Energy & its usage

Energy :- Energy is the capacity to do work (W). ~~or~~.
everything from propelling an automobile to heating a home to lighting a room. Many forms of work involve an energy transformation.

e.g.1 A Light Bulb transforms electrical energy into heat & light energy.

e.g.2 A Internal Combustion engine converts chemical energy into heat & mechanical energy.

e.g.3 A Dynamo changes mechanical energy into heat & electrical energy.

Since energy and work are two sides of same coin, they are measured with same units.

SI units of energy / work is Joule (J)

Different forms of energy :-

1. Mechanical Energy (Kinetic & Potential
2. Thermal or Heat Energy
3. chemical energy
4. Electrical Energy
5. Nuclear Energy

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6. Electromagnetic Energy
7 Gravitational Energy.

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Characteristics of Energy :-

1. Available in different forms
2. Can neither be created nor destroyed
3. Can be transformed from one form to another
4. can be stored
5. Can be ~~transformed~~ ~~transported~~ transported from one system to other system or from one place to other.

Usage of Energy :-

1. Food cooking
2. Generation of electricity for Household usage.
3. Transportation of vehicles
4.

Energy has many usage from Household (food cooking, electrical appliances) to generation of electricity at power plants by nuclear energy, solar energy, Tidal energy etc.

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=> ~~Energy~~ Energy consumption differs greatly between developed and developing countries

=> In less developed countries per capita energy consumption (GJ/a), share of commercial energy sources (fossils, NCER) to tradition energy sources (fuel wood, animal dung and agricultural residues) are far less than developed countries.

=> Similarly energy use for different sectors differ from country to country.

Basic data ~~for~~ of India (FY 2019)

Population - 136.34 crore, 2020 -> 138 crore
Electricity coverage -> 99.93%
Installed capacity - 375,323 mW
Production - 1598 TWh
Share of Fossil energy -> 79.8%
Share of renewable energy - 17.3%
Avg. Electricity use -> 1208 Kwh Per capita

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Consumption by sector (% of Total)

Residential	24.76
Industrial	41.16
Agricultural	17.69
Commercial	8.24
Traction	1.52

Joule discovered the relationship b/w heat & mechanical work, which led to development of the laws of Thermodynamics.

1 Joule equals the work done by a force of one newton moving an object one meter. ($J = N \cdot m$)
Newton meter

1 Joule also equals the energy required to move an electric charge of one coulomb through an electric potential difference of one volt ($J = C \cdot V$)
(coulomb volt)

Power (P) :- rate at which energy is transferred or converted.
Thus, power equals work divided by time

$$P = \frac{W}{t}$$ SI unit ⇒ watt

~~1 watt = J/s~~ 1 watt equals one Joule Per second ($W = J/s$)
~~1 W = VA~~
1 watt equals one volt time one Ampere ($W = VA$)

Energy is ability to cause change by work
Power is rate of energy moved or used -
Power is How fast energy is used or transmitted

Force :- A Force is a push or pull upon an object resulting from the object's interaction with another object. Whenever there is an interaction b/w two objects, there is a force upon each of the objects.

Physicists have identified 4 fundamental Forces or interactions:

1. Electromagnetic Force acts b/w electric charges
2. Gravitational Force acts b/w masses and (3) strong & (4) weak forces hold together atomic nuclei.

Push & Pull of these forces manifest as energy.

e.g; Electromagnetic Force pulls electrons through conductor, creating electric current.
Gravity Pulls water through turbine at a hydroelectric Plant.

SI unit of Force is Newton (N)
Newton, the unit, is force that accelerates a one Kilogram mass at the rate of one meter per second squared ($N = Kg\, m/s^2$)

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The force of Earth's gravity on a 70 Kg (154 lb) human is about 686 Newtons

Coulomb:- Standard unit of electric charge is coulomb (C)

Charles-Augustin de Coulomb (1736-1806) was a French Physicist who discovered relationship b/w electric charges, distance and force.

Electric Potential :-
SI unit of Electric Potential is volt(V)

A volt is ~~equal~~ equivalent to one joule of energy per coulom of charge (V = J/c).

~~Point~~

Electric current :- SI unit = Ampere or Amp

French Physicist Andre-Marie Ampere (1775-1836) was one of the main discovers of electromagnetism

One Ampere equals the displacement of one coulomb of charge per second (A = C/s)

1 BTU :- How much energy your AC uses to remove Heat from your Home with in an Hour.

(lb is Pound)

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Most Household ckts pull less than 15A.

British Thermal Unit (BTU)

is used to describe the energy content of fuels and Power of Heating and cooling systems.

One BTU is the amount of energy required to raise the temperature of one Pound of water by one degree Fahrenheit.

1 BTU = 1055 J = 780 ft-lb (Foot-Pound) and 0.3 W-hours (watt)

Calorie :- (Cal)

The Small or gram calorie (cal) is the amount of energy needed to increase the temperature of one gram of water by one degree celsius.

The Large or Kilogram calorie (KCal) is energy needed to raise the temp^r of one Kg of water by 1c.

Nutritional calories are based on Kg. calories

1 Cal = 4.18 J

1 Kcal = 4.18 KJ ≈ 4 BTU

Therm :- A unit describing the energy contained in natural gas.

1 Therm = 100,000 BTU

Therm is approximately equal to amount of energy released by burning 100 cubic feet of natural gas.

Use Home heat appliances.

Quad :- 1 quad = 10^{15} BTU

The quad equals a quadrillion (10^{15}) BTU and is used when discussing the energy budget of whole countries.

1 quad = 10^{15} BTU = 1.055 EJ

1 Exa joule 1 EJ = 10^{18} J

1 Tera watt year 1 TW yr = 8.67×10^{12} kWh = 31.54 EJ 29.89 quad

Example :- In 1950, the U.S. consumed 34.6 quad of energy.

By 1970 total consumption grew to 67.8 quad

By 1990 84.7 quad

By 2006, 99.9 quad.

Thermal Power :- is measured in BTU Per Hour (BTU/h), often abbreviated to just BTU.

Most heating and cooling rating in BTU are really BTU/h

1 watt = 3.41 BTU/h

Units and scales of Energy

SI unit → Joule

1 Joule $= 1 Kg m^2/s^2$ = Newton-meter

CGS unit → erg , 1 Joule $= 10^7$ erg

Basic unit of electricity → Kwh

1 Kwh is the amount of energy used by a 1 Kw electrical applicance for 1 hour.

$1\ eV = 1.602 \times 10^{-19}\ J$

1 BTU = 1.055 KJ

1 TNT ≃ 4.184 GJ

1 Kwh ≃ 3.6 mJ

1 Barrel of oil equivalent ≃ 6.1184 GJ

1 Ton of coal equivalent ≃ 29.3076 GJ

1 Quad ≃ 1.055 EJ

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Basic SI units:

Dimension	Basic unit	Symbol
length	meter	m
mass	Kilogram	Kg
time	second	s
electric current	Ampere	A
temperature	Kelvin	°K

Derived SI units

Dimension	Unit	Symbol
Area	square meter	m^2
Volume	cubic meter	m^3
speed	meter Persecond	m/s
acceleration	meter Per square second	m/s^2
Pressure	Pascal	$Pa = (N/m$
volume flow	cubic meter Persecond	m^3/s
mass flow	Kilogram Per second	Kg/s
density	Kilogram Per cubic meter	Kg/m^3
force	newton	$N (Kgm/s^2$
energy	Joule	$J (= N \cdot m)$
Power	watt	$W (= J/s$
Energy Flux	watt Per square meter	W/m^2
Calorific value	Joule Per Kilogram	J/Kg
Specific heat	Joule Per Kilogram Kelvin	$J/Kg \cdot K$
voltage	volt	$V = (W/A)$

Electricity :- A unit of electrical energy, particularly for ~~ett~~ utility bill, is Kilowatt hour (KWh).

Kilowatt - hour (KWh)

Kilowatt hour is a standard unit of electricity production and consumption. Amount of Energy from steady Production or consumption of one KW Power for one hour

$1 \text{ Kwatt} = 1000 \text{ watt}$

$1 \text{ Kw hour} = 3.6 \times 10^6 \text{ J}$

$1 \text{ Kwh} = 3412 \text{ Btu}$

Natural Gas :-

Natural gas is often sold in units of energy content or by volume.

Common units for selling by energy content are joules or Therms.

1 Therm = 1055 Mega Joules.

Common units for selling by volume are cubic metres or cubic feet.

Natural gas in US is sold in Therms or 100 cubic feet ($100 ft^3 = 1 Ccf$)

In Australia N.G. is sold in cubic meters.

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1 cubic meter = 38 mega Joules
In most of the world, NG is sold in giga Joules.

Food Industry :- Calorie is defined as the amount of thermal energy necessary to raise the temp^r of 1 gram of water by 1°Celsius;

For thermochemistry, 1 cal. = 4.184 J.

Atomic Physics and chemistry :-
1 eV is equivalent to kinetic energy acquired by an electron in passing through a potential difference of 1 volt in vacuum.

Spectroscopy :- It is common to measure energy levels in units of reciprocal centimeters (cm^{-1})

giving ... for a tonne of TNT.

Table 1.1 Different Units for Measuring Energy

Unit	Definition	Used in	Equivalent to
British Thermal Unit (BTU)	A unit of energy equal to the amount of energy needed to raise the temperature of one pound of water by one degree Fahrenheit. Equivalent to energy found in the tip of a match stick.	Heating and cooling industries	1 BTU = 1055 Joules (J)
Calorie or small calorie (calorie)	The amount of energy needed to raise the temperature of one gram of water by one degree Celsius.	Science and Engineering	1 calorie = 0.003969 BTU
Food Calorie, Kilocalorie or large calorie (Cal, kcal, Calorie)	The amount of energy needed to raise the temperature of one kilogram of water by one degree Celsius. Food calorie is often used for measuring the energy content of food.	Nutrition	1kCal = 1000 cal, 4,187 J or 3.969 BTU
Joule (J)	It is a smaller quantity of energy than calorie and much smaller than a BTU.	Science and Engineering	1 Joule = 0.2388 calories and 0.0009481 BTU
Kilowatt Hour (kWh)	An amount of energy from the steady production or consumption of one kilowatt of power for a period of one hour.	Electrical fields	1 kWh = 3,413 BTU or 3,600,000 J
Therm	A unit describing the energy contained in natural gas.	Home heating appliances	1therm = 100,000 BTU

Mechanical Energy & Transport

ME is the energy i.e; possessed by an object due to its motion or due to its position.
ME can be either K.E or potential Energy.
Object have ME if they are in motion and /or if they are at some position relative to a position of zero potential Energy.

eg; A brick held at its hight above the ground or zero height position. (P.E)
A moving car possesses ME due to its motion (K.E)

Total M.E :-
Total Amount of ME is merely sum of P.E. and K.E.

$$\text{Total M.E} = P.E + K.E = mgh + \frac{1}{2}mv$$

There are two form of PE - Gravitational PE and Elastic P.E

$$TME = PE_{grav} + PE_{spring} + K.E$$

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Any object that possesses M.E is able to do work.

Any object that possesses ME whether it is in the form of P.E. or KE. is able to do work.

i.e Its ME enables that object to apply a force to another object in order to cause it to be displaced.

A M.E Transfer takes place when work is done by a force over a displacement (Parallel with that force)

When an object falls, energy is transferred by gravity from G.P.E store of object to K.E. store of object.

Scales of Energy :-

(A) Potential Energy :- PE is stored and energy of ~~motion~~ position.

(i) Chemical Energy :- C.E is energy stored in the form of bonds of atoms and molecules.

e.g; Biomass, Petroleum, Natural Gas, Propane & coal are example of chemical Energy.

(ii) Nuclear Energy :- NE is the energy stored in nucleus of atoms. The energy that holds together Nucleus of uranium atom is an example of nuclear energy.

(iii) Stored Mechanical Energy is stored in object by the application of force.

e.g; Compress Spring, Streatched rubber

(iv) Gravitational Energy :- is the energy of place or position.

e.g; water in a reservoir behind hydropower dam

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(B) Kinetic Energy :- is the energy ~~of~~ in motion.
The motion of wave, electron, atoms molecules or substances.

(i) Radiant Energy :- is the Electromagnetic energy that travel in ~~Transverse~~ transverse wave form.

~~[illegible]~~

Radiant Energy include visible energy, X-Ray, Gamma Rays, Radio-wave solar Energy.

(ii) Thermal Energy / Heat Energy is the internal energy in substances. The atoms or molecule are move in the form of vibration.
e.g; Geothermal Energy

(iii) Sound Energy :- sound is movement of energy through substance in longitudinal wave form. (vibration in forward direction)

(iv) Electrical Energy :- is movement of electron.
e.g; electricity, lighting

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Transport of ME

⇒ Energy transport is also known as Energy conversion in this possess energy, changes from one form to to another form.

⇒ ME is are transport in Heat Energy & ~~mechanical~~ electrical Energy.

⇒ ME can be converted in Heat energy & Heat Energy can be converted in M.E.

⇒ ME can be converted into electrical energy e.g. Electric generator

⇒ Electrical Energy → ME
e.g; electric motor.

Heat Energy : conversion b/w Heat & Mechanical Energy

⇒ Heat Energy is the result of movement of tiny particle called atoms molecules, ions in solid, liquid and gases.

⇒ Heat energy can be transferred from one object to another object. The transfer or flow due to the difference in temperature between two object

⇒ Heat is total motion of molecules in substance. The transfer of thermal Energy from hotter object to cooler object.

Heat Transfer :-

Heat may be transfer from one object to another are in three ways.

1. Conduction
2. Convection
3. Radiation

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1. Conduction :-
The way heat transfer in solid through direct touch.

Example 1. A heating Pan on stove
2. A spoon hot on a cup of coffee

2. Convection :- The way of Heat transfer in liquid or gases (fluids) moves in current.

e.g: ~~water Boilation~~
1. Boiling water on a stove
2. Heating a room ~~on~~ by heater.

3. Radiation :- Heat energy are in rays or waves; does not required to travel on medium.

eg; Sun heating the earth.

Heat and Temperature :-
Heat is the total amount of Kinetic energy in substance.
Temp^ is the avg amount of Kinetik energy in substance.

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Heat is measure in Joule, kilojoule and calorie
Temp^r are measure in degree celcius °K, °F

Conversion b/w heat & ME

* Heat Energy can be converted into ME and ME can be converted HE This physical observation is known as Mechanical equivalent of Heat.

* Thermal Energy of steam converted in ME in Turbine.

* This means one can change internal energy of the system by either doing work to the system or adding heat to the system.

* This concept is the fundamental to thermodynamic which ~~sis~~ the applies idea of Heat & work.

* This idea of Heat and work equivalen stated is Thermodynamics first Law.

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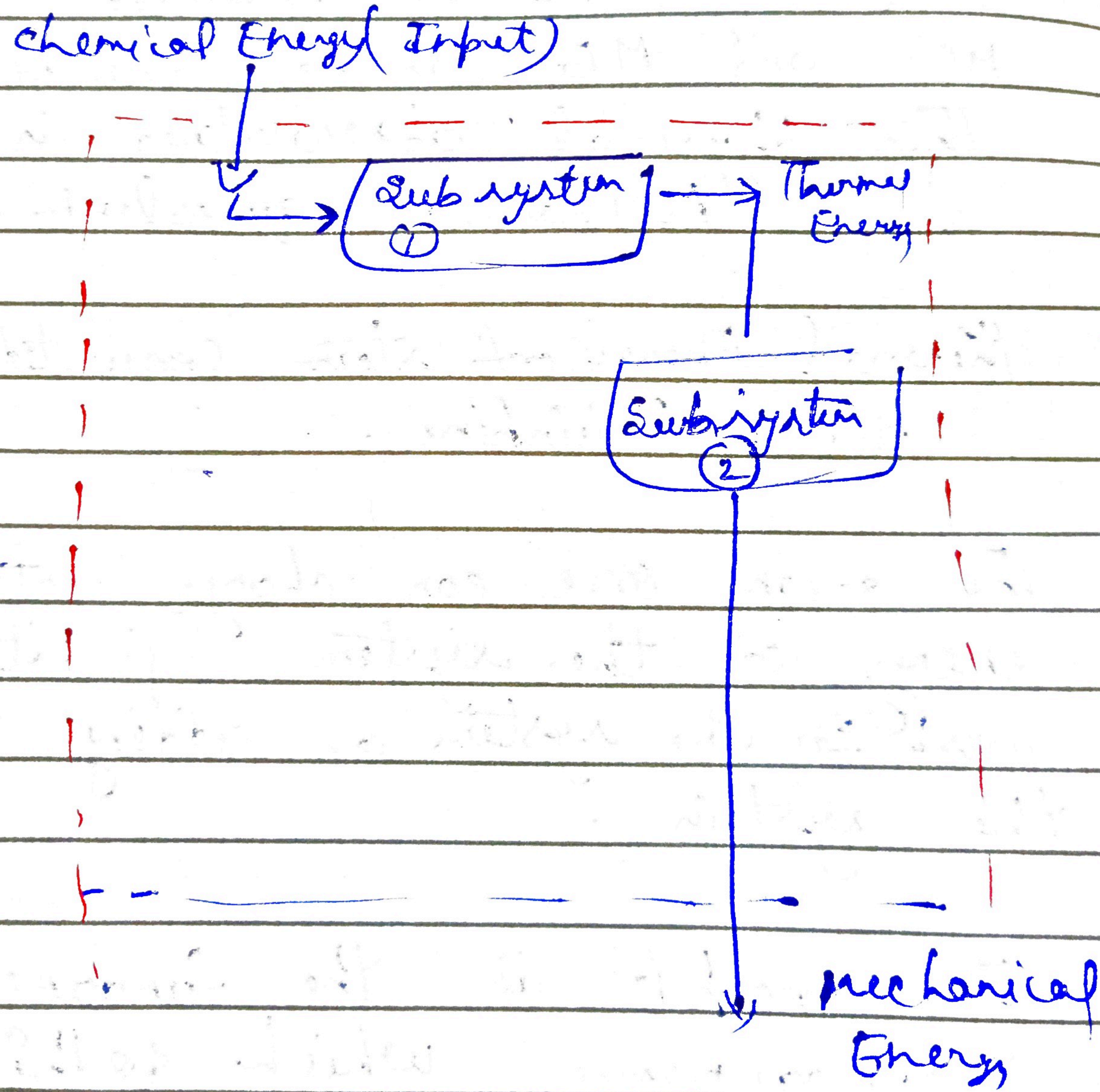
* Heat Energy → $\boxed{\text{Energy Conversion Devices}}$ ⇒ Mechanical Energy

Heat Energy → $\boxed{\text{Heat Engine}}$ → Mechanical Energy

Eg: Bike



This idea of work and Heat equivalence is stated in First law of Thermodynamics which says that change in internal energy of a system is the sum of work done and Heat added to any system.

From this, if a system is observed at any state, it is impossible to tell whether it reached this state from an i/P of work, an input of Heat, or a combination of two.

