Module-1

• INTRODUCTION :

Energy is the ability of a physical system to do work on other physical systems.
It's the capability of doing work.
Work = Force × Displacement.

- Energy produces light.
- Energy produces heat.
- Energy produces motion.
- Energy produces sound.
- Energy produces growth.
- Energy powers technology.

Units :

$1 \text{ J} = 1 \text{ N-m} = 10^7 \text{ ergs} = 10^7 \text{ dyne-cm}$

$1 \text{ J} = 2.778 * 10^{-7} \text{ kWh} = 0.23901 \text{ cal}$

$1 \text{ J} = 0.7376 \text{ lbf.ft} = 9.486 * 10^{-6} \text{ Btu}$.

• LAWS :

First Law of Thermodynamics : Energy can neither be created nor destroyed. This means that we can't make energy out of nothing - the total amount of energy in the universe is a constant.

Second Law of Thermodynamics : The total entropy of a system, which is isolated, can only increase with time. The second law refers to the state of energy and is reflected in a measurement of the degree of disorder (a measurement called entropy).

Third Law of Thermodynamics : The third law is that everything does come to a stop only when the temperature is at -273.15°C. This is called absolute zero and is where the entropy measurement is 0.

• FORMS OF ENERGY:

1. Potential Energy - It is the energy stored and the energy of position or gravitational energy. There are several forms of potential energy including:
   - Chemical Energy is energy stored in the bonds of atoms and molecules. Biomass, petroleum, natural gas and propane are examples of stored chemical energy.
   - Stored Mechanical Energy is energy stored in objects by the application of a force. Compressed springs and stretched rubber bands are examples of stored mechanical energy.
   - Nuclear Energy is energy stored in the nucleus of an atom - the energy that holds the nucleus together. The energy can be released when the nuclei are combined or split apart.
   - Gravitational Energy is the energy of position or place. Hydropowder, such as water in a reservoir behind a dam, is an example of gravitational potential energy.

2. Kinetic Energy: It is motion - the motion of waves, electrons, atoms, molecules, substances and objects.
   - Electrical Energy is the movement of electrons. Atoms are made of ~~even~~ smaller particles called electrons, protons and neutrons and everything is made up of tiny particles called atoms. Lightning is an example of electrical energy.
   - Radiant Energy is electromagnetic energy that travels in transverse waves. It includes visible light, x-rays, gamma rays and radio waves. Solar energy is a type of radiant energy.
   - Thermal Energy or heat, is the internal energy in substances - the vibration and movement of atoms and molecules within substances. Geothermal energy is an example of thermal energy.
   - Sound Energy is the movement of energy through substances in logitudinal waves.
   - Motion Energy is the movement of objects and substances from one place to another.

• TERMINOLOGY :

- Energy source defines an energy type or an energy carrier, which can be natural or artificially generated, without a quantitative estimation.

- Energy Resource, combine the type and the amount of energy, prevailing the second issue.

- Energy carrier represents the material support of the energy, which allows transporting, converting or utilizing every type of energy. Energy carriers may be solid, liquid or gaseous material, as well as radiation, electromagnetic field, etc.

• SOURCES CLASSIFICATION :

Criterion	Categories	Examples
1. Origin	Solar	Solar Radiation Wind energy Hydropower Bio mass Fossil fuels
	Other (Non-solar)	Nuclear energy Geothermal energy
2. Durability	Non-renewable	Fossil Fuels Nuclear fuel
	Renewable	Solar Radiation Wind energy Hydropower Biomass Geothermal energy
3. Participation to world consumption	Conventional	Fossil fuels Hydropower Nuclear fuel
	Unconventional	Solar radiation Wind energy Biomass Geothermal energy
	Non-commercial	Vegetable and cattle waste
4. The mobility of the energy carrier	Transportable	Fossil fuels Nuclear fuel Biomass
	Non-transportable	Solar Radiation Wind energy Hydropower Geothermal energy

- **ENERGY- Sources Features:**

a) the source capacity;
b) the specific energy content;
c) the durability of the resource;
d) the highest rate of resource exploitation;
e) the possibilities for energy conversion (the number of conversio stages, the conversion efficiency);
f) the transportation possibilities of the energy carrier, (efficiency costs);
g) the storage possibilities of the energy carrier (efficiency, costs);
h) the non-energetic utilizations of the energy carrier;
(i) the environmental consequences of the resource utilization.

- **Prospects of Renewable Energy:**

Renewable Energy -
- Energy that comes from the sources which are continuously replenished such as sunlight, wind, rain, tides, waves and geothermal energy.
- About 16% of global energy ~~sources~~ comes from renewable resources.
- 10% of all energy from traditional biomass.
- 3.4%:- hydroelectricity and 3% - new renewables.

Benefits of Renewable Energy -
- Avoid the high cost involved in transmission capex.
- Avoid distribution losses - Technical & otherwise.
- Avoid recurring fuel cost.
- Boost the rural economy.
- Encourage self help groups & self dependence.
- Enable village cooperatives to supply and/or monitor distribution
- Make available much needed energy for basic needs at the doorstep at affordable prices.

Why renewable energy for India?

- Power shortage
- Rising prices of oil and gases.
- Ecological hazards
- Ample resources and sites available.
- Abundant sunshine.
- Government incentive.
- Increased financing options.

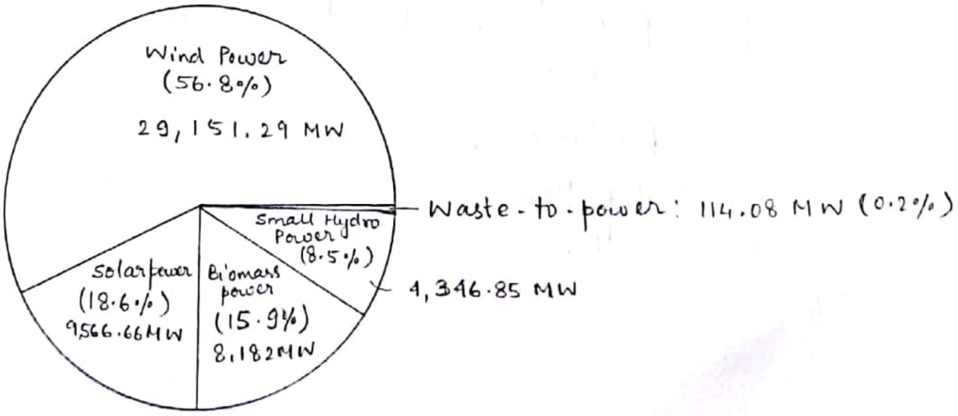
Total renewable installed capacity in India -

The renewable installed capacity of India stands at 69.022GW as of 31 March 2018.

Source	Total installed capacity (MW)	2022 Target (MW)
Wind power	34,046	60,000
Solar power	21,651	100,000
Biomass power (Biomass & Gasification and Bagasse cogeneration)	8,701	*10,000
Waste-to-Power	138	
Small hydropower	4,486	5,000
Total	69,022	175,000

* The target is given for "bio-power" which includes biomass power and waste to power generation.

