

BRANCH: MECHANICAL ENGINEERING
SEMESTER: 3RD
SUBJECT: THERMAL ENGINEERING - I
FACULTY: Er. SIBASISH SAHU

COURSE CONTENT:

1. Thermodynamic concept & Terminology

- 1.1 Thermodynamic Systems (closed, open, isolated)
- 1.2 Thermodynamic properties of a system (pressure, volume, temperature, entropy, enthalpy, Internal energy and units of measurement).
- 1.3 Intensive and extensive properties
- 1.4 Define thermodynamic processes, path, cycle, state, path function, point function.
- 1.5 Thermodynamic Equilibrium.
- 1.6 Quasi-static Process.
- 1.7 Conceptual explanation of energy and its sources
- 1.8 Work, heat and comparison between the two.
- 1.9 Mechanical Equivalent of Heat.
- 1.10 Work transfer, Displacement work

2. Laws of Thermodynamics

- 2.1 State & explain Zeroth law of thermodynamics.
- 2.2 State & explain First law of thermodynamics.
- 2.3 Limitations of First law of thermodynamics
- 2.4 Application of First law of Thermodynamics (steady flow energy equation and its application to turbine and compressor)
- 2.4 Second law of thermodynamics (Clausius & Kelvin Planck statements).
- 2.5 Application of second law in heat engine, heat pump, refrigerator & determination of efficiencies & C.O.P (solve simple numerical)

3. Properties Processes of perfect gas

- 3.1 Laws of perfect gas:
Boyle's law, Charles's law, Avogadro's law, Dalton's law of partial pressure, Gay Lussac law, General gas equation, characteristic gas constant, Universal gas constant.
- 3.2 Explain specific heat of gas (C_p and C_v)
- 3.3 Relation between C_p & C_v .
- 3.4 Enthalpy of a gas.
- 3.5 Work done during a non-flow process.
- 3.6 Application of first law of thermodynamics to various non-flow process (Isothermal, Isobaric, Isentropic and polytropic process)
- 3.6 Solve simple problems on above.
- 3.7 Free expansion & throttling process.

4. Internal combustion engine

- 4.1 Explain & classify I.C engine.
- 4.2 Terminology of I.C Engine such as bore, dead centers, stroke volume, piston speed & RPM.
- 4.3 Explain the working principle of 2-stroke & 4-stroke engine C.I & S.I engine.
- 4.4 Differentiate between 2-stroke & 4-stroke engine C.I & S.I engine.

5. Gas Power Cycle

- 5.1 Carnot cycle
- 5.2 Otto cycle.
- 5.3 Diesel cycle.
- 5.4 Dual cycle.
- 5.5 Solve simple numerical.

6. Fuels and Combustion

- 6.1 Define Fuel.
- 6.2 Types of fuel.
- 6.3 Application of different types of fuel.
- 6.4 Heating values of fuel.
- 6.5 Quality of I.C engine fuels Octane number, Cetane number.

Chapter-1

Thermodynamic concept & Terminology

THERMODYNAMICS:

- The name thermodynamics comes from Greek word theme(heat)and dynamic(power)
- It is that branch of science which deals with different form of energy and its transformation
- Energy transformation- mostly involve heat into work

1.1 System/Thermodynamic system

It is defined as a certain quantity of matter or a prescribed region in space chosen for thermodynamic study (Study of pressure, temperature, Volume etc.)

Surrounding:

Everything outside the system boundary is called Surrounding

Boundary:

The real or imaginary surface that separate the system from surrounding is called boundary

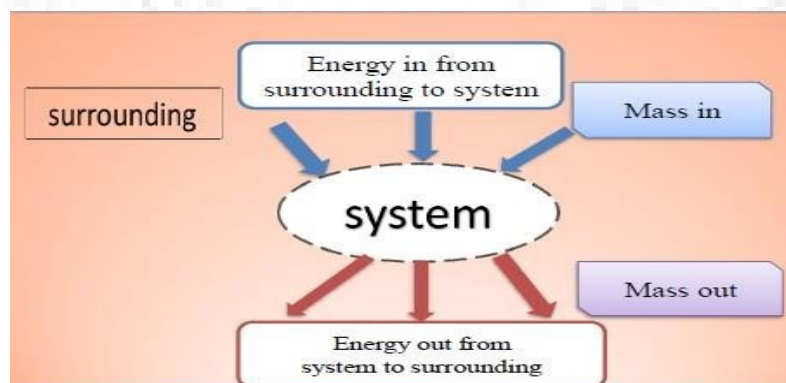
Note- Boundary may be fixed or movable

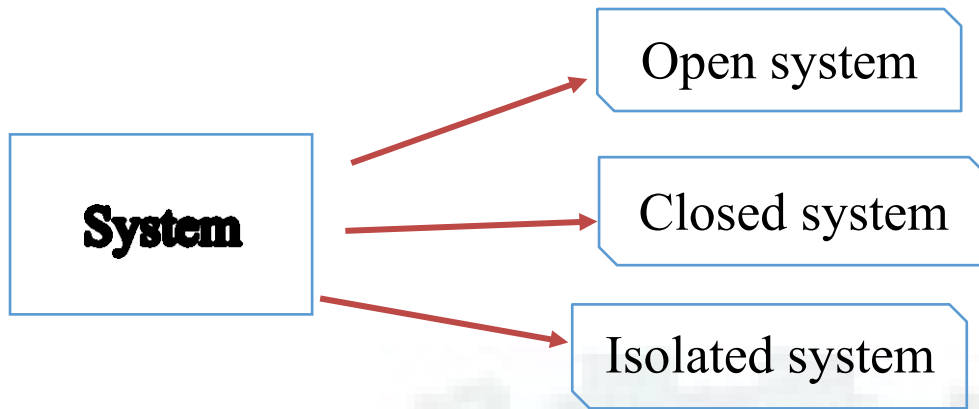
Universe:

