LECTURE NOTES

ON

THERMAL ENGG-I (TH4)

For

3RD SEM MECHANICAL ENGG

(SCTE&VT SYLLABUS)

Prepared by

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THERMAL ENGINNERING-1

CHAPTER 1:

CONCEPTS AND TERMINOLOGY

- **Thermodynamics**

  It is defined as the science of heat energy transfer and its effect on physical property of the substance.

  OR

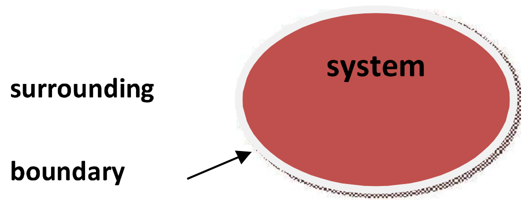
  It may be defined as the science which deals with the conversion of heat into mechanical work or energy by using a suitable medium.

- **Thermodynamic System**

  System: A system is defined as any quantity of matter or a region in space having certain volume upon which our attention is concerned in analysis of problem.

  Surrounding: Anything external to the system constitute as surrounding.

  Boundary: System is separated from the surrounding by system boundary. This boundary may be fixed or movable.



system are classified into three types :-

- Open system
- Closed system
- Isolated system

Open System

It is also known as *flow system.* Open system is one in which both mass and energy crosses the boundary. Open system is also called control volume. Ex- reciprocating air compressor, turbine, pump etc.

Closed System

It is also known as *non-flow system*. In this system the mass within the boundary remains constant only energy interaction takes place with respect to the surrounding. Ex – Cylinder piston arrangement, Tea kettle.

Isolated System

An isolated system is one in which there is no interaction between the system and surrounding. There is no mass and energy transfer across the system. Ex- Universe, thremoflask etc.

MACROSCOPIC AND MICROSCOPIC APPROACH

Study of thermodynamics is done by two different approaches.

- **Macroscopic approach**: The term macroscopic is used in regard to larger units which is visible to the naked eye. In macroscopic approach certain quantity of matter is considered without taking into consideration the events occurring at molecular level. In other words macroscopic approach is concerned with overall behaviour of matter. This type of study is also known as *classical thermodynamics*.
- **Microscopic approach**: In microscopic approach matter is considered to be composed of tiny particles called molecules and study of each particle having a certain position, velocity and energy at a given instant is considered such a study is also called as *Statistical thermodynamics.*

CONCEPT OF CONTINUUM

The system is regarded as a continuum i.e. the system is assumed to contain continuous distribution of matter. Thus, from the continuum point of view, the matter is seen as being distributed through space and treats the substance as being continuous disregarding the action of individual molecules. There are no voids and values of action of many molecules and atoms.

THERMODYNAMIC PROPERTY

- **PROPERTY-**A thermodynamic property refers to the characteristics by which the physical condition or state of a system can be described such as pressure, volume, temperature etc. & such characteristics are called properties of a system.
- **PRESSURE-**Pressure is defined as force per unit area.

Units of pressure are as follows In S.I Pascal (Pa) and 1 Pa= 1N/m^2

1 Bar= 10^5 N/m^2 = 100 KPa

1 ATM=760mm of Hg or 1.013 bar or 101.325KPa

- **TEMPERATURE-**The temperature is a thermal state of a body which determines the hotness or coldness of a body. The temperature of a body is proportional to the stored molecular energy i.e. the average molecular kinetic energy of the molecules in a system.
  Units of temperature are degree Celsius or Kelvin.

Intensive and Extensive Property:

- Intensive property: The properties which are independent of mass of the system are known as intensive properties. Its value remains the same whether one considers the whole system or only a part of it. The intensive property includes pressure, temperature, specific volume, specific energy, specific density etc.

- Extensive property: the property which depends upon mass of the system are known as extensive property. The extensive properties include volume, energy, enthalpy, entropy etc.

State: The condition of physical existence of a system at any instant of time is called state.

Thermodynamic Processes:

When any property of a system changes, there is a change in state and the system is then said to have undergo a thermodynamic process.

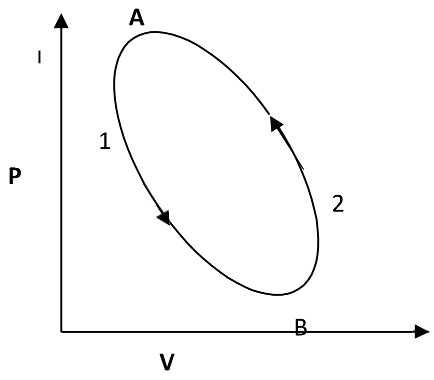
The commonly used processes are:

1. Isochoric Process – The process which takes place at constant volume is said to be isochoric process.
2. Isobaric Process – The process which takes place at constant pressure is said to undergo an isobaric process.
3. Isothermal Process- The process which takes place at constant temperature is said to undergo an isothermal process.
4. Adiabatic Process- The process where there is no heat transfer between the system and the surrounding. The reversible adiabatic process is known as isentropic process.

   The other processes are polytrophic process, throttling process, free expansion process and hyperbolic process.

Thermodynamic Cycle:

When a process is performed in such a way that the final state is identical with the initial state, it is then known as a thermodynamic cycle or cyclic process.



In the fig above:

and **A-2-B** represents *process*

Whereas **A-1-B-2-A** represent a *thermodynamic cycle*.

THERMODYNAMIC EQULIBRIUM:

A system is said to be in thermodynamic equilibrium when no change in any macroscopic property is registered, if the system is isolated from its surrounding.

Thermodynamics mainly studies the properties of physical system that are found in equilibrium state.

A system will be said to be in thermodynamic equilibrium if the following three conditions of equilibrium is satisfied.

a) Mechanical Equilibrium
b) Chemical Equilibrium
c) Thermal Equilibrium

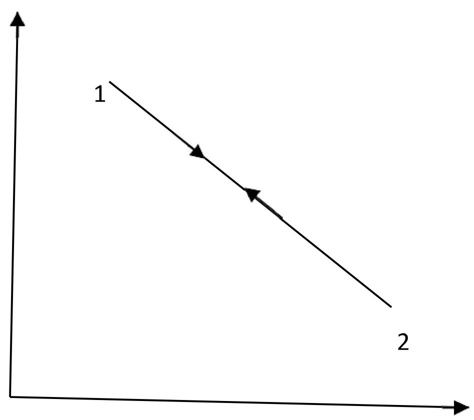
Mechanical Equilibrium- when there is no unbalanced force on any part of the system or in-between the system and surrounding then the system is said to be in mechanical equilibrium. For example if the pressure is not uniform throughout the system, then internal changes in the state of the system will take place until the mechanical equilibrium is reached.

Chemical Equilibrium- when there is no chemical reaction or transfer of matter from one part of the system to another such as diffusion or solution, then the system is said to exists in a state of chemical equilibrium.

Thermal Equilibrium- when there is no temperature difference between the parts of the system or between the system and the surrounding, it is then said to be in thermal equilibrium.

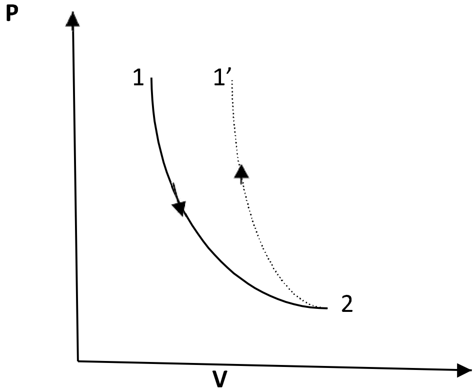
REVERSIBLE PROCESS:

A process which can be reversed in direction and the system retraces the same continuous series of equilibrium states it is said to be reversible process. A reversible process should be carried out with absolute slowness, so that the system will be always in equilibrium. In actual practise a reversible process cannot be attained, but it can be approximated as a closely as a possible. For example a gas confined in a cylinder with a well lubricated piston can be made to undergo a reversible process by pushing or pulling the piston in slow motion.



IRREEVERSIBLE PROCESS

A process in which the system passes through a sequences non-equilibrium state i.e. The property such as pressure, volume, temperature is not uniform throughout the system it is known as an irreversible process. This process will not retrace the reverse path to restore the original state. The heat transfer by convection, combustion of air and fuel etc are few examples of irreversible process.



QUASI-STATIC PROCESS

The word quasi means *almost.* This process is a succession of equilibrium states and infinite slowness is the characteristic feature of quasi-static process. A quasi-static process is also called as reversible process, the basic difference is that in a quasi static process not all the point but almost major points is in equilibrium condition.

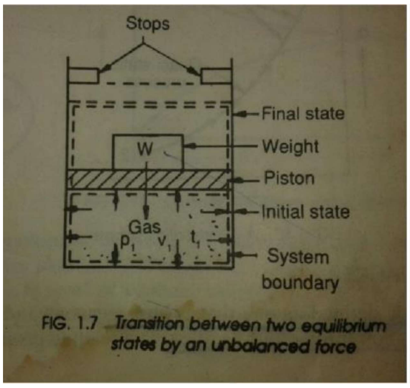


Fig 1

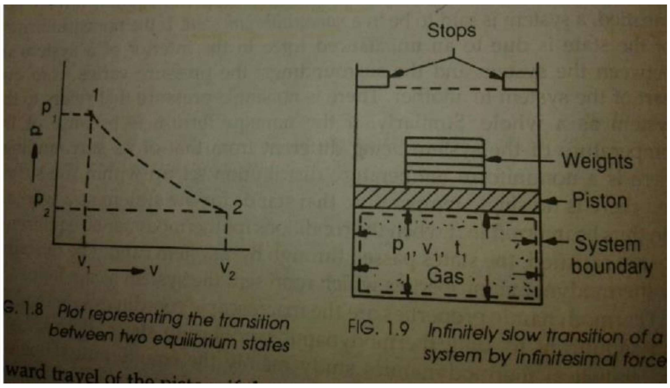


Fig 2

Let us consider a system of gas contained in a cylinder as shown in fig 1 . The system is initially an equilibrium state. The weight W on the piston just balances the upward force exerted by the gas. If the weight is removed there will be an unbalanced force between the system and the surrounding, and the piston will move upward till it hits the stops .the system will be again in a equilibrium state but if the same process as shown if fig 2 is done by slowing removing very small pieces of weight one by one then the piston will move upward slowly thus the system will be in equilibrium.

ENERGY AND WORK TRANSFER

A closed system interacts with the surrounding by energy transfer and this energy transfer takes place in two ways i.e. *Work transfer* and *Heat transfer.*

Heat and work are the main mode of energy transfer and there are certain similarities and differences between heat and work.

- The heat and work are boundary phenomena. They are observed at the boundary of the system.
- When a system undergoes a change in state, heat transfer or work done may occur.
- Heat and work are path function and depends upon the process. Hence they are not thermodynamic property and are inexact differential.
- Work is said to be *high grade energy* and heat low *grade energy*. The complete conversion of low grade energy into high grade energy is impossible.

Work Transfer

The action of a force on a moving body is identified as work. For the work transfer the system has to be such selected that its boundary just move. There cannot be work transfer in a closed system, without moving the system boundaries. In a cylinder piston arrangement the top of the system is moving system boundary and the work is transferred by the movement of the piston.

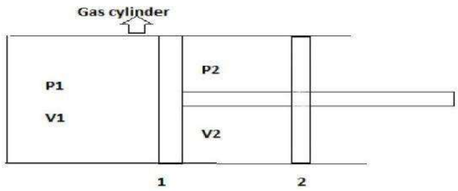
Work done by the system is considered to be *positive* and work done on the system is taken as *negative.*

Work done= force X displacement

Unit of work: Newton-meter (N-m) or Joule(J)

The rate at which work is done upon or by the system is known as *power.* The unit of power is J/s or watt.

PdV work or Displacement Work



Let us consider a gas in the cylinder as shown in the fig above. Let the system initially be at pressure P1 and volume V1. The system is in thermodynamic equilibrium , the piston is the system boundary which moves due to gas pressure. Let the piston move out to a new final position 2 which is also in thermodynamic equilibrium specified by pressure P2 and volume V2. When the piston moves an infinitesimal distance ***dl*** if ***a*** be the area of the piston.

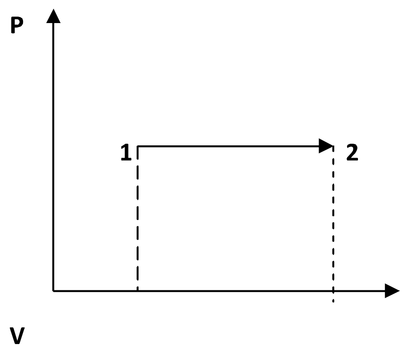
The force F acting on the piston will be
F= p X a
The amount of work done by the gas on the piston will be
dW = F. dl = p X a X dl = pdV
where dV= a X dl
when the piston moves out from position 1 to position 2 then the amount of work done b the system will be
$W_{1-2}= \int_{v1}^{v2} pdv$
The above equation represents the displacement work.