Installed grid interactive renewable power capacity in India as of 28 February 2016 (excluding large hydro)



India's Renewable Energy Future Prospects :

- India stands among top 5 countries in the world in terms of renewable energy.
- The installed base is 9% of total power generation capacity & contributes 3% of the electricity mix.
- The National Action Plan on Climate change in June 2018 indentified solar energy development.
- In November 2009, the GoI approved National Solar Mission which aims to enable 20,000 MW to be deployed in India by 2022.
- India occupies 5th position in the world in Wind Energy, hydro projects upto 25MW capacity.

• Energy Conservation : Principle of Energy Conservation and Energy Audit.

Principle of Energy Conservation –

The law of conservation of energy states that energy is neither created nor destroyed, it can be changed from one form to another.

Efficiency is the amount of useful energy a system can provide. A perfect energy efficient machine would change all energy put in it into useful work which is a technological impossibility today.

Converting one form of energy into another always involve a loss of usable energy. Most energy transformations are not very efficient. Eg- our body has an efficiency of 15%, the use of the energy transforms to heat.

Energy loss in any industrial process or plant is inevitable. These losses are due to designs that do not incorporate energy efficient specifications such as heat recovery options, etc. Reducing these losses will substantially increase plant's efficiency, but for that we need data to identify and quantify the losses and subsequently suggest suitable techno-economic solutions to minimize the losses. This data can be acquired through energy audits.

Energy Audit :

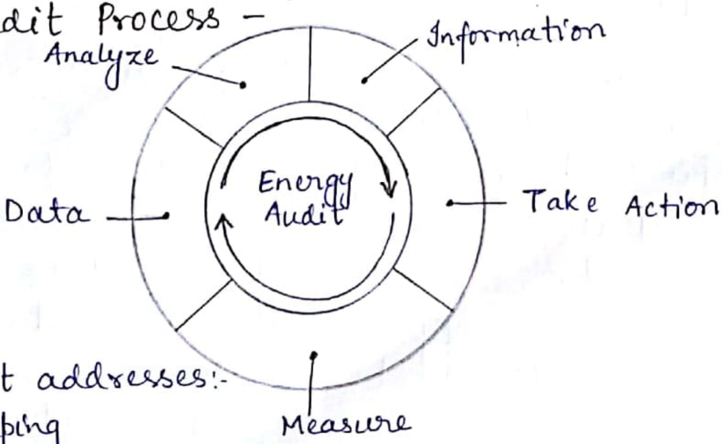
Energy Audit is a periodic examination of an energy system to ensure that energy is being used as efficient as possible. It i "the verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption."

Energy Audit is the first step towards systematic efforts towards conservation of energy. It involves collection and analysis of energy related data on regular basis and in a methodology manner.

Objectives –

1. Identifying the quality and cost of various energy inputs.
2. Assessing present pattern of energy consumption in different cost centres of operations.
3. Relating energy inputs and production output.
4. Identifying potential areas of thermal and electrical energy economy.
5. Highlighting wastage in major areas.
6. Fixing of energy saving potential targets for individual cost centres.
7. Implementation of measures for energy conservation and realization of savings.

Energy Audit Process –



Enery Audit addresses:-

- House keeping
- Operational Improvement / Retrofits
- Capital Projects requiring investment
- New Technology

Energy Audit helps to achieve "Saving through invisibles".

Types of Energy Audit -

It can be categorized into 2 types -

(i) Walk through / Preliminary

(ii) Detail Audit

(i) Walk - Through / Preliminary Audit

It comprises -

a) one day or few days visit to plant.

b) output is a simple retort based on observation and historical data provided during the visit.

c) The findings will be a general comment based on rule of thumbs, energy best practices or the manufacturer's data.

Preliminary Energy Audit

- Establish energy consumption in the organization.
- Establish the scope for saving
- Identify the most likely and the easiest areas for attention.
- Identify immediate (especially no/low cost) savings or improvements.
- Set a reference point.
- Identify areas for more detailed study or measurement.
- Preliminary energy audit use existing, or easily obtained data.

Detailed Energy Audit

The detailed audit goes beyond quantitative estimates of costs and savings. It includes engineering recommendations and well-defined projects, giving due priorities. Approximately 95% of all the energy is accounted for during the detailed audit. The detailed audit is conducted after preliminary energy audit. Sophisticated instrumentation including flowmeter, flue gas analyzer, scanners and other advanced instruments are used to compute energy efficiency. The process includes :

(i) elaboration and discussion of audit methodology.

(ii) selection of plant items to be audited.

(iii) Collection of more detailed energy and production data.

(iv) Comprehensive measurements at selected plant items
  - process flow and utility diagram.
  - measurement survey / performance trials.

(v) Detailed analysis and calculations.

(vi) Elaboration of energy and material balance for the audited plant items.

(vii) Investigation of energy saving options (improved maintenance of equipments, improved energy management, modification or rationalization of process configurations, improved insulation / control of refrigeration, etc.).

(viii) Recommendation of feasible energy efficiency measures.

(ix) Financial analysis of recommended measures, including cost benefit calculation.

(x) Ranking of measures and elaboration of energy saving action plan.

(xi) Reporting

(xii) Presentation to plant management.

• ENERGY CONSERVATION TECHNOLOGIES :

(A) Co-Generation / Combined Heat & Power (CHP) Systems :

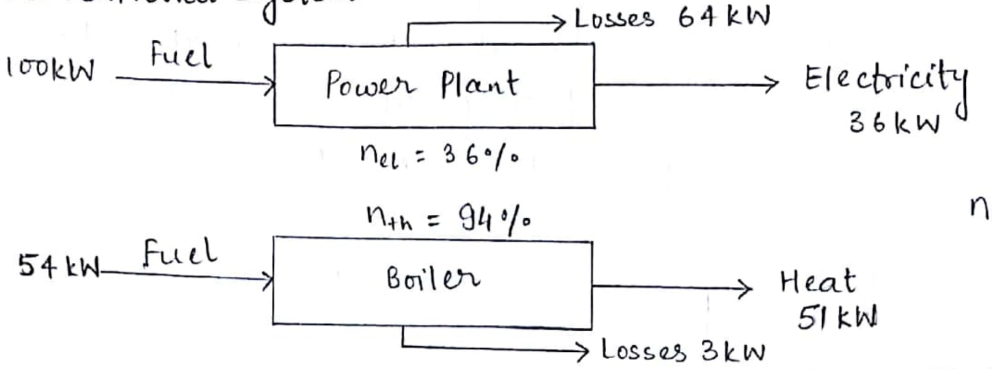
A cogeneration system is the sequential for simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system.

Cogeneration - Combined Heat and Power (CHP)

Trigeneration - Cooling, Heating and Power (CHP).

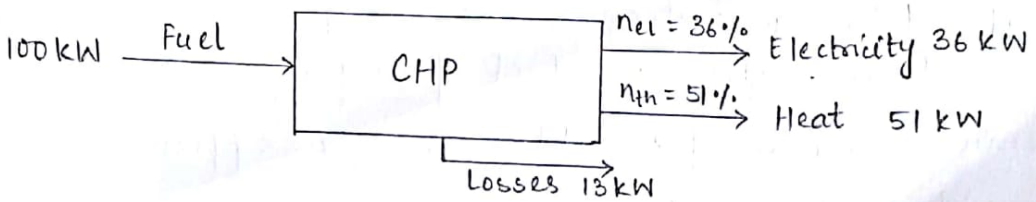
Integrated Energy System (IES) - Building Cooling, Heating and Power (BCHP).