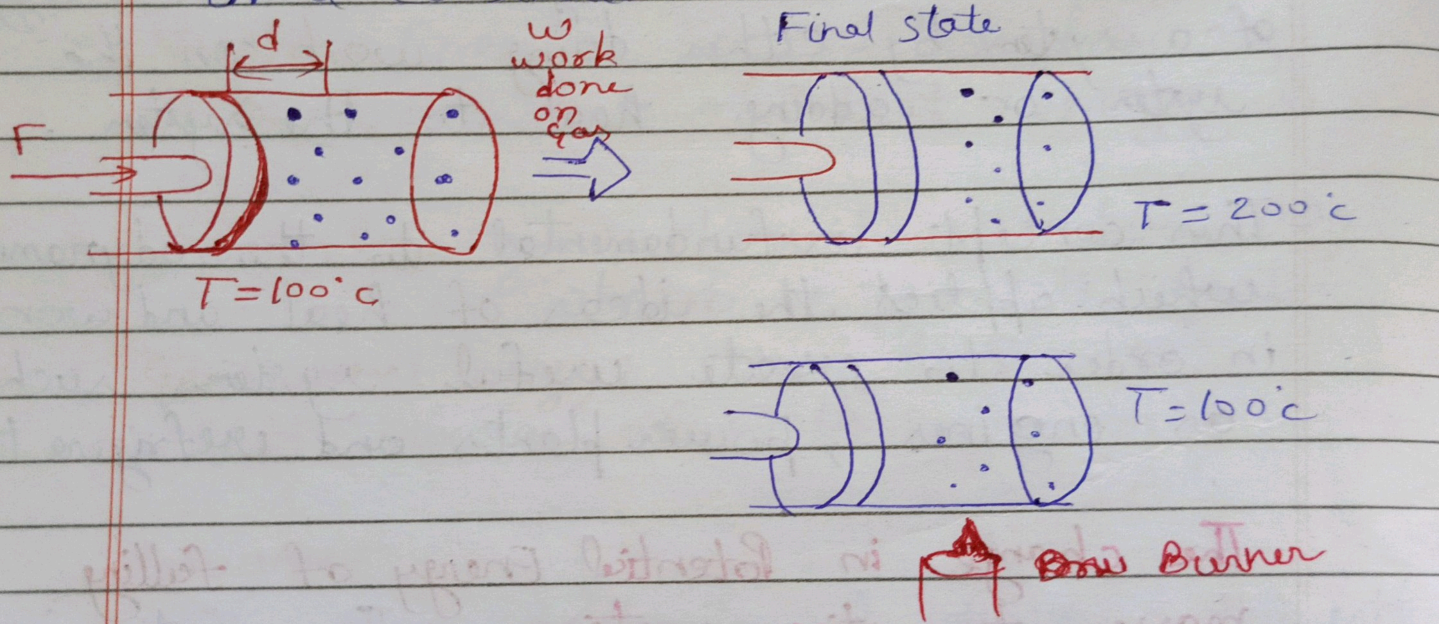
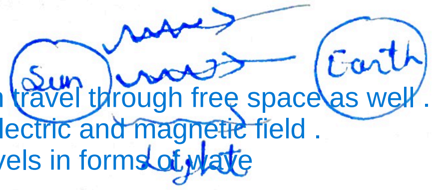


fig: conversion b/w Heat & ME

The Final states are indistinguishable i.e., you can not tell whether the gas reached the final state by being Heated, having work done on it, or a combination of Both.

M.E into Heat Energy

- When wood or coal is burnt on the Hearth, Heat is produced first and then light.
- When iron is heated, its colour changes from black to red and thus the heated iron beings to produce light.



Electromagnetic energy can travel through free space as well .
it is a combination of both electric and magnetic field .
Electromagnetic energy travels in forms of wave

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Electromagnetic Energy : Storage , Conversion, Transmission and Radiation

Electromagnetic ~~Energy~~ Radiation / Energy

EM energy is a form of energy that is reflected or emitted from object in the form of electric and magnetic ~~field~~ wave that can travel through free space.

In EM energy both electric and magnetic effect are present.

EM energy travels in waves and spans a broad spectrum from very long radio waves to very short gamma rays.

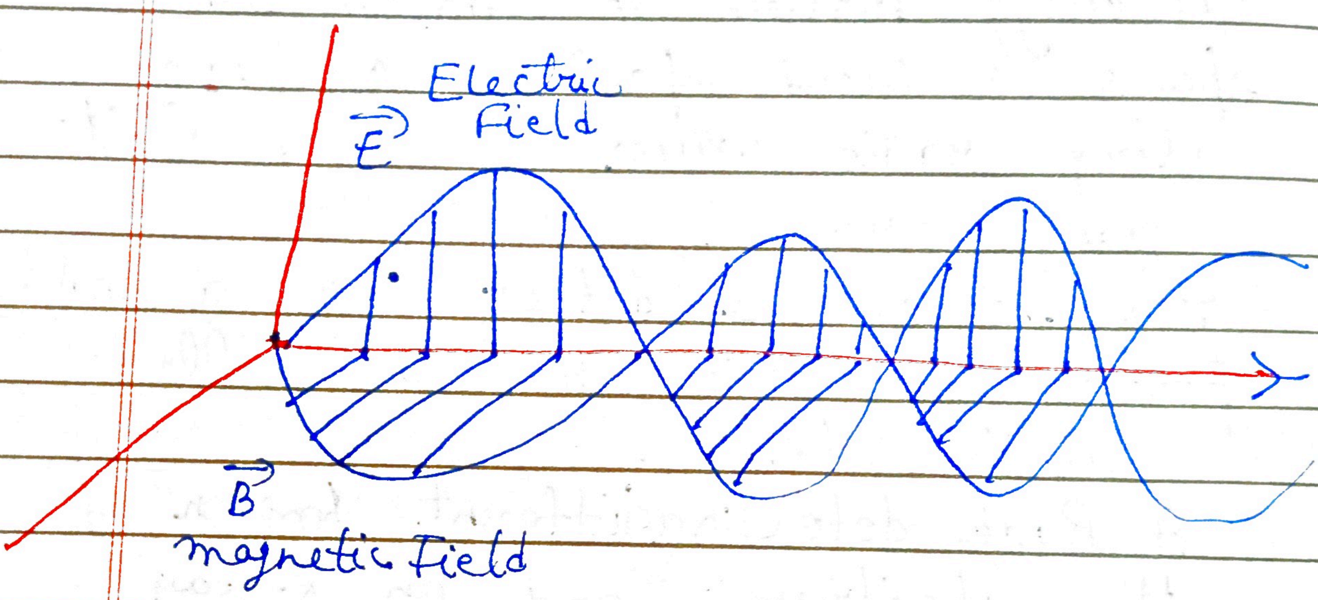
Human eye can detect only a small portion of this spectrum called visible light.

A Radio detects a different portion of the spectrum, and an X-ray machine uses yet another portion.

Our Sun is the source of energy across the full spectrum, and its electromagnetic radiation bombards our atmosphere constantly.

Gamma ray	X-ray	U-V ray	Visible Light	Infrared Ray	micro wave	Radio wave

V	I	B	G	Y	O	R



EM energy : Storage :-

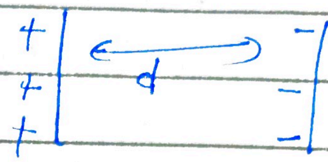
EM energy can be stored in the form of E field or a magnetic field. Energy stored in chemical fuel can be used for Power Generation and ~~for~~ transport

Since chemical fuel are rapidly converted into mechanical or electric field.

EM energy stored in capacitor:

A charged capacitor stores energy in the electric field b/w its plate.

work done in transferring an additional charge is $dW = V\,dQ$



$$dW = \frac{Q}{C}\,dQ$$

$$\left\{ \frac{W}{q} = V \right\} \quad \left\{ C = \frac{Q}{V} \right\}$$

Total work done is charging the plate

$$W = \int_0^q \frac{Q}{C}\,dQ$$

$$\boxed{\text{Energy } U = W = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2}$$

EM energy store in Inductor

In an inductor, energy is stored with in a magnetic field.
Energy stored in a magnetic field is equal to the work needed to produce a current through the inductor.

Due to energy conservation, the energy needed to drive the original current must have an outlet.

The energy stored by an inductor is equal to the work needed to produce ~~an~~ current through the inductor.

$$\text{Energy } E = \frac{1}{2} L i^2$$

~~Electromagnetic conversion~~

Energy conversion :-

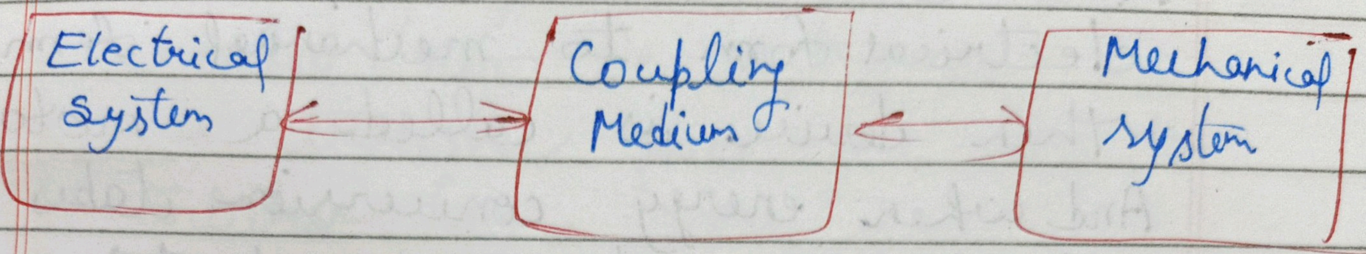


fig : Energy conversion .

Conversion of Electromechanical energy takes Place via two mediums. One is the magnetic field and other is electric field .

Most converters use the magnetic field as coupling medium for the electrical and mechanical systems.

Large energy storing capacity of magnetic field (as compare to electricfield) is the reason to use magnetic field as coupling medium b/w electrical and mechanical system .

Electromechanical energy conversion is a reversible process . This means that the energy can be converted back and forth b/w electrical and mechanical form .

Electromechanical energy conversion is used extensively in synchronous Induction, and DC Machines.

When conversion takes place from electrical form to mechanical form, then device is called a motor.

And when energy conversion takes place from mechanical to electrical form, then device is called generation

The energy conversion results from following electromagnetic phenomena:-

- When a current-carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.
- When a conductor moves in magnetic field, a voltage is induced in the conductor.

Conservation of Energy

According to principle of conservation of energy, energy can neither be created nor be destroyed. It may transfer from one form to another form.

Energy balance Eqn

Electrical Energy I/P = Energy to Electrical losses + Mechanical Energy O/P + Energy to field storage in electrical system

For generating action, Balance eqn

Total mechanical energy I/P = Electrical Energy O/P + Total Energy stored + Total Energy dissipated.

Transmission :-

Transmission is when an electromagnetic wave passes right through an object. If an object is transparent than the light passes through it. So window glass is transparent to visible light.

Now transmitted light can experience two important and related effects.

(i) Refraction (ii) Absorption.

Refraction Refraction is bending of light as it passes from one transparent substance into another

Refraction of light by a glass is a phenomenon of all sorts of eyeglasses and optical devices.

This phenomenon can be seen through a magnifying glass lens that they bend light, therefore change the appearance of object behind that lens.

In addition, whenever light is transmitted through any material, anything other than the vaccum, it slows down.

The amount of that slowdown is directly related to amount of refraction, the amount of bending that you see with the lens.

(ii) Absorption :- Interaction of light with matter

The 2nd effect light experiences with matter is called absorption.

Electromagnetic Energy can be transferred

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from one object to another, and it can be absorbed by materials, and that absorption is one of ~~pl~~ the processes that happens.
When this happens, light is often converted into heat energy.

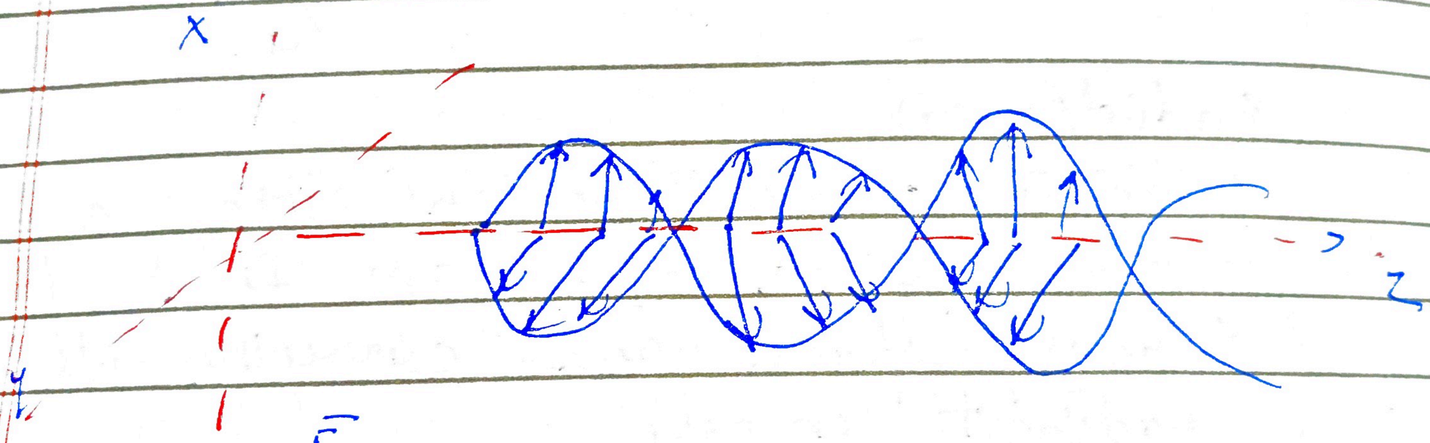
Radiation:-

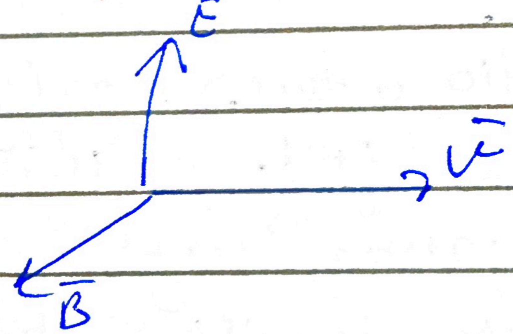
Electromagnetic Radiation (EMR) consists of waves of EM field, propagating through space and carrying electromagnetic radiant energy.
It includes radio waves, microwaves, infrared, (visible light, ultraviolet, X rays, and gamma rays.
All ~~of~~ of these waves form part of Electromagnetic spectrum.

EM radiation consists of EM wave, which are synchronized oscillation of electric and magnetic fields.
EM radiation are created due to periodic change of electric or magnetic field.
Depending on how this periodic change occurs and power generated, different wavelength of EM spectrum are produced.

In a vaccum, EM waves travel at the speed of light, denoted by c

In homogeneous, isotropic media, the oscillation of two fields are perpendicular to each other and perpendicular to direction of energy and wave propagation, forming a transverse wave.





Electromagnetic Energy storage

EM energy can be stored in the form of an electric field or a magnetic field.

Practical electrical energy storage technologies include electrical double-layer capacitors (EDLCs or ultra capacitors) and superconducting magnetic energy storage (SMES).

Electric Double-layer capacitors (EDLC) :-

EDLCs are charge storage devices, which are similar to lithium ion batteries in design and assembly. EDLCs are composed of two electrodes, an electrolyte and a

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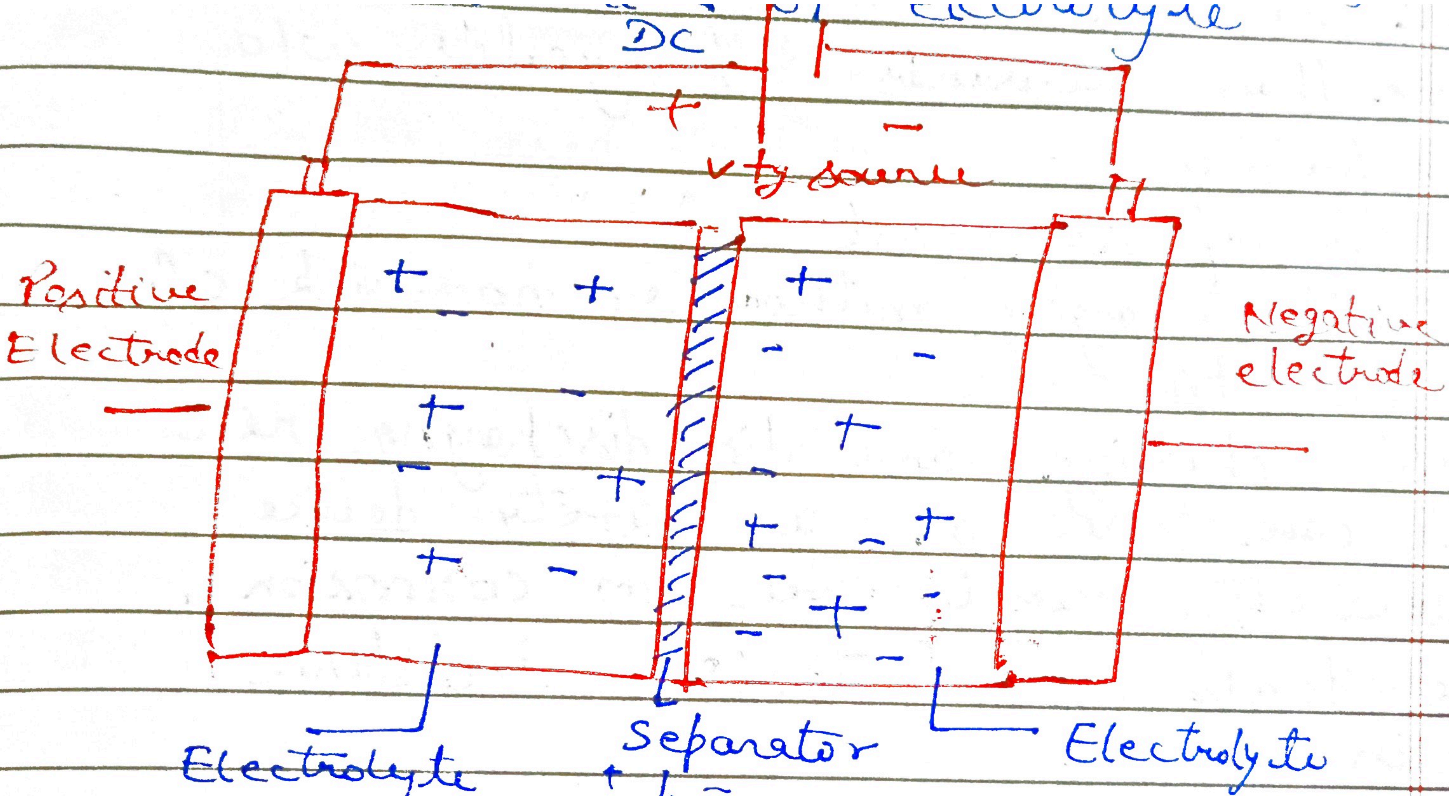
separator.
The separator electrically insulates the positive electrode and negative electrode in an organic electrolyte system.