Displacement work applied to different thermodynamic process

1. **Isobaric process**

$W_{1-2}= \int_{v1}^{v2} pdv$

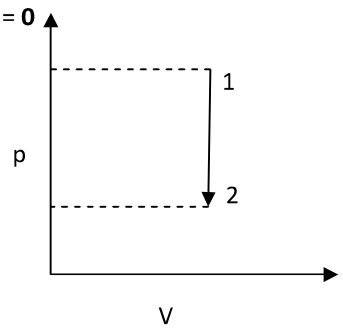
$= p(v_2 - v_1)$



2. **Isochoric process**

$W_{1-2}= \int_{v1}^{v2} pdv$

= **0**



3. Isothermal process

In this process pv= constant

$pV = P_1V_1 = C$

$P= P_1V_1/ V$

$W_{1\text{-}2}= \int^{v2}_{v1} pdv$

$W_{1\text{-}2}= p_1V_1\int^{v2}_{v1} dV/V$

$= p_1V_1 \ln p_1/p_2$

4. Polytrophic process

The process in which expansion and contraction takes lace according to the law $pV^n=C$

$pV^n = p_1v_1^n = p_2V_2^n = C$

$W_{1\text{-}2}= \int^{v2}_{v1} pdv$

$= \int^{v2}_{v1}(p_1V_1^n/ V^n). dV$

$= p_1V_1^n[V^{-n+1}/ -n+1]_{v1}^{v2}$

$= [p_2V_2^n *V_2^{1-n} – p_1V_1^n *V_1^{1-n}]/ (1-n)$

$= (p_1V_1 – p_2V_2) / (n-1)$

HEAT TRANSFER

Heat is defined as the form of energy that is transferred across a boundary by virtue of temperature difference between the system and the surroundings.

It the heat flows into the system or the system receives heat then heat transfer Q is taken as *positive* and if heat is rejected from the system then Q is taken as *negative.*

The heat transfer takes place by three different modes

1. Conduction: the transfer of heat between two bodies in direct contact is called conduction. It is a process of heat transfer from one particle of a body to another in the direction of fall of temperature. For example heat transfer through solids is by conduction.
2. Convection : The process of heat transfer from one particle to another by convection currents i.e. transfer of heat between the wall and fluid system in motion. In this case, the particles of the body move relative to each other.
3. Radiation : Heat transfer between two bodies separated by empty space or gases through electromagnetic waves is radiation.

Sensible heat: The heat required for change from liquid state to vapourisation/boiling point is called sensible heat. It is the amount of heat absorbed by one kg of water, when heated at a constant pressure, from the freezing point (0^0C) to the temperature of formation of steam.

Latent heat: It is the amount of heat absorbed to evaporate one kg of water at its boiling point without change of temperature.

Specific Heat : The amount of heat required to raise the temperature of unit mass of a substance through one degree is known as specific heat.

The unit of specific heat is KJ/kg K

Mathematically heat required to raise the temperature of a body is

$Q = m\,C(T_2-T_1)$ in kJ

Where, m= mass of the substance in kg

C= specific heat in KJ/Kg K
T_1= initial temperature in degree Celsius or Kelvin
T_2= final temperature in degree Celsius or Kelvin

Specific heat at constant volume (Cv) : It is defined as amount of heat required to raise the temperature of a unit mass of a gas by one degree at constant volume.

Specific heat at constant pressure (Cp) : It is defined as amount of heat required to raise the temperature of a unit mass of a gas by one degree at constant pressure

ENERGY:

The energy is defined as the capacity to do work. In broad sense energy is classified as *stored energy* and *transient energy.*

The energy that remains within the system boundary is called ***stored energy*** e.g. potential energy, kinetic energy and internal energy.

The energy which crosses the system boundary is known as energy in transition e.g. heat, work, electricity etc.

DIFFERENT FORM OF STORED ENERGY

1. POTENTIAL ENERGY-The energy posed by a body by a virtue of its position or state of rest is known as potential energy
   P.E=W X h=mgh
   W=weight of the body in N
   M=mass of the body in kg
   g=acceleration due to gravity
   h=height in meter

CHAPTER - 1

1. Define and classify system ?

Ans : <u>System</u> :- It is defined as a definite area where some thermodynamic process are takes place.

Type of System :-

(i) Closed System

(ii) Open System

(iii) Isolated System

<u>Closed System :</u> :- It is the system in which their is only energy energy transfer and no mass is transfer across the system boundry.

Example : Gas contained inside a cylinder.

<u>Open System</u> :- It is the system both mass as well as energy is transfered is known as open system.

Example : *Flow of liquid inside a pipeline.*

<u>Isolated system</u> :- It is the system neither energy nor mass is transfered across the system boundry.

2. Difference between intensive property and extensive property?

Intensive Property :- Property is defined as a state of a system. It is of 2 types.

1) External
2) Internal

It is property which is independent of the mass of the system. ***Example :-*** Pressure, Temp., Specific heat.

Extensive Property :-

It is the property which depend on the mass of the system or the value for the entire system is equal to the sum of the value for the individual system.

Example :- Total mass, total volume.

3. Define Mechanical equivalent of heat state it volume.

Mechanical equivalent of heat is defined as joule which the ratio of work done to the heat supplied J=W/Q,

4. Define thermodynamic process ? When a system changes its state from one equilibrium state to a anotherequlibrium state it is known as thermodynamic system of process.

5. Define point function and path function?

Path function :- It is depend on path of the system Example : - Heat, work

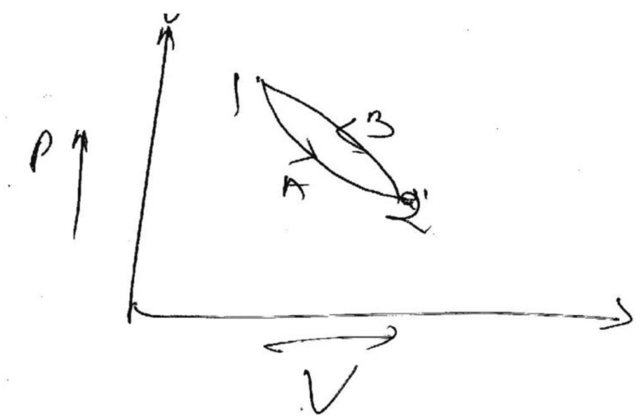
Point function :- It doesn't depend on path of the system. Example :- Energy, Internal energy, P_1V_1T.

6.Define heat and work and state their unit

Ans : The heat is defined as the energy transfermed without transfer of mass, across the boundry of a system because of a temperature difference between the system and the surroundings. It is usually represented by Q and is expressed in joule (J) or Kilo-Joule (KJ)

<u>Thermodynamic Cycle</u>

When the Initial state X final state in identical then it is called cycle or thermodynamic cycle.



1 - A - 2 --- Process

2 - B - 1 --- Process

1 - A - 2 - B - 1 --- cycle.

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CHAPTER-2

THERMAL ENGINEERING

FIRST LAW OF THERMODYNAMIC

Introduction

Heat and work are different forms of the same entity called energy. Energy is always conserved. Energy may enter a system as heat and leave as work and vice-versa.

Energy has two forms-transit energy and stored energy.

The internal energy is the stored energy. Whenever heat and work enters a system, stored energy increases and when heat & work leaves the system stored energy decreases.

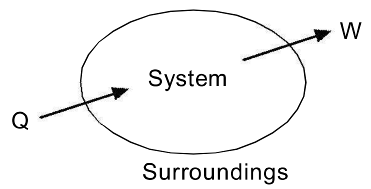
3.1 First law of thermodynamics

Whenever heat is absorbed by a system it goes to increases its internal energy plus to do some external work (Pdv work) i.e.

$$Q = \Delta E + W$$

Where Q is the energy entering a system, ΔE increase in internal energy, W – producing some external work.

$$\delta Q = dE + Pdv$$

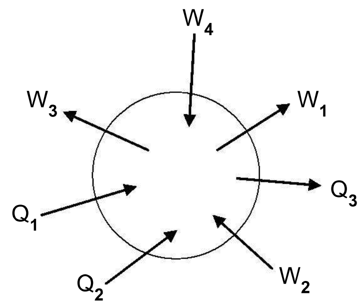


Sometimes more than two energy transfers, so it becomes.

$$Q_1 + Q_2 - Q_3 = \Delta E + W_1 - W_2 + W_3 - W_4$$

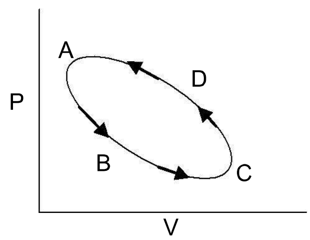
Sign convention

It will be '+Q' if heat goes into the system and '-Q' if heat goes out of the system +W when it is done by the system and –w is done on the system.



Cyclic process

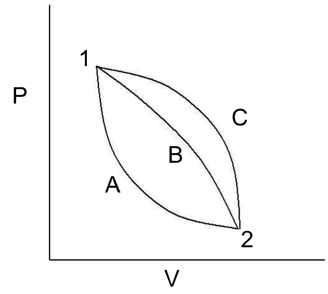
For a cyclic process, the work done is the area enclosed by the PV curve.



Clock wise = + W
anticlockwise = - W

3.2 Energy as a system property

Let a system changes from state 1 to state 2 via path A path B and Path C, which as follows



Applying first law of thermodynamics to path A.

$Q_A = \Delta E_A + W_A$

For path B $Q_B = \Delta E_B + W_B$

If process A & B form a complete cycle

$\Sigma Q = \Sigma W$

$(Q_A + Q_B) = \Delta E_A + E_B + (W_A + W_B)$

$\Sigma Q = \Delta E_A + E_B + \Sigma W$

$\Rightarrow \Delta E_A = -\Delta E_B$

Similarly $\Delta E_A = -\Delta E_B$

$\Rightarrow \Delta E_B = \Delta E_C$

So it is independent of path hence a property extensive or in nature.

Different forms of stored energy

Energy can be store in a system by two modes.

(i) Macroscopic mode

(ii) Microscopic mode

(i) Macroscopic mode

In this mode, the mode of stored energy stored in two forms,

$E_{KE} = \left(\frac{1}{2}\right)MV^2$

$E_{PE} = mgz$

(ii) Microscopic mode

This mode of stored energy refers to energy stored in molecular and atomic structure. Hence it is called molecular internal energy on simply internal energy. Then including

1. Translational KE
2. Rotational KE
3. Vibration energy
4. Electronic energy
5. Chemical energy
6. Nuclear energy

$L = L_{translation} + L_{rotational} + L_{vibrtion} + L_{electronic} + L_{chemical} + L_{nuclear}$

Total energy

$E = E_{KE} + E_{PE} + U$

In absence of motion, gravity $E_{KE}, E_{PE} = 0$

$$So\ E = U$$

$$Q = \Delta U + \int P dv$$

3.3 First law for a closed system undergoing a cyclic process.

3.5 Enthalpy concept

Enthalpy is a state property of a system. It is denoted by

H = U + Pv

It is a point function and an intensive property.

Specific enthalpy is given by

$$h = u + \frac{1}{m} PV = u + Pv$$

3.6 First law for a steady flow process

Steady flow process

A flow process is the one in which a fluid enters the system and then leaves if after a work interaction.

The mass flow rate and energy flow rate across the system boundary are constant.

Important terms

Flow work – whenever a certain amount of mass enters a system, an amount of work is required to push the mass into the system and out of it to maintain the continuity of flow.

i.e. Flow work = PV

Control Volume

For computation of mass and energy notes during a flow process, it is convenient to focus attention upon a certain fixed region in space called control volume.

Control surface

The boundary line defining the control volume is called control surface.

Stored energy of a system in a flow process

During a steady state flow, there is neither any accumulation of mass nor energy.

$$(\text{Mass flow rate})_{in} = (\text{Mass flow rate})_{out}$$

$$\sum \text{Energy}_{in} = \text{Energy}_{out}$$

Now, the total energy of a fluid at any section of the control volume.

$$E = U + \frac{1}{2}(MV^2) + mgz$$

$$e = u + \frac{1}{2}V^2 + gz$$

STEADY FLOW ENERGY EQUATION

As all energy is conserved

$$\Sigma \text{Energy}_{in} + \text{Heat flux} = \Sigma \text{Energy}_{in} + \text{Work}_{output}$$

i.e.

$$U_1 + \frac{1}{2}mV_1^2 + mgz_1 + P_1V_1 + Q$$

$$= U_2 + \frac{1}{2}mV_2^2 + mgz_2 + P_2V_2 + W$$

$$\left[h_1 + \frac{1}{2}mV_1^2 + mgz_1 + Q\right] + \left[h_2 + \frac{1}{2}mV_2^2 + mgz_2 + W\right]$$

On the basis of per unit mass flow rate

$$h_1 + \frac{V_1^2}{2} + gz_1 + Q/m$$

$$h_2 + \frac{V_2^2}{2} + gz_2 + W/m$$

$$\boxed{\text{or } h_1 + \frac{V_1^2}{2} + gz_1 + Q = h_2 + \frac{V_2^2}{2} + gz_2 + W}$$