Conventional System -



$\eta_{el}/\eta_{th} = 56\%$

Co-generation / CHP system -



$\eta_{el}/\eta_{th} = 87\%$

CHP systems consist of a number of individual components - prime mover (heat engine), generator, heat recovery and electrical interconnection - configured into an integrated whole.

Prime movers for CHP systems include reciprocating engines, combustion or gas turbines, steam turbines, micro-turbines, and fuel cells - Mechanical energy from fuel.

Mechanical Energy from the primer mover - to drive a generator to produce electricity.

Thermal Energy.

Co-generation / CHP System Benefits -

- Improves energy efficiency.
- Conserves natural resources (fossil fuels).
- Lower emissions (including CO_2).
- Lower energy costs.
- If heat fits demand, cheapest way of electricity production
- Improves security of supply.
- Reduces transmission and distribution losses.
- Enhances competition.

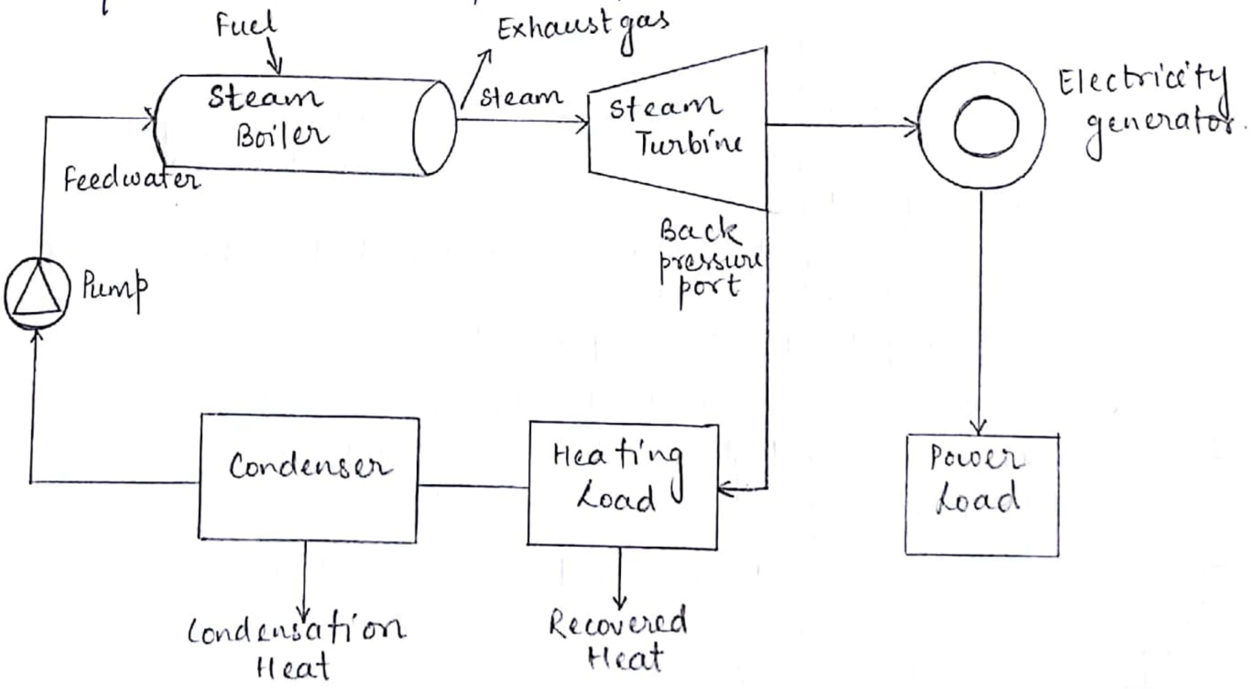
→Types of Co-Generation Systems :

- Based on Prime Mover
  1. Steam turbine co-generation system
     - Back Pressure Steam Turbine
     - Extraction Condensing Steam Turbine
  2. Gas turbine co-generation system
     - → Open cycle gas turbine
     - → Closed cycle gas turbine
  3. Reciprocating Engine co-generation system.
- Based on sequence of energy use and the operating schemes adopted
  1. Topping cycle cogeneration system
     - → Combined-cycle topping system
     - → Steam-turbine topping system
     - → Heat recovery topping system
     - → Gas turbine topping system
  2. Bottoming cycle co-generation system.

★Steam Turbine Co-generation System –

(i) Back Pressure Steam Turbine :

- Steam exits the turbine at a pressure higher or atleast equal to the atmospheric pressure.



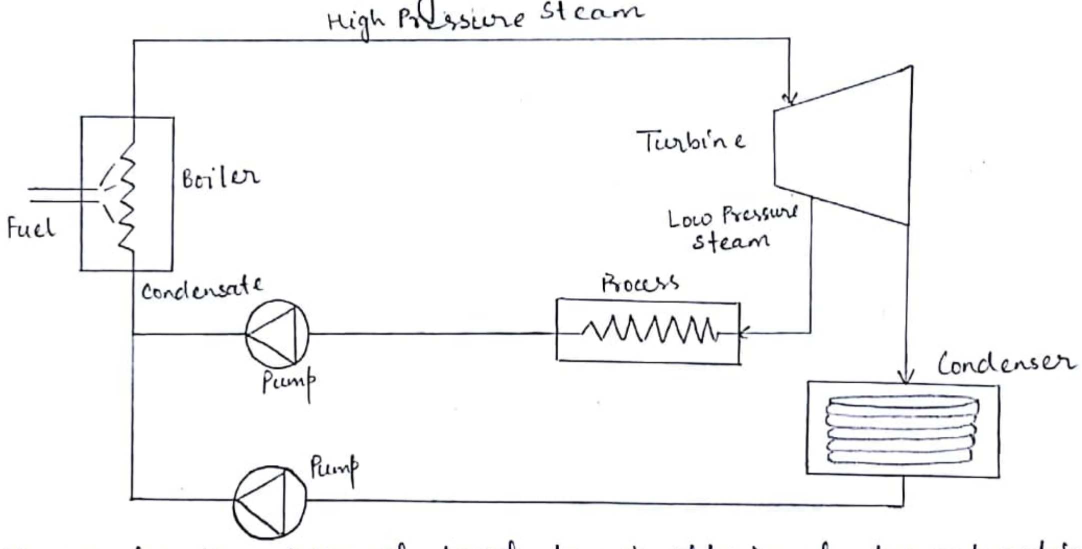
Advantages:

- Simple configuration
- The costs of expensive low-pressure stages of the turbine are avoided.
- Low capital cost.
- Reduced or even no need of cooling water.
- High total efficiency, because there is no heat rejection to the environment through condenser.

