH_3 and S to H_2S . This provides colour stability.

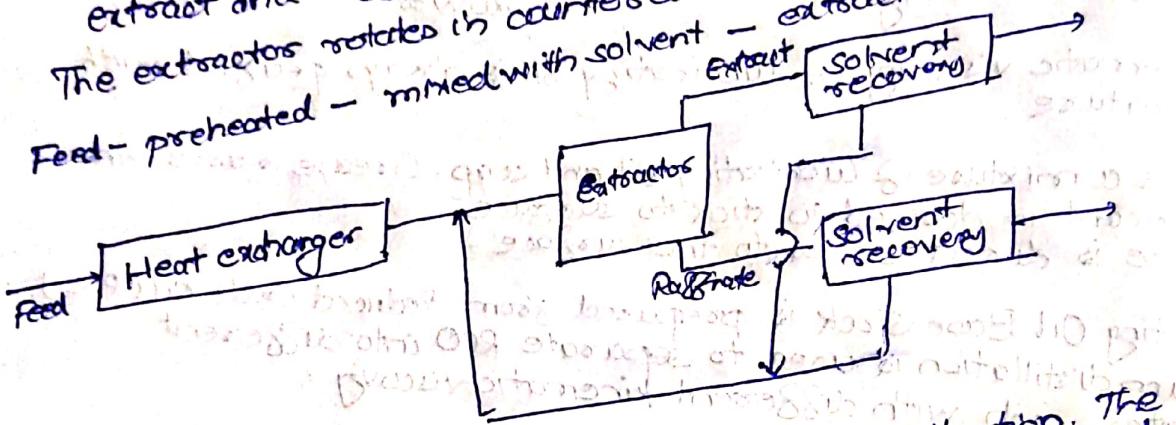
Hydro treatment increases light intensity, which is due to removal of nitrogen species.

Deasphalting unit:

- It uses solvent extraction to remove aromatics.
- Extraction takes place in rotating disc contactors.
- Solvent: Earliest: Phenol/Furfural
Now: NMP (n-methyl Pyrrolidone)
- They dissolve aromatic.

The aromatic extraction unit consists of an extractor and a recovery unit. The solvent recovery takes place from both extract and raffinate phases.

The extractors rotates in counter-clockwise fashion, mixed with solvent - extractor - phase separator.



Dewaxing unit:
Wax is removed by cooling, crystallisation and filtration. The feed is cooled, it crystallises and then crystals are filtered. The crystals must be monodispersed i.e. they must neither be too big nor too small.

- Too large crystals have solvent trapped in between them
- Too small crystals clog the filters media
- Too small crystals are very important. Controlled cooling of crystals

Hence, cooling rate is very important. Controlled cooling of crystals takes place in double pipe heat exchangers.

Coolant: Vaporising ammonia (NTG refrigerant)

To decrease diffusional resistance, some solvent with low viscosity is added so that wax molecules come together with low resistance.

The solvent should be such that it doesn't dissolve wax.

Feed + Solvent + (Homogenised the feed) -> Preheated to 90°C -> cooled gradually (NTG refrigerant) -> Filtered -> Solvent recovery and recycle

During solvent recovery, both crystals and filtrate are heated and solvent is recovered. In this process, the more volatile component of solvent is lost more. Hence during make up process, more volatile component must be added in greater composition.

Order of volatility: Methyl ethyl ketone > benzene > toluene
Make up composition: Methyl ethyl ketone > benzene > toluene

Various Unit Operations in a refinery:-

- Separation
 - Distillation
 - Extraction
 - Absorption / Stripping
- Crystallisation and Filtration
- Mixing
- Crushing, Grinding, Sieving (Found in coking unit)
- Adsorption: Water adsorption using alumina takes place wherever instrumentation air is required. The instrumentation air must be moisture free else it will clog the nozzle of flapless nozzle system. Hence, adsorption is used.
 - A vacuum distillation column is wider than crude distillation column. This is because at lower pressure, higher flow rates are observed.

Various Unit Operations in a refinery

- Separation
- Distillation
- Extraction
- Absorption / Stripping
- Crystallization and Filtration

- Mixing

Cutting, Grinding, Sieving (Found in cooking unit)

Absorption: Water adsorption using alumina takes place where ever instrumentation air is required. The instrumentation air must be moisture free else it will clog the nozzle of flappers nozzle system. Hence, adsorption is used.

A vacuum distillation column is wider than crude distillation column. This is because at lower pressure, higher flow rates are observed.

Industrial Grade:

Net Calorific Value: It is the quantity of heat produced by combustion of a fuel when the water vapour produced by combustion remains in gaseous phase. This is also known as lower heating value (LHV).

Gross Calorific Value: It is the quantity of heat produced by combustion of fuel when water vapour produced by combustion settles to liquid phase at room temperature. This is also known as higher heating value (HHV).

Gross calorific value is greater than net calorific value because it includes the latent heat of vapourisation of water as well.

Solid Fuels:

Coal: Coal is available in different forms. They are:-

- Peat
- Lignite
- Bituminous Coal
- Anthracite

These are different grades because of different extent of changes that they have undergone.

Coke: Coke is formed by destructive distillation of coal. Coal is heated in the absence of air. During this process, all the volatile gases escape out. Carbon and inorganic material remain.

- Ash in coal has inorganic origin. Ash is formed from metal oxides and silica. These inorganics remain in coke after coking process.

- 1g coal leads to the formation of coke which is less than 1g. But the amount of inorganics remain the same. Hence, inorganic content (in %) increases in coke.