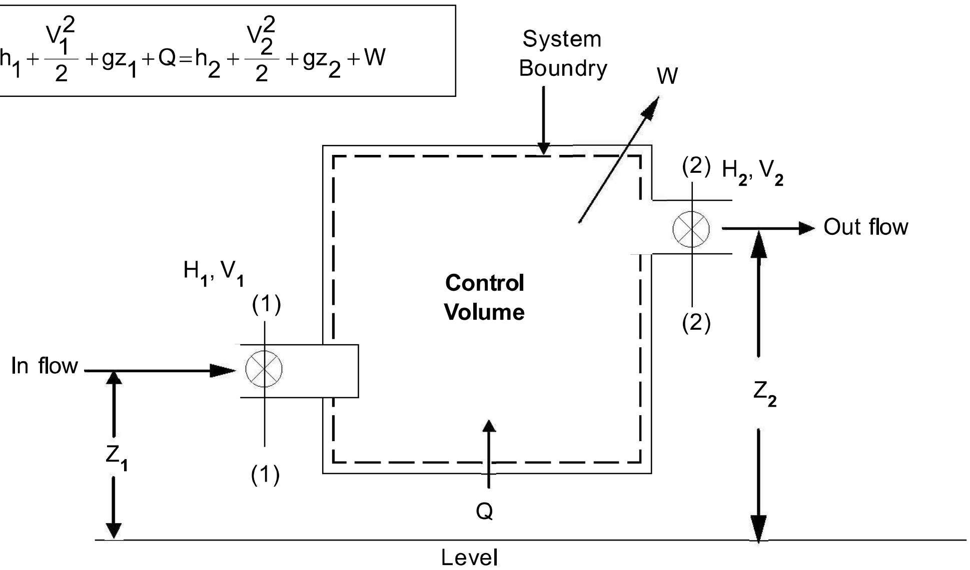


Fig- Steady flow

NOZZLE

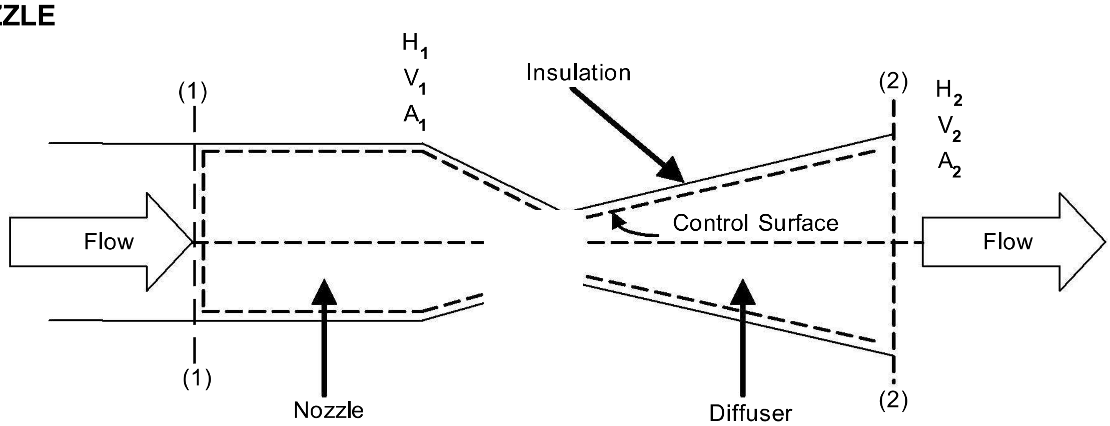


Fig- A Steady flow process through a nozzle.

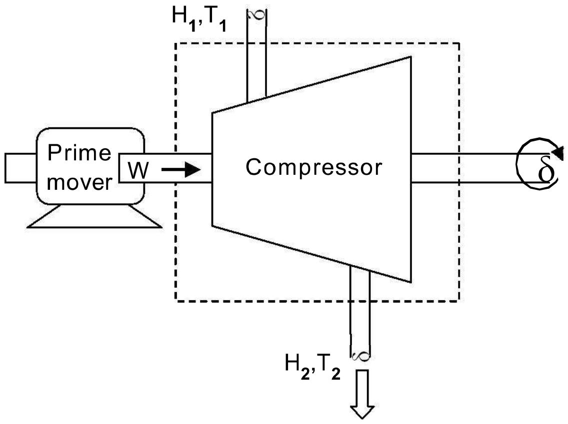
A nozzle is a device used to throttle a fluid whereupon its pressure energy is converted into kinetic energy. The enthalpy of fluid decreases as the velocity of the fluid increases because of a higher fluid velocity at the nozzle outlet, a nozzle is harnessed to gain a high thrust in rockets and jet engines and drive impulse type steam and gas turbines.

Compressor

A compressor compresses air or a gas by harnessing external work fed from a prime mover. The increase in the gas pressure is accompanied by the temperature rise. If the compressor is perfectly insulated and the compression is adiabatic then it requires the minor work input to increase the gas pressure. All the generated heat of compression is expanded to compresses the gas as no heat is allowed to escape.

So Q = 0

Mass flow route of the gas = M and $V_1 = V_2$



Z1 = Z2,

By applying SFEE

$h_1 = h_2 + (-W_C)$

(-) sign before Wc refers to the work done on the gas (system)

$W_C = M(h_2 - h_1)$

$= MC_P (T_2 - T_1)$

Example

An air compressor compresses air from 0.1MP$_a$ / 300K to 1 MP$_a$. The compressor casing is well insulated, yet there is a heat loss to the surrounding to the extent of 5% of the compressor work.

Determine air temp at outlet and power input given

V_1 = 40m/s, V_2 = 100m/s, A_1 = 100cm^2, A_2 = 20cm^2, $C_P = 10^3 J\ Kg^{-1}\ K^{-1}$

Solution

$P_2V_2 = RT_2$ or $T_2 = P_2\ {}^{V_2}/_{R}$, V_2 - Specific volume.

We have $m_1 = m_2$

$$\frac{a_1V_1}{v_1} = \frac{a_2V_2}{v_2}$$

$$P_1v_1 = RT_1$$

$$v_1 = \frac{RT_1}{P_1} = \frac{287 \times 300}{0.1 \times 10^6}$$

$$= 0.861 m^3\ kg^{-1}$$

$$\text{and } v_2 = \frac{a_2v_2}{a_1v_1} \times V_1 = \left(\frac{20}{100}\right)\left(\frac{100}{40}\right) \times 0.861$$

$$= 0.4305 m^3\ kg^{-1}$$

$$T_2 = P_2v_2 / R$$

$$= \frac{1 \times 10^6 \times 0.4305}{287} = 1500K$$

$Z_1 = Z_2$

$Q = 5\% \, W_C$

$-Q$ as rejected

$-W \cap$ W.D on the system

$H_1 + \frac{1}{2} MV_1^2 + (-Q)$

$= H_2 + \frac{1}{2} MV_2^2 + (W_C)$

$-0.5 W_C + W_C$

$= M(h_2 - h_1) + m\left(V_2^2 - V_1^2\right)$

$0.95 W_C = 0.4646 \, x \, C_P \left[(T_2 - T_1) + \frac{1}{2}(V_2^2 - V_1^2) \right]$

$m = \frac{A_1 V_1}{V_1}$

$= \left(100 \, x \, 10^4 m^2\right) x \frac{40 m^5 - 1}{0.861} = 0.46457 kg5^{-1}$

W_C

$= 0.4646 \, x \left[10^3 (1500 - 300) + \frac{1}{2}\left(100^2 - 40^2\right) \right]$

$= 59889 / 7 w$

$= 588.9 kw$ (Ans)

Nozzle

There is no work output : W = O

No heat influx or escape Q = 0

For a horizontal disposition

$Z_1 = Z_2$

And so the SFEE applied to the nozzle boils down to

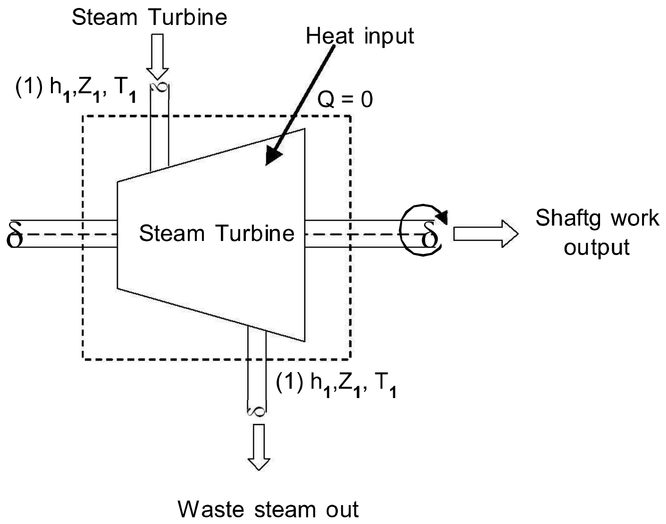
$h1 + \frac{1}{2}(V_1)^2 = h2 + \frac{1}{2}(V_2)^2$

If $V_2 >> V_1$, then

$V_2 = \sqrt{2(h_1 - h_2)}$

$= \sqrt{2 C_P (T_1 - T_2)}$

Turbine



A steam turbine receives a superheated, high pressure steam that experiences its. Enthalpy drop as the steam passes over the turbine blades. This enthalpy drop is converted into the kinetic energy of rotation of the blades mounted on the turbine drum. The turbine is well insulated which gives rise to the maximum work output. The turbine is well insulated.

Q = 0

Steam velocity at the turbine input = the steam velocity at the output

i.e. $V_1 = V_2$

The turbine is positioned horizontally

$Z_1 = Z_2$

Applying SFEE to the control volume

$H_1 = h_2+W$

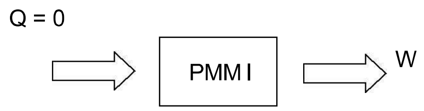
$W = h_1-h_2$

$= C_P (T_1-T_2)$

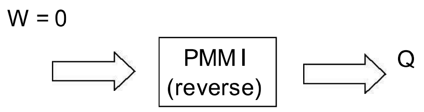
$W = MC_P (T_1-T_2)$

3.7 perpetual motion machine

PMMI refers to the perpetual motion machine of the first kind. It is a hypothetical machine that will continuously churn out work but without absorbing heat from its surroundings.



But such a machine is not feasible from a practical point of view, for it violates law of conservation of energy (first law of thermodynamics).



The reverse of perpetual machine is also not true. It s a hypothetical machine which is not feasible as if violates the first law of thermodynamics.

SECOND LAW OF THERMODYNAMICS

4.1 Limitation of first law

There are two basic limitations of the first law of thermodynamics

(1) First law does not differentiate between heat and work.

It assumes complete inter-convertibility of the two. Though work being a high grade energy can be fully converted into heat but heat cannot be completely converted to work.

(2) It does not permit us to know the direction of energy transfer. We cannot ascertain whether heat will flow from a higher temperature body to a lower temperature body vice versa.

4.2 Thermal Reservoir

A thermal reservoir is a heat source or heat sink that remains at a constant temperature, regardless of energy interaction.

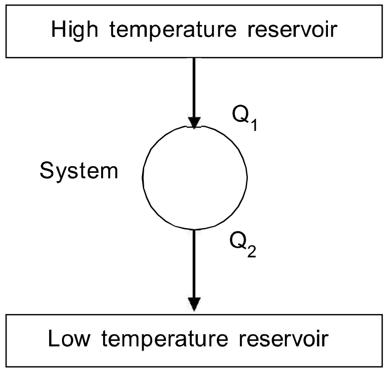
Otherwise a thermal energy reservoir (TER) is a large system body of infinite heat capacity which is capable of absorbing or rejecting a finite amount of heat without any changes in its thermodynamic co-ordinates.

The high temperature reservoir (T_H) that supplies heat is a source.

Sink – Low temperature reservoir to which heat is rejected.

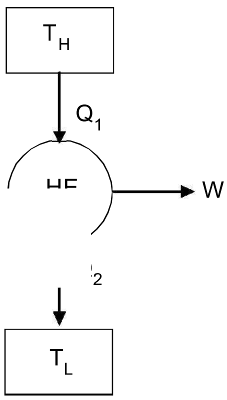
Example

Ocean water and atmospheric air are two good examples.



4.3 Concept of heat engine

A heat engine is a device that can operate continuously to produce work receiving heat from a high temperature T_H and rejecting non-converted heat to a low temperature sink.



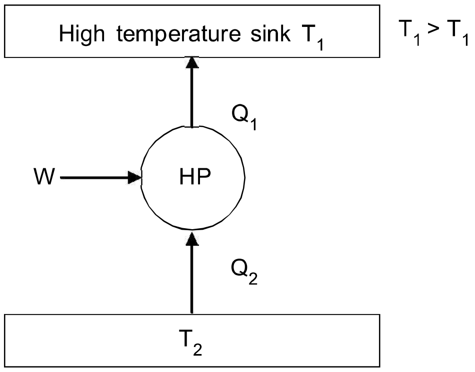
$$\text{Effect} = \frac{\text{out put}}{\text{input}} = \frac{W}{Q_1}$$

But, $W = Q_1 - Q_2$ in a cycle

So $\eta_{thermal} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$

Heat Pump

A heat pump is a reversed heat engine. It receives heat from a low temperature reservoir (source) and rejects it to high temperature reservoir (since) for which an external work which is supplied to the pump.



The efficiency of a heat pump cycle is usually called the coefficient of performance. It is the desired effect upon the external work supplied for obtaining that desired effect.

$$COP = \frac{\text{Desired effect}}{\text{Work input}}$$

$$COP_{HP} -= \frac{Q_1}{W}$$

$$\text{Again } \sum_{cycle} Q = \sum_{cycle} W$$

$$\therefore Q_1 - Q_2 = W$$

$$COP_{HP} = \frac{Q_1}{Q_1 - Q_2}$$

Refrigerator

A refrigerator is similar to a heat pump. It operates as a reversed heat engine. Its duty is to extract heat as much as possible from the cold body and deliver the same to high temperature body.