System and surrounding together called universe

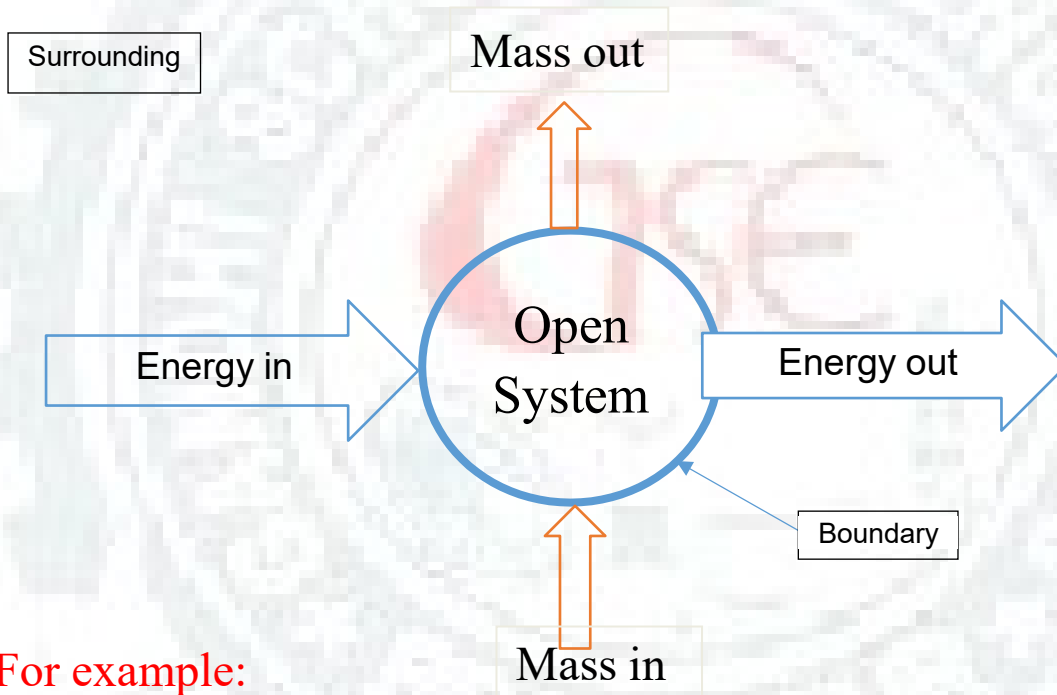
There are two type of exchange occur between the system and surroundings

1. Exchange of Energy (may be heat or work)
2. Exchange of matter(i.e. mass)



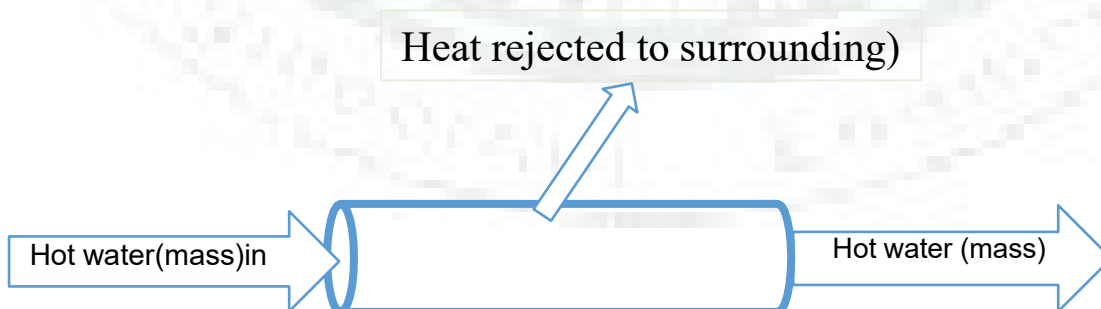


Open system- It is a system where both mass and energy (Heat or Work) can cross the system boundary.



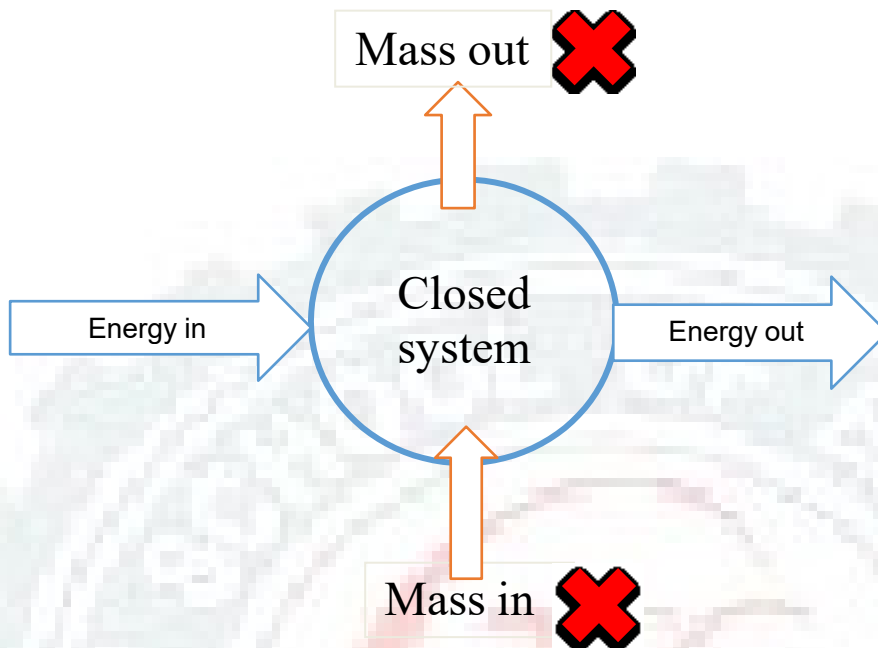
For example:

1. Hot water flow through a pipe



2. An open cup of coffee

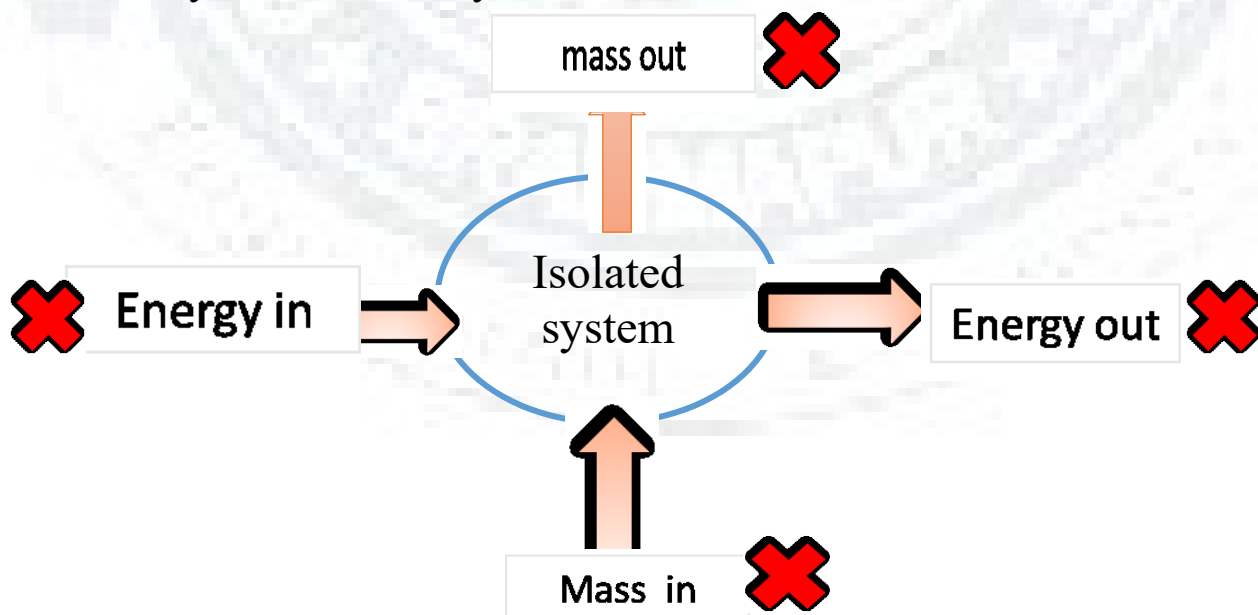
Closed system- It is a system where mass cannot cross the system boundary but energy can cross.



For example:

1. Food item in a pressure cooker
2. A capped cup of coffee

Isolated system: It is a system where both mass and energy cannot cross the system boundary



For example: Coffee in a close well-insulated thermos flask

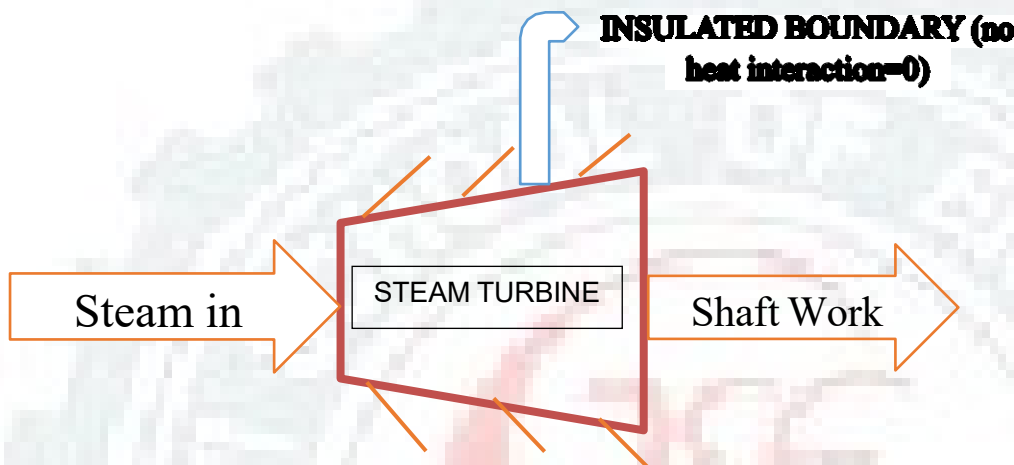
Adiabatic system:



It is a special type of open system, in which mass can cross the control surface, but energy in the form of heat is not allowed to cross the boundary of the system