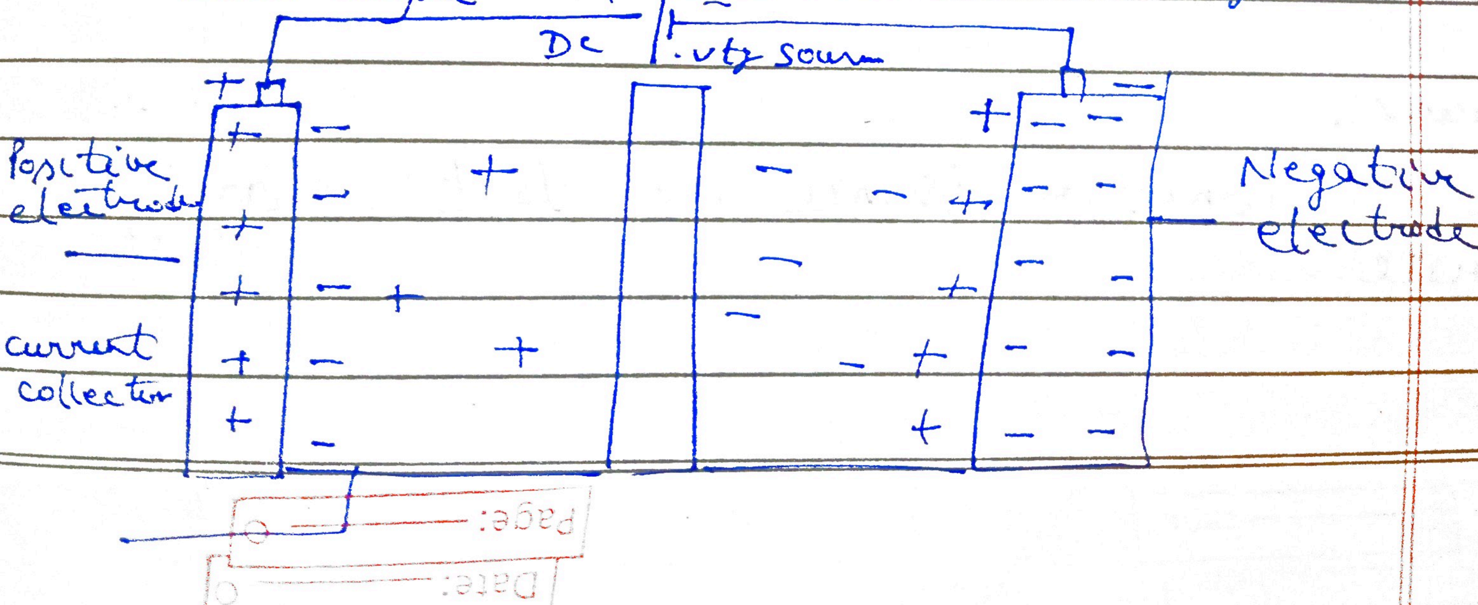
As shown in fig; the EDLCs derives from the separation of electric charges, which is generated by directional alignment of ions and electrons at the interface b/w electrode material and electrolyte.

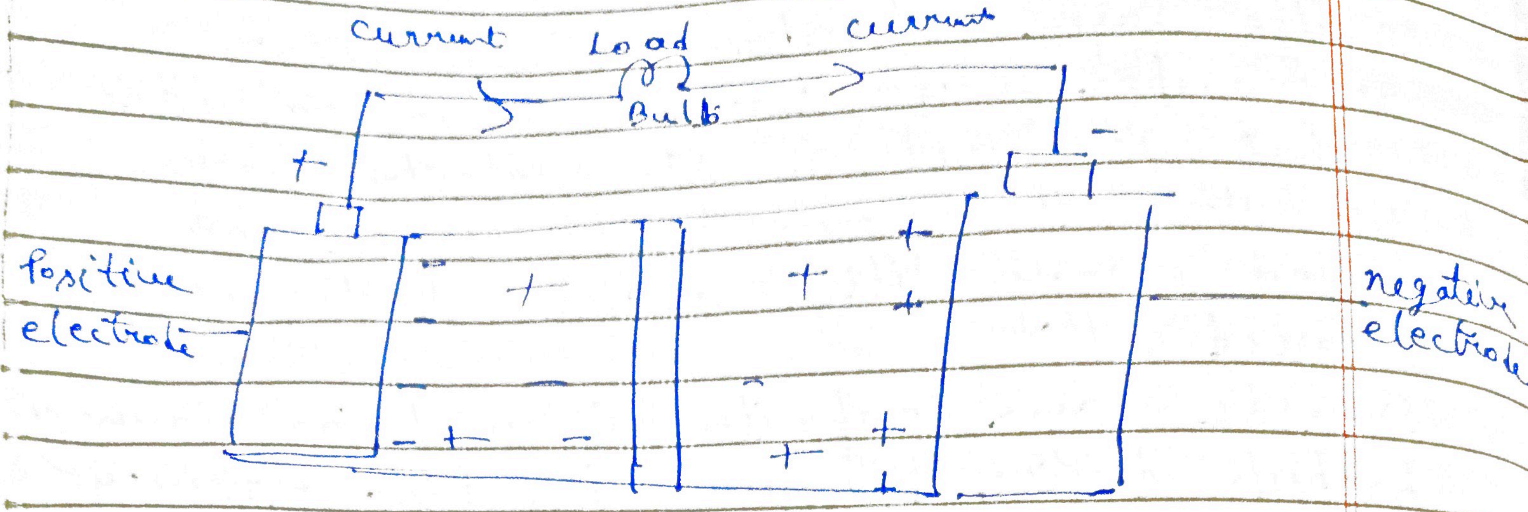
In particular, the excess electric charge aggregate on the positive or negative electrode surfaces, while electrolyte ions ~~wf~~ with compensating charges accumulate in electrolyte solution to maintain electrical neutrality.

When the system is given an external load or is charged, -ve ion in the electrolyte migrate towards positive electrode & +ve ion migrate towards negative electrode.
While electrons travel through the external ckt from negative to positive electrode.
In this way double layer is formed at interface with the electrodes.

When an external load is removed or charging finishes, positive electric charges on the electrode & -ve ions in electrolyte attract each other while negative electric charges on the electrode & positive ions in eletrolyte attract each other in order to stabilize the double layers on the electrodes
Thus a relatively stable vtg is generated.


DC
+
−
vtg source
Positive Electrode
Negative electrode
Separator
Electrolyte
Electrolyte


DC
.vtg sour
Positive electrode
current collector
Negative electrode



Adv :-

- DLC has long life service it perform more than thousands of cycles w/o any problem
- Low operating cost
- Simple charging method so no risk of overheating
- High charging and ~~disf~~ discharging rate
- we can use as a safety device
- electrolyte remain free from corrosion.
- we dont use toxic substance in DLC.

Disadv.

Low internal resistance so fast charging rate

- short ckt is more dangerous than the capacitor.
- It has high electrostatic absorption among all types of capacitor.
- Self discharge rates very high.
- Switching equipment is required that will cause energy loss.

Application.

1. It is used in electronic devices as a memory backup.
2. It is used for batter load levelling
3. It is used for memory harvesting
4. It is used for energy regeneration in automobiles.

SMES - Superconducting magnetic energy storage.

Superconducting magnetic storage is a type of energy storage system in which energy stores in the form of magnetic field. When current flow in normal conductor then resistance resist the flow of current but superconductor made up of special material which occur zero resistance below critical tempr.

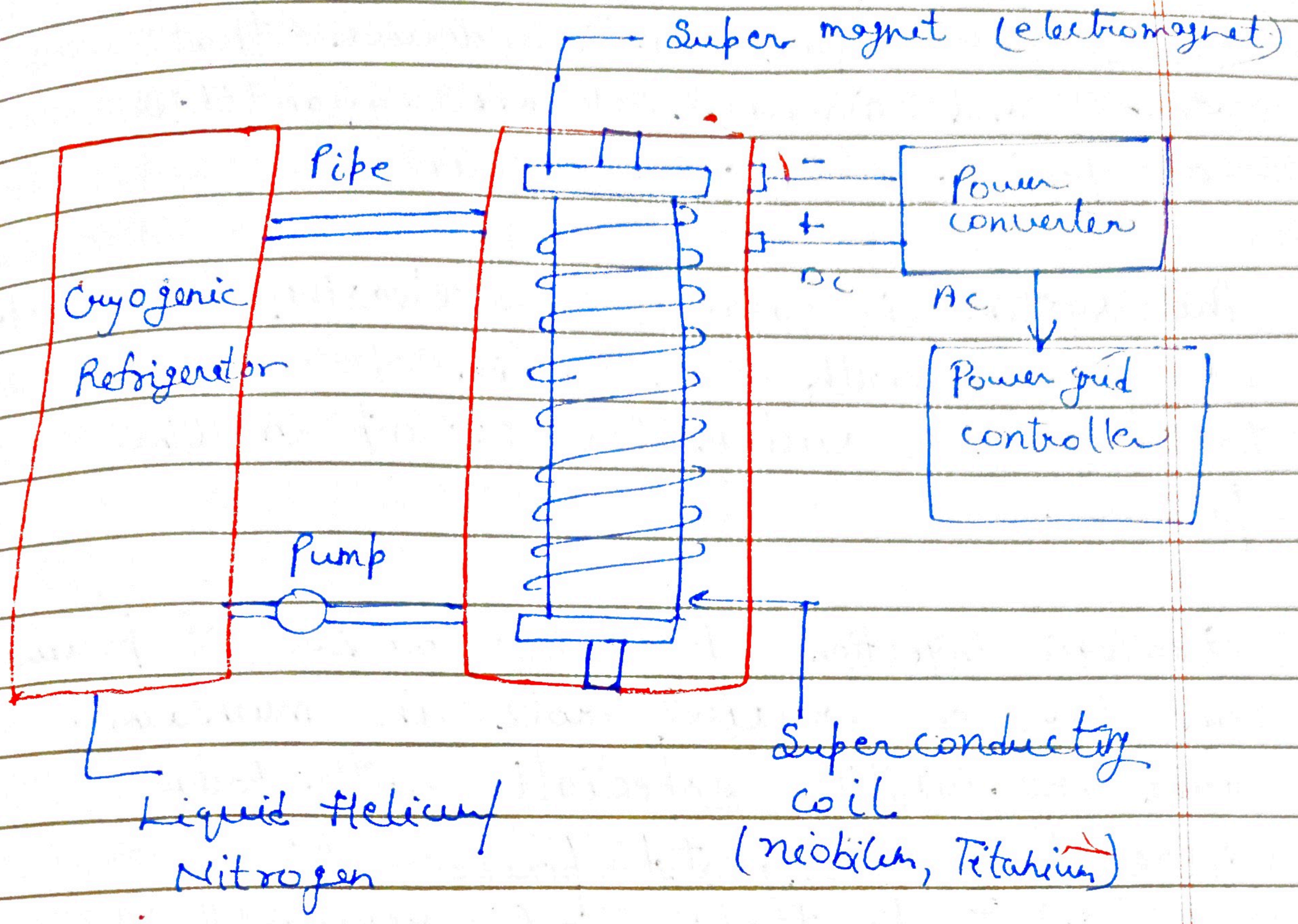
When temperature of conductor decrease then resistance also decrease and at a point resistance suddenly get zero value that point is known as critical temperature.

When resistance of conductor get zero value then we flow dc current in conductor and stores the energy in the form of magnetic field.

Material used in superconductors are niobium, ~~tital~~ titanium, vanadium mercury, -- etc.
(4.2K)

T↓ R↓

Material	Critical Tempr
Aluminium	1.2K
Indium	3.4K
Mercury	4.2K
Lead	7.2K



SMES was originally proposed for large scale, load levelling, but, because of its rapid-discharge capabilities, it has been ~~cafeb~~ implemented on electric power systems for pulsed power and system stability application.

SMES ~~coo~~ is a novel technology that stores electricity from the grid within the magnetic field of a coil comprised of a superconductor wire with a near-zero loss of energy. The main parts installed in SMES are motionless making the device highly reliable.

SMES is a grid-enabling device that stores and discharges large quantities of power almost instantaneously

The system is capable of releasing high levels of power with in a fraction of a cycle to replace a sudden loss or dip in line power.

Strategic injection of brief bursts of power can play a crucial role in maintaining grid reliability especially with today's increasingly congested power lines and high penetration of renewable energy sources, such as wind and solar.

A Typical SMES consists of two parts:-

Cryogenically cooled superconducting coil and power conditioning system - which are motionless and result in higher reliability than many other power storage devices.

Ideally, once the superconducting coil is charged, the current will not decay and magnetic energy can be stored indefinitely.

Benefits of SMES

1. Improved power quality for critical loads and provides carry over energy during momentary vtg sags and power outages

2. Improve load leveling b/w renewable energy source (wind, solar) and transmission and distribution n/w.

3. Environmentally beneficial as compared to batteries; superconductivity does not rely on a chemical reaction and no toxins are produced in the process.

4. Enhances transmission line capacity and performance - SMES features a high dynamic range, an almost infinite cycling capability, and an energy recovery rate close to 100%.

5. Ultra-high field operation enables long-term shorter storage SMES system in a compact device with cost advantages in material and system costs.

B

Introduction to Quantum, Energy Quantization, Energy in chemical system & Processes :-

Introduction to Quantum

Quantum mechanics is the study of matter and its interaction with energy on the scale of atomic and subatomic particles.

A photon is electrically neutral and has no mass . The energy stored in a photon is quantised and can be measured.
A photon is a bundle of electromagnetic energy .
Energy associated with each photon is E = h . frequency
h= plancks constant

Quantum Mechanics shows that light along with all other forms of electromagnetic radiation, comes in discrete units, called Photons, and predicts its spectral energies, and ~~intent~~ intensities of its light beams.

A single photon is a quantum, or smallest observable particle, of the electromagnetic field.

Quantum Mechanics is the branch of physics needed to deal with submicro-scopic objects.. Because these objects are smaller than we can observe directly with our senses and must be observed with the aid of instruments

~~The~~ Atoms, molecules and fundamental electron and proton charges are all examples of physical entities that are quantized, that is, they appear only in certain discrete values and donot have any conceivable value.

Quantized is the opposite of 'continuous', we can not have a fraction of an atom or part of an electron charge.

Quantum physics is the branch of physics that deals with small objects and quantization of various entities including energy and angular momentum.

Energy Quantization

= bundles / packets of energy

The quantization of energy refers to the fact that at subatomic levels, energy is best thought of as occuring in discrete "Packets" called Photons.

In quantum physics, photons are packages of energy and corresponds to different colors in the spectrum or different types of Electromagnetic radiation.
(radio wave, microwave, x-rays etc.

A red photon has specific energy value different from blue photon.
The red and blue photons are therefore "Quantized" just as rupee note denomination are "Quantized."

Each photons contains a unique amount of discrete energy.

Quantization of energy is related to Planck's constant, which specifies how quantized energy can get.

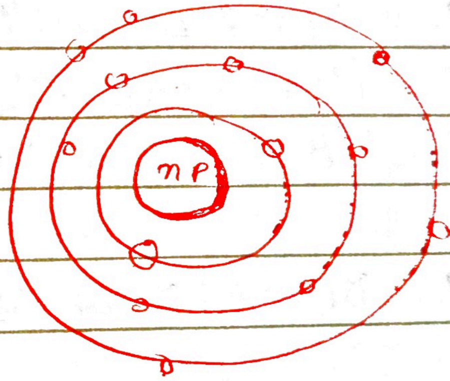
$$\boxed{E = hf}$$

$h \Rightarrow$ Planck constant $= 6.62 \times 10^{-36}\ kg\,m^2/sec.$

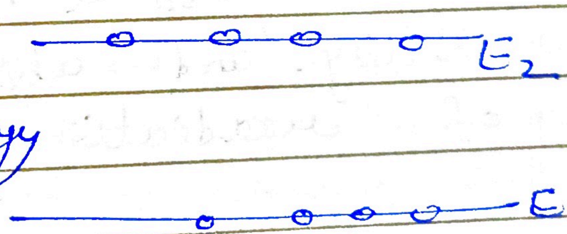
f = frequency.

h is very tiny constant called Planck's constant. This constant regulates and "quantizes" the energy of the universe.

Quantization of energy refers to absorption or emission of energy in discrete Packet or quanta.

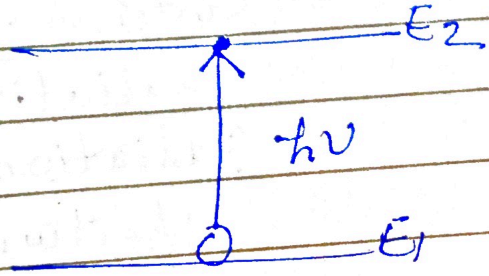


$E_2 - E_1 = h\nu$.
$= 1$ Photon Energy



Suppose that two energy level E_1 & E_2 have possessed some amount of energy

$E_2 - E_1 = h\nu$



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As the intensity of electromagnetic energy increases (or decreases), it steps up (or down) from one quantized level to another, rather than follow a smooth and continuous wave.

The establishment of energy quantization called for the replacement of classical mechanics

1. Black Body Radiation
2. Heat capacity
3. Atomic and molecular spectra

1. Black Body Radiation :-

Black body is a material capable of emitting and absorbing all wavelength of radiation uniformly.

~~Black body radiation~~,
Energy radiated by any object or system that absorbs all incident radiation.
Radiation usually refers to the spectrum of light emitted by any heated object.

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The spectral intensity of black body radiation peaks at a frequency that increases with the tempr of emitting body.

Factors that affect amount of radiation of a particular wavelength given off from a surface include the type of material absorbing the incident radiation and tempr of surface.

This means that different materials can given off different amounts of energy, even if materials are at the same tempr.

An object that gives off maximum amount of energy for its absolute tempr is termed as Black body.

Heat capacities :-

The Heat capacity of a substance may simply be defined as the amount of heat required to raise its tempr through 1°c.

Molar Heat capacity :- Amount of Heat required to raise the tempr of 1 mole of substance through 1°c.

Specific Heat Capacity :- The amount of Heat required to raise the tempr of 1 gram of substance through 1°c.

$R = Nk$ $N \Rightarrow$ Avogadro No. $k \Rightarrow$ Boltzmann constant

$R \Rightarrow$ Gas Constant

$R = 8.3145\ J\ mol^{-1}\ K^{-1}$

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According to classical physics, the heat capacity of all monoatomic solids should be equal to $3R$ and are close to $2^5\ JK\ mol$.

(Quantum Mechanics) It was found that molar heat capacities of all monoatomic solids are lower than $3R$ at low tempr. and that the value approaches zero at $T \to 0$

~~Eisnt~~ Einstein assumed that each atom oscillated about its equilibrium position with a single freq ν.

1.6 FLOW OF CO_2, ENTROPY AND TEMPERATURE

Carbon dioxide (chemical formula CO_2) is an acidic colorless gas with a density about 53% higher than that of dry air. Carbon dioxide molecules consist of a carbon atom covalently double

C02 is an acidic colorless gas.
It consists of 2 atoms of oxygen covalently double bonded with 1 atom of carbon . O=C=O

It occurs in earth's atmosphere as a trace gas .
CO2 is solube in water therefore it is found in underground water , lakes , rivers . Its other natural sources are volcanos , forest fires ,respiration , decomposition ,etc

bonded to two oxygen atoms. It occurs naturally in Earth's atmosphere as a trace gas. The current concentration is about 0.04% (412 ppm) by volume, having risen from pre-industrial levels of 280 ppm.

Natural sources of CO_2 include volcanoes, forest fires, hot springs, geysers, and it is freed from carbonate rocks by dissolution in water and acids. Because carbon dioxide is soluble in water, it occurs naturally in groundwater, rivers and lakes, ice caps, glaciers and seawater. It is present in deposits of petroleum and natural gas. Carbon dioxide has a sharp and acidic odour and generates the taste of soda water in the mouth. However, at normally encountered concentrations it is odourless.

1.6.1 How is CO_2 Produced?

Carbon dioxide is produced during the processes of decay of organic materials, the fermentation of sugars and frrom bread, beer and wine making. It is produced by combustion of wood, peat and other organic materials and fossil fuels such as coal, petroleum and natural gas.

Partial decomposition of vegetable matter in the wet condition.

1.6.2 Flow of CO_2

A flow meter measures the volume of gas passing through the nozzle per unit of time. Generally, the flow meter measures the amount of CO_2 in litres per minute. Some flow meters deliver smaller amounts of gas, 0.5 – 5 litres per minute, and others higher rates.