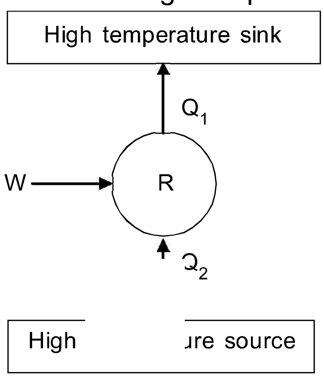
The desired effect of a refrigerator is to remove Q_2 heat infiltrating into the cold space. By using the external work it rejects Q_1 heat to the high temperature reservoir. Therefore,

$$COP_{ref} = \frac{Q_2}{W}$$

$$\text{Again } \sum_{cycle} Q = \sum_{cycle} W$$

$$\therefore Q_1 - Q_2 = W$$

$$COP_{ref} = \frac{Q_2}{Q_1 - Q_2}$$



4.4 Statement of second law of the thermodynamics

Clausius statement

It is impossible to construct a device that will produce no effect other than the transfer of heat from a low temperature body to a high temperature body while operating in a cycle.

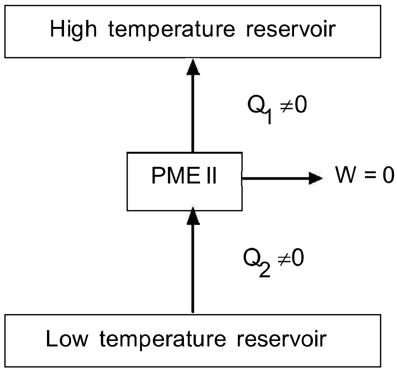
Kelvin Planck statement

No heat engine, operating in cycle, can convert entire heat into work. It is impossible to build a heat engine that can register 100% efficiency.

Note – T_C K-P statement is of relevance to a heat engine. The C-statement relates more directly to a reversed heat engine.

Perpetual motion machine II

It is a hypothetical machine that will continuously pump out heat from a low temperature reservoir (T_2) and delivers the same to a high temperature reservoir at (T_1) without taking up any input work from surroundings.



4.5 Carnot cycle

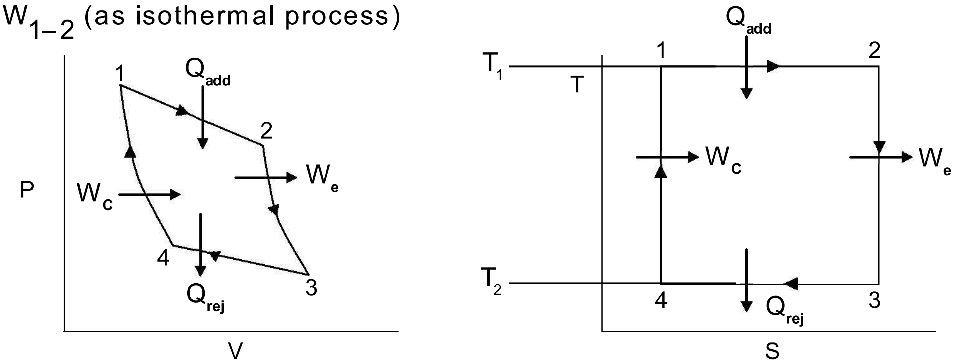
The cannot cycle is a hypothetical cycle developed Nicholas Sadi Carnot (1796-7832) a French military engineer. It is meant for a heat engine or a reversed heat engine. All the process involved in this cycle are reversible, thereby ensuring the best possible device that once could construct. This cycle comprises 4 reversible processes.

Process 1-2 reversible isothermal heat addition

Heat (Q_{add}) flows from a high temperature reservoir to the working fluid which is at a constant temperature but only infinitesimally below that of the source.

$$Q_{add} = \Delta U + W_{1-2}, \ \Delta U = 0$$

$$Q_{add} = W_{1-2} \text{ (as isothermal process)}$$



(a) PV diagram (b) TS diagram

Process 2-3 (adiabatic expansion)

The working fluid expands through a turbine or expander adiabatically producing a net positive work output.

here $Q = 0$

$$\therefore O = \Delta U_{2-3} + W_{2-3}$$

Process 3-4 (Isothermal heat rejected)

Heat (Qrej) is rejected by the fluid to the sink-both one at a constant temperature, but differ only by an infinitesimal amount.

$\Delta U = 0$, isothermal proces

$\therefore - Q_{rej} = - W_{3-4}$

– Q implies heat has been rejected by the system.

– W implies work has been done on the system.

Process 4-1 (Reversible adiabatic compression)

The temperature of the working fluid is raised back to the temperature level of high temperature through adiabatic compression, i.e. Q = 0

$O = \Delta U_{4-1} + - W_{4-1}$

$\therefore \Delta U_{4-1} = W_{4-1}$

As the two isothermal and two adiabatic complete the cycle.

So $\sum_{cycle} Q_{net} = \sum_{cycle} W_{net}$

Or, $Q_{add} + (-Q_{rej}) = W_{1-2} + W_{2-3} - (W_{3-4} + W_{4-1})$

$Q_{add} - Q_{rej} = W_e - W_c$

So, the efficiency

$$\eta = \frac{\text{Net work output}}{\text{Net heat input}} = \frac{W_e - W_c}{Q_{add}}$$

$$= \frac{Q_{add} - Q_{rej}}{Q_{add}} = 1 - \frac{Q_{rej}}{Q_{add}}$$

<u>Aliter</u>

Refer to the TS diagram

Ne work done, W_{net} = area 1-2-3-4

$= \text{Side } 1-4 \text{ x Side } 1-2$

$= T_1 - T_2 \text{ x } S_2 - S_1$

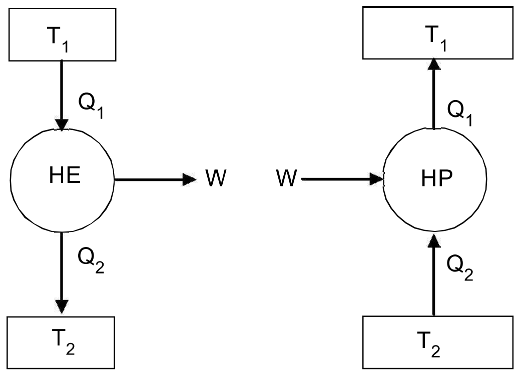
$Q_{add} = T_1 (S_2 - S_1)$

So efficiency, $\eta = \frac{W_{net}}{Q_{add}} = \frac{(T_1 - T_2)\Delta S}{T_1 \Delta S} = 1 - \frac{T_2}{T_1}$

Clausius statement

According to second law without work input heat cannot flow from low temperature to high temperature.

Case of heat engine



Kelvin plank statement

No heat engine operating in a cycle can convert entire heat into work.

in the above engine.

$Q_1 = Q_2 + W$

that means, Q_2 is rejected along with W output

$\Rightarrow Q_1 \neq W$

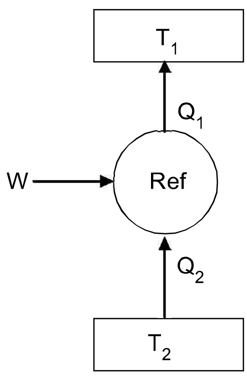
In a heat pump

$W + Q_2 = Q_1$

$W = 0, Q_2 = Q_1$

which is impossible, $\Rightarrow W \neq 0$

In a refrigerator



as like heat pump.

$$(COP)_{HP} = \frac{D.E}{Work_{input}} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

as $\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$ (according to carnot's theory)

$$(COP)_{ref} = \frac{D.E}{Work_{ref}} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

$$1 + COP_{ref} = 1 + \frac{T_2}{T_1 - T_2} = \frac{T_1 - T_2 + T_2}{T_1 - T_2}$$

$$\boxed{1 + (COP)_{ref} = COP_{HP}}$$

If installed backward, your household air conditioner will function as a heat pump cooling the surrounding but heating the room.

Possible Question & Answer

1.Define entropy ?

Ans : ENTROPY :-

It is thermodynamics property, which increases with the addition of heat & decreases with the removal of heat. It is denoted by = "S"

$$S=dQ/T$$

2 State Zeroth Law of thermodynamics ?

Ans : STATEMENT :-

When two bodies are thermal equilibrium with the 3rd body than the two bodies are thermal equilibrium with each other.

If A & B are thermal equilibrium to the body C, than A & B are thermal equilibrium with each others.

4. Define Kelvin Plank Statement.

Ans : KELVIN PLANK STATEMENT :

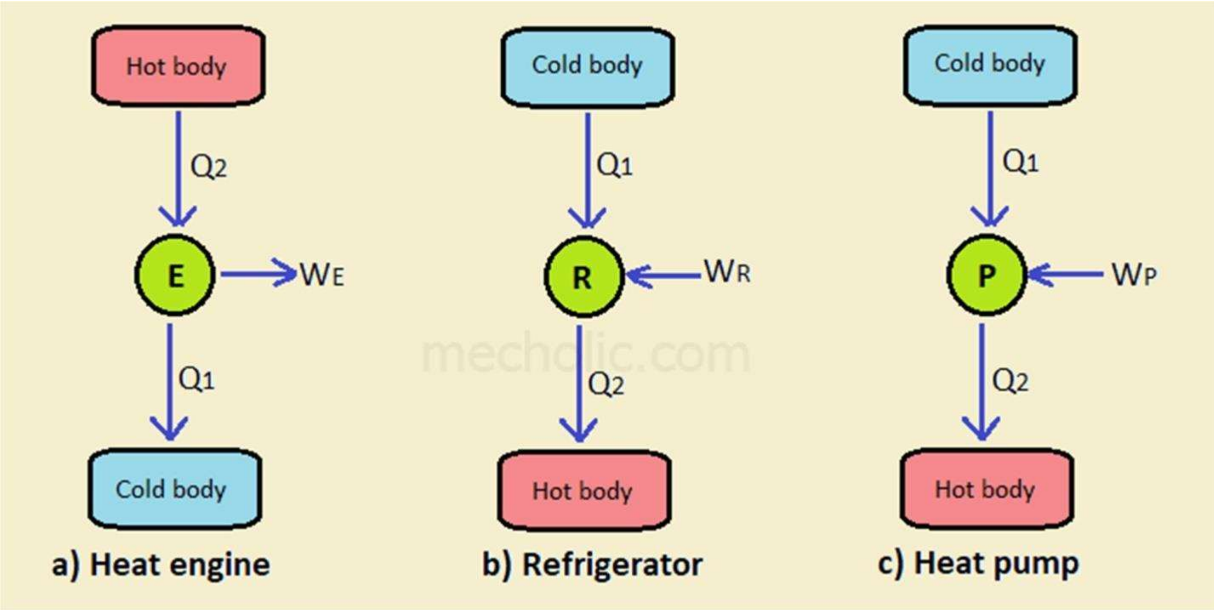
It state that is impossible for a self acting machine which working in a cyclic process, whose sole purpose is to convert energy from a single thermal reserve.

5. Define Clausious Statement.

CLAUSIOUS STATEMENT :

It state that it is impossible for a self acting machine working in a cyclic process sole purpose is to convert / transform heat from a body at a lower temperature to higher temperature.

6. Define heat engine, refrigerator, heat pump ?



Heat engine

Fig a shows a schematic diagram of the heat engine. The C.O.P. of an engine is express as its efficiency.

Heat engine took Q2 amount of heat from the hot body and did work equivalent to W . The heat supplied to
sink is equal to Q1. Here the useful effect is Work done, W ., it is equal to Q2 – Q1
The C.O.P of heat engine, engine efficiency η= Work done/ Heat applied

η = W /Q2,

$$\eta = \frac{Q2 - Q1}{Q2}$$

Refrigerator

Fig b shows a diagram of refrigeration. Q1 amount of heat is extracted from the cold body and deliver Q2
amount of heat to the hot body with the help of input work W . Here Q2 = Q1 + W
.

In refrigeration systemthe useful effect is the extraction of heat Q1, then the C.O.P of refrigeration is

$$(C.O.P.)_R = \frac{Q1}{W_R} = \frac{Q1}{Q2 - Q1}$$

Heat pump

Fig c shows a schematic diagram of the heat pump. The heat flow is similar to the

refrigerator; but in this
case, the desired effect is the heat delivered Q2
Then the coefficient of performance of a heat pump is

$$(C.O.P.)_p = \frac{Q2}{W_p} = \frac{Q2}{Q2 - Q1}$$

The relation between the COP of refrigerant and COP of heat pump

$$(C.O.P.)_p = \frac{Q2}{Q2 - Q1} = 1 + \frac{Q1}{Q2 - Q1}$$

$$(C.O.P.)_p = 1 + (C.O.P.)_R$$

7 What do you mean by refrigeration ?

Ans : The term Regrigeration is used for the process of removing heat (that is cooling) from a substance it also includes the process of reducing and maintaining the temperature of a body below the general temperature of its sorounding.

8 What is Nozzle ?

Ans : Nozzle is a Mechanical device which is used for increasing the kinetic energy of the liquid by converting heat energy in to kinetic energy.

Due to friction heat energy converted in to kinetic energy.

Types of Nozzles :

(a) Convergent nozzle

(b) Divergent nozzle

(c) Convergent Divergent nozzle

Chapter-4

Internal combustion engine:

Heat engine:

A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work.

It is classified into two types-

(a) External combustion engine

(b) Internal combustion engine

External combustion engine: In this engine, the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle.

Examples:

- In the steam engine or a steam turbine plant, the heat of combustion is employed to generate steam which is used in a piston engine (reciprocating type engine) or a turbine (rotary type engine) for useful work.
- In a closed cycle gas turbine, the heat of combustion in an external furnace is transferred to gas, usually air which the working fluid of the cycle.

Internal combustion engine:

In this engine, the combustion of air and fuels take place inside the cylinder and are used as the direct motive force.