Disadvantages:

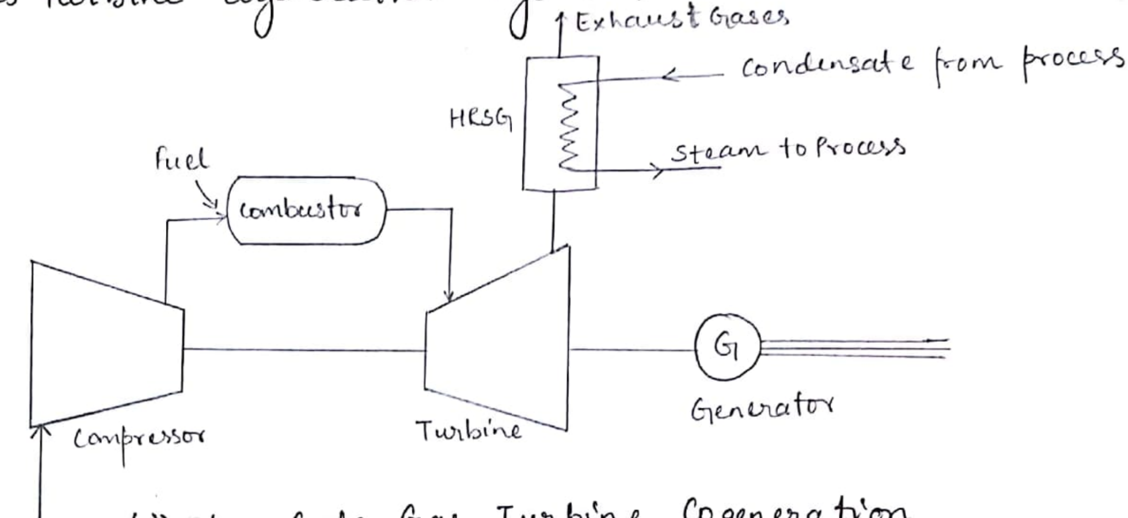
- Steam turbine is larger for the same power output, because it operates under a lower enthalpy difference of steam
- Electricity and steam dependency on thermal load.

(ii) Extraction Condensing Steam Turbine:



- Steam for the thermal load ~~by~~ is obtained by extraction from one or more intermediate stages at the appropriate pressure and temperature.
- The remaining steam is exhausted to the pressure of the condenser, which can be ~~less~~ as low as 0.05 bar with a corresponding condensing temperature of about 33°C.
- In comparison to the back-pressure system, the condensing type turbine has a higher capital cost and, in general, a lower total efficiency.
- However, to a certain extent, it can control the electrical power independent of the thermal load by proper regulation of the steam flow rate through the turbine.

★ Gas Turbine Cogeneration System:



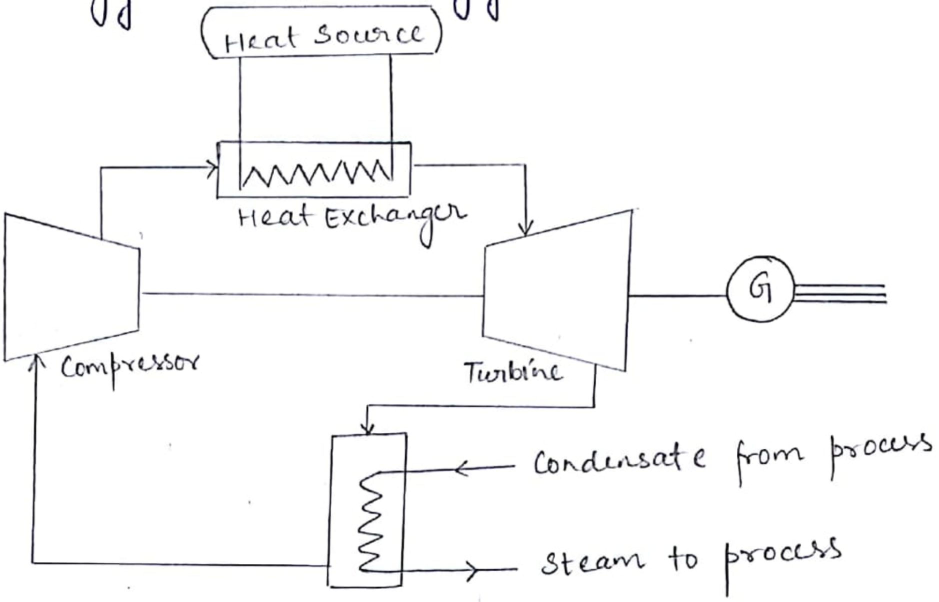
(i) Open Cycle Gas Turbine Cogeneration

- Gas Turbine systems - thermodynamic cycle - Brayton cycle.
- Brayton cycle - atmospheric air is compressed, heated, and then expanded, with the excess of power produced by the turbine or expanded over that consumed by the compressor used for power generation.
- Natural gas is most commonly used, other fuels such as light fuel oil or diesel can also be employed.
- The typical range of gas turbines varies from a fraction of a MW to around 100 MW.
- Compressor - Air pressure & temperature increased.
- Air is delivered through a diffuser to a constant-pressure combustion chamber, where fuel is injected and burned.
- Combustion takes place with high excess air. The high pressure and temperature gases - turbine producing mechanical work to ~~give~~ drive the compressor and the load.
- Combustor gas – upto 1300°C & turbine gas - upto 600°C for heat recovery.

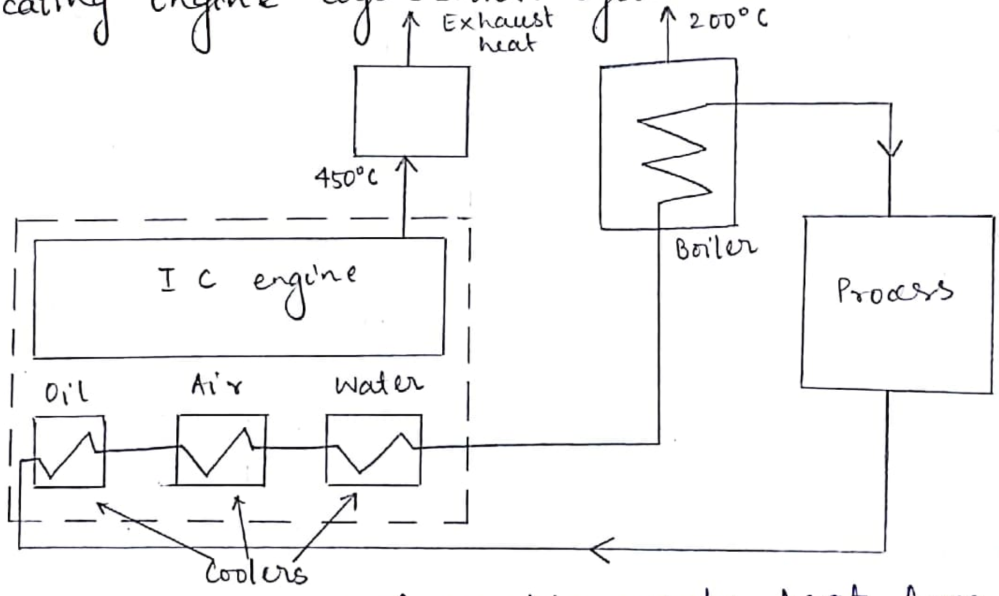
(ii) Closed-cycle gas turbine cogeneration systems -

- In the closed-cycle system, the working fluid (usually helium or air) circulates in a closed circuit.
- It is heated in a heat exchanger before entering the turbine, and it is cooled down after the exit of the turbine releasing useful heat.

- Thus, the working fluid remains clean and it does not cause corrosion or erosion.
- Source of heat can be external combustion of any fuel. Also, nuclear energy or solar energy can be used.