Properties of Carbon Dioxide:

1. It is a colourless and odourless gas. बिना गंध
2. It is a non-flammable gas.
3. It is slightly toxic. – Poisonous विषैली
4. It is denser than air. -56.6
5. It has a melting point of – 55.6°C and has a boiling point of –78.5°C.
6. It has a density of 1.977g/ml. 1.87 kg/m3 – 1.5 times heavier than air
7. It is soluble in water, solubility decreases as temperature increases.
8. It forms a weak carbonic acid when dissolved in water. It turns lime water milky.
9. Equation which shows CO_2 behaves as an acid is:
$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+(aq) + HCO_3^-(aq)$$
(The reaction is reversible in nature).
10. It reacts with alkali to give carbonates and bicarbonates.
$$CO_2 + NaOH \rightarrow NaHCO_3$$
$$NaHCO_3 + NaOH \rightarrow Na_2CO_3 + H_2O$$

Uses of Carbon Dioxide

1. Plants convert carbon dioxide to oxygen during the process of photosynthesis, using both carbon and oxygen to make carbohydrates.
2. Carbon dioxide is also used as a refrigerant.

3. It is used as a fire extinguisher.
4. It is used in promoting the growth of plants in greenhouses.
5. It is used in beverages, soft drinks, and beers to make them fizzy.
6. Large quantities of solid carbon dioxide are used in large-scale refrigeration.
7. It is one of the parts of medical gases because it promotes exhalation.
8. The carbon dioxide released by baking powder or yeast that makes cake batter rise is the best example of the uses of carbon dioxide in everyday life.

Entropy of CO_2

The entropy of carbon dioxide gas has been calculated from the calorimetric data and the third law of thermodynamics to be **51.11 cal./deg. per mole at 298.1K**. This value is in excellent agreement with the value 51.07 cal./deg per mole.

- ***Temperature of CO_2***

It is a colourless and odourless gas (with a slightly pungent odour at high concentrations). Liquid state: carbon dioxide can exist as a liquid below the critical temperature of 31°C and above the triple point with a temperature of **– 56.6 °C** and 4.18 bar gauge, see also P-T–Diagram.

1.6.3 Entropy-Temperature Graph of CO_2

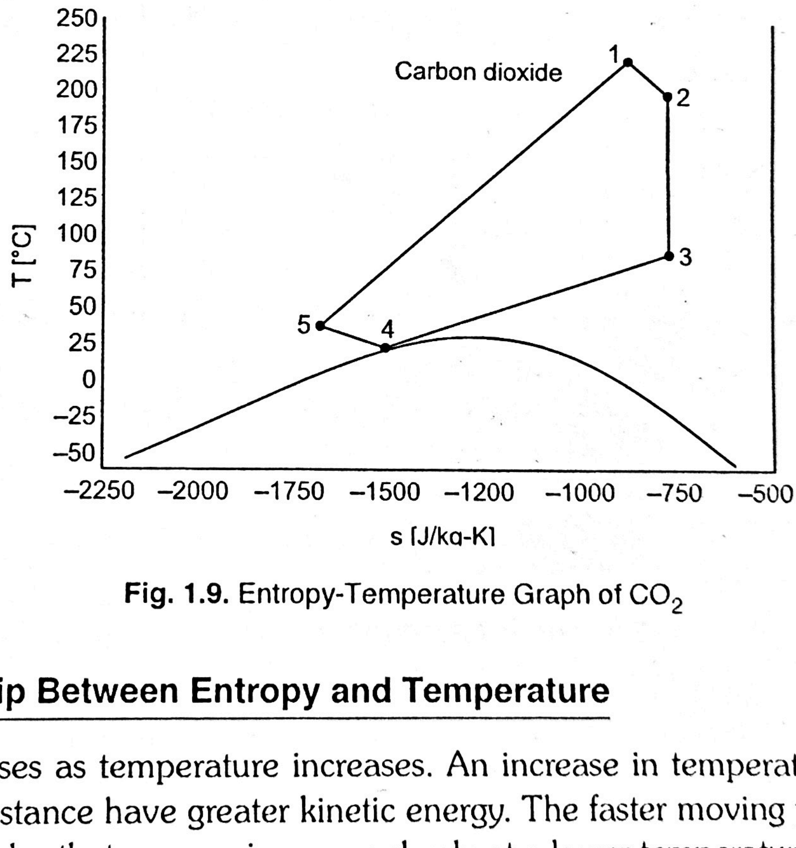

Fig. 1.9. Entropy-Temperature Graph of CO_2

1.6.4 Relationship Between Entropy and Temperature

Entropy increases as temperature increases. An increase in temperature means that the particles of the substance have greater kinetic energy. The faster moving particles have more disorder than particles that are moving more slowly at a lower temperature.

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Heat Engine

A Heat Engine is a system that converts heat to usable energy, particularly mechanical energy, which can then be used to do mechanical work.

Heat Reservoir :- It is defined as the source of infinite heat energy and a finite amount of heat absorbed or heat rejected from heat reservoir will not have any effect on its tempr. i.e. heat reservoir is maintained at a constant tempr.

Heat Source :-

Thermal reservoir which supplies heat to a system is known as source. This is at high tempr.
e.g; boiler furnace, combustion chamber nuclear reactor etc.

Heat Sink :-

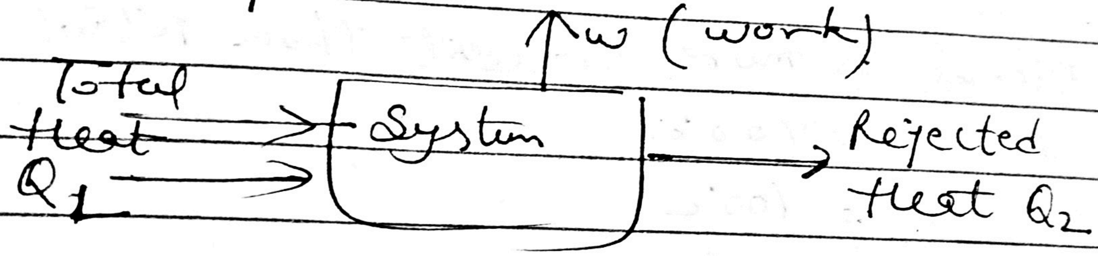
Thermal reservoir which absorbs heat from a system is known as sink.
This is at low tempr e.g; ocean, river etc.

Heat engine :-

Heat engine is a device which converts heat into work through cyclic process

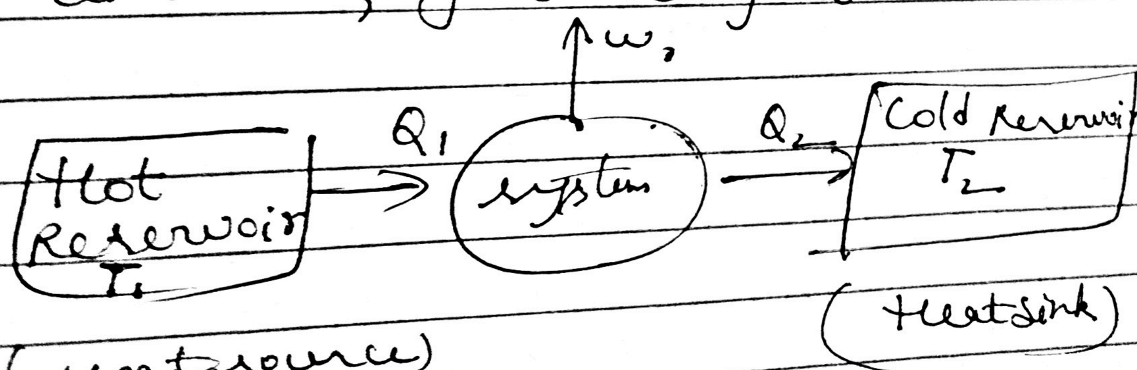
Principle of Heat Engine

A system converts heat into thermal or chemical Energy which is used to do mechanical work through cyclic process.



It always goes from High Tempr to low tempr

Some amount of Energy (Q_2) which unused, get rejected.



Bike:- Engine. Petrol Heat generate
wheel Rotate
Silencer Heat Rejected

work done in Heat Engine

Given Heat $= Q_1$
Rejected Heat $= Q_2$
work done $=$ ~~[illegible]~~ $Q_1 - Q_2$

efficiency of Heat Enegine

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

Diesel is more efficeent than Petrol
Petrol $= 400^\circ c$
Diesel $= 700^\circ c$
$\eta_{Diesel} > \eta_{Petrol}$

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Entropy

The term $\frac{\delta Q}{T}$ is called entropy and change from state 1 to state 2 during reversible process

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_{rev} = \int_1^2 dS = S_2 - S_1$$

Entropy is a measure of degree of randomness of molecule comprising a system. Higher the disorderness, greater is the increase in entropy.

Entropy is the fn of quantity of heat which shows the possibility of conversion of that heat into work.
On heat addition entropy of system increases and on heat rejection it decreases.

1.7 CARNOT AND STIRLING HEAT ENGINES

1.7.1 Carnot Engine

Carnot engine is a theoretical thermodynamic cycle proposed by Nicolas Leonard Sadi Carnot in 1824. Carnot state that a hot body is required that can generate heat and a cold body is reqired to which the caloric is conveyed and which produces mechanical work in the process. It is also stated that the said work is free of the material that is used to create heat and the construction and design material of the machine.

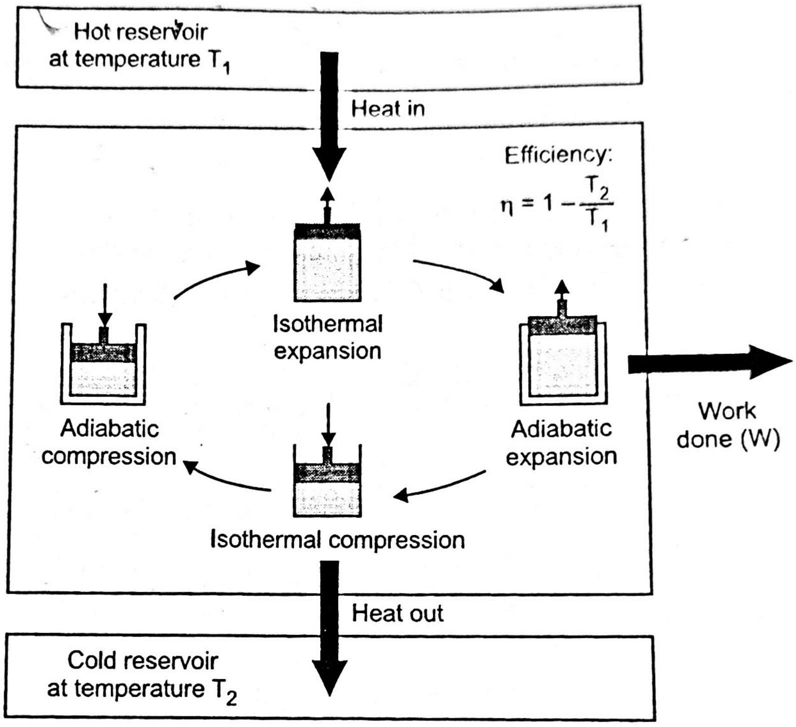

Fig. 1.10. Carnot engine cycle diagram

Principles of Carnot Engine

Carnot principles are only for cyclical devices such as heat engines, which state that:

- The effectiveness of an irreversible heat engine is always less than the efficiency of a reversible one functioning between the similar two reservoirs.
- The effectiveness of all reversible heat engines working between the similar two reservoirs is equal.

To increase the thermal efficiency of a gas power turbine, it is essential to increase the temperature of the combustion room, because turbine blades cannot bear the high temperature gas as it causes their early fatigue.

Efficiency of Carnot's Cycle

Carnot cycle is a reversible cycle signifying the upper limit on the efficiency of an engine cycle. Practical engine cycles are irreversible and therefore have inherently much lower efficiency than the Carnot efficiency when working at similar temperatures. One of the factors determining efficiency is the addition of the working fluid in the cycle and its removal. The Carnot cycle reaches maximum efficiency because all the heat is pushed to the working fluid at the maximum temperature.

Carnot Cycle

Step 1: Isothermal Expansion : Heat is transferred reversibly from high temperature reservoir at constant temperature T_h (isothermal heat addition or absorption).

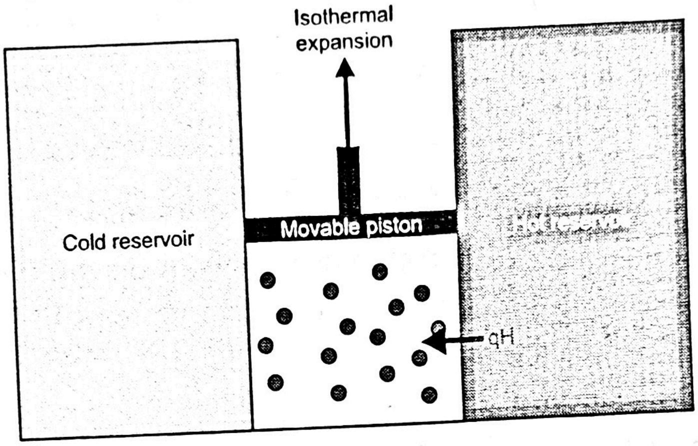

Fig. 1.11. Isothermal expansion

Stage one: At this stage heat is released from the hot reservoir and is absorbed by the ideal gas particles within the system. Thus, the temperature of the system rises. The high temperature causes the gas particles to expand; pushing the piston upwards and doing work on the surroundings.

Step 2: Isentropic (Reversible Adiabatic) : Expansion of the gas (isentropic work output).

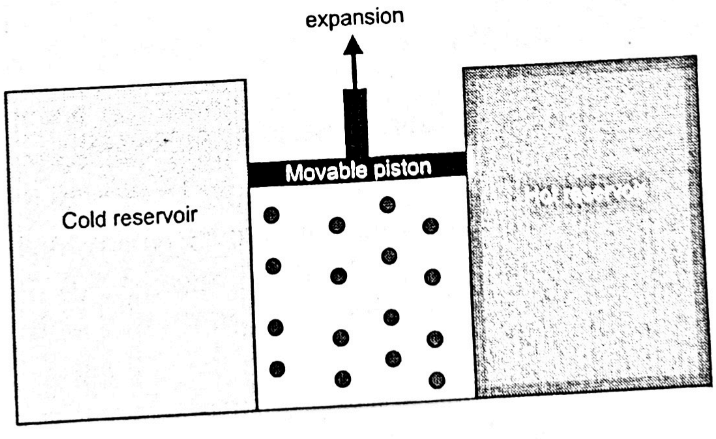

Fig. 1.12. Isentropic

Stage two: At this stage expansion continues. However, there is no heat exchange between the system and surroundings. Thus, the system is undergoing adiabatic expansion. The expansion allows the ideal gas particles to cool, decreasing the temperature of the system.

Step 3: Isothermal Compression. Heat is transferred reversibly to low temperature reservoir at constant temperature T_c. (isothermal heat rejection)

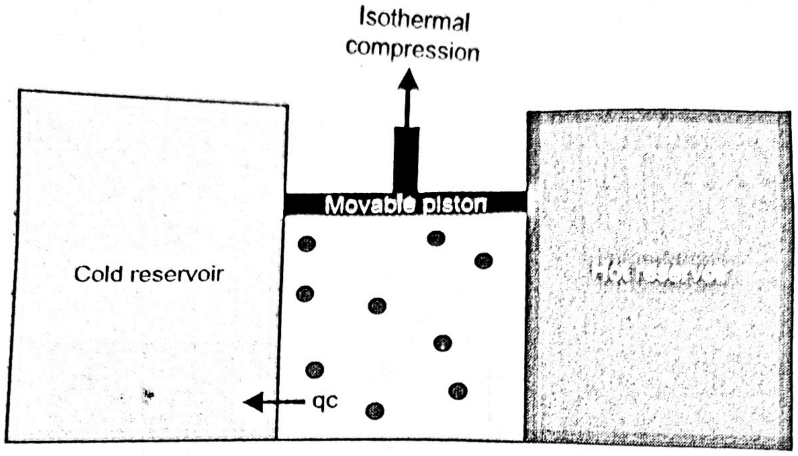

Fig. 1.13. Isothermal compression

Stage three: At this stage the surroundings do work on the system which causes heat to be released (qc). The temperature within the system remains the same. Thus, isothermal compression occurs.

Step 4: Adiabatic Reversible Compression.

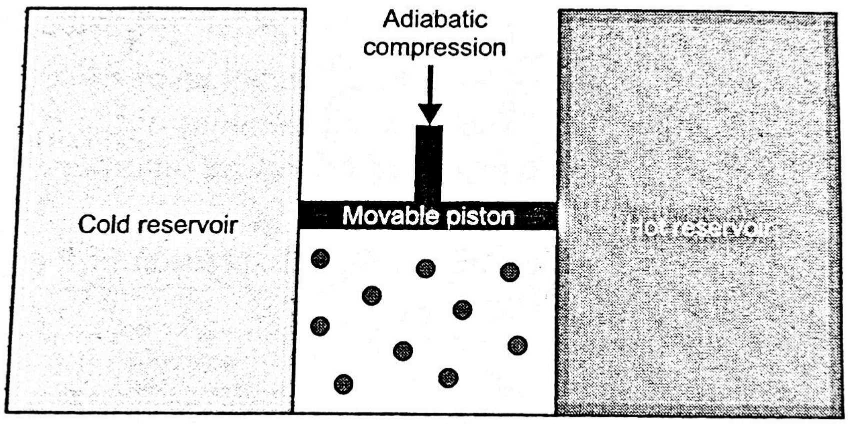

Fig. 1.14. Adiabatic reversible compression

Stage four: No heat exchange occurs at this stage. However, the surroundings continue to do work on the system. Adiabatic compression occurs which raises the temperature of the system as well as the piston is sent back to its original state.

Applications of the Carnot Cycle

Thermal machines or thermal devices are one of the applications of the Carnot cycle. Some of the other examples heat pumps to generate heating, refrigerators to yield cooling, steam turbines that are used in the ships, combustion engines of the combustion vehicles and the reaction turbines of an airplane.