It can be classified into the following types:

1. According to the basic engine design-
   - Reciprocating engine (Use of cylinder piston arrangement)
   - Rotary engine (Use of turbine)
2. According to the type of fuel used-
   - Petrol engine
   - diesel engine
   - gas engine (CNG, LPG)
   - Alcohol engine (ethanol, methanol etc)
3. According to the number of strokes per cycle-
   - Four stroke and
   - Two stroke engine
4. According to the method of igniting the fuel-
   - Spark ignition engine
   - compression ignition engine
   - hot spot ignition engine
5. According to the working cycle-
   - Otto cycle (constant volume cycle) engine
   - diesel cycle (constant pressure cycle) engine
   - dual combustion cycle (semi diesel cycle) engine
6. According to the number of cylinder-
   - Single cylinder and
   - multi-cylinder engine

7. Method of cooling-
- water cooled, or
- air cooled

8. Speed of the engine-
- Slow speed,
- medium speed and
- high speed engine

9. Cylinder arrangement-
- Vertical,
- horizontal,
- inline,
- V-type,
- radial,
- opposed cylinder or piston engines.

Comparison between external combustion engine and internal combustion engine:

External combustion engine	Internal combustion engine
Combustion of air-fuel is outside the engine cylinder (in a boiler)	Combustion of air-fuel is inside the engine cylinder (in a boiler)
The engines are running smoothly and silently due to outside combustion	Very noisy operated engine
Higher ratio of weight and bulk to output due to presence of auxiliary apparatus like boiler and condenser. Hence it is heavy and cumbersome.	It is light and compact due to lower ratio of weight and bulk to output.
Working pressure and temperature inside the engine cylinder is low; hence ordinary alloys are used for the manufacture of engine cylinder and its parts.	Working pressure and temperature inside the engine cylinder is very much high; hence special alloys are used
It can use cheaper fuels including solid fuels	High grade fuels are used with proper filtration
Lower efficiency about 15-20%	Higher efficiency about 35-40%
Higher requirement of water for dissipation of energy through cooling system	Lesser requirement of water
High starting torque	IC engines are not self-starting

Main components of reciprocating IC engines:

Cylinder:

It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above 2000^0 C.

The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum 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 inlet and exhaust valve, spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

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 higher temperature.

Piston rings:

These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature.

2 types of piston rings-

- Compression 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 rings: Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

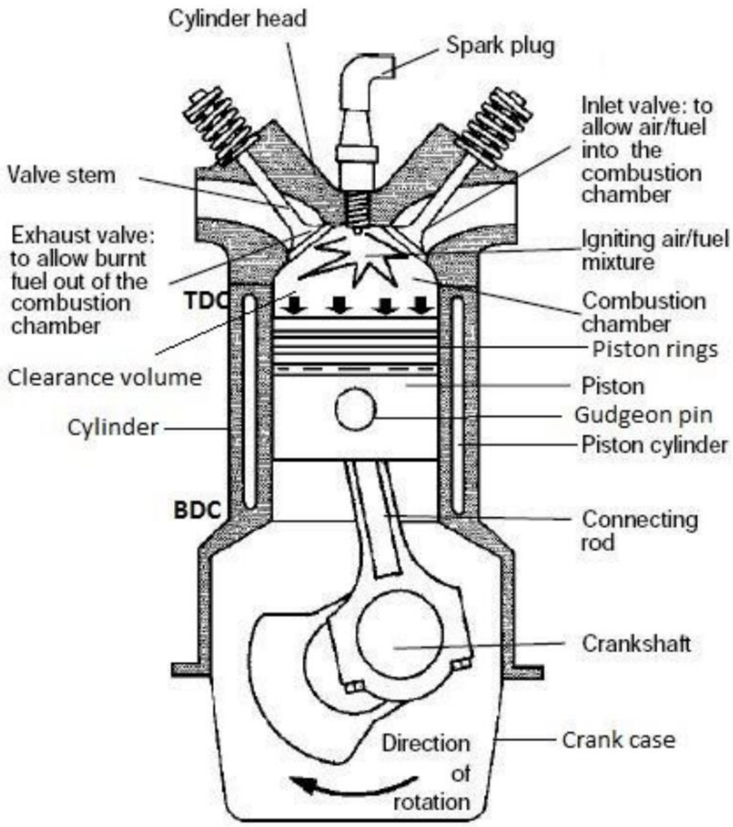


Fig.(Different parts of IC engine)

Connecting rod:

It converts 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 and bigger end of the connecting rod is connected with the crank with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

Crankshaft:

It converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called crank.

Crank case:

It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil.

Flywheel:

It is big wheel mounted on the crankshaft, whose function is to maintain its speed constant. It is done by storing excess energy during the power stroke, which is returned during other stroke.

Terminology used in IC engine:

- Cylinder bore (D):
  The nominal inner diameter of the working cylinder.
- Piston area (A):
  The area of circle of diameter equal to the cylinder bore.
- Stroke (L):
  The nominal distance through which a working piston moves between two successive reversals of its direction of motion.
- Dead 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.
- Displacement volume / swept volume (Vs):
  Swept volume can be defined as the volume swept by the engine piston during one stroke. Swept volume is also the product of piston area and stroke.
  The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as,
  $$V_s = A \times L$$
- Clearance volume (Vc):
  Clearance volume can be defined as the volume that remains in the cylinder when the engine piston is in the top centre position.
  Clearance volume can also be defined as the difference between the total cylinder volume and the swept volume. The space covered by the clearance volume also forms the combustion chamber.
  The nominal volume of the space on the combustion side of the piston at the top dead centre.
- Cylinder volume (V):
  Total volume of the cylinder. $V = V_s + V_c$
- Compression ratio (r):
  Compression ratio , in an internal-combustion engine, degree to which the fuel mixture is compressed before ignition. It is defined as the maximum volume of the combustion chamber divided by the volume with the piston in the full-compression position.
  Compression ratio, $r = V_s / V_c$

  Piston speed:

  The mean piston speed is the average speed of the piston in a reciprocating engine. It is a function of stroke and RPM. There is a factor of 2 in the equation to account for one stroke to occur in 1/2 of a crank revolution (or alternatively: two strokes per one crank revolution) and a '60' to convert seconds from minutes in the RPM term.

- RPM(Revolution per minute):
  Revolutions per minute (abbreviated rpm, RPM, rev/min, r/min, or with the notation min^{-1}) is the number of turns in one minute. It is a unit of rotational speed or the frequency of rotation around a fixed axis.

Four stroke engine: -

Cycle of operation completed in four strokes of the piston or two revolution of the piston.

(i) Suction stroke (suction valve open, exhaust valve closed)-charge 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)-fresh charge is compressed into clearance volume by the return stroke of the piston and ignited by the spark for combustion. Hence pressure and temperature is increased due to the combustion of fuel

(iii) Expansion stroke (both valves closed)-high pressure of the burnt gases force the piston towards BDC and hence power is obtained at the crankshaft.

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

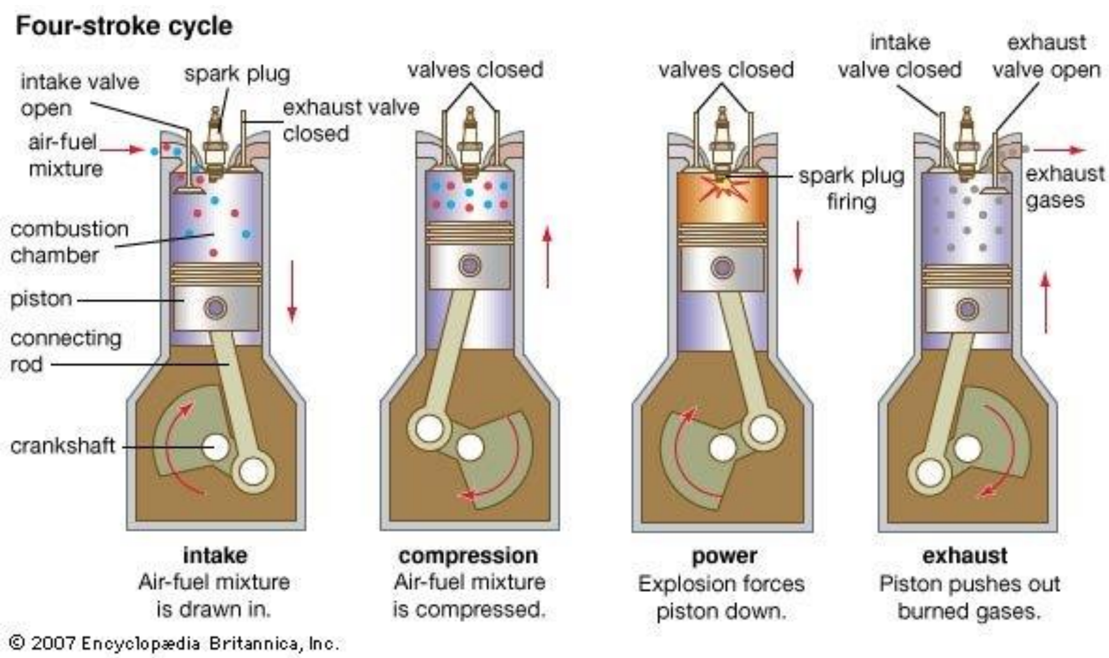
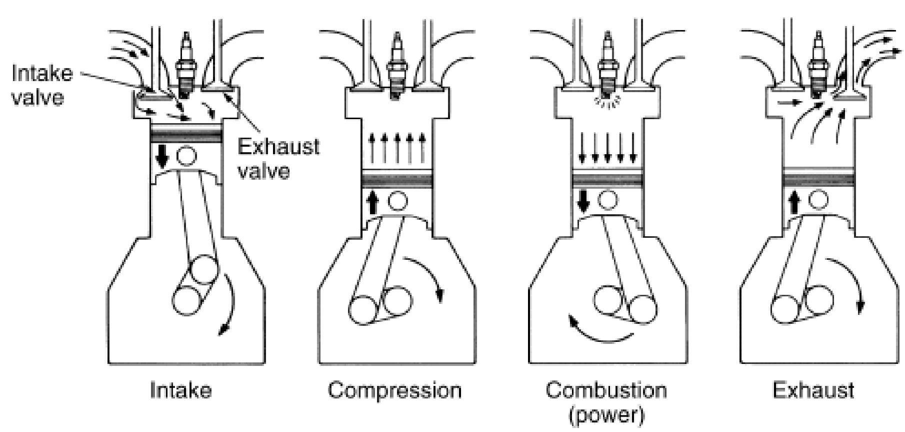


Fig. Cycle of operation in four stroke engine



Two stroke engine:

No piston stroke for suction and exhaust operations -

- Suction is accomplished by air compressed in crankcase or by a blower
- Induction of compressed air removes the products of combustion through exhaust ports
- Transfer port is there to supply the fresh charge into combustion chamber

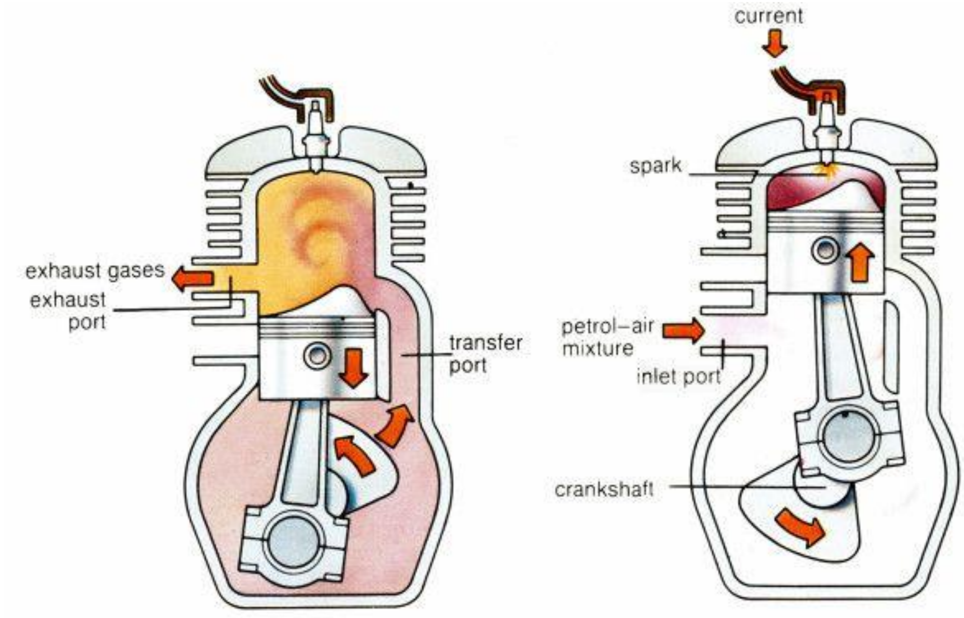


Fig. Cycle of operation in two stroke engine

- A two-stroke engine performs all the same steps, but in just two piston strokes. The simplest two-stroke engines do this by using the crankcase and the underside of the moving piston as a fresh charge pump. Such engines carry the official name "crankcase-scavenged two-strokes."
- As the two-stroke's piston rises on compression, its underside pulls a partial vacuum in the crankcase. An intake port of some kind (cylinder wall port, reed valve or rotary disc valve) opens, allowing air to rush into the crankcase through a carburetor.
- As the piston nears Top Dead Center, a spark fires the compressed mixture. As in a four-stroke, the mixture burns and its chemical energy becomes heat energy, raising the pressure of the burned mixture to hundreds of psi. This pressure drives the piston down the bore, rotating the crankshaft.
- As the piston continues down the bore, it begins to expose an exhaust port in the cylinder wall. As spent combustion gas rushes out through this port, the descending piston is simultaneously compressing the fuel-air mixture trapped beneath it in the crankcase.
- As the piston descends more, it begins to expose two or more fresh-charge ports, which are connected to the crankcase by short ducts. As pressure in the cylinder is now low and pressure in the crankcase higher, fresh charge from the crankcase rushes into the cylinder through the fresh-charge (or "transfer") ports. These ports are shaped and aimed to minimize direct loss of fresh charge to the exhaust port. Even in the best designs, there is some loss, but simplicity has its price! This process of filling the cylinder while also pushing leftover exhaust gas out the exhaust port is called "scavenging."
- While the piston is near Bottom Dead Center, mixture continues to move from the crankcase, up through the transfer ports, and into the cylinder.
- As the piston rises, it first covers the transfer ports, leaving only the exhaust port still open. If there were no way to stop it, much of the fresh charge would now be pumped out the exhaust.