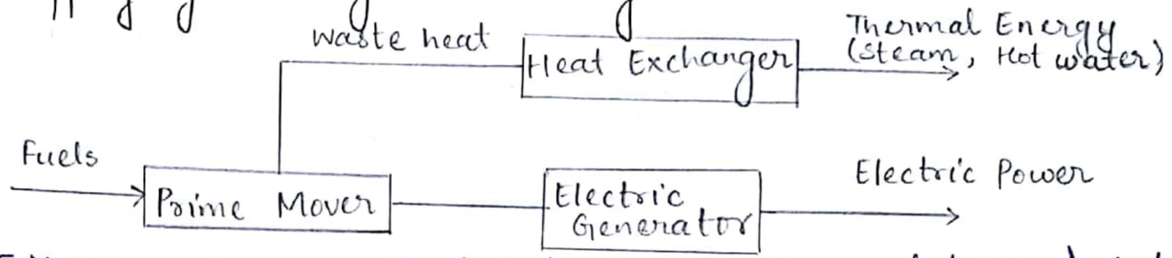


★ Reciprocating Engine Cogeneration System –



There are four sources of usable waste heat from a reciprocating engine: exhaust gas, engine-jacket-cooling water, lube oil cooling water, and turbocharger cooling. Recovered heat is generally in the form of hot water or low-pressure steam (< 30 psig). The high temperature exhaust can generate medium pressure steam (up to about 150 psig), but the hot exhaust gas contains only about one half of the available thermal energy from a reciprocating engine.

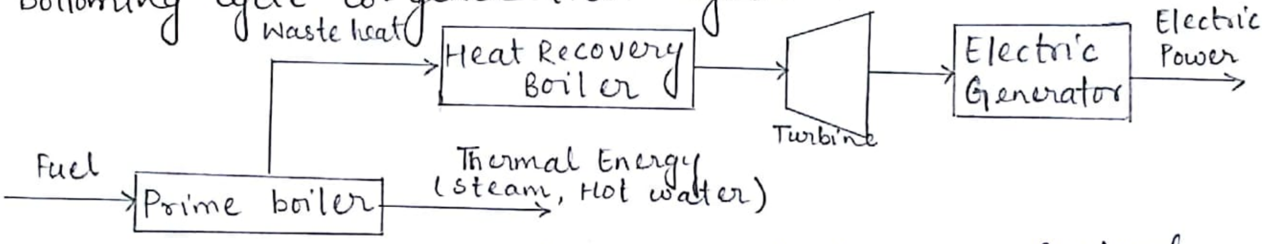
★ Topping Cycle Co-generation System:



Topping cycle, the electricity (or mechanical power) is produced first, and then heat is recovered to meet the thermal loads of the facility.

It is generally found in facilities which do not have extremely high process temperature requirements. The basic Brayton and Rankine cycles work as topping cycles.

★ Bottoming Cycle Co-generation System:



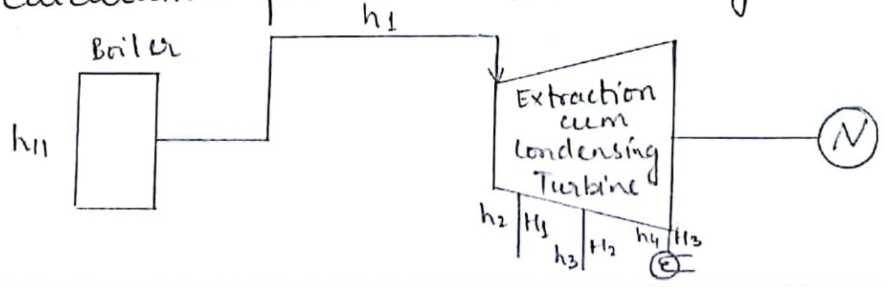
Bottoming cycle the thermal energy is the main desired product and it is produced directly from the combustion of a fuel.

This energy usually takes the form of stream that supplies process heating loads.

Process heat waste is always present, can be heat recovered and used as an energy source for running a turbine producing electric or mechanical power.

Common system which use this cycle are industrial applications with high temperature processes such as steel reheat furnaces, clay and glass kilns and aluminium re-melt furnaces.

→ Calculation for steam Turbine Cogeneration system:



Heat extraction from inlet to stage 1 extraction (h_5): $h_5 = (h_1 - h_2)$ kcal/kg

Heat extraction from stage 1 to stage 2 extraction (h_6): $h_6 = (h_2 - h_3)$ kcal/kg

Heat extraction from stage 2 to condenser (h_7) : $h_7 = (h_3 - h_4)$ kcal/kg

Step 1: Calculate the actual heat extraction in turbine at each stage

Steam enthalpy at turbine inlet : h_1, kcal/kg
steam enthalpy at stage 1 extraction : h_2, kcal/kg
steam enthalpy at stage 2 extraction : h_3, kcal/kg
steam enthalpy condenser : h_4, kcal/kg

Step 2: Estimate theoretical heat extraction from the Mollier diagram (H-f diagram) estimate the theoretical heat extraction for conditions mentioned in step 1.

Theoretical enthalpy after 1st extraction : H1
Theoretical enthalpy after 2nd extraction : H2
Theoretical enthalpy at condenser condition : H3

Theoretical heat extraction from inlet to stage 1 extraction (h8) : $h1 - H1$
Theoretical heat extraction from stage 1 to 2 extraction (h9) : $H1 - H2$
Theoretical heat extraction from stage 2 extraction Condensation (h10) : $H2 - H3$

Step 3: Compute turbine efficiency.

$$\text{Efficiency of stage 1}, \left(\frac{h5}{h8}\right) = \frac{\text{Heat Extraction Actual}}{\text{Heat Extraction Theo.}} = \frac{h1 - h2}{h1 - H1}$$

$$\text{Efficiency of stage 2} \left(\frac{h6}{h9}\right) = \frac{\text{Heat Extraction Actual}}{\text{Heat Extraction Theo.}} = \frac{h2 - h3}{H1 - H2}$$

$$\text{Efficiency of condensing stage} \left(\frac{h7}{h10}\right) = \frac{\text{Heat Extraction Actual}}{\text{Heat Extraction Theo.}} = \frac{h3 - h4}{H2 - H3}$$

Step 4: Calculate plant heat rate

$$\text{Heat rate (kcal/kWh)} = \frac{M(h1 - h11)}{P}$$

M = Mass flow rate of steam (kg/hr)
h1 = Enthalpy of inlet steam (kcal/kg)
h11 = Enthalpy of feed water (kcal/kg)
P = Average power generated (kW).

(B) Waste Heat Utilization:

- Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose.
- The essential quality of heat is not the amount but rather its value. The strategy of how to recover this heat depends upon the temperature of waste heat gases and the economics involved.
- Large quantities of hot flue gases is generated from Boilers, Kilns, Ovens and Furnaces. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. The energy lost in waste gases cannot be fully recovered. However, much of the heat could be recovered and loss minimized by adopting definite measures.

→Benefits of Waste Heat Recovery -

Benefits of 'waste heat recovery' can be broadly classified in two categories:

(i) Direct benefits: Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & cost and process cost.

(ii) Indirect benefits:

a) Reduction in pollution - A number of toxic combustible waste such as CO, sour gas, carbon black off gases, oil sludge, Acrylonitrile and other plastic chemicals etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.

b) Reduction in equipment sizes - Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gases handling equipments such as fans, stacks, ducts, burners, etc.

c) Reduction in auxiliary energy consumptions - Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps, etc.