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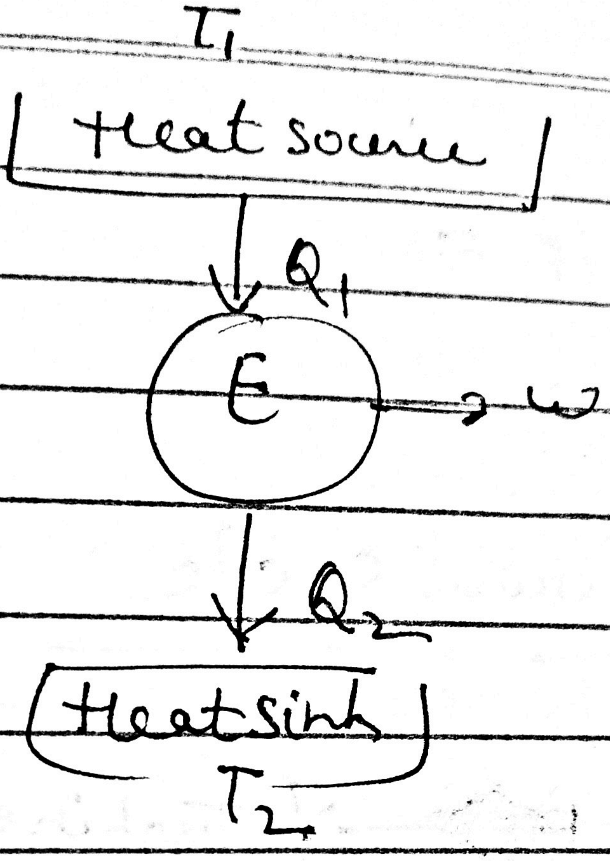

Carnot vapour cycle

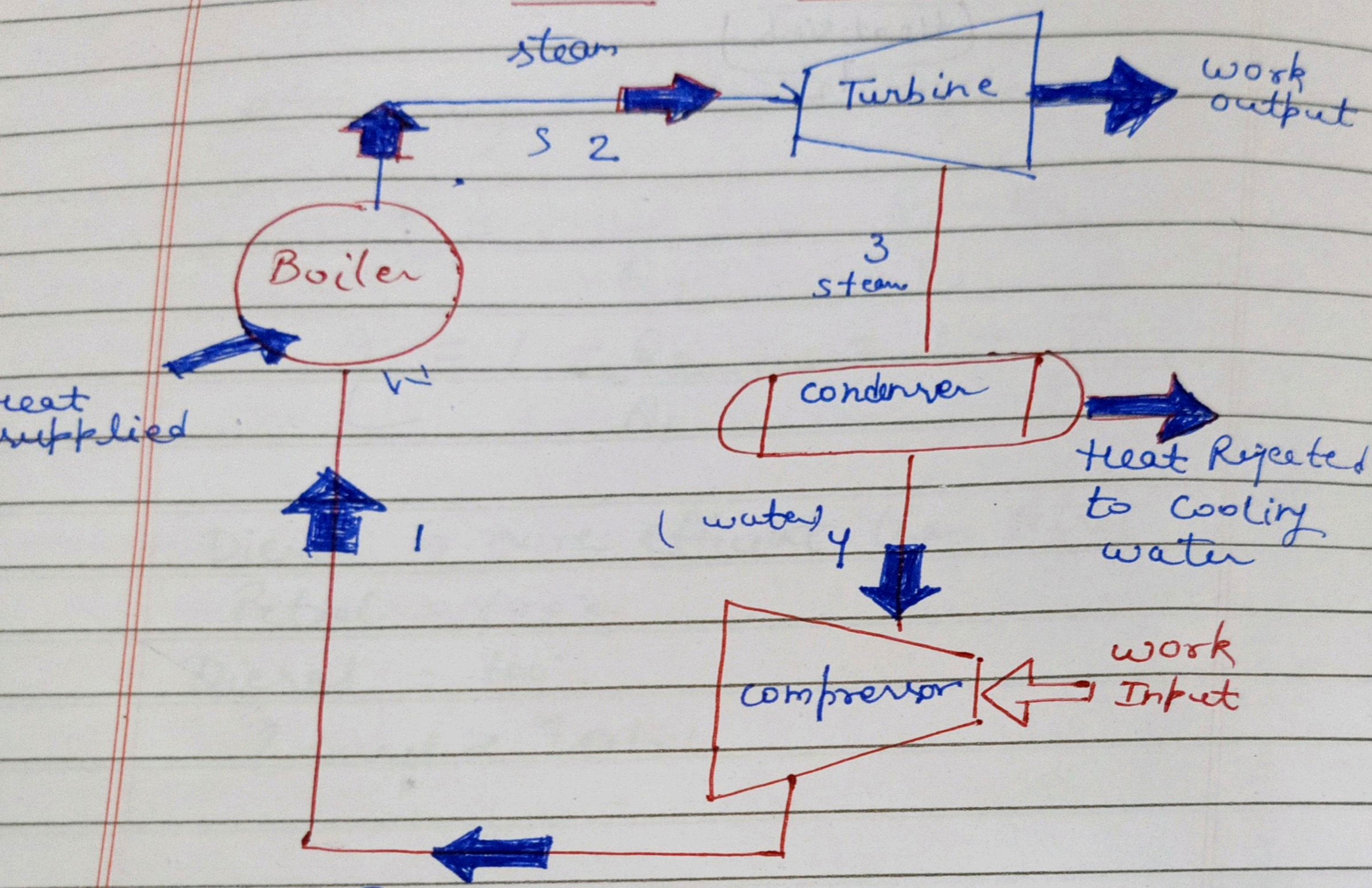

fig (a)

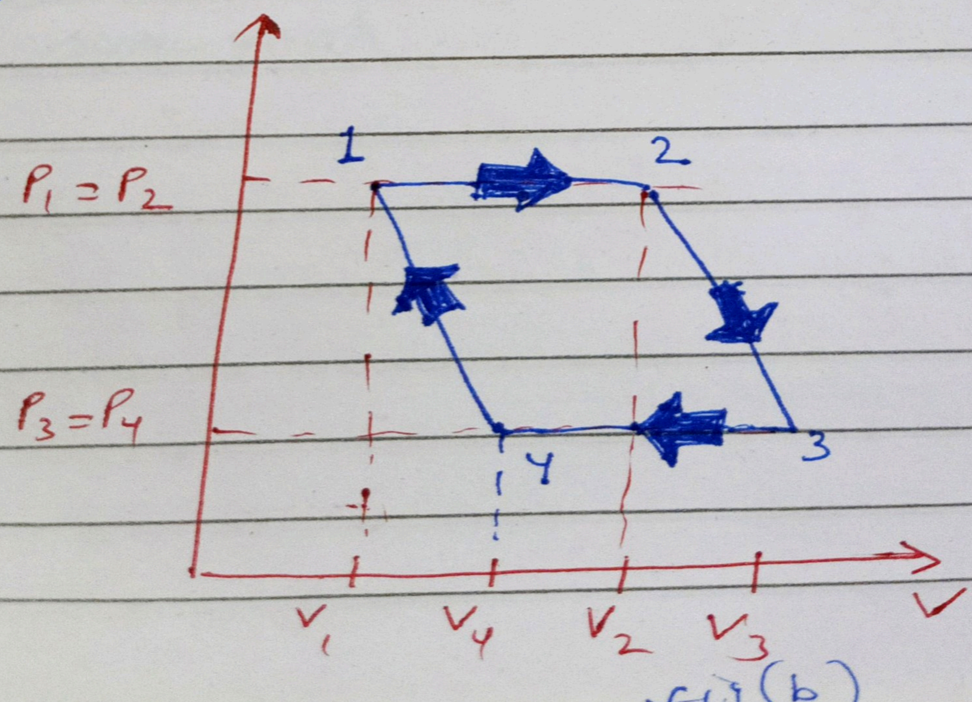

fig (b)

Carnot vapour cycle

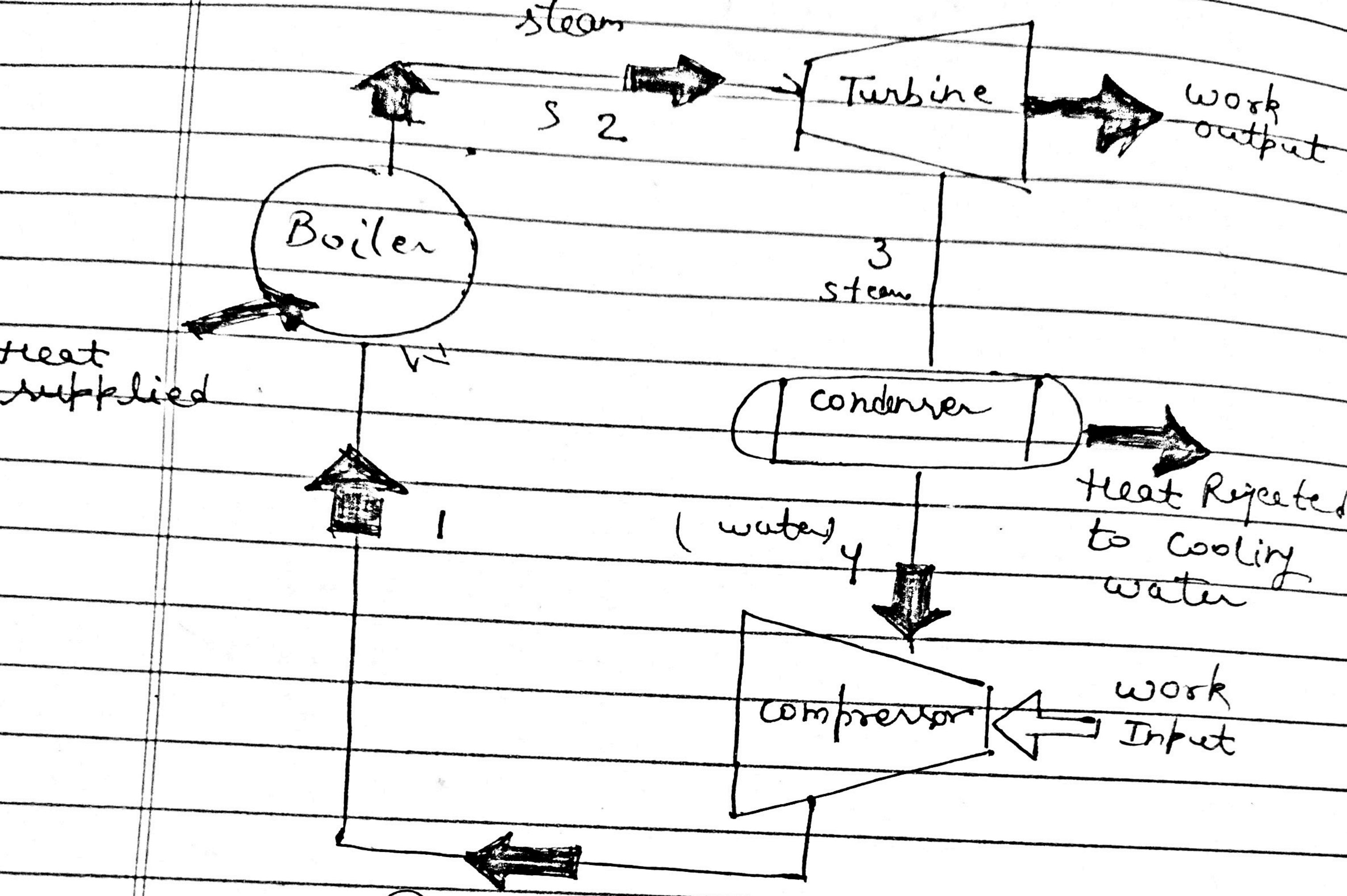

fig (a)

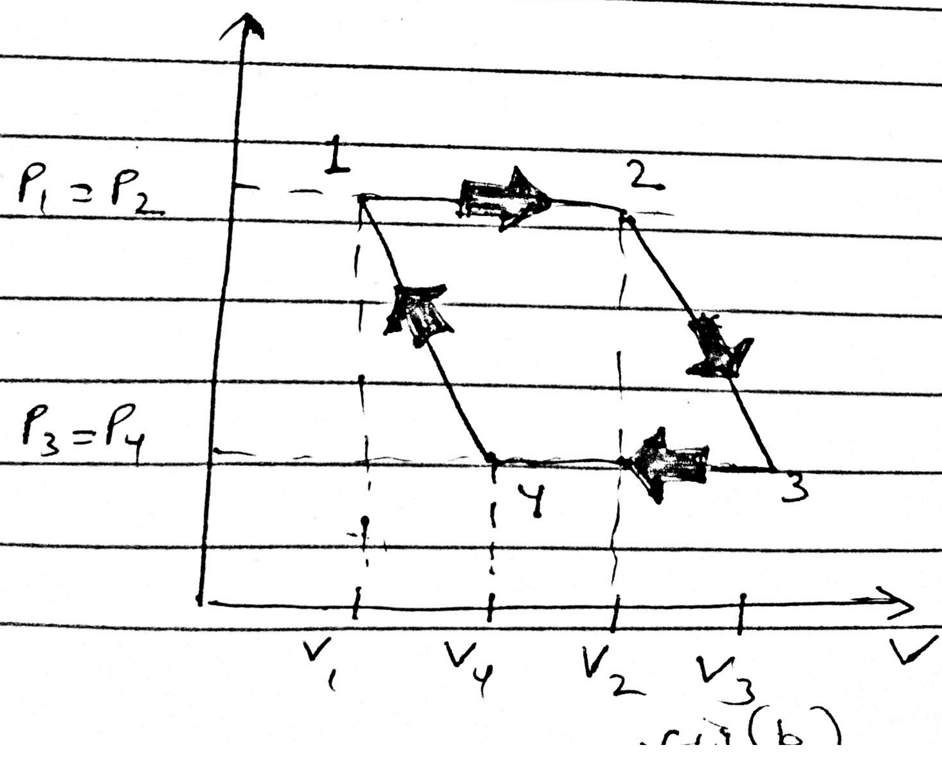

fig (b)

In carnot vapour cycle, steam or any other vapour is used as working substance in place of a perfect gas.
Component and arrangement of carnot vapour cycle is shown in fig (a) and same is represented on P-V dgm in fig (b)

Process (1-2) This isothermal heat addition in the boiler
Isothermal process having ~~$T_1 = T_2$~~ = Constant temp^r constant.
This is also constant pressure process saturated water at point 1 is isothermally converted into dry saturated steam in boiler
(1-2) Pressure is constant and but volume is increased due to phase change of liquid to steam

Process (2-3) :- This is reversible adiabatic expansion of steam in the turbine
Supplied steam to turbine and blade of turbine get rotate & we get some work O/P.
(Pressure Reduce & volm increase)
The dry steam at point 2 expands adiabatically in the steam turbine develops work W_T

Pressure ratio
Specific heat ra

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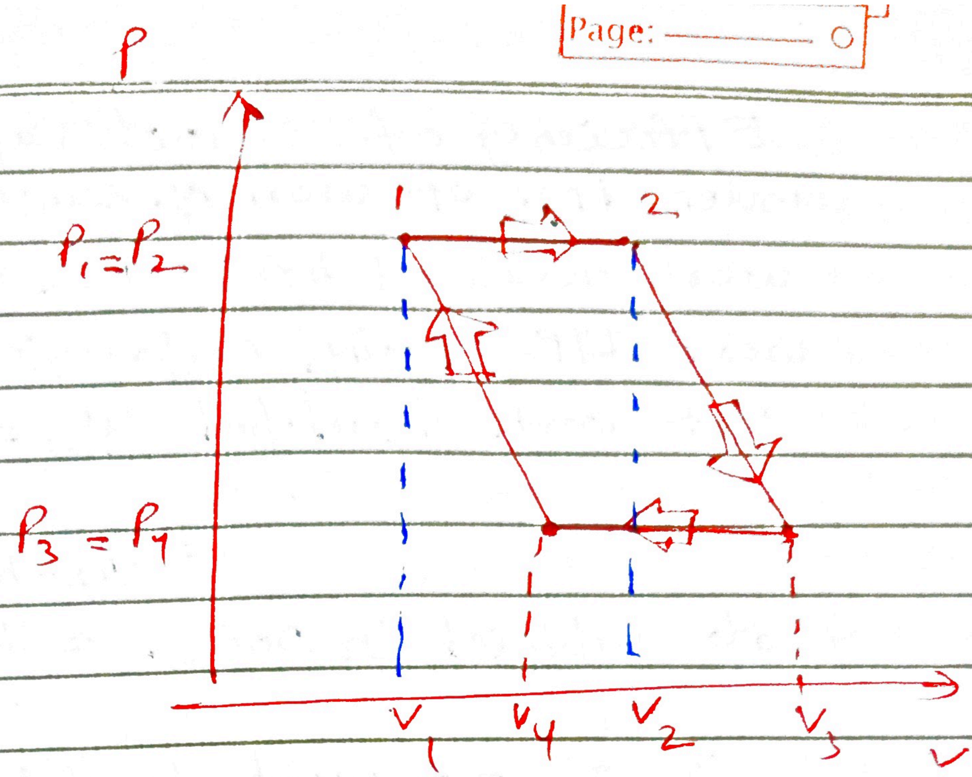
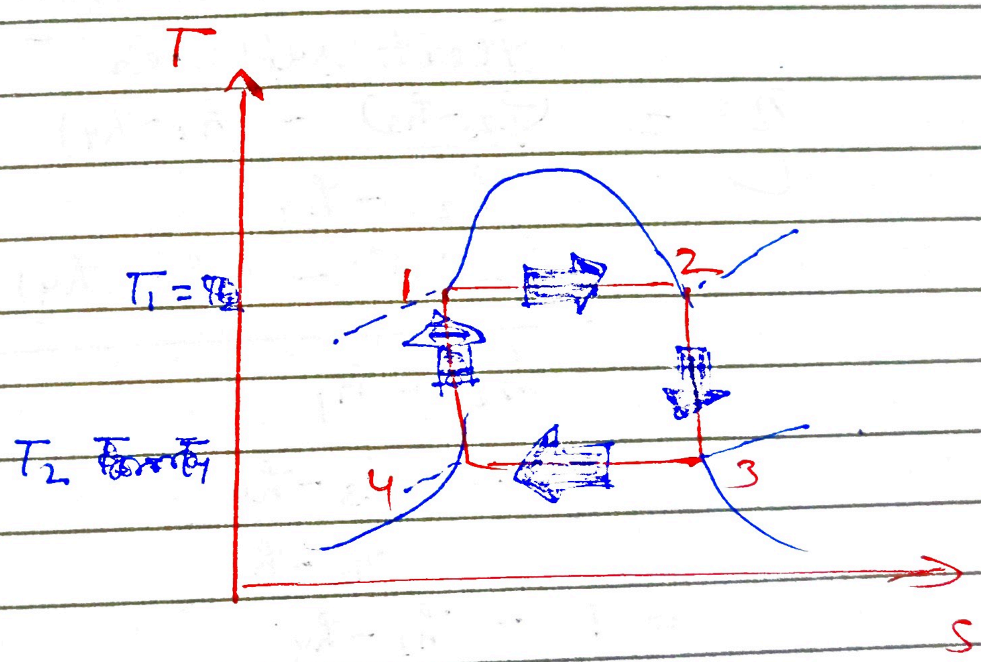
Process (3-4) This isothermally heat ($T_3 = T_4$) rejection in the condenser condenser converts steam into water at constant pressure and tempr as shown in dgm

Process (4-1) :- This is reversible adiabatic compression process

Steam and water enters into compressor in which pressure increase from P_4 to P_1 & compressor consumes some power W_c, this complete the cycle.


P
1
2
P1 = P2
P3 = P4
V1
V4
V2
V3
V


T
T1 =
T2
1
2
3
4
S

Efficiency of carnot vapour cycle

Consider 1 Kg. of working substance

work developed by turbine $W_t = h_2 - h_3$

work I/P during compression $W_c = h_1 - h_4$

Net work developed $W_{net} = W_T - W_c$

$$= (h_2 - h_3) - (h_1 - h_4)$$

Heat supplied in Boiler $= h_2 - h_1$

$$\eta = \frac{\text{net work developed}}{\text{Heat supplied}}$$

$$\eta = \frac{(h_2 - h_3) - (h_1 - h_4)}{h_2 - h_1}$$

$$= \frac{(h_2 - h_1) - (h_3 - h_4)}{h_2 - h_1}$$

$$= 1 - \frac{h_3 - h_4}{h_2 - h_1}$$

$$= 1 - \frac{h_3 - h_4}{h_2 - h_1}$$

Heat Rejected by condenser $Q_R = h_3 - h_4$.