- However ,energy in other form(work) can enter and leave the system

For example: steam turbine, pump and water turbine



Difference between open and closed system

Open system	Close system
1. It is also called flow system.	1. It is also called non-flow System.
2. Mass as well as energy can enter or leave the boundary of system.	2. No mass can cross the boundary, while energy can enter or leave the boundary of the system.
3. If heat transfer does not take place across control surface then the open system is called adiabatic system.	3. If energy transfer does not takes place across the system boundary is called Isolated system
4.For example: Water flow through pipe, a cup of coffee	4.For example: A pressure cooker, capped cup of coffee

Difference between isolated and adiabatic system

Isolated system	Adiabatic system
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1. It is a special type of closed system.	1.It is a special type of an open system
2.Mass and energy do not cross the boundary of the system	2.Mass and energy ,except heat energy , can cross the boundary of the system
3.It is a closed system ,which is insulated at its boundaries ,thus it becomes isolated from its surrounding	3.It is an open system ,which is insulated at its real boundaries , thus heat cannot cross it
4.E.g. Thermos flask	4.E.g. Insulated steam turbine, water pump etc.

1.2 Thermodynamic properties of a system

Pressure:

- It is defined as normal force exerted by a fluid per unit area
- If F is the normal force to the area A ,then

$$P = \frac{F}{A}$$

Where force F= mass (m) × acceleration due to gravity (g)

We know

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

$$\rightarrow \text{Mass } (m) = \text{density } (\rho) \times \text{volume}(V)$$

$$\rightarrow \text{Volume} = \text{area } (A) \times \text{depth } (h)$$

$$\rightarrow \text{Mass} = \rho \times A \times h$$

$$\rightarrow F = \rho \times A \times h \times g$$

$$\rightarrow P = \frac{F}{A} = \frac{\rho \times A \times h \times g}{A} = \rho \times g \times h$$

$$\mathbf{P = \rho \times g \times h}$$

Where ρ = density of fluid in (kg/m^3)

g = acceleration due to gravity ($9.81 \text{ m}/\text{s}^2$)

h = height of fluid in (m)

- Pressure is expressed in, N/M^2 ,Pascal(pa), bar



$$1\text{pa} = 1\text{N}/\text{M}^2$$

$$1\text{bar} = 10^5\text{pa}$$

$$1\text{Kpa} = 10^3\text{pa}$$

$$1\text{Mpa} = 10^6\text{pa}$$

$$1\text{Gpa} = 10^9\text{pa}$$

Pressure is measured by pressure gauge

1. Barometer
2. Manometer
3. Piezometer
4. Bourdon tube pressure gauge etc.

NOTE:

- Density of water is $1000\text{kg}/\text{m}^3$
- Density of mercury is $13600\text{kg}/\text{m}^3$

Types of pressure:

1. **Atmospheric Pressure:** It is the pressure exerted by envelope of air surrounding the earth's surface

The standard atmospheric pressure (P_{atm}) = 1.01325 bar or 101,325 pa

$$P_{atm} = 760\text{mm high column of mercury}$$

$$P_{atm} = 10.33\text{ m high column of water}$$

2. **Absolute pressure:** It is defined as the pressure, which is measured with reference to absolute zero pressure.

- It designated as P_{abs} or simply P

NOTE

- ❖ Absolute zero pressure: It is the pressure below which there is no movement of molecules
- ❖ pressure is related to momentum while temperature is related to kinetic energy

3. **Gauge pressure:** It is defined as the pressure that is measured with the help of a pressure-measuring instrument, by taking

atmospheric pressure as datum.



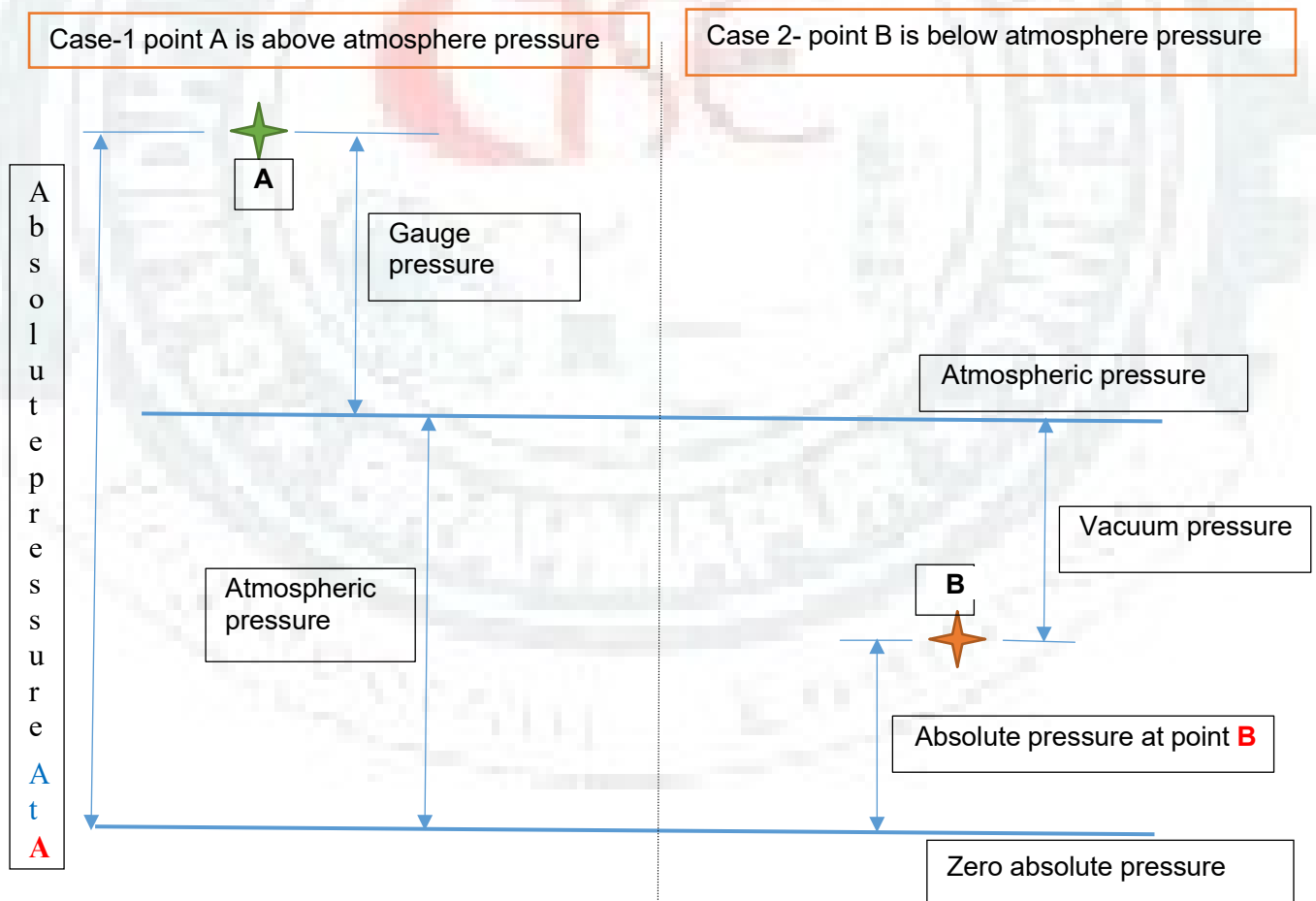
- The pressure above atmospheric pressure is called gauge or positive pressure
- It is designated as P_{gauge}