→ Waste Heat Recovery Technologies:

There are four general technologies used to recover waste heat. These include:

(i) Direct usage
(ii) Heat exchangers
(iii) Heat pumps
(iv) Vapour Recompression.

(i) Direct usage – Direct usage as the name implies involves using the waste heat discharge "as is". Typical examples might include –

- using boiler off gases for drying.
- using spent cooling water from a heat exchanger for hot water.
- using hot air from a mechanical room to heat a storage area.

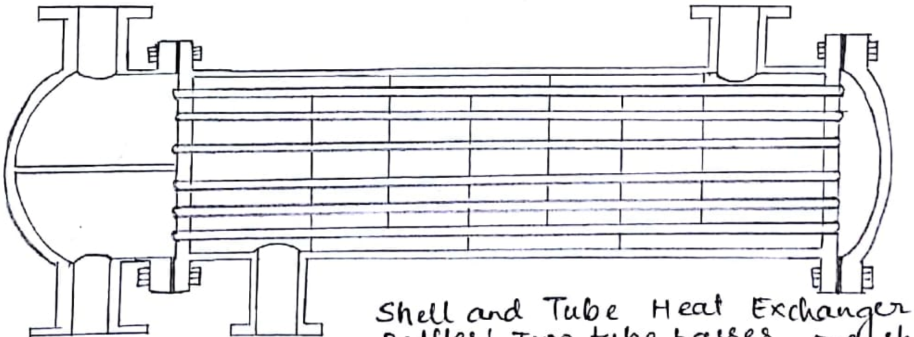
In some cases only minimal alterations may be required to permit utilization of the wast heat discharge. However, special attention must be paid to the condition of waste heat discharge especially in regards to potential contaminants such as harmful chemicals or unwanted moisture.

(ii) Heat Exchangers – Heat exchangers provide a means of transferring heat from one steam to another without the actual mixing of the two streams. The two streams may need to be separated for either of the following reasons:

- to prevent one stream from contaminating the other.
- to maintain a pressure difference that may exist between the two streams.

In a heat exchanger the two fluids may flow:

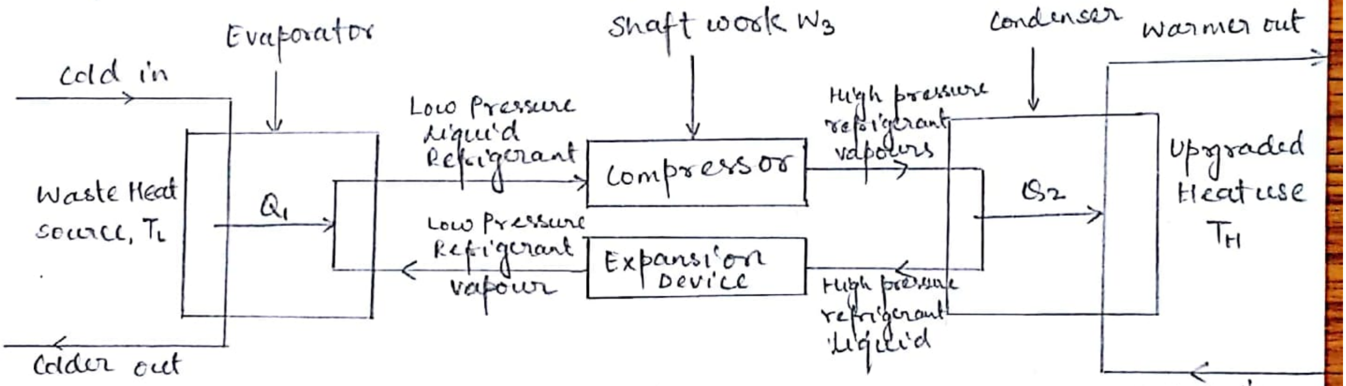
- in opposite directions or "counterflow".
- in the same direction or "parallel flow".
- perpendicular to each other or "crossflow".



Shell and Tube Heat Exchanger with Segmental Baffles: Two tube passes, one shell pass.

(iii) **Heat Pumps** - Heat pumps provide a means of raising the temperature of waste heat to increase its usefulness. For example, a heat pump may be used to recover heat from a building exhaust stream, raise the temperature of this heat, and recycle it for heating the building.

Low temperature waste heat is used to evaporate a liquid refrigerant under low pressure in the evaporator. The refrigerant vapour is then compressed to achieve an increase in its temperature due to the absorption of the mechanical energy of compression. The high temperature vapour passes through the condenser where its heat is released as it condenses to a liquid. The condensed fluid is then expanded to reduce its temperature and pressure before returning it to the evaporator.



Heat Pump cycle

Heat pump performance is expressed by a term called "coefficient of performance", which is defined as:

$$COP = \frac{Q_H}{W}$$

where, Q_H = total heat recovered in the condenser (kJ or W)
W = work input to the compressor (kJ or W).

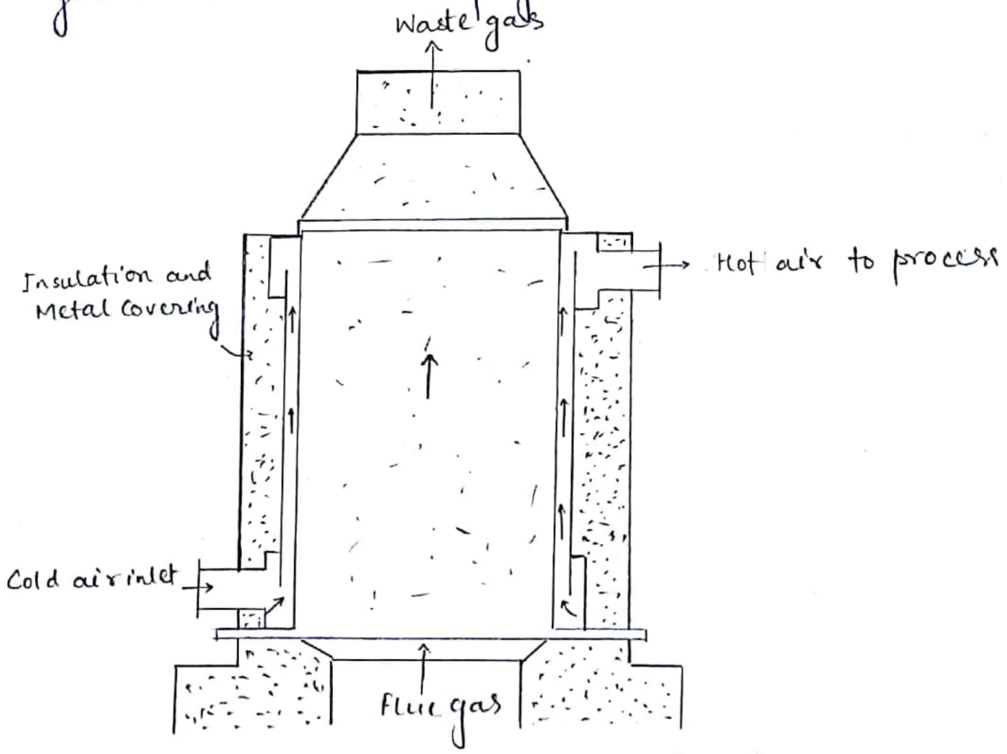
The value of COP depends on the difference between the temperature at which the heat is delivered and the temperature at which the heat is extracted, i.e., the degree of upgrading required. The larger this difference, the greater is the amount of work input, and smaller the COP.