Heat supplied by boiler $Q_S = h_2 - h_1$

$$\boxed{\eta = 1 - \frac{Q_R}{Q_S}}$$

Entropy $ds = \int \frac{dQ}{T}$

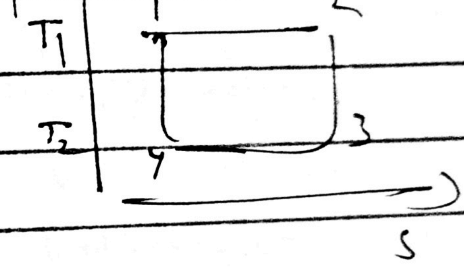
$$dQ = T\,ds$$

$Q_R = T_2 (S_3 - S_4)$ $\qquad$ $Q_S = T_1 (S_2 - S_1)$

$$\eta = 1 - \frac{T_2 (S_3 - S_4)}{T_1 (S_2 - S_1)}$$

But Process (2-3) & (4-1) are isentropic

$S_2 = S_3$, $S_1 = S_4$



$$\boxed{\eta = 1 - \frac{T_2}{T_1}}$$

where T_1 max^m Temp^r of the cycle

T_2 maximum Temp of cycle.

Date ....

Stirling Engine :-

A Stirling Engine is a heat Engine that is operated by the cyclic compression and expansion of air or other gas between different Temperatures, resulting in a net conversion of heat energy to mechanical work.

Stirling engine is a closed-cycle regenerative heat engine, with a paramanent gaseous working fluid.
Closed cycle means a thermodynamics system in which working fluid is permanently contained with in the system.
Regenerative is a specific type of internal heat exchanger and thermal store, known as regeneration.

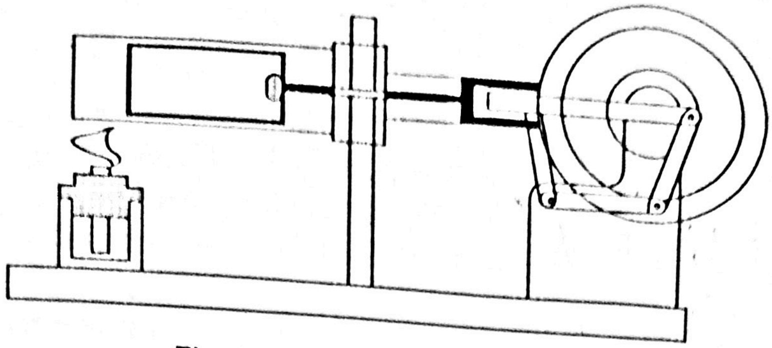


Fig. 1.15. Stirling engine diagram

Main Components of the Stirling Engine

- **Power Piston:** A small tightly sealed piston that moves up when the gas inside the engine expands.
- **Displacer:** The larger piston that is kept very loose in its cylinder so that air can move easily between the heated cooled sections of the engine as the displacer moves up and down.
- These pistons move by the action of compression and expansion.
- Difference in the pressure causes the piston to move and produce power.

Working Principle of Stirling Engine

- One side of the engine is continuously heated while the other side is continuously cooled.
- First, the air moves to the hot side, where it is heated and expands, pushing the piston upward.
- Then the air moves through the regenerator to the cold side, where it cools off and contracts pulling the piston down.
- Temperature change inside the engine produces the pressure change needed to push the piston and make the engine run.

Configurations

There are three major types of Stirling engines that are distinguished by the way they move the air between the hot and cold areas:

- The alpha configuration
- The beta configuration
- The gamma configuration

Efficiency

- Theoretically,
  - Stirling engine efficiency= Carnot efficiency
  - Unfortunately, the working fluid or gas is not ideal which causes the efficiency to be lower than the Carnot efficiency.

- Stirling engine efficiency depends on:
  - Temperature ratio (proportionally)
  - Pressure ratio (inversely proportional)
  - Specific heat ratio (inversely proportional)

Applications of Stirling Engine

- Water pump stations
- Combined heat and power plant
- Solar power generation
- Stirling cryocoolers
- Marine engines
- Nuclear power
- Aircraft engines

Phase change

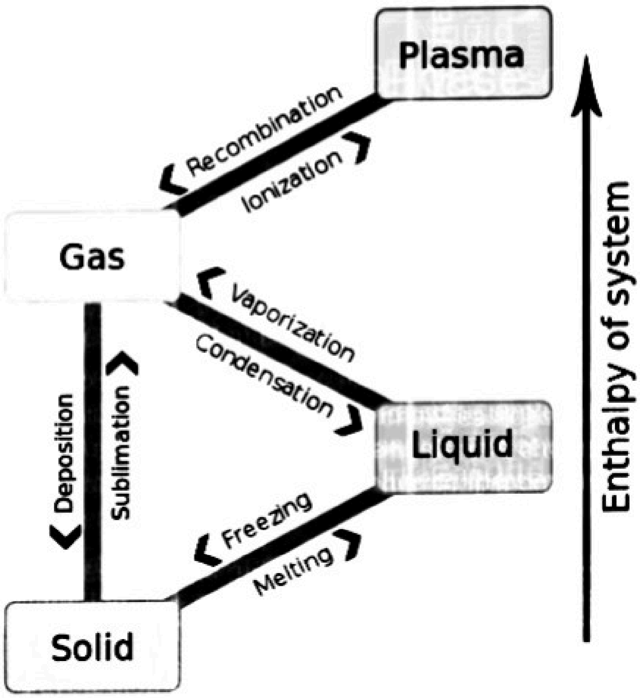


Figure 1: Diagram of phase transitions.[1]

A **phase change** is when matter changes to from one state (solid, liquid, gas, plasma) to another. (see figure 1). These changes occur when sufficient energy is supplied to the system (or a sufficient amount is lost), and also occur when the pressure on the system is changed. The temperatures and pressures under which these changes happen differ depending on the chemical and physical properties of the system. The energy associated with these transitions is called latent heat.

Water is a substance that has many interesting properties that influence its phase changes. Most people learn from an early age that water melts from ice to liquid at 0°C, and boils from a liquid to a gas at 100°C; but this isn't true in all circumstances. The pressure affects these transition points, so for water, the boiling point actually decreases as the pressure decreases. Water also has certain intermolecular forces which govern the temperatures at which these transitions occur.[2] This difference in boiling point is why the directions for cooking at high altitudes are sometimes slightly different (like boiling pasta longer).

The relatively large amount of energy needed to change the phase of water is one of the reasons why water is used to cool power plants. It's also part of why humans sweat in order to stay cool (through evaporation) and dogs pant. This high latent heat also makes water important for moderating the climate.

Boiling/condensing and freezing/melting are the most common pairs of phase changes experienced on Earth. However, there are other phase changes such as sublimation—which is going straight from a solid to a gas. Figure 1 also shows phase changes that are rare (on Earth, at least) known as plasma. However, figure 1 does not show what happens when gases or liquids get to sufficiently high pressures and temperatures that they can't be distinguished. This phase is called the supercritical fluid state (which is useful for some modern power plants).

1.8.2 Energy of Phase Changes

We take advantage of changes between the gas, liquid, and solid states to cool a drink with ice cubes (solid to liquid), cool our bodies by perspiration (liquid to gas), and cool food inside a refrigerator (gas to liquid and vice versa). We use dry ice, which is solid CO_2, as a refrigerant (solid to gas), and we make artificial snow for skiing and snowboarding by transforming a liquid to a solid. In this section, we examine what happens when any of the three forms of matter is converted to either of the other two. These changes of state are often called phase changes. The six most common phase changes are shown in Fig. 1.17.

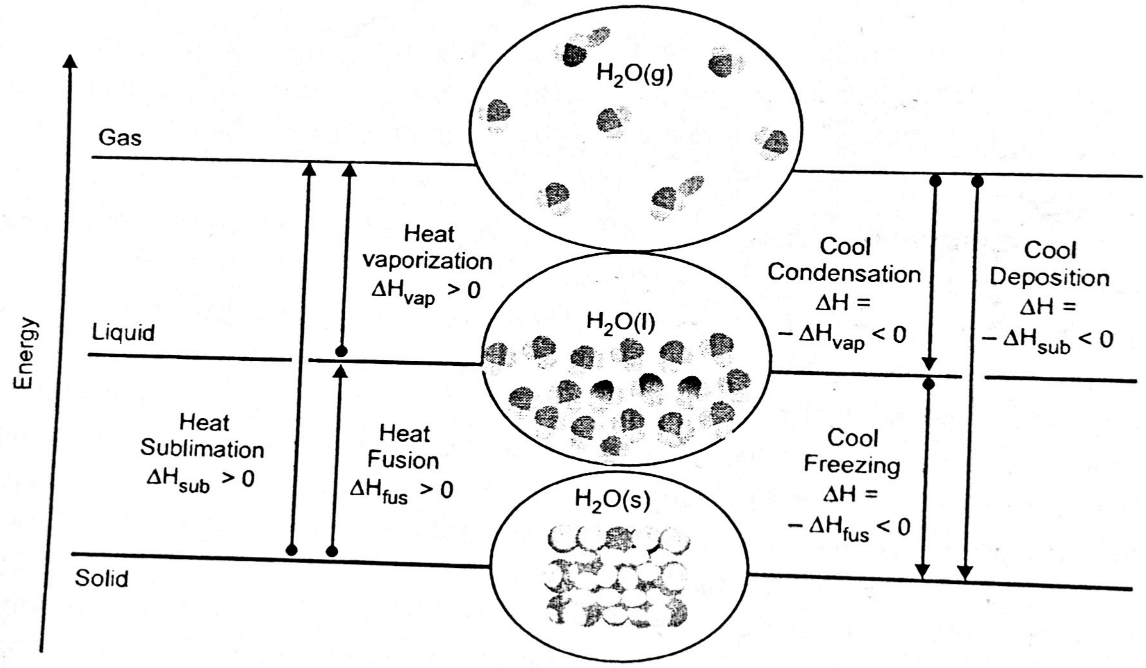


Fig. 1.17. Enthalpy changes that accompany phase transitions

1.8.3 Energy that Accompanies Phase Change

Phase changes are *always* accompanied by a change in the energy of the system. For example, converting a liquid, in which the molecules are close together, to a gas, in which the molecules are, on average, far apart, requires an input of energy (heat) to give the molecules enough kinetic energy to allow them to overcome the intermolecular attractive forces. The stronger the attractive forces, the more energy is needed to overcome them. Solids, which are highly ordered, have the strongest intermolecular interactions, whereas gases, which are very disordered, have the weakest. Thus, any transition from a more ordered to a less ordered state (solid to liquid, liquid to gas, or solid to gas) requires an input of energy; it is **endothermic**. Conversely, any transition from a less ordered to a more ordered state (liquid to solid, gas to liquid, or gas to solid) releases energy; it is **exothermic**.

1.8.4 Temperature Curves

The processes of freezing, condensation, and deposition, which are the reverse of fusion, sublimation, and vaporization—are exothermic. Thus, heat pumps that use refrigerants are essentially air-conditioners running in reverse. Heat from the environment is used to vaporize the refrigerant, which is then condensed to a liquid in coils within a house to provide heat. The energy changes that occur during phase changes can be quantified by using a heating or cooling curve.

Refrigeration cycle & Heat Pumps

~~Refrigerator~~ :-

Thermodynamic heat pumps and refrigeration cycles are the models for heat pumps and refrigerators.
Difference b/w the two is that heat pumps are intended to keep a place warm and refrigerators are designed to cool it.
Technically a refrigerator cycle is also a heat pump cycle.

W

Refrigerator :-

A refrigerator is a cyclic device, which absorbs heat from a heat sink and reject heat to a heat source by consuming work.
The working fluid is called Refrigerant, which usually undergoes phase changes in the cycle.

A Typic vapour - compression refrigeration system consists of mainly 4 pieces of equipment, as shown in fig :

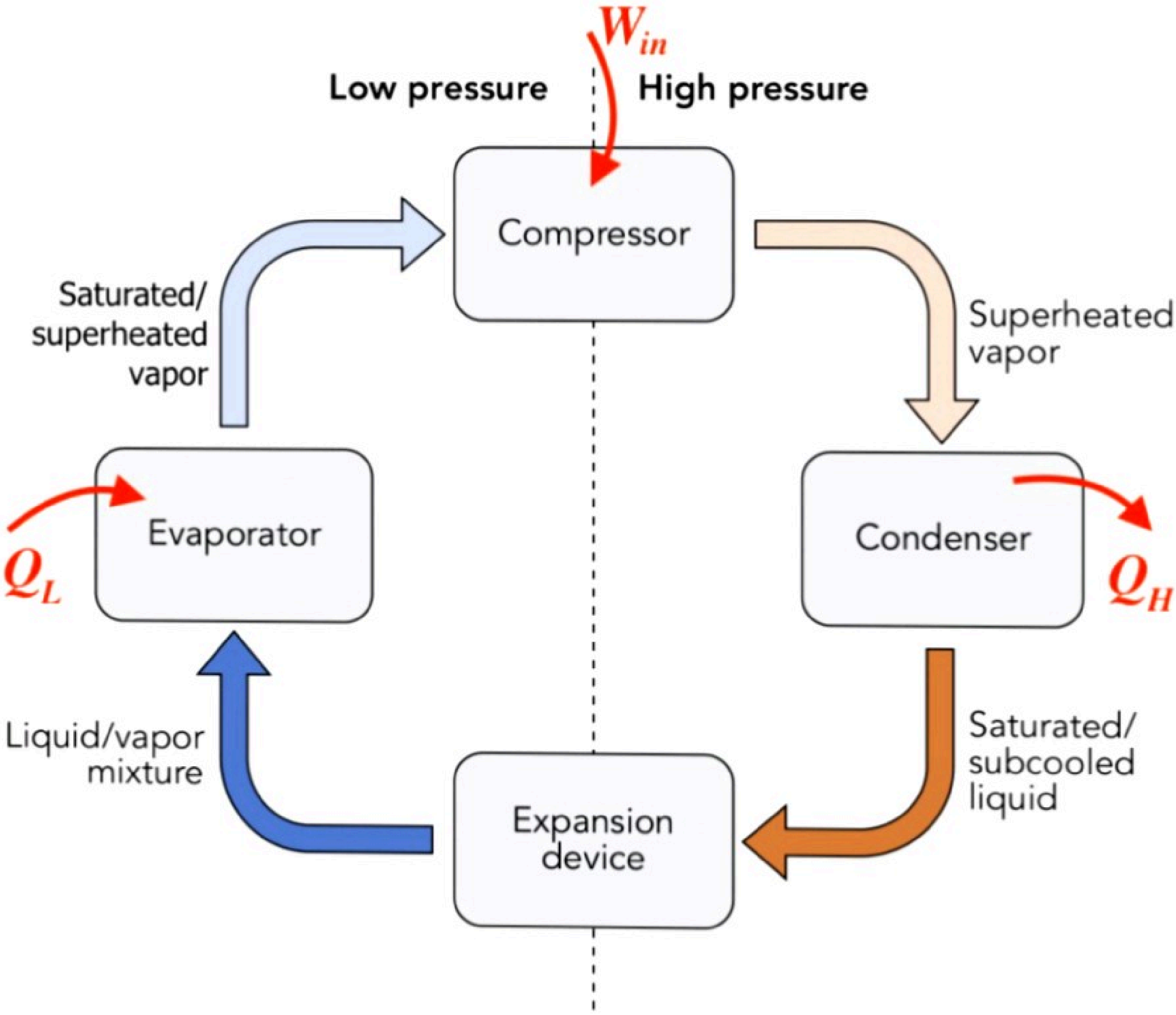


Figure 6.2.1 *Vapor compression refrigeration cycle consisting of a compressor, condenser, expansion device, and evaporator*

1. Evaporator :-
An evaporator, through which low pressure, low tempr refrigerant absorbs heat from a heat sink (e.g; a freezer compartment or a space to be refrigerated) and changes from a two phase mixture to a saturated or superheated vapour.

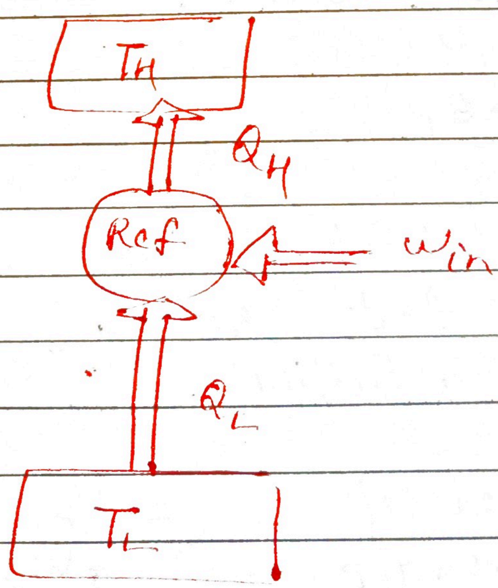
2. A compressor :- , which is used to increase the pressure and tempr of refrigerant vapour by consuming work.

3. A condenser, through which heat is rejected to a heat source. (e.g; Kitchen or outdoor air) At the exit of condenser, the refrigerant is typically a two-phase mixture or a liquid.

4. An Expansion valve, which is used to reduce pressure and temp^r of refrigerant in order to achieve a liquid - vapour mixture of desirable quality at the exit of expansion valve.

A heat can not be transferred from a low temp^r body to a high temp^r body spontaneously in nature.
Refrigerator must consume work in order to operate b/w heat sink and heat source even under ideal condition.

fig shows energy conservation ool in a refrigerator



Schematic of a refrigerator or (Heat Pump)

Date ....

$W_{in} = Q_H - Q_L$

Coefficient of Performance

$$COP_R = \frac{\text{desired O/P}}{\text{required input}} = \frac{Q_L}{W_{in}}$$

$$= \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

A Higher COP_R indicates a better performance.
$COP_R > 1$ is a well designed refrigerator.

Heat Pump :-

A heat pump uses the same vapour compression refrigeration cycle, as a refrigerator.
It absorbs heat from a heat sink (e.g; outdoor air in the winter) and delivers more heat to a heat source (e.g indoor air) by consuming work.

$W_{in} = Q_H - Q_L$

The main purpose of heat pump is to add heat, Q_H to a heat source, such as an indoor space of a buiding.

$$COP_{HP} = \frac{\text{derired O/P}}{\text{required I/P}} = \frac{Q_H}{W_{in}}$$

$$= \frac{Q_H}{Q_H - Q_L} = \frac{Q_H/Q_L}{\frac{Q_H}{Q_L} - 1}$$

level are reached.

1.9 INTERNAL COMBUSTION ENGINES

In an internal combustion engine, the combustion of air and fuels takes place inside the cylinder and is used as the direct motive force. It can be classified into the following types:

1. According to the basic engine design- (a) Reciprocating engine (use of cylinder piston arrangement), (b) Rotary engine (use of turbine).
2. According to the type of fuel used-(a) petrol engine, (b) diesel engine, (c) gas engine (CNG, LPG), (d) Alcohol engine (ethanol, methanol etc.)
3. According to the number of strokes per cycle-(a) Four stroke and (b) two stroke engine
4. According to the method of igniting the fuel-(a) spark ignition engine, (b) compression ignition engine and (c) hot spot ignition engine.
5. According to the working cycle-(a) Otto cycle (constant volume cycle) engine, (b) diesel cycle (constant pressure cycle) engine, (c) dual combustion cycle (semi-diesel cycle) engine.
6. According to the fuel supply and mixture preparation-(a) Carburetted type (fuel supplied through the carburettor), (b) Injection type (fuel injected into inlet ports or manifold, fuel injected into the cylinder just before ignition)
7. According to the number of cylinders –(a) Single cylinder, (b) multi-cylinder engine.
8. Method of cooling – water cooled or air cooled.
9. Speed of the engine- slow speed, medium speed and high speed engine.