- But there is a simple way to stop it—using exhaust pressure waves in the exhaust. If we shape and dimension the exhaust pipe right, a reflection of the original pressure pulse, generated as the exhaust port opened, will bounce back to the port just as fresh charge is being pumped out of it. This pressure wave stuffs the fresh charge back into the cylinder just as the rising piston covers the exhaust port

Comparison of Four-stroke and two-stroke engine:

Sl.no	Four-stroke engine	Two-stroke engine
1.	Four stroke of the piston and two revolution of crankshaft	Two stroke of the piston and one revolution of crankshaft
2.	One power stroke in every two revolution of crankshaft	One power stroke in each revolution of crankshaft
3.	Heavier flywheel due to non-uniform turning movement	Lighter flywheel due to more uniform turning movement
4.	Power produce is less	Theoretically power produce is twice than the four stroke engine for same size
5.	Heavy and bulky	Light and compact
6.	Lesser cooling and lubrication requirements	Greater cooling and lubrication requirements
7.	Lesser rate of wear and tear	Higher rate of wear and tear
8.	Contains valve and valve mechanism	Contains ports arrangement
9.	Higher initial cost	Cheaper initial cost
10.	Volumetric efficiency is more due to greater time of induction	Volumetric efficiency less due to lesser time of induction
11.	Thermal efficiency is high and also part load efficiency better	Thermal efficiency is low, part load efficiency lesser
12.	12. It is used where efficiency is important. Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation etc.	It is used where low cost, compactness and light weight are important. Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.

Comparison of Petrol(SI) and Diesel (CI) engine:

Sl.no	Petrol(SI) engine	Diesel (CI) engine
1.	Working cycle is Otto cycle.	Working cycle is diesel cycle.
2.	Petrol or gasoline or high octane fuel is used.	Diesel or high cetane fuel is used.
3.	High self-ignition temperature.	Low self-ignition temperature
4.	Fuel and air introduced as a gaseous mixture in the suction stroke.	Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke.
5.	Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced.	Injector and high pressure pump used to supply of fuel. Quantity of fuel regulated in pump.
6.	Use of spark plug for ignition system	Self-ignition by the compression of air which increased the temperature required for combustion
7.	Compression ratio is 6 to 10.5	Compression ratio is 14 to 22

8.	Higher maximum RPM due to lower weight	Lower maximum RPM
9.	Maximum efficiency lower due to lower compression ratio	Higher maximum efficiency due to higher compression ratio
10.	Lighter	Heavier due to higher pressures

PNS SCHOOL OF ENGG & TECHNOLOGY

LECTURES NOTE ON

THERMAL-I

PREPARED BY

RAMAKANT SWAIN

HOD MECHANICAL

Chapter-5
Air standard cycle:

Introduction:

- Deal with systems that produce power in which the working fluid remains a gas throughout the cycle (in other words, there is no change in phase).
- Spark Ignition (gasoline) engines, Compression ignition (diesel) engines and conventional gas turbine engines (generally refer to as Internal Combustion engines or IC Engines) are some examples of engines that operate on gas cycles.
- Internal combustion engines: Combustion of fuel is non-cyclic process. Working fluid, air-fuel mixture undergoes permanent chemical change due to combustion Products are thrown out of the engine & Fresh charge is taken in.

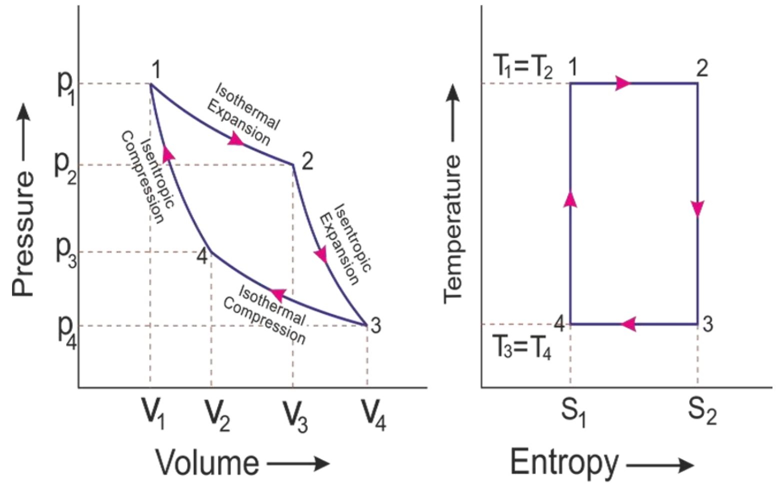
Carnot cycle:

In 1824 Carnot suggested a particular cycle of operation for a CHPP which avoided all irreversibilities.

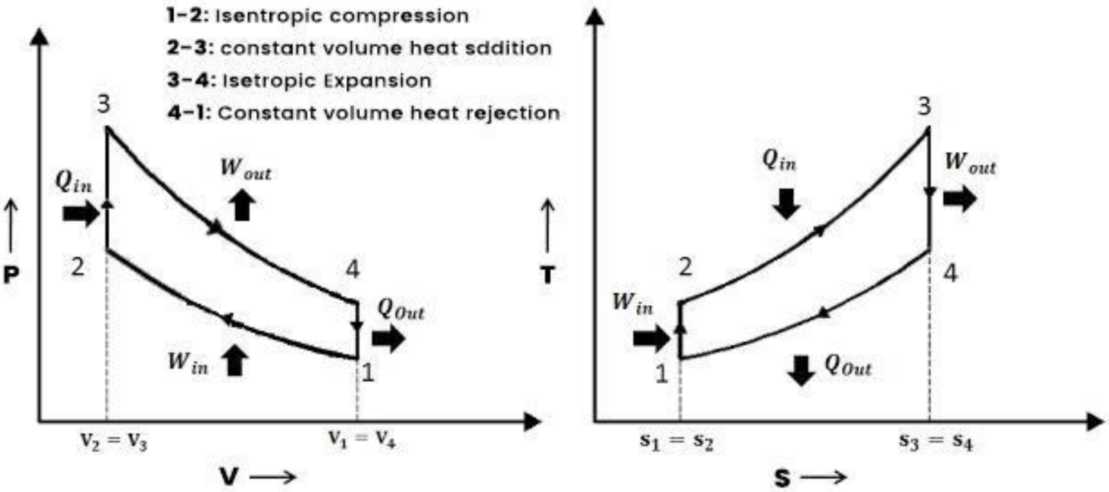
- It consisted of four processes, two isothermal and two adiabatic.
- The process take place between a heat source at temperature (T_H) and a heat sink at temperature (T_C).
- The most efficient heat engine cycle is the Carnot cycle.

Following are the four processes of the Carnot cycle:

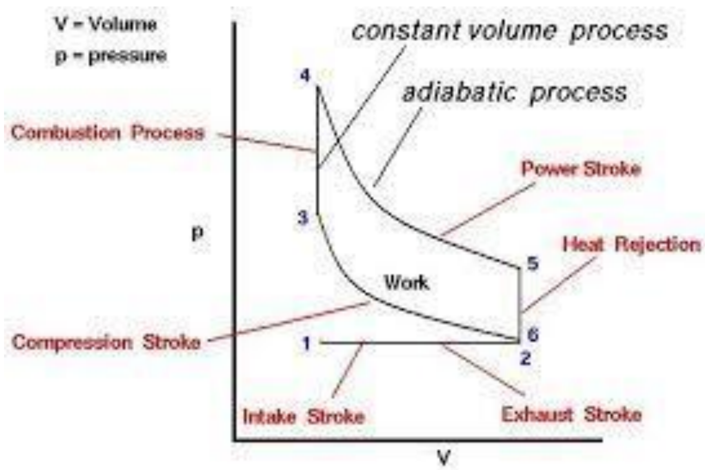
- The first process is reversible isothermal gas expansion. In this process, the amount of heat absorbed by the ideal gas is Q_{in} from the heat source, which is at a temperature of T_H. The gas expands and does work on the surroundings.
- The second process is reversible adiabatic gas expansion. Here, the system is thermally insulated, and the gas continues to expand and work is done on the surroundings. Now the temperature is lower, T_L.
- The third process is reversible isothermal gas compression process. Here, the heat loss Q_{Out} occurs when the surroundings do the work at temperature T_H.
- The last process is reversible adiabatic gas compression. Again the system is thermally insulated. The temperature again rises back to T_H as the surrounding continue to do their work on the gas.



(a) p-v diagram (b) T-S diagram]



P-V and T-S Diagram of Otto Cycle



Heat supplied, $q_s = C_v(T_3 - T_2)$

Heat rejection, $q_R = C_v(T_4 - T_1)$

Compression ratio, $r_k = \frac{V_1}{V_2}$

Thermal efficiency, $\eta_{th} = \frac{q_s - q_R}{q_s} = \frac{Cv(T3-T2) - Cv(T4-T1)}{Cv(T3-T2)} = 1 - \frac{T4-T1}{T3-T2}$

In process 1-2, adiabatic compression process,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$=> T_2 = T_1.(r_k)^{\gamma-1}$$

In adiabatic expansion process, i.e. 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$=> T_3 = T_4.(r_k)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_4.(r_k)^{\gamma-1} - T_1.(r_k)^{\gamma-1}}$$

$$= 1 - \frac{1}{(r_k)^{\gamma-1}}$$

Work done (W)

Pressure ratio, $r_p = \frac{P_3}{P_2} = \frac{P_4}{P_1}$

$$\frac{P_2}{P_1} = \frac{P_3}{P_4} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r_k)^{\gamma}$$

$$W = \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= \frac{1}{\gamma - 1}\left[P_4V_4\left(\frac{P_3V_3}{P_4V_4} - 1\right) - P_1V_1\left(\frac{P_2V_2}{P_1V_1} - 1\right)\right]$$

$$= \frac{1}{\gamma - 1}\left[P_4V_1({r_k}^{\gamma-1} - 1) - P_1V_1({r_k}^{\gamma-1} - 1)\right]$$

$$= \frac{P_1V_1}{\gamma - 1}\left[r_p({r_k}^{\gamma-1} - 1) - ({r_k}^{\gamma-1} - 1)\right]$$

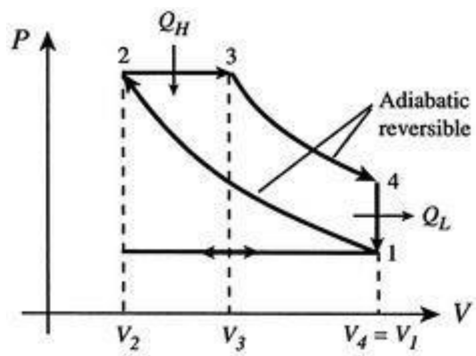
$$= \frac{P_1V_1}{\gamma - 1}\left[({r_k}^{\gamma-1} - 1)(r_p - 1)\right]$$

Mean effective pressure, $P_m = \frac{work\ done}{Swept\ volume} = \frac{work\ done}{V_1 - V_2}$

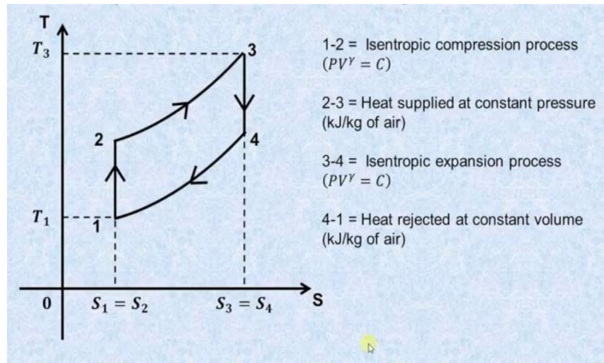
$$P_m = \frac{\frac{P_1V_1}{\gamma - 1}\left[({r_k}^{\gamma-1} - 1)(r_p - 1)\right]}{V_1 - V_2} = \frac{P_1 r_k\left[({r_k}^{\gamma-1} - 1)(r_p - 1)\right]}{(\gamma - 1)(r_k - 1)}$$

Diesel cycle:

- Thermodynamic cycle for low speed CI/diesel engine -Reversible adiabatic compression and expansion process -Constant pressure heat addition (combustion) and heat rejection process (exhaust).
- This cycle can operate with a higher compression ratio than the Otto cycle because only air is compressed and there is no risk of auto-ignition of the fuel.