(iv) Vapour Recompression – In case where a waste heat stream is in/the form of low temperature vapours, recompression is often a viable option. vapour compression involves compressing the waste stream vapour to increase its temperature and pressure in order to provide a useful source of energy. The compressed vapour is returned to the process for supplying the heat of evaporation. Thus the only energy input is power to the compressor. The coefficients of performance for vapour recompression can be very high (5 – 10).

Vapour recompression can be achieved either mechanically or thermally.

→ Commercial Waste Heat Recovery Devices –

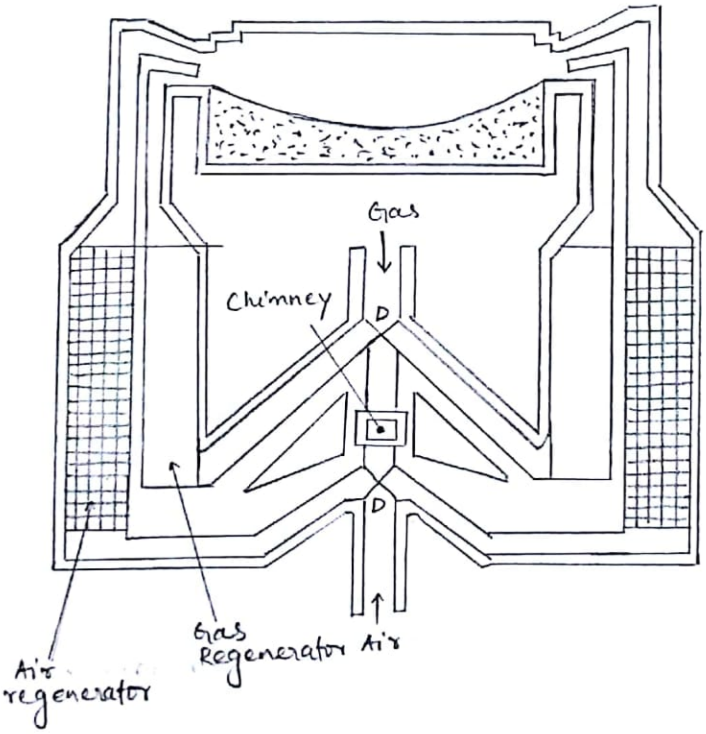
1. Heat Recuperators :
   - In a recuperator, heat exchange takes place between the flue gases and the air through metallic or ceramic walls.
   - Duct or tubes carry the air for combustion to be pre-heated, the other side contains waste heat stream.
   - A recuperator for recovering waste heat from flue gases is shown in figure.



Metallic Radiation Recuperator.

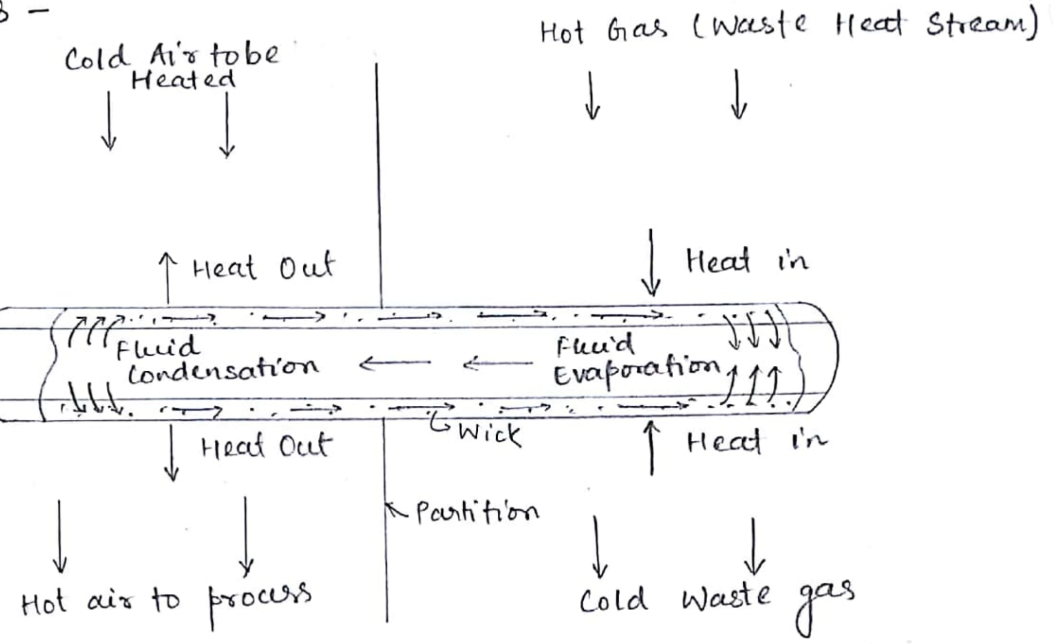
2. Heat Regenerators -

- The regeneration which is preferrable for large capacities have been very widely used in glass and steel melting furnaces.
- Important relations exists between the size of the regenerator time between reversals, thickness of brick, conductivity of brick and heat storage ratio of the brick.
- In a regenerator, the time between the reversals is an important aspect.
- Long periods would mean higher thermal storage and hence higher cost. Also, long periods of reversal result in lower average temperature of preheat and consequently reduce fuel economy.
- Accummulation of dust and slagging on the surfaces reduce efficiency of heat transfer as the furnace becomes old.
- Heat losses from the walls of the regenerator and air in leaks during the gas period and outleaks during air period also reduces the heat transfer.



Heat Regenerator

3. Heat Pipes -



Heat Pipe

- Heat pipe consists of three elements - a sealed container, a capillary wick structure and a working fluid.
- The capillary wick structure is integrally fabricated into the interior surface of the container tube and sealed under vacuum.
- Thermal energy applied to the external surface of the heat pipe is in equilibrium with its own vapour as the container tube is sealed under vacuum.
- Thermal energy applied to the external surface of the heat pipe causes the working fluid near the surface to evaporate instantaneously.
- Vapour thus formed absorbs the latent heat of vapourisation and this part of the heat pipe becomes an evaporator region.
- The vapour then travels to the other end of the pipe where the thermal energy is removed causing the vapour to condense into liquid again, thereby giving up the latent heat of the condensation. This part of the heat pipe works as the condenser region. The condensed liquid then flows back to the evaporated region.

— Advantages of Heat Pipes:

(i) Very high thermal conductivity - Less temperature difference needed to transport heat than traditional materials (thermal conductivity up to 90 times greater than copper for the same size resulting, in low thermal resistance).

(ii) Power flattening - A constant condenser heat flux can be maintained while the evaporator experiences variable heat fluxes.

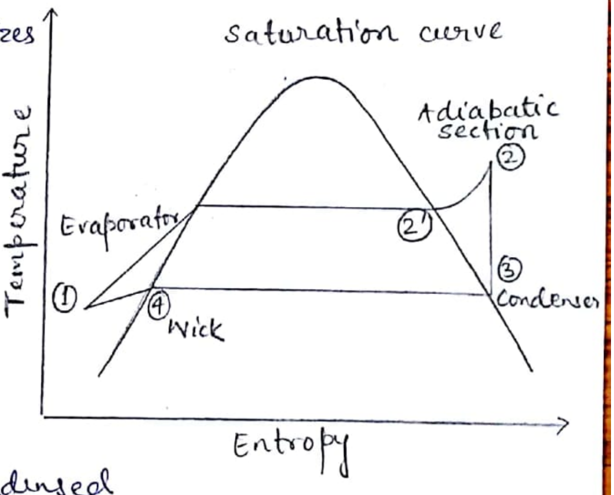
(iii) Efficient transport of concentrated heat.