10. Cylinder arrangement- Vertical, horizontal, inline, V- type, radial, opposed cylinder or piston engines.
11. Valve or port design and location- Overhead (I head), side valve (L head); in two stroke engines: cross scavenging, loop scavenging, uniflow scavenging.
12. Method governing – Hit and miss governed engines—quantitatively governed engines and qualitatively governed engine.
13. Application- Automotive engines for land transport, marine engines for propulsion of ships, aircraft engines for aircraft propulsion, industrial engines, prime movers for electrical generators.

Main Components of Reciprocating IC Engines:

- **Cylinder:** It is the main part of the engine inside which piston moves to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above 2000 C. The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminium alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.
- **Cylinder Head:** The top end of the cylinder is covered by cylinder head over which are mounted inlet and exhaust valve, spark plug or injector. A copper or asbestos gasket is provided between the engine cylinder and the cylinder head to make an air tight joint.

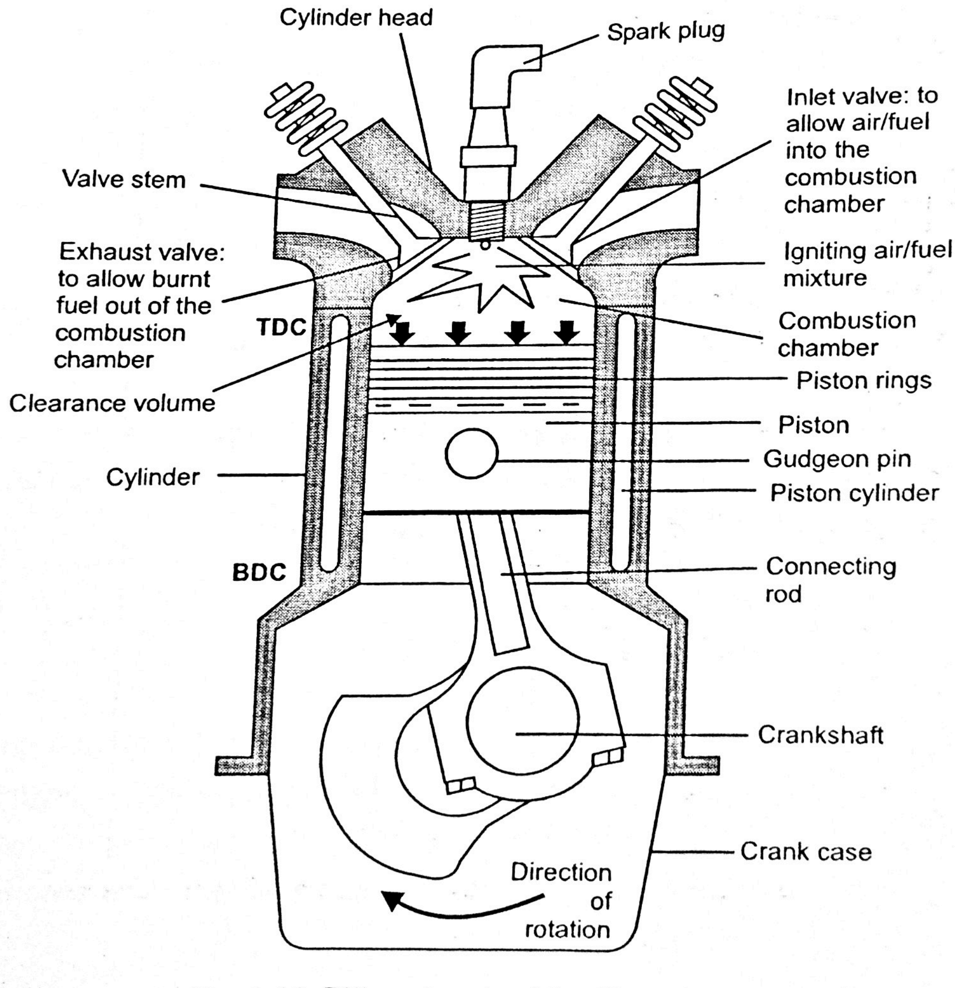


Fig. 1.19. Different parts of the IC engine

- **Piston:** Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at high temperatures.
- **Piston rings:** These are housed in the circumferential grooves provided on the outer surface of the piston and are made of steel alloys which retain elastic properties even at high temperature. There are two types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is the lower ring which provides effective seal to prevent leakage of the burnt gases into the lower portion. Oil ring is the lower ring which provides effective seal to prevent leakage of oil into the engine cylinder.
- **Connecting rod:** It converts the reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin while the bigger end of the connecting rod is connected with the crank with crank pin.
- **Crankshaft:** It converts the reciprocating motion of the piston into the rotary motion with the help of the connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called rank.
- **Crank case:** It houses the cylinder and crank shaft of the IC engines and also serves as sump for the lubricating oil.
- **Flywheel:** It is a big wheel mounted on the crankshaft, whose function is to maintain its speed constant. This is done by storing excess energy during the power stroke, which returned during other stroke.

Terminology used in IC engines:

1. **Cylinder bore (D):** The nominal inner diameter of the working cylinder.
2. **Piston area (A):** The area of circle equal to the cylinder bore.
3. **Stroke (L):** The nominal distance through which a working piston moves between two successive reversals of its direction of motion.
4. **Deal centre:** The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).
   (a) **Bottom dead centre (BDC):** Dead centre when the piston is nearest to the crankshaft.
   (b) **Top dead centre (TDC):** Dead centre when the position is farthest from the crankshaft.
5. **Displacement volume or swept volume (V_s):** The nominal volume generated by the working piston when travelling from one dead centre to the next one. It is given as,
$$V_s = A \times L$$
6. **Clearance volume (V_c):** The nominal volume of space on combustion side of the piston at the top dead centre.

7. **Cylinder volume (V):** Total volume of the cylinder.

$$V = V_s + V_c$$

8. **Compression ratio (r):** $r = V_s/V_c$

1.9.1 Types of Internal Combustion Engine

There are two types of engines: (a) Four-stroke, and (b) Two-stroke.

(a) **Four-stroke engine:** The cycle of operations completed in four strokes of the piston or two revolutions of the piston. The four strokes are:

(i) **Suction stroke** (suction valve open, exhaust valve closed)— Thecharge consisting of fresh air mixed with the fuel is drawn into the cylinder due to the vacuum pressure created by the movement of the piston from TDC to BDC.

(ii) **Compression stroke** (both valves closed)— The fresh charge is compressed into clearance volume by the return stroke of the piston and is ignited by the spark for combustion. Hence, the pressure and temperature increase due to the combustion of the fuel.

(iii) **Expansion stroke** (both valves closed)— High pressure of the burnt gases forces the piston towards BDC and hence power is obtained at the crankshaft.

(iv) **Exhaust stroke** (exhaust valve open, suction valve closed)— The burned gases expel out due to the movement of the piston from BDC to TDC.

Figure 1.20 shows the cycle of operation of a four-stroke engine.

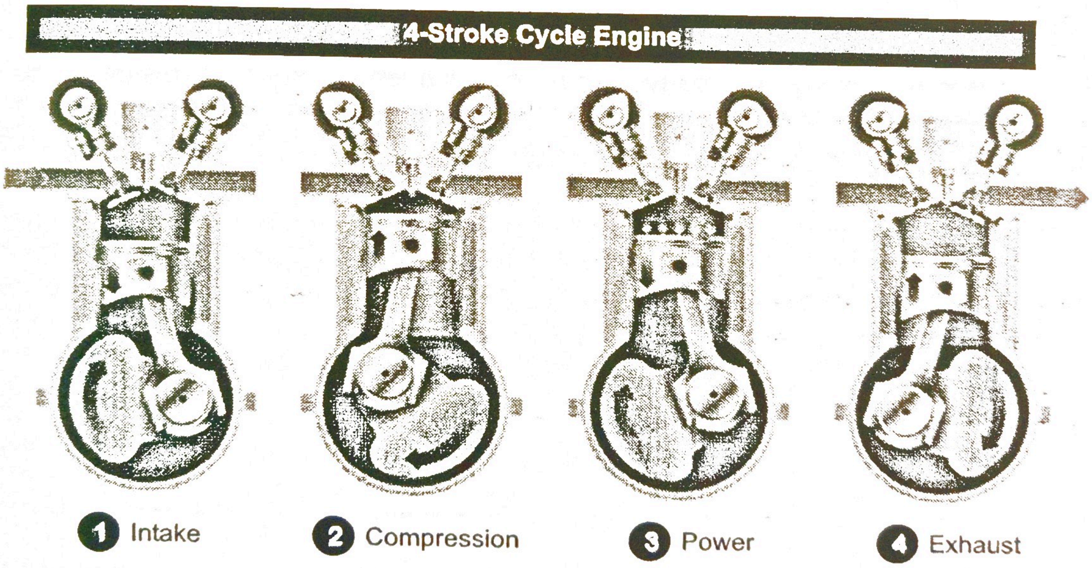


Fig. 1.20. Cycle of operation in a four-stroke engine

(b) **Two-stroke engine:** There is no piston stroke for suction and exhaust operations in a two stroke engine. Suction is accomplished by the air compressed in crankcase or by a blower. Induction of the compressed air removes the products of combustion through exhaust ports. Transfer port is there to supply the fresh charge into combustion chamber. Figure 121 represents the operation of a two-stroke engine.

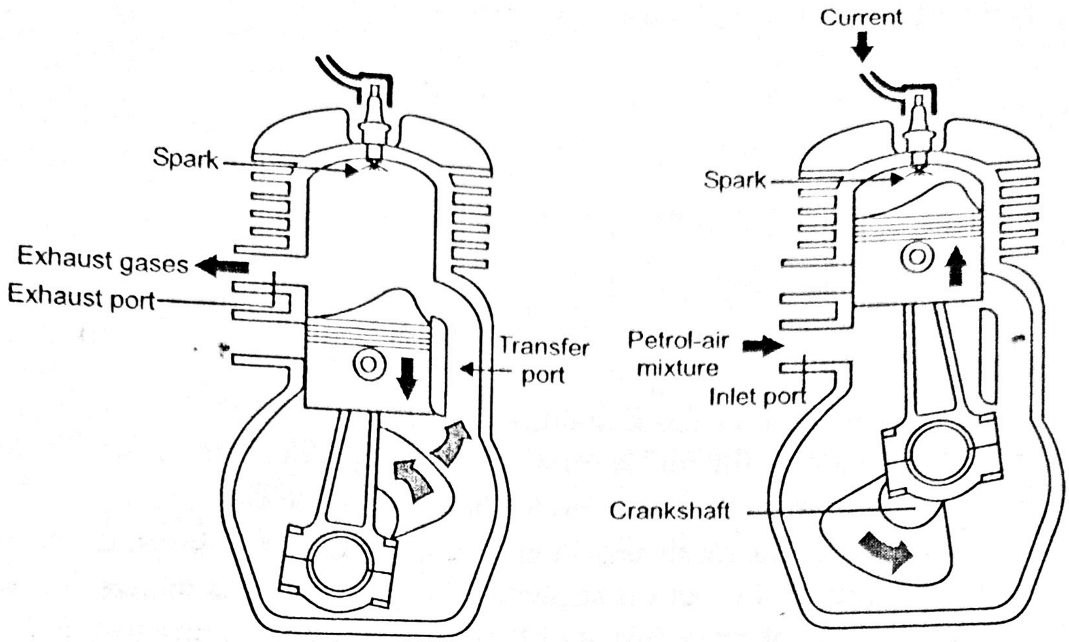


Fig. 1.21. Cycle of operation in a two-stroke engine

Comparison of Four-stroke and two-stroke engine:

Two-Stroke and Marine Diesel Engine	Four-Strock Marine Diesel Engine
It has one revolution of the crankshasft.	It has two revolutions of the crankshaft during one power stroke.
It generates high torque	It generates less torque.
It has a larger ratio in terms of power to weight.	It has a lesser ratio in terms of power to weight.
It generates more smoke and shows less efficiency.	It generates less smoke and shows more efficiency.
Crankshaft to camshaft ratio is 1 : 1	Crankshaft to camshaft ration is 1 : 2
One centrally mounted exhaust valve is there in uniflow scavenging. The exhaust valve is opened hydraulically and closed by air spring.	Two exhaust valves are provided. Opening and closing of exhaust value is done by push rods and tappets.
They are slow speed engines.	They are medium-speed and high-speed engines.
Combustion air comes from scavenge manifold via scavenge ports in the liner.	Combustion air comes from scavenge manifold via inlet valve.
Stuffing box is provided.	There is no stuffing box
They are crosshead engines.	They are trunk piston engines.
Piston rod is present.	No piston rod.
No gudgeon pin.	Gudgeon pin present
High thermal efficiency.	Low thermal efficiency.
Constant pressure turbocharging system.	Pulse turbo charging system.

1.10 STEAM AND GAS POWER CYCLES, PHYSICS OF POWER PLANTS

The engineering aspect of power plant management has evolved with technology and has become progressively more complicated. The introduction of nuclear energy and the progression of other existing technologies have allowed power to be created in more ways and on a larger scale than was previously possible. The assignment of different types of engineers to the design, construction, and operation of a new power plant is dependent on the type of system to be built, such as whether it is a fossil fuel, thermal power plant, nuclear power plant, hydroelectric power plant or solar plant.

1.10.1 First Law of Thermodynamics

In simple terms, the first law of thermodynamics states that energy cannot be created nor destroyed; however, power can be converted from one form of energy to another form of energy. This is especially important in power generation because power production in nearly all types of power plants relies upon the use of a generator which involve conversion of mechanical energy into electrical energy; for example, wind turbines utilize a large blade connected to a shaft which turns the generator when rotated by the wind. The generator then creates electricity due to the interaction of a conductor within a magnetic field. In this case, the mechanical energy generated by the wind is converted, through the generator, into electric energy. Most power plants rely on these conversions to create usable electric power.

1.10.2 Second Law of Thermodynamics

The second law of thermodynamics conceptualizes that the entropy of a closed system can never decrease. As the law relates to power plants, it dictates that heat is to flow from a body at high temperature to a body at low temperature (the device in which electricity is being generated). This law is particularly relevant to thermal power plants which derive their energy from the combustion of a fuel source.

An important application of thermodynamics is the analysis of power cycles through which the energy absorbed as heat can be continuously converted into mechanical work. The purpose of a thermodynamic cycle is either to produce power, or to produce refrigeration/pumping of heat. Therefore, the cycles are broadly classified as follows:

(a) Heat engine or power cycles.

(b) Refrigeration/heat pump cycles.

Any thermodynamic cycle is essentially a closed cycle in which, the working substance undergoes a series of processes and is always brought back to the initial state. However, some of the power cycles operate on open cycle system. It means that the working substance is taken into the unit from the atmosphere at one end and is discharged back to the atmosphere after undergoing a series of processes at the other end. The following are illustrations of heat engines operating on open cycle:

(i) **Petrol and diesel engines** in which the air and fuel are taken into the engine from a fuel tank and products of combustion are exhausted into the atmosphere.

(ii) Steam locomotives in which the water is taken in the boiler from a tank and steam is exhausted into the atmosphere.

Different types of working fluids are employed in power plants. The nature of the working fluids can be classified into two groups: vapours and gases. The power cycles are accordingly classified into two groups as:

1. **Vapour power cycles** in which the working fluid undergoes a phase change during the cyclic process.
2. **Gas power cycles** in which the working fluid does not undergo any phase change.

In the thermodynamic analysis of power cycles, estimating the energy conversion efficiency or the thermal efficiency is important. Thermal efficiency of a heat engine is defined as the ratio of the net work delivered to the energy absorbed as heat.

In steam power plants and refrigeration cycles, the working fluid changes from liquid to vapour and back to the liquid state. This succession of processes is called vapour cycle. In steam power plants, water is the working fluid in the form of steam and vapour. In refrigeration cycles gases such as freon, CO_2, and ammonia (aqua-ammonia) are used as working substances.

1.10.3 Types of Power Plants

All power plants are created with the same goal: to produce electric power as efficiently as possible. However, as technology has evolved, the sources of energy used in power plants has evolved as well. The introduction of more renewable/sustainable forms of energy has caused an improvement and creation of certain power plants.

1. Hydroelectric power plants

Hydroelectric power plants generate power using the force of water to turn generators. They can be categorized into three different types; impoundment, diversion and pumped storage.

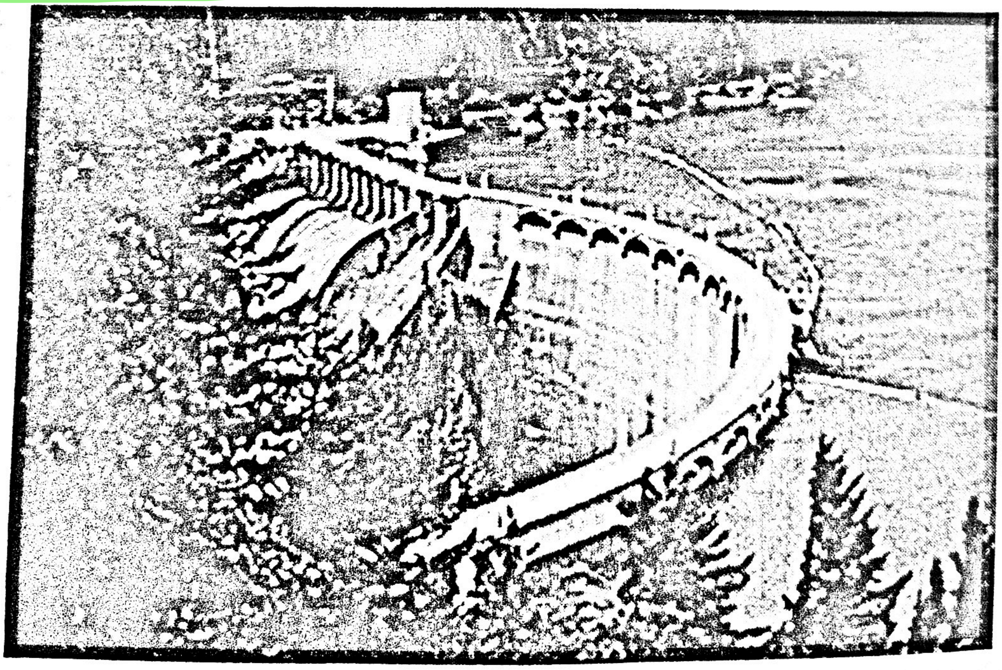


Fig. 1.22. Hydroelectric Dam

Impoundment and diversion hydroelectric power plants operate similarly, in that each involves creating a barrier to keep water from flowing at an uncontrollable rate, and then controlling the flow rate of water to pass through turbines to create electricity at an ideal level. Mechanical engineers are in charge of calculating flow rates and other volumetric calculations necessary to turn the generators at the electrical engineer specifications. Pumped storage hydroelectric power plants operate in a similar manner but only function at peak hours of power demand. At calm hours the water is pumped uphill, then is released at peak hours to flow from a high to low elevation to turn turbines. The engineering knowledge required to assess the performance of pumped storage hydroelectric power plants is very similar to that of impoundment and diversion power plants.

2. Thermal Power Plants

Thermal power plants are of two different categories; those that create electricity by burning fuel and those that create electricity via prime mover. A common example of a thermal power plant that produces electricity by the consumption of fuel is the nuclear power plant. Nuclear power plants use a nuclear reactor heat to turn water into steam this steam is sent through a turbine which is connected to an electric generator. Another example of a fuel burning power plant is coal power plant. Coal power plants operate in a manner similar to nuclear power plants in that the heat from the burning coal powers a steam turbine and electric generator. There are several types of engineers that work in a thermal power plant. Mechanical engineers maintain performance of the thermal power plants while keeping the plants in operation. Nuclear engineers generally handle fuel efficiency and disposal of nuclear waste; though they work directly with nuclear equipment. Electrical engineers deal with the power generating equipment as well as the calculations.