(P-V diagram)



(T-S diagram)

Heat supplied, $Q_1 = C_p(T_3 - T_2)$

Heat rejection, $Q_2 = C_v(T_4 - T_1)$

Compression ratio, $r_k = \frac{V_1}{V_2}$

Cut off ratio, $r_c = \frac{V_3}{V_2}$

Thermal efficiency, $\eta_{th} = \frac{Q_1 - Q_2}{Q_1} = \frac{C_p(T_3 - T_2) - C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)}$

In adiabatic compression process i.e. 1-2,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1}$$

$$=> T_2 = T_1.(r_k)^{\gamma - 1}$$

In process 2-3, pressure constant, then

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$$

$$=> T_3 = T_2.r_c = T_1.(r_k)^{\gamma - 1}.r_c$$

In adiabatic expansion process i.e. 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma - 1} = \left(\frac{V_3}{V_2} * \frac{V_2}{V_4}\right)^{\gamma - 1} = (r_c)^{\gamma - 1} * \frac{1}{(r_k)^{\gamma - 1}}$$

$$=> T_4 = T_3.(r_c)^{\gamma - 1} * \frac{1}{(r_k)^{\gamma - 1}} = T_1.(r_k)^{\gamma - 1}.r_c.(r_c)^{\gamma - 1} * \frac{1}{(r_k)^{\gamma - 1}} = T_1.r_c$$

$$\eta_{th} = 1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{1}{\gamma.(r_k)^{\gamma - 1}}\left[\frac{(r_c)^{\gamma} - 1}{r_c - 1}\right]$$

Although for a given compression ratio the Otto cycle has higher efficiency, because the Diesel engine can be operated to higher compression ratio, the engine can actually have higher efficiency than an Otto cycle when both are operated at compression ratios that might be achieved in practice.

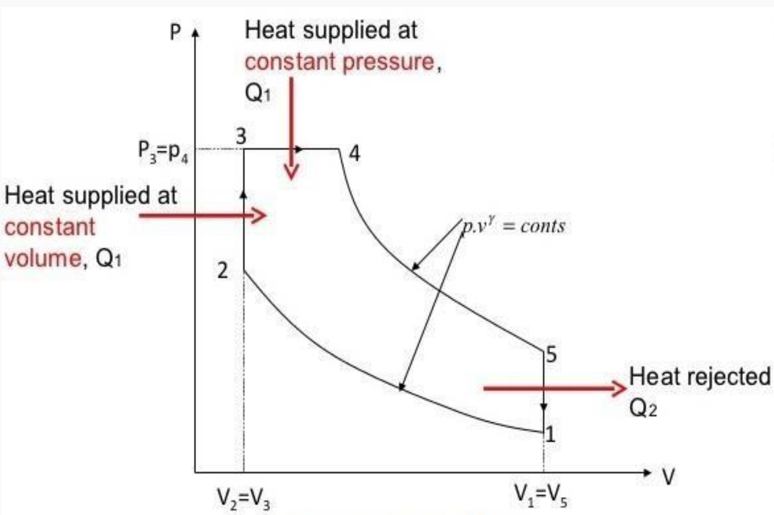
Dual combustion cycle/Dual cycle :

The combustion process in a spark ignition engine does not occur exactly at constant volume, nor does the combustion process in an actual compression ignition engine occur exactly at constant pressure, therefore another idealized cycle known as Dual cycle has been developed that more closely approximate the actual spark-ignition and compression-ignition engines.

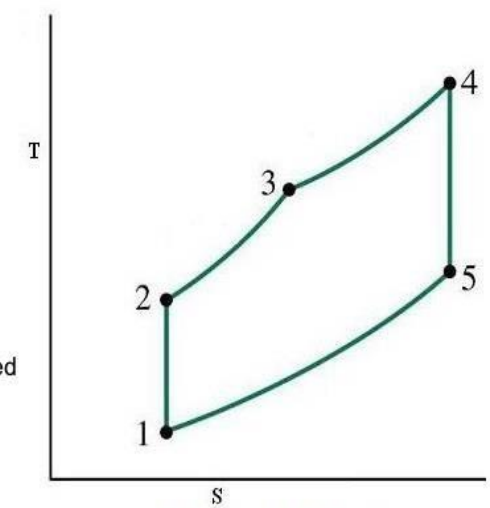
In this cycle, part of heat addition occurs at constant volume while the rest is at constant pressure. The dual cycle is also called mixed or limited pressure cycle.

The process description of Dual cycle is as below:

- Reversible adiabatic compression (1-2)
- constant volume heat addition(2-3)
- Constant pressure heat addition(3-4)
- Reversible adiabatic expansion(4-5)
- constant volume heat rejection process(5-1)



PV Diagram of Dual cycle



T-S Diagram of dual cycle

Total heat supplied, $Q_1 = C_v(T_3-T_2) + C_p(T_4-T_3)$
Heat rejection, $Q_2 = C_v(T_5-T_1)$
Compression ratio, $r_k = \frac{V_1}{V_2}$
Cut off ratio, $r_c = \frac{V_4}{V_3}$
Pressure ratio, $r_p = \frac{P_3}{P_2}$

Figure 9 shows the P-V diagram of Dual cycle.

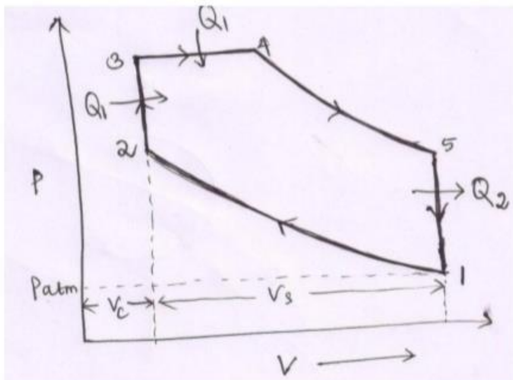


Fig. 9. Dual cycle

$$\text{Thermal efficiency, } \eta_{th} = \frac{Q_1-Q_2}{Q_1} = \frac{C_v(T_3-T_2)+C_v(T_4-T_3)-C_v(T_5-T_1)}{C_v(T_3-T_2)+C_v(T_4-T_3)} = 1 - \frac{(T_5-T_1)}{(T_3-T_2)+\gamma(T_4-T_3)}$$

In adiabatic compression process i.e. 1-2,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r_k)^{\gamma-1}$$

In constant volume combustion process i.e. 2-3,

$\frac{P_3}{P_2} = \frac{T_3}{T_2} = r_p$

$$=> T_2 = \frac{T_3}{r_p}$$

In constant pressure combustion process i.e. 3-4,

$\frac{V_3}{V_4} = \frac{T_3}{T_4}$

$$=> T_4 = T_3 . r_c$$

In adiabatic expansion process i.e. 4-5,

$$\frac{T_4}{T_5} = \left(\frac{V_5}{V_4}\right)^{\gamma-1} = \left(\frac{V_1}{V_4}\right)^{\gamma-1} = \left(\frac{r_k}{r_c}\right)^{\gamma-1}$$

$$=> T_5 = r_c * T_3 * \left(\frac{r_c}{r_k}\right)^{\gamma-1}$$

$$\eta_{th} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} = 1 - \frac{1}{(r_k)^{\gamma-1}}\left[\frac{r_p.(r_c)^{\gamma} - 1}{(r_p - 1) + \gamma r_p(r_c - 1)}\right]$$

<u>Work done (W)</u>

$$W = P_3(V_4 - V_3) + \frac{P_4V_4 - P_5V_5}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$

$$= P_3V_3(r_c - 1) + \frac{(P_4r_cV_3 - P_5r_kV_3) - (P_2V_3 - P_1r_kV_3)}{\gamma - 1}$$

$$= \frac{P_1V_1.r_k^{\gamma-1}\left[\gamma r_p(r_c - 1) + (r_p - 1) - .r_k^{\gamma-1}(r_pr_c^{\gamma} - 1)\right]}{\gamma - 1}$$

Mean effective pressure,

$$P_m = \frac{\frac{P_1V_1.r_k^{\gamma-1}\left[\gamma r_p(r_c - 1) + (r_p - 1) - .r_k^{\gamma-1}(r_pr_c^{\gamma} - 1)\right]}{\gamma - 1}}{V_1 - V_2}$$

$$= \frac{P_1r_k^{\gamma}\left[r_p(r_c - 1) + (r_p - 1) - .r_k^{1-\gamma}(r_pr_c^{\gamma} - 1)\right]}{(\gamma - 1)(r_k - 1)}$$

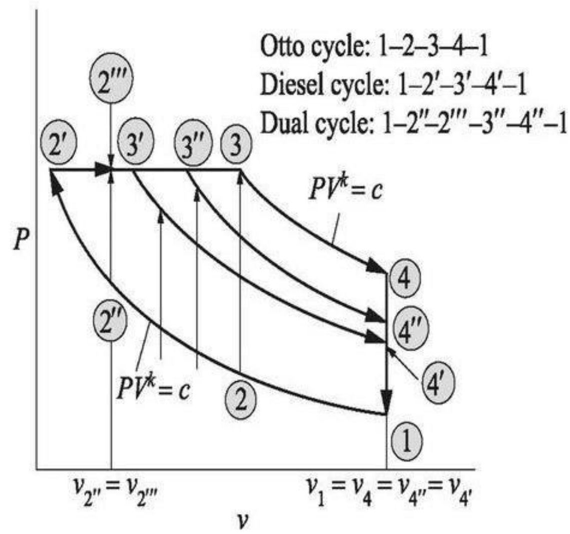
Comparison of Otto, Diesel and Dual cycles:

- **For Same Compression Ratio and Heat Rejection;**
  $Efficiency_{OTTO\ CYCLE}$ > $Efficiency_{DUAL\ CYCLE}$ > $Efficiency_{DIESEL\ CYCLE}$

- **For Same maximum pressure and heat input**

Comparison of Otto, Diesel and Dual Cycles

Same maximum pressure and Heat input



Let the three cycles operate with same maximum pressure and same heat input.

$$W_{net,Otto} = area 1-2-3-4$$

$$W_{net,Diesel} = area 1-2'-3'-4$$

$$W_{net,Dual} = area 1-2''-2'''-3''-4''$$

It is evident that,

$$W_{net,Diesel} > W_{net,Dual} > W_{net,Otto}$$

Hence,

$$\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$$

Chapter-6

Fuels and combustion:

Fuel:

We always need a certain substance to convert one form of energy into another for accomplishing various jobs. We call such materials as fuels. In other words, any substance which upon combustion produces a usable amount of energy is known as **fuel**. Example: fossil fuels, biogas, nuclear energy, etc.

Some properties of ideal fuel are:

- An ideal fuel is readily available.
- An ideal fuel is cheap.
- An ideal fuel burns easily in the air at a moderate rate.
- It releases a large amount of energy.
- It should not leave behind any undesirable substances which can be harmful to us.
- It should not affect the environment adversely.

Types of Fuels:

Fuels can be generally classified into two factors:

1. On the basis of their fuels state:
    - Solid Fuels
    - Liquid Fuels
    - Gaseous Fuels
2. On the basis of their occurrence:
    - Natural Fuels
    - Artificial Fuels

Examples of Fuels:

Natural Fuels	Artificial Fuels
Solid Fuels	
Wood, Coal, Oil Shale	Tanbark, Bagasse, Straw, Charcoal, Coal, Briquettes

Liquid Fuels

Petroleum	Oils from distillation of petroleum, Coal Tar, Shale-Oil, Alcohols, etc.

Gaseous Fuels

Natural Gas	Coal gas, Producer Gas, Water Gas, Hydrogen, Acetylene, Blast Furnace Gas, Oil Gas

Solid Fuels:

Fuels which are found in their solid state at room temperature are generally referred to as Solid Fuels. They were the first kind of fuel known to be used by man, basically wood to create fire. Coal was another one of the influential fuels known to man as it leads the way for the industrial revolution, from firing furnaces to running steam engines.

Advantages:

- Easier transportation and storage.
- Low production cost.
- Moderate ignition temperature.

Disadvantages:

- Large portion of energy is wasted.
- Cost of handling is high and controlling is also hard.
- Ash content is high & burn with clinker formation.

Liquid Fuel:

Most liquid fuels are derived from the fossilized remains of dead plants and animals by exposure to heat and pressure in the Earth's crust. The fumes of the liquid fuel are flammable instead of the liquid.

Advantages:

- Higher calorific value per unit mass.
- Burn without ash, clinkers, etc.

- Controlling the combustion is easier.
- Transportation easier through pipes and stored indefinitely without loss.
- Loss of energy is comparatively lower.
- Require less furnace space for combustion.

Disadvantages:

- Cost of liquid fuel is much higher compared to solid fuel.
- Storage methods are costlier.
- Greater risk of fire hazards.
- Special burning equipment required for more efficient combustion.

Gaseous Fuel:

Gaseous fuels occur in nature, besides being manufactured from solid and liquid fuels. Most gaseous fuels are composed of hydrocarbons, carbon monoxide, hydrogen or a mixture of them all.

Advantages:

- Transportation through pipes is easy.
- Sparking combustion is really easy.
- They have a higher heat content.
- Clean after use.
- Do Not require any special burner technology.

Disadvantages:

- Large storage tanks required.
- As they are highly inflammable, the chance for fire hazards are extremely high and strict safety measures need to be followed.

What are fossil fuels?

Fossil fuels are the dead and decayed remains of plants and animals subjected to decades of pressure and temperature under the earth's crust. Primarily fossil fuels are hydrocarbons. They are convenient and effective. They provide the calorific value required to fulfil our needs. Even though they are available in plenty right now, they are a non-renewable source of energy. The burning of fossil fuels is responsible for a large section of the world's pollution index.

Types of fossil fuels:

- Coal
- Oil
- Natural Gas

Nuclear Fuel:

Any material consumed to give out nuclear energy is a nuclear fuel. Technically speaking, any material can be made to give out nuclear energy. But looking at its practicality and feasibility, we pick materials which do not require extreme constraints to release nuclear energy.