4. Vacuum pressure: It is defined as the pressure below the atmospheric pressure is called vacuum pressure or negative pressure

- It is designated as P_{vacuum}

Relationship between P_a , P_{atm} , P_{gauge} & P_{vac}

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



Temperature: It is a thermodynamic property, which determine the degree of hotness or the level of heat intensity of a body

- It is measured with the help of thermometer.
- High temperature is measured by pyrometer.



The followings are the two commonly scale for measuring the temperature of body

1. Celsius scale or degree centigrade (written as °c)
2. Fahrenheit scale(written as °F)

Note: The relation between Celsius scale and Fahrenheit scale is given by

$$C = (F-32) \times \frac{5}{9}$$

- The SI unit of temperature is kelvin(written as K)
- Conversion of °c(degree centigrade) to kelvin $K = °C + 273$

Volume: The volume of a thermodynamic system typically refers to the volume of the working fluid, such as, for example, the fluid within a piston.

- It is expressed in m^3 (cubic meter), lt. (liter)
- It is denoted by symbol V

Enthalpy: The enthalpy is the measure of energy in a thermodynamic system

- It is the thermodynamic quantity equivalent to the total heat contain of a system
- The enthalpy is defined to be the sum of the internal energy (U)plus the product of the pressure (p) and volume(V)
I.e. $H = U + PV$
- It is denoted by symbol H
- It is expressed in joule(J) or kilojoule(KJ)

Entropy: It is defined as the property of system which measure the degree of randomness or dis- orderness of the molecules in the system

- It is denoted by symbol S
- It is expressed in J/K or KJ/K

Internal energy: It is the energy possessed by a body or a system due to its molecular arrangement and motion of the molecules.

- It is denoted by U
- It is expressed as J or KJ

Note: The total energy of a system (E) is equal to sum of potential energy, kinetic energy and internal energy

$$E = PE + KE + U$$



- When system is stationary and the effect of gravity is neglected ,the PE=0 and KE=0 such a case

$$E=U$$

1.3 Intensive and extensive properties:

1.3 **Thermodynamic property:** To describe and analyses a system it is necessary to know some quantities that are characteristics of it .These quantities are called properties

E.g. pressure, volume, temperature, enthalpy & entropy etc.

Types of property: It may be classified as

- i. Intensive properties
- ii. Extensive properties

- i. **Intensive properties:** These are the property which are independent of mass ,size and extent of the system

E.g. Temperature, pressure, velocity, density, viscosity and specific heat etc.

- ii. **Extensive properties:** These are the properties of the system which depend upon size and extent such as mass & volume of the system

- Example: Total volume , total energy, weight , total Mass, area, Enthalpy, Entropy, Internal energy, Heat capacity

Specific properties:

It is defined as extensive properties per unit mass

- Specific volume(P) = $\frac{\text{Volume}(V)}{\text{Mass}(m)}$ (unit $\frac{m^3}{Kg}$)
- Specific enthalpy(h) = $\frac{\text{Enthalpy}(H)}{\text{Mass}(m)}$ (unit $\frac{J}{Kg}$)
- Specific entropy(s) = $\frac{\text{Entropy}(S)}{\text{Mass}(m)}$ (unit $\frac{J}{Kg \times K}$)