3. Combined Cycle Power Plants

In combined cycle power plants there are two key cycles: Brayton (gas turbine) cycle and Rankine (steam turbine) cycle, within each of which there are further subdivisions. A combination of Brayton and Rankine cycles, often known as the combined cycle, has been found to obtain efficiencies as high as 60% and consequently is now used extensively worldwide as the main source of power. It is also more commonly being used in combined heat and power (CHP) plants that provide power and other sources of energy such as heat and air conditioning for major complexes or parts of cities.

Combined-cycle power plants as shown in Fig. 1.23 include compound gas turbine–steam turbine systems wherein the extreme hot exhaust from a gas turbine is employed to run a boiler, and the steam thus produced is fed into a steam turbine to generate power. These plants can deliver high power output at efficiencies as high as 50%–60% with low emissions and produce 50% more electricity than a simple-cycle plant consuming the same amount of fuel. Combined cycle power plants may be either single-shaft, wherein both of the gas turbine and steam turbine are connected to the same generator in a tandem arrangement, or multi-shaft, with each gas turbine and steam turbine driving separate generators.

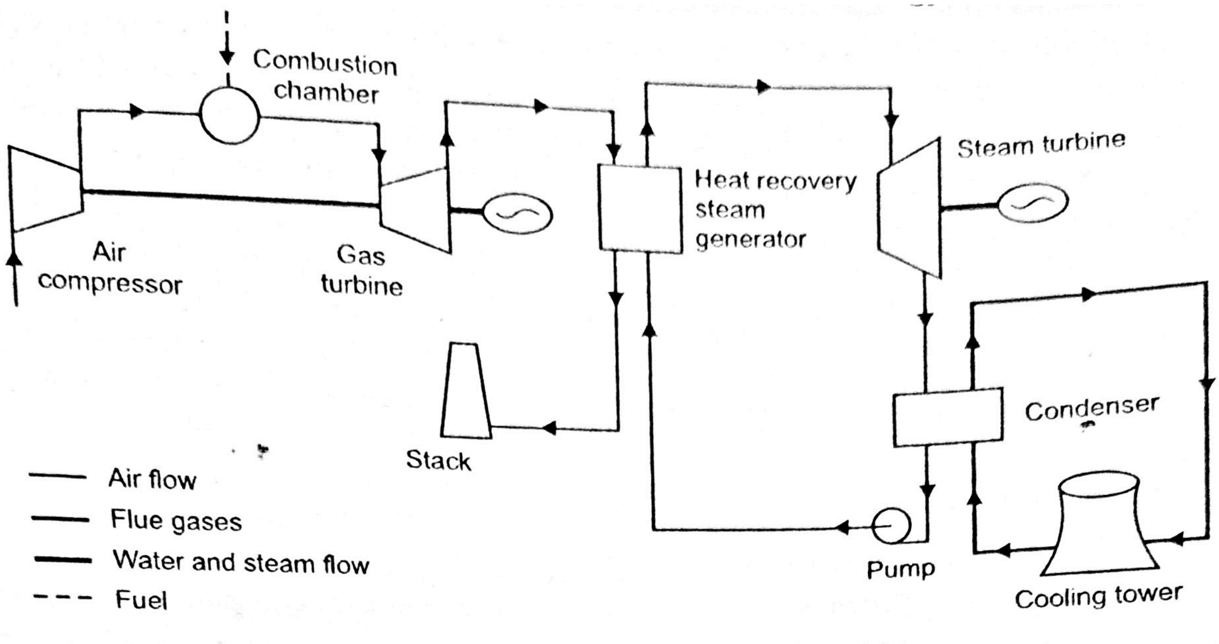


Fig. 1.23. Gas & steam turbine system

Heat Recovery Steam Generators: HRSG is a key component of a combined cycle power plant. Its role is to convert as much of the heat as possible from the exhaust gas of gas turbine into steam for a steam turbine. The temperature of the exhaust gases from the steam turbine will be between 400°C and 650°C, which is low compared to the gases exiting the boiler of a coal-fired power plant. The heat in this gas is captured by water and steam that flows through tubes placed in the path of the hot gases. These tubes will have fins welded to them to increase their surface area so that they can absorb more heat from hot gases. These tubes are arranged in modules, sometimes called racks, with each module serving a slightly different function.

From the perspective of water heating, the first module is called the *economizer*. This takes relatively low grade heat and uses it to heat the feed-water that is returning from the steam turbine to the boiler. This hot water is then fed into another module called the *evaporator* which heats the water to its boiling point. The temperature at which the water boils may be much higher than 100°C because the system is operated under pressure. At the top of the evaporator is a steam drum where water and steam are separated. The water cycles back through the evaporator while steam is collected and taken to the third module, called the *superheater*. This dries the steam and raises its temperature above the boiling point, before piping it to the steam turbine.

The three modules are arranged in the hot gas path so that the superheater is exposed to the hottest gas. This is followed by the evaporator while the economizer takes heat from the coolest exhaust gas, before it is released through the plant stack. Complexity can be added because many modern combined cycle plants use HRSGs with two or three of these economizer–evaporator and drum–superheater arrangements to provide steam at two or three pressures. In this case the multiple modules are arranged in order of decreasing steam and water temperature. In some designs there may also be one more module, called the *reheater*, which reheats steam from a high pressure steam turbine before it is fed to an intermediate pressure steam turbine as in the GE H system described earlier.

There are a number of alternative designs for HRSGs although they all share many common features. The variants include steam generators in which the exhaust gas path is vertical and the boiler tubes are arranged horizontally in the gas path and steam generators with a horizontal gas path and vertical steam tube modules. The way in which water and steam circulate within the boiler tubes varies too, with some using forced or pumped circulation and others using natural circulation. Natural circulation HRSGs usually have a horizontal exhaust gas path, while forced circulation boilers are often vertical.

The temperature of the turbine exhaust gases fall as they pass through the various stages of the HRSG. Emission control to remove nitrogen oxides requires the gases to be at a specific temperature for the process to be carried out efficiently. The point at which the exhaust gases reach this temperature often lies within the HRSG. This means that these emission control systems must be installed inside the boiler.

It is possible to add heat to the exhaust gases by installing gas burners within the steam generator, a technique known as supplementary firing. Supplementary firing can make the system more flexible by allowing more steam generation where needed or to supply additional heat if the gas turbines are operating at less than full load. Supplementary firing is less efficient thermally and is rarely used in very large combined cycle plants. However, it is common in stations that supply steam for process heat as well as electricity.

Advantages

Combined cycle power plants and cogeneration power plants that use the gas turbine engine as their primary driver have been popular for a number of years for a number of reasons.

Efficiencies of over 60% based on lower heating of the fuel have been achieved by these facilities. Other fossil fuel power plants, such as plants with conventional boilers, have efficiencies in the range 40–42% for supercritical technology, and 45–47% for ultrasupercritical technology based on lower heating value of the fuel.

Gaseous emissions from gas turbine–based power plants are very low. Oxidizing catalysts can be used to convert carbon monoxide to carbon dioxide, and NO_x reduction catalysts that utilize ammonia can be used to convert oxides of nitrogen to nitrogen and water vapour and reduce these two types of emissions to 2 ppm. Due to their high efficiency and the fact that they usually burn natural gas fuel, gas turbine–based power plants also emit far less carbon dioxide than other types of fossil fuel power plants. Capital cost is lower than other power plants.

(d) Solar power plants

Solar power plants derive their energy from sunlight, which is made accessible via photovoltaic (PVs). Photovoltaic panels, or solar panels, are constructed using photovoltaic cells which are made of silica materials that release electrons when they are warmed by the thermal energy of the sun. The new flow of electrons generates electricity within the cell. While PVs are an efficient method of producing electricity, they do burn out after a decade and thus, must be replaced, however, their efficiency, cost of operation,

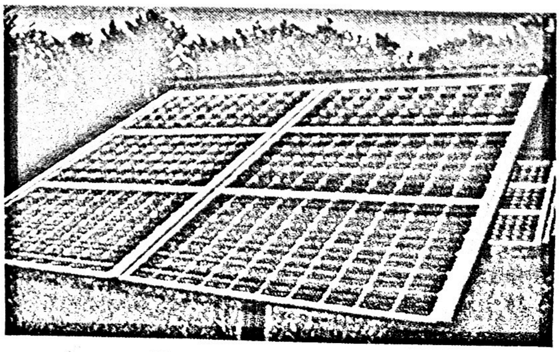


Fig. 1.24. Solar field

noiselessness and lack of physical pollutants make them one of the cleanest and least expensive forms of energy. Solar power plants require the work of many facets of engineering: electrical engineers are especially crucial in constructing the solar panels and connecting them into a grid, computer engineers code the cells themselves so that electricity can be produced effectively and efficiently, and civil engineers play the very important role of identifying areas where solar plants are able to collect the most energy.

(c) Wind Power Plants

Wind power plants, also known as wind turbines, derive their energy from the wind by connecting a generator to the fan blades and using the rotational motion caused by wind to power the generator. Then the generated power is fed back into the power grid. Wind power plants can be implemented on large, open tracts of land or on large bodies of water such as oceans; they simply rely on being in areas that experience significant amounts of wind. Technically, wind turbines are a form of solar power in that they rely on pressure differentials caused by uneven heating of the earth's atmosphere. Wind turbines solicit the knowledge from mechanical, electrical, and civil engineers. Knowledge of fluid dynamics from the help of mechanical engineers is crucial in determining the viability of locations for wind turbines. Electrical engineers ensure that power generation and transmission is possible. Civil engineers are important in the construction and utilization of wind turbines.

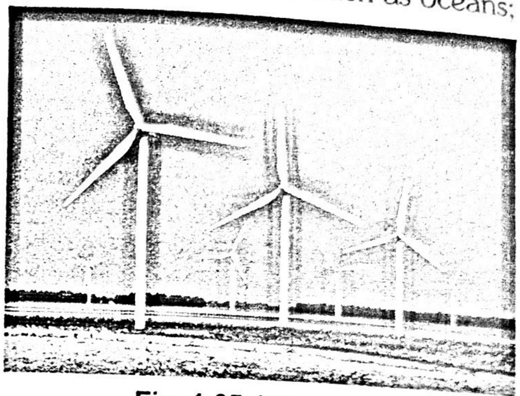


Fig. 1.25. Wind mills

1.11 SOLID STATE PHENOMEN A INCLUDING PHOTO, THERMAL AND ELECTRICAL ASPECTS

WIP

1.11.1 Solid State Phenomena Including Photon

- When the energy of a photon is equal to or greater than the band gap of the material, the photon is absorbed by the material and excites an electron into the conduction band.
- Both a minority and majority carrier are generated when a photon is absorbed.
- The generation of charge carriers by photons is the basis of the photovoltaic production of energy.

Photons incident on the surface of a semiconductor will be (i) either reflected from the top surface, will be (ii) absorbed in the material or, failing either of the above two processes, will be (iii) transmitted through the material. For photovoltaic devices, reflection and transmission are typically considered loss mechanisms as photons which are not absorbed do not generate power. If the photon is absorbed it has the possibility of exciting an electron from the valence band to the conduction band. A key factor in determining if a photon is absorbed or transmitted is the energy of the photon. Therefore, only if the photon has enough energy will the electron be excited into the conduction band from the valence band. Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap:

- $E_{ph} < E_G$ Photons with energy E_{ph} less than the band gap energy E_G interact only weakly with the semiconductor, passing through it as if it were transparent.
- $E_{ph} = E_G$ photons have just enough energy to create an electron hole pair and are efficiently absorbed.
- $E_{ph} > E_G$ Photons with energy much greater than the band gap are strongly absorbed. However, for photovoltaic applications, the photon energy greater than the band gap is wasted as electrons quickly thermalize back down to the conduction band edges.

The effect of the three classes of photons on the semiconductor is shown in the two animations below.

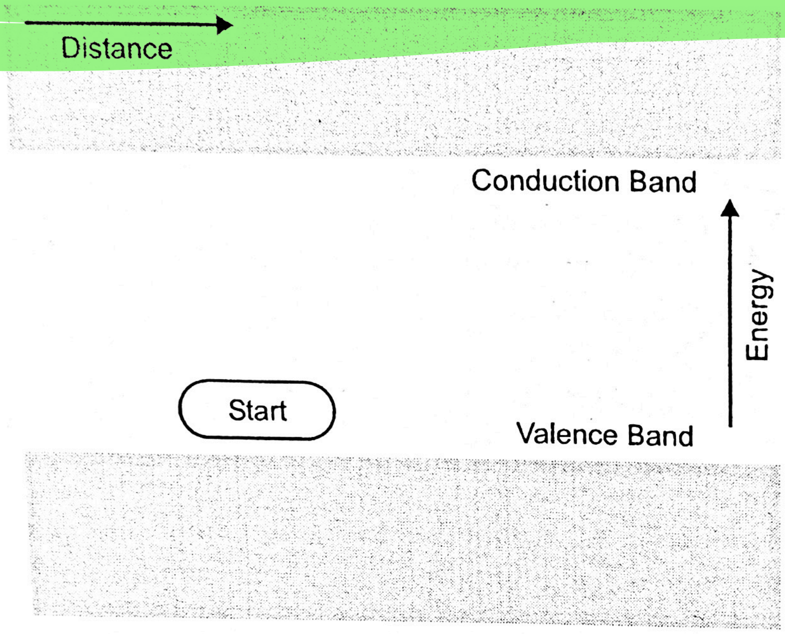


Fig.1.26. The creation of electron-hole pairs when illuminated with light $E_{ph} = hf$, where $E_{ph} > E_G$.

The absorption of photons creates both a majority carrier and a minority carrier. In many photovoltaic applications, the number of light-generated carriers are of the magnitude less than the number of majority carriers already present in the solar cell due to doping. Consequently, the number of majority carriers in an illuminated semiconductor does not alter significantly. However, the opposite is true for the number of minority carriers. The number of photo-generated minority carriers outweighs the number of minority carriers existing in the doped solar cell in the dark (because in doping the minority carrier concentration is so small), and therefore the number of minority carriers in an illuminated solar cell can be approximated by the number of light generated carriers.

1.11.2 Solid State Phenomena Including Thermal Aspects

At absolute zero temperature, all the valence electrons are revolving around the nucleus of the atom. Hence, there are no free electrons present in the conduction band to carry electric current from one place to another. Therefore, the semiconductor behaves as a perfect insulator at absolute zero temperature.

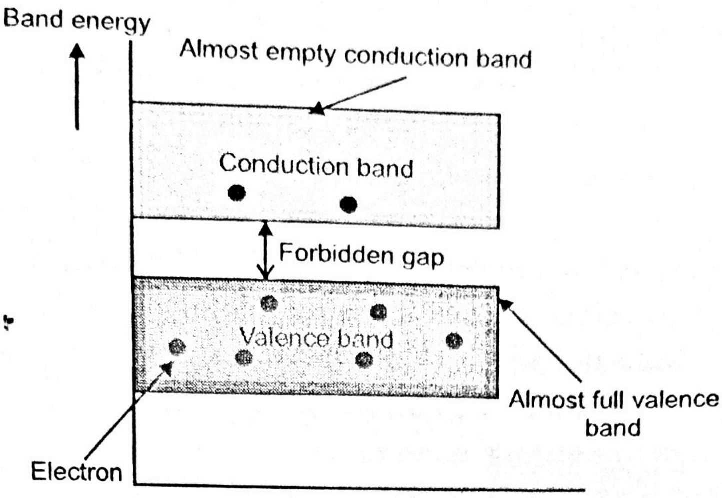


Fig. 1.27. Energy band diagram of semiconductor

When the temperature is increased above the absolute zero temperature, some of the valence band electrons or valence electrons gain enough energy in the form of heat to break the bonding with the parent atom and they jump into the conduction band. The electrons present in the conduction band are not attached to the parent atom. Hence, they move freely from one place to another place. These conduction band electrons are called free electrons.

When the electron leaves the valence band and jumps into the conduction band, a vacancy is created at the electron position in the valence band. This vacancy is called the hole. Thus, both the free electrons in the conduction band and holes in the valence band are generated at the same time. The free electrons carry the negative charge or electric current from one place to another place in the conduction band, whereas the holes (vacancies) carry the positive charge, (or electric current) from one place to another place in the valence band.

If the temperature or heat energy applied on the semiconductor is further increased then even more number of valence electrons gain enough energy to break the bonding with the parent atom and they jump into the conduction band. This results in the increase in number of free electrons in the conduction band. If a greater number of electrons leaves the valence band and jumps into the conduction band then a greater number of holes (vacancies) are created in the valence band at the electrons position. Thus, a small increase in heat generates a greater number of charge carriers (electrons and holes).

In case of conductors, increase in the temperature increases the vibration of atoms. These vibrating atoms oppose the flow of electrons. This results in reduction of current flow in the conductor. The reduction in flow of electrons or current means increase in the resistance. Thus, the electric current in the conductor decreases with increase in temperature.

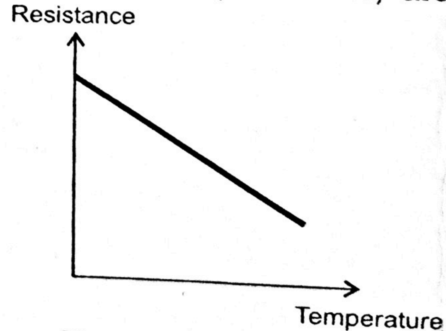


Fig. 1.28. R v/s T curve

Just like the conductors, the increase in temperature increases the vibrations of atoms in the semiconductor. However, the vibrating atoms in the semiconductor oppose only a few electrons and the remaining large number of electrons flow freely from one place to another place. This increases current flow in the semiconductor. The increase in current flow means decrease in resistance. Thus, the electric current in the semiconductor increases with the increase in temperature or heat (Semiconductor has negative temperature coefficient).

1.11.3 Solid State Phenomena Including Electrical Aspects

VVIP

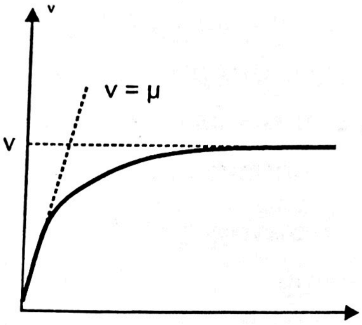


Fig. 1.29. Relationship between Drift velocity, mobility and electric field

A relation between drift velocity, mobility and electric field in the context of semiconductors is given by

$$\upsilon = \text{uxE}$$

where υ is drift velocity u is mobility and E is external applied electric field

Now, an increase in external field will first increase the velocity of current carriers (at first the mobility remains constant), which in turn will increase the current in the semiconductor. If we continue to increase the electric field then the mobility first decreases sub linearly and then decreases linearly. So now the velocity of the carrier increases slowly and then saturates because the increase in electric field is exactly compensated by the decrease in mobility. A large electric field across the semiconductor will have a tendency to knock out more and more electrons from the silicon atom which will hinder the current flow just like metals and hence the decrease in mobility. The point in electric field axis after which this decrease in mobility starts taking place is termed as critical electric field Ec. This result is also very intuitive as you can't simply go on increasing the velocity of the electrons due to higher limit that is imposed by the speed of light. Generally, speed of electrons is around 0.7c – 0.9c. The typical value of critical electric field is 1200 V/cm.