- Volatile matters that leaves is mainly moisture and light hydrocarbons and some hydrogen as well.

Hydrogen % is higher in volatile matters than initial coal sample. Thus coke has lower % of hydrogen than coal. Because hydrogen has higher calorific value than carbon and coke has more carbon % and less hydrogen %, the calorific value of coke is lower than coal.

Hence, during coking process:-

- Volatile matters leaves
- Ash content increases
- Carbon % increases
- Hydrogen % decreases
- Calorific value decreases

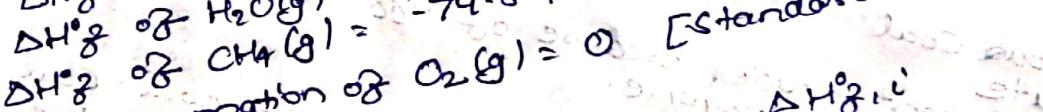
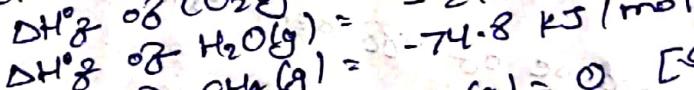
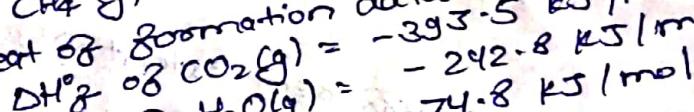
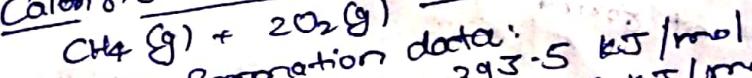
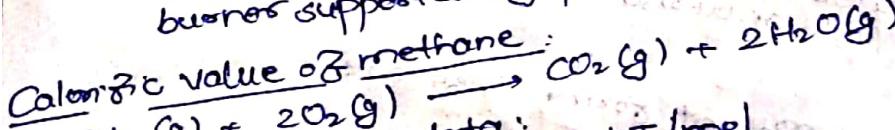
The conversion of coal to coke is carbonisation process. These are two types of carbonisation processes:-

- Low temperature carbonisation: It takes place at lower temp. less amount of volatile matters leaves and more He is left in coke. Hence, coke formed is soft.
- High temperature carbonisation: It takes place at higher temp. More volatile matters leaves and less He is left in coke. Hence, hard coke is formed.

Firing a solid fuel:

A solid fuel can be fired in two ways:-

- Grate firing: Big particles of solid fuel are burnt.
- Pulverised firing: This is a system where fine solid particles are entrained in air are burnt. The fuel is transported to fire box by pneumatic transport. Coal is burnt on a burner supported by pilot burner using light diesel oil.



$$\begin{aligned} \text{Heat of formation of O}_2(g) &= \sum \Delta H_f^\circ, i \text{ reactants} \\ \text{Heat of reaction} &= \sum \Delta H_f^\circ, i \text{ products} \\ \Delta H_r^\circ &= \sum \Delta H_f^\circ, i \text{ products} - \sum \Delta H_f^\circ, i \text{ reactants} \\ &= 2(-242.8) - 393.5 - (-74.8) \end{aligned}$$

$$= -804.8 \text{ kJ/mol}$$

Because water is formed in vapour phase, this is net calorific value of CH_4 .

Water is formed in liquid state,

$$\Delta H_f^\circ \text{ of } \text{H}_2\text{O}(l) = -286.2 \text{ kJ/mol}$$

$$\Delta H_f^\circ \text{ of } \text{H}_2\text{O}(g) = 2(-286.2) - 393.5 + 74.8$$

Net calorific value = -891.1 kJ/mol

For a pure component, the standard heat of reaction is reported as its calorific value. For a mixture, this is generally determined experimentally.

If elemental composition in % is given for a fuel mixture, the calorific value of fuel is weighted average of calorific values of respective elements with % composition as weight

Coke is used in steel industries in blast furnace as a reducing agent. Coke is burnt with low grade oxygen. This forms CO which reduces iron ore. The coke fed in blast furnace must have following desired properties:-

- It should have a high carbon content.
- It should have a minimum level of hardness so that it doesn't get crushed into powder easily.

Coke used in blast furnace is hard coke. It is formed by high temperature carbonisation in coke oven.

Soft Coke Production:

Soft coke is produced by low temp. combustion of coal. Along with soft coke, a good amount of coal gas is also produced.

The gas produced in coke oven contains N₂, NH₃, H₂, lighter hydrocarbons and naphthalene. It also contains some tarry material which will condense. The NH₃ present in gas is removed because it is not required. Whatever uncondensed part of gas is left is known as coke oven gas -

By product recovery plant in steel industries handle dry distillate obtained from coke oven.

- Coke oven gas is mainly used as a fuel in industries. The major component that burns and contributes to calorific value of coke oven gas is H₂.

- Blast furnace gas is another gas produced by steel industry. Of coke oven gas and blast furnace gas is CO.

- The major burning component of blast furnace gas is H₂. Blast furnace gas has a higher calorific value than blast furnace gas.

- Due to presence of good amount of H₂, coke oven gas has a higher calorific value than blast furnace gas.

- Separate burners are used for combustion of blast furnace gas and coke oven gas.

• A gaseous fuel

- has higher calorific value / kg

- has lower volumetric calorific value

- requires bigger firebox for burning

• A liquid fuel

- has higher volumetric calorific value due to higher concentration of hydrocarbons (thus H₂)

- provides intense heat generation

• A solid fuel

- is cheap

- requires indirect heating

- calorific value is not very high