(iv) Temperature control - The evaporator and condenser temperature can remain nearly constant (at Tsat) while heat flux into the evaporator may vary.

(v) Geometry control - The condenser and evaporator can have different areas to fit variable area spaces. High heat fluxes inputs can be dissipated with low heat flux outputs only using natural or forced convection.

— Thermodynamic Cycle:

- 1-2 : Heat applied to evaporator through external sources vapourizes working fluid to a saturated (2') or superheated (2) vapour.
- 2-3 : Vapour pressure drives vapour through adiabatic section to condenser.
- 3-4 : Vapour condenses, releasing heat to a heat sink.
- 4-1 : Capillary pressure created by menisci in wick pumps condensed fluid into evaporator section.



— Heat Pipe Applications:

(i) Electronics cooling - small high performance components cause high heat fluxes and high heat dissipation demands. Used to cool transistors and high density semi-conductors.

(ii) Aerospace - cool satelite solar array, as well as shuttle leading edge during re-entry.

(iii) Heat Exchangers - Power industries uses heat pipe heat exchangers as air heaters on boilers.

(iv) Other applications – production tools, medicine and human body temperature control, engines and automotive industry.

— Types of Heat Pipes:

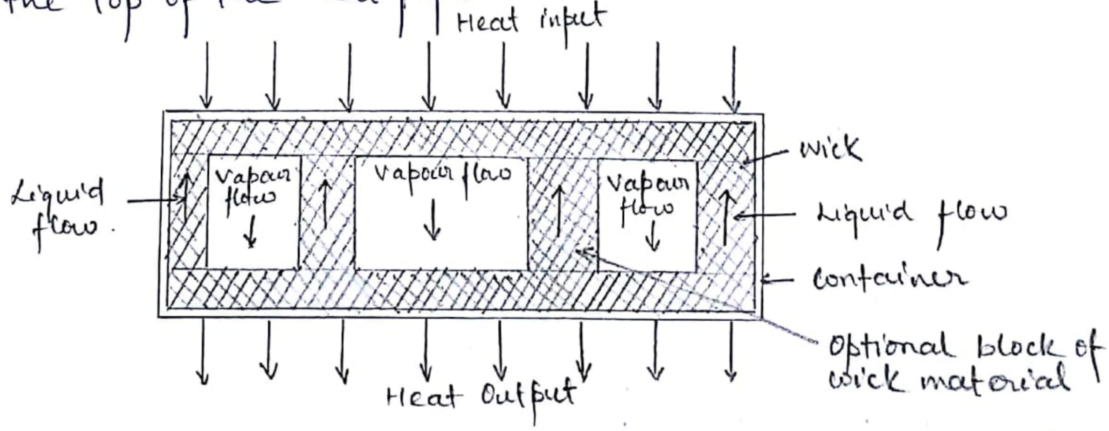
(i) Thermosyphon – Gravity assisted wickless heat pipe. Gravity is used to force the condensate back into the evaporator. Therefore, condenser must be above the evaporator in a gravity field.

(ii) Leading edge – placed in the leading edge of hypersonic vehicles to cool high heat fluxes near the wing leading edge.

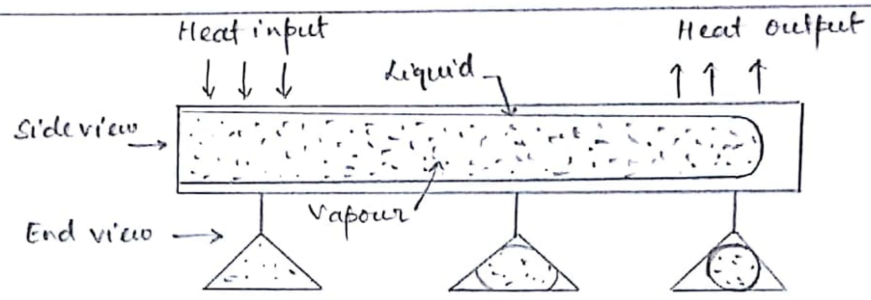
(iii) Rotating and revolving – condensate returned to the evaporator through centrifugal force. No capillary wicks required. Used to cool turbine components and armatures for electronic motors.

(iv) Cryogenic – Low temperature heat pipe. Used to cool optical instruments in space.

(v) Flat plate – much like traditional cylindrical heat pipes but are rectangular. Used to cool and flatten temperatures of semiconductor or transistor packages assembled in arrays on the top of the heat pipe.

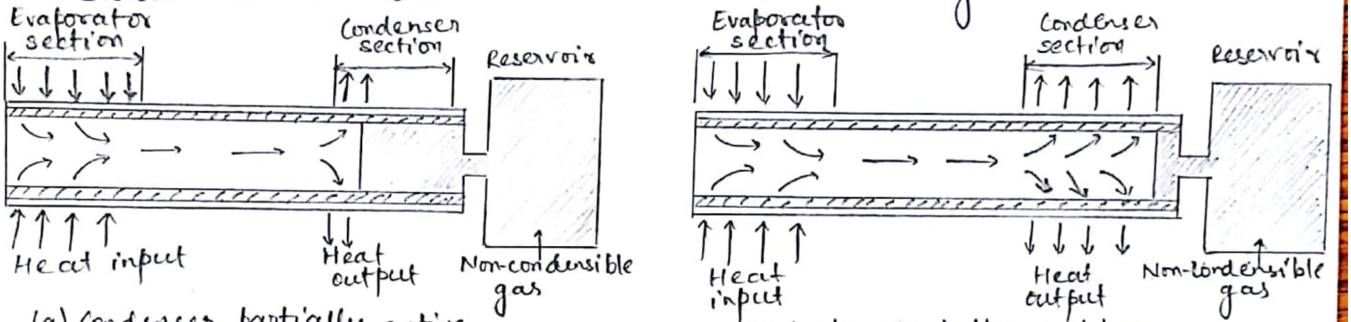


(vi) Micro heat pipes – small heat pipes that are non circular and use angled corners as liquid arteries. Characterized by the equation : $\frac{r_c}{r_h} \geq 1$ where r_c is the capillary radius and r_h is the hydraulic radius of the flow channel. Employed in cooling semiconductors (improve thermal control), laser diodes, photovoltaic cells, medical devices.



Micro-heat pipe operation.

(vii) Variable Conductance – allows variable heat fluxes into the evaporator while evaporator temperature remains constant by pushing a non-condensable gas into the condenser when heat fluxes are low and moving the gas out of the condenser when heat fluxes are high, thereby, increasing the condenser surface area. They come in various forms like excess-liquid or gas-loaded form. The gas loaded form is shown below. Used in electronic cooling.



(a) Condenser partially active

(b) Condenser fully active.

(viii) Capillary pumped loop heat pipe – for systems where the heat fluxes are very high or where the heat from the heat source needs to be moved far away. In the loop heat pipe, the vapour travels around in a loop where it condenses and returns to the evaporator. Used in electronics cooling.