Most nuclear fuels contain heavy fissile elements that are capable of nuclear fission. When these fuels are struck by neutrons, they are in turn capable of emitting neutrons when they break apart. This makes possible a self-sustaining chain reaction that releases energy at a controlled rate in a nuclear reactor or with a very rapid uncontrolled rate of a nuclear weapon.
Some common examples of nuclear fuel are uranium-235 (^{235}U) and plutonium-239 (^{239}Pu).

Heating values of fuel:

The heat value of a fuel is the amount of heat released during its combustion. Also referred to as energy or calorific value, heat value is a measure of a fuel's energy density, and is expressed in energy (joules) per specified amount (*e.g.* kilograms).

FUEL	Heating value
Hydrogen (H_2)	120-142 MJ/kg
Methane (CH_4)	50-55 MJ/kg
Methanol (CH_3OH)	22.7 MJ/kg
Dimethyl ether - DME (CH_3OCH_3)	29 MJ/kg
Petrol/gasoline	44-46 MJ/kg
Diesel fuel	42-46 MJ/kg
Crude oil	42-47 MJ/kg
Liquefied petroleum gas (LPG)	46-51 MJ/kg
Natural gas	42-55 MJ/kg
Hard black coal (IEA definition)	>23.9 MJ/kg
Hard black coal (Australia & Canada)	c. 25 MJ/kg
Sub-bituminous coal (IEA definition)	17.4-23.9 MJ/kg
Sub-bituminous coal (Australia & Canada)	c. 18 MJ/kg
Lignite/brown coal (IEA definition)	<17.4 MJ/kg
Lignite/brown coal (Australia, electricity)	c. 10 MJ/kg
Firewood (dry)	16 MJ/kg
Natural uranium, in LWR (normal reactor)	500 GJ/kg
Natural uranium, in LWR with U & Pu recycle	650 GJ/kg
Natural uranium, in FNR	28,000 GJ/kg
Uranium enriched to 3.5%, in LWR	3900 GJ/kg

Uranium figures are based on 45,000 MWd/t burn-up of 3.5% enriched U in LWR
MJ = 10^6 Joule, GJ = 10^9 J
MJ to kWh @ 33% efficiency: x 0.0926
One tonne of oil equivalent (toe) is equal to 41.868 GJ

Calorific value of fuel:

Calorific value is the amount of heat energy present in food or fuel and which is determined by the complete combustion of specified quantity at constant pressure and in normal conditions. It is also called calorific power. The unit of calorific value is kilojoule per kilogram i.e. KJ/Kg.

Fuel	**Calorific values**
Cow Dung	8000 KJ/Kg
Wood	22000 KJ/Kg
Coal	33000 KJ/Kg
Biogas	40000 KJ/Kg
Diesel	45000 KJ/Kg
kerosene	45000 KJ/Kg
Petrol	45000 KJ/Kg
Methane	50000 KJ/Kg
LPG	55000 KJ/Kg

Quality of I.C engine fuels:

Octane number:

Octane number indicates the tendency of fuels to knock. The higher the octane number the more difficult the auto-ignition.

– n-Heptane (C_7H_{16}) has a octane number 0,

– iso-octane (C_8H_{18}) has a octane number 100.

– Gasoline has a octane number 93 – 97.

Cetane number:

It can be defined as the percentage by volume of normal cetane in a mixture of normal cetane and alpha methyl naphthalene which has the same ignition characteristics as the test fuel when combustion is carried out in a standard engine under a set of specified working conditions.

Difference between octane number and cetane number:

IMPORTANT QUESTION & ANSWER

1.DIFFERENCE BETWEEN OCTANE NUMBER & CETANE NUMBER

Octane number	Cetane number
The octane number of a fuel may be defined as the percentage of iso-octane in a mixture of iso-octane and n-heptane which just matches with the knocking tendency of the fuel under test.	The cetane number of diesel oil is defined as the percentage by volume of cetane in a mixture of cetane and α-methyl naphthalene which exactly matches in its knocking characteristics with the oil under test.
The **octane Number** is a measure of the auto ignition resistance of gasoline (petrol) and other fuels used in spark-ignition internal combustion engines.	The **Cetane Number** is a measure of the combustion quality of diesel fuel under compression.
The higher the octane number, the better is the resistance of Gasoline to combustion prematurely, known as **Knocking.**	The Higher Cetane number means that the Diesel will ignite readily and, therefore, perform better in a diesel engine
Isooctane is given a maximum octane number, i.e. **100.** n-heptane is given a minimum octane number, i.e. **0.**	Cetane is given a maximum cetane number, i.e.**100** while α -methylnaphthalene is given a minimum cetane number, i.e.**0.**
Octane numbers are only used between 0 and 100. The fuels having better anti-knocking property than isooctane are rated in other scales like octane Performance.	Cetane numbers are only used for the relatively light distillate diesel oils. For heavy (residual) fuel oil two other scales are used CCAI and CII

2.WRITE SHORT NOTE ABOUT CARNOT CYCLE

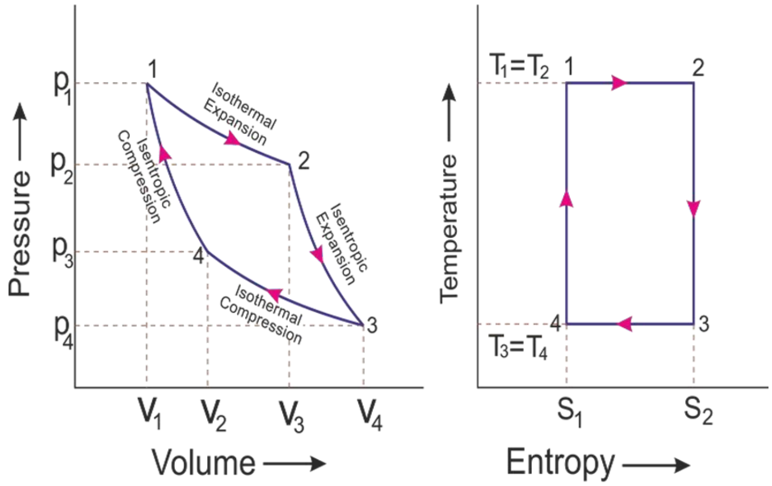
Carnot cycle:

In 1824 Carnot suggested a particular cycle of operation for a CHPP which avoided all irreversibilities.

- It consisted of four processes, two isothermal and two adiabatic.
- The process take place between a heat source at temperature (T_H) and a heat sink at temperature (T_C).
- The most efficient heat engine cycle is the Carnot cycle.

Following are the four processes of the Carnot cycle:

- The first process is reversible isothermal gas expansion. In this process, the amount of heat absorbed by the ideal gas is Q_{in} from the heat source, which is at a temperature of T_H. The gas expands and does work on the surroundings.
- The second process is reversible adiabatic gas expansion. Here, the system is thermally insulated, and the gas continues to expand and work is done on the surroundings. Now the temperature is lower, T_L.
- The third process is reversible isothermal gas compression process. Here, the heat loss Q_{Out} occurs when the surroundings do the work at temperature T_H.
- The last process is reversible adiabatic gas compression. Again the system is thermally insulated. The temperature again rises back to T_H as the surrounding continue to do their work on the gas.

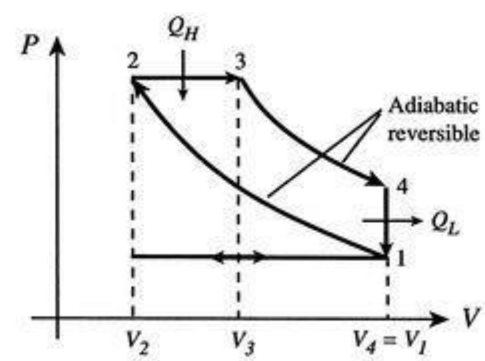


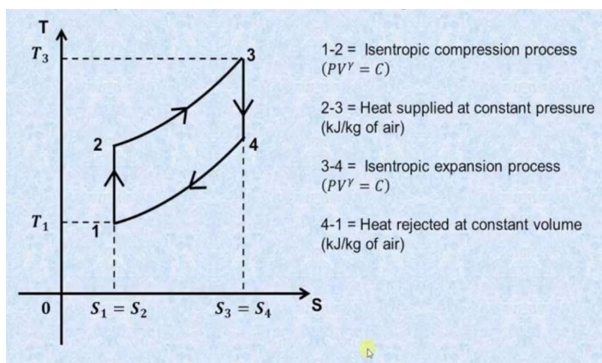
(a) p-v diagram (b) T-S diagram

3.Derive efficiency of Diesel cycle

Diesel cycle:

- Thermodynamic cycle for low speed CI/diesel engine -Reversible adiabatic compression and expansion process -Constant pressure heat addition (combustion) and heat rejection process (exhaust).
- This cycle can operate with a higher compression ratio than the Otto cycle because only air is compressed and there is no risk of auto-ignition of the fuel.





Heat supplied, $Q_1 = C_p(T_3 - T_2)$

Heat rejection, $Q_2 = C_v(T_4 - T_1)$

Compression ratio, $r_k = \frac{V_1}{V_2}$

Cut off ratio, $r_c = \frac{V_3}{V_2}$

Thermal efficiency, $\eta_{th} = \frac{Q_1 - Q_2}{Q_1} = \frac{C_p(T_3 - T_2) - C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)}$

In adiabatic compression process i.e. 1-2,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1}$$

$$=> T_2 = T_1 . (r_k)^{\gamma - 1}$$

In process 2-3, pressure constant, then

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c$$

$$=> T_3 = T_2 . r_c = T_1 . (r_k)^{\gamma - 1} . r_c$$

In adiabatic expansion process i.e. 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma - 1} = \left(\frac{V_3}{V_2} * \frac{V_2}{V_4}\right)^{\gamma - 1} = (r_c)^{\gamma - 1} * \frac{1}{(r_k)^{\gamma - 1}}$$

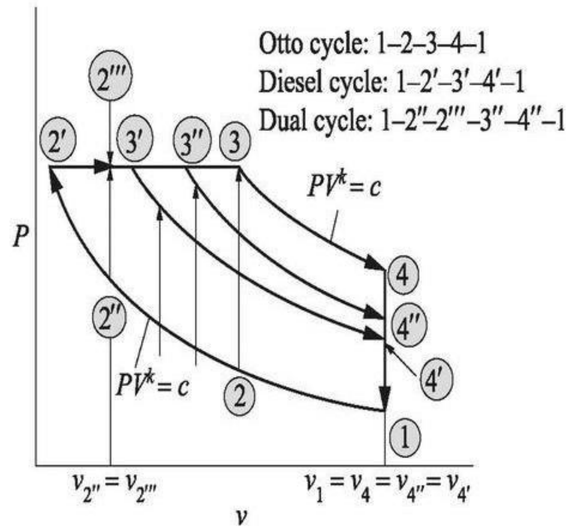
$$=> T_4 = T_3 . (r_c)^{\gamma - 1} * \frac{1}{(r_k)^{\gamma - 1}} = T_1 . (r_k)^{\gamma - 1} . r_c . (r_c)^{\gamma - 1} * \frac{1}{(r_k)^{\gamma - 1}} = T_1 . r_c$$

$$\eta_{th} = 1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{1}{\gamma . (r_k)^{\gamma - 1}}\left[\frac{(r_c)^\gamma - 1}{r_c - 1}\right]$$

4.Comparision between Otto Diesel and dual cycle

Comparison of Otto, Diesel and Dual Cycles

Same maximum pressure and Heat input



Let the three cycles operate with same maximum pressure and same heat input.

$$W_{net,Otto} = area\, 1-2-3-4$$

$$W_{net,Diesel} = area\, 1-2'-3'-4$$

$$W_{net,Dual} = area\, 1-2''-2'''-3''-4''$$

It is evident that,

$$W_{net,Diesel} > W_{net,Dual} > W_{net,Otto}$$

Hence,

$$\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$$

5. Define calorific value of fuel

Calorific value of fuel:

Calorific value is the amount of heat energy present in food or fuel and which is determined by the complete combustion of specified quantity at constant pressure and in normal conditions. Itis also called calorific power.

The unit of calorific value is kilojoule per kilogram i.e. KJ/Kg.

6. Some properties of ideal fuel are:

- An ideal fuel is readily available.
- An ideal fuel is cheap.
- An ideal fuel burns easily in the air at a moderate rate.
- It releases a large amount of energy.
- It should not leave behind any undesirable substances which can be harmful to us.
- It should not affect the environment adversely.

7.Write advantages & disadvantages of solid fuel

Solid Fuels:

Fuels which are found in their solid state at room temperature are generally referred to as Solid Fuels. They were the first kind of fuel known to be used by man, basically wood to create fire. Coal was another one of the influential fuels known to man as it leads the way for the industrial revolution, from firing furnaces to running steam engines.

Advantages:

- Easier transportation and storage.
- Low production cost.
- Moderate ignition temperature.

Disadvantages:

- Large portion of energy is wasted.
- Cost of handling is high and controlling is also hard.
- Ash content is high & burn with clinker formation.

8. What are fossil fuels?

Fossil fuels are the dead and decayed remains of plants and animals subjected to decades of pressure and temperature under the earth's crust. Primarily fossil fuels are hydrocarbons. They are convenient and effective. They provide the calorific value required to fulfil our needs. Even though they are available in plenty right now, they are a non-renewable source of energy. The burning of fossil fuels is responsible for a large section of the world's pollution index.

Types of fossil fuels:

- Coal
- Oil
- Natural Gas