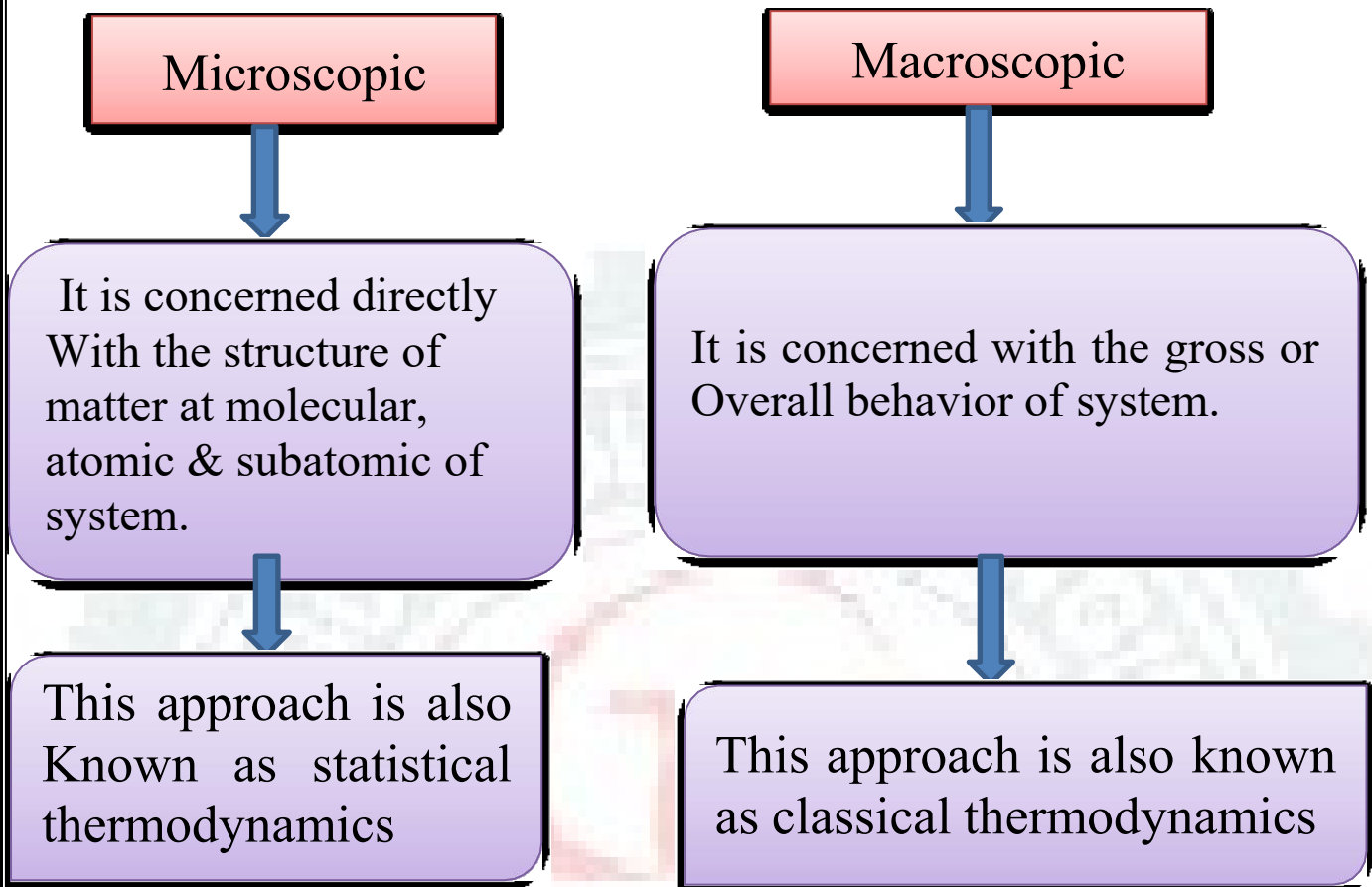
Note: Extensive property per unit mass is intensive property

- Specific volume, specific internal energy, specific entropy,

specific enthalpy etc. all are intensive properties.



Microscopic vs. macroscopic Approach:



1.4 Define thermodynamic processes, path, cycle, state

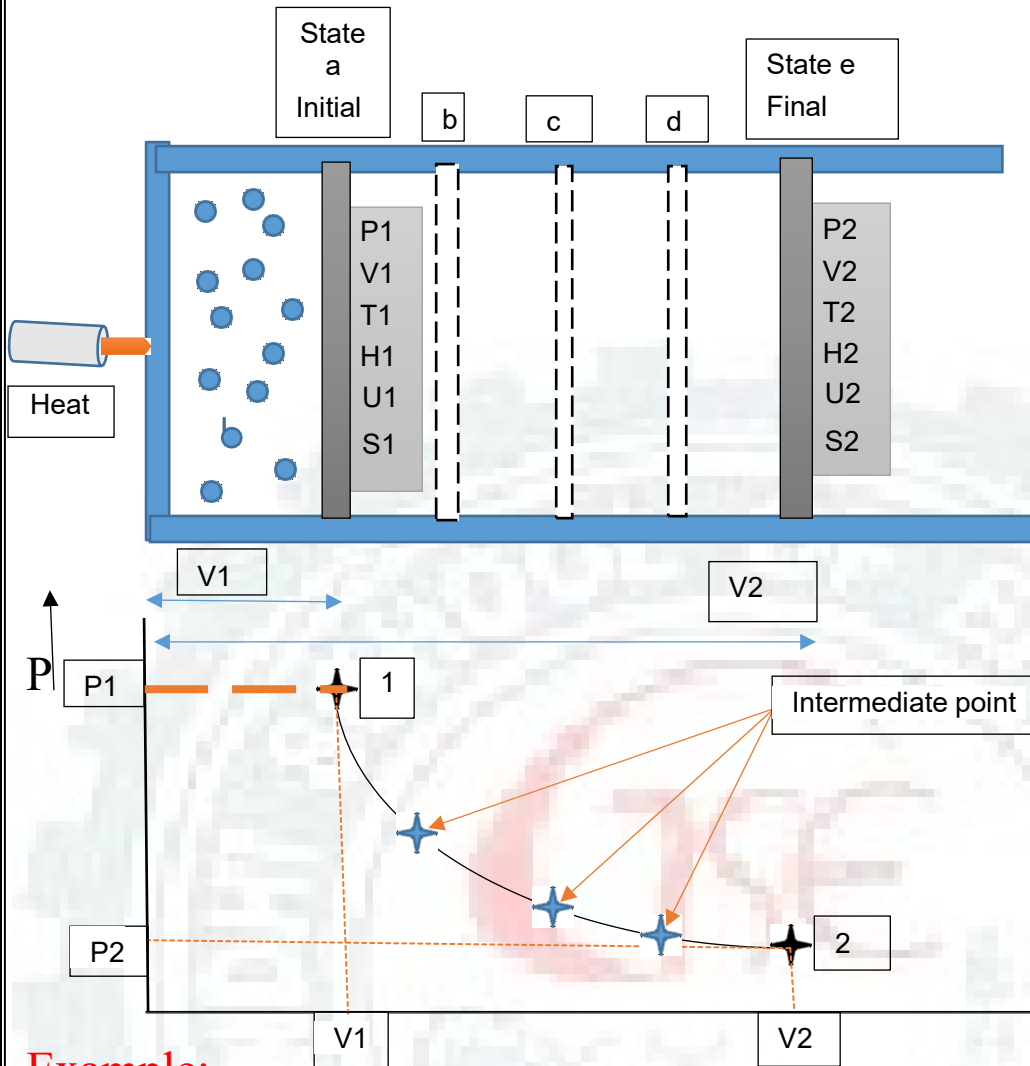
State: Thermodynamic state is defined as the condition of the system at any given point of time

- State is described by its properties
- Whenever there is change in anyone of the property, then the system is said to have a change of state

Path: A locus of series of state through which a system passes between initial to final state is called a path

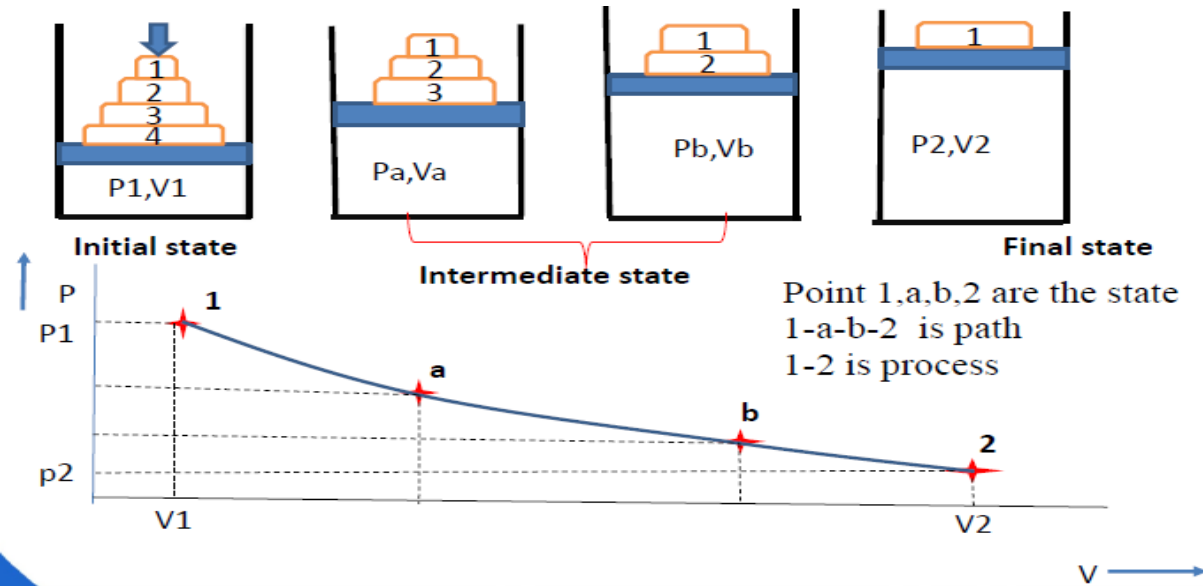
Process: When any property of system changes, the state changes and the system is said to have undergone a process

- The state change due to mass and energy interaction with the surrounding.

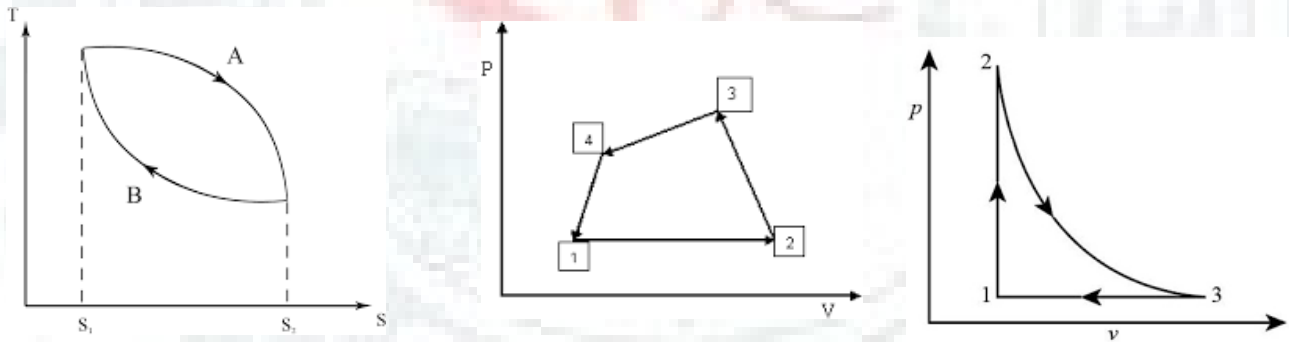


Example:

- Suppose in a piston cylinder arrangement air is trapped inside at pressure, (P_1) and volume (V_1) as shown in above fig i.e. initial state.
- When heat is added the piston gradually start change its state and reach a final state at pressure (P_2) and volume (V_2).
- From initial to final state piston pass through an intermediate state i.e. state b ,c & d , if we join initial to final state and all intermediate state by line is called path
- If all the state is specified by properties is process(as shown in above p-v diagram 1-2 is process)



Cycle: When a process or processes are performed on a system in such a way that its initial and final state are identical, it is known as thermodynamic cycle.



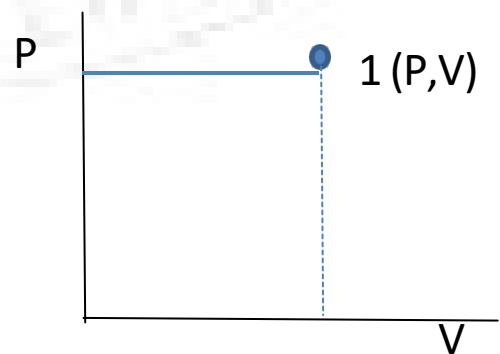
Point function: If a point is located on a graph by two properties of system

- For example- Pressure, temperature, Volume etc.
- It is an exact differentiation

$$\text{i.e. } \int_1^2 dp = p_2 - p_1$$

$$\int_1^2 dT = T_2 - T_1$$

$$\int_1^2 dV = V_2 - V_1$$

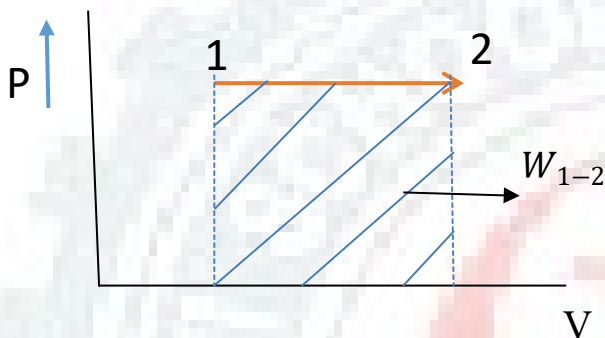


Path function: There are certain quantity, which cannot be located on graph by a single point, but they can be known by area under process. Such quantities are known as path function.

- It is an inexact differentiation.
- Heat and work are path function

i.e. $\int_1^2 \delta Q$, $\int_1^2 \delta W$

- It depends upon path
- Also can be written as Q_{1-2} , W_{1-2}



1.5 Thermodynamic Equilibrium: A system is said to be equilibrium if its satisfy following type of equilibrium.

- I. Thermal equilibrium
- II. Mechanical equilibrium
- III. Chemical equilibrium

- I. Thermal equilibrium:** In this equilibrium, the temperature is same throughout the entire system, because temperature difference is potential to heat flow
- II. Mechanical equilibrium:** In this equilibrium, in which there is no unbalance force within the system and also between system and surrounding.
- III. Chemical equilibrium:** In this equilibrium, there is no chemical reaction takes place within the system or its chemical composition does not change with time.

1.6 Quasi-static Process

- Quasi means almost static condition
- When a process proceed in such a manner that the system remains, infinitesimally close to an equilibrium in state at all times is called quasi-static process.
- Infinite slowness is the characteristic of quasi-static process.
- In this process all, the intermediate states are in equilibrium phase.

1.7 Energy and its sources:

A system is said to possess energy, when it is capable of doing some work.

- The energy of a system may be

I. **Stored energy:** This is the energy, which contained within the system boundaries.

E.g. potential energy & kinetic energy- Macroscopic form of energy
Internal energy- microscopic form of energy

II. **Transit energy:** This is the energy, which crosses the system boundaries.

E.g. Heat, work and electrical energy

Note

Flow energy: It is the energy due to transfer of mass across the boundaries of a system.

- It is sometimes called flow work
- Force exerted on section a-a is $(P \times A)$

The work done by fluid in pushing 1kg of fluid at section b-b will be $(P \times A \times l)$

Flow work = $P \times \frac{kg}{m^3}$

Where P- is the pressure in $\frac{N}{m^2}$

P is specific volume in $\frac{kg}{m^3}$

Source of energy: The various source of energy available are

1. **Fuel:** solid fuel , liquid fuel, gaseous fuel



They contain chemical energy that may be transfer into heat energy by their combustion. The energy further converted into mechanical energy by heat engine.

2. **Water:** The water is available at certain height; it is possess potential energy (PE). The PE may be transform into kinetic energy by bringing into low level and then KE may converted into mechanical energy by a hydraulic prime mover(water turbine)
3. Winds
4. Ocean tide and waves
5. Solar energy
6. Nuclear energy
7. Geothermal energy

1.8 Work, heat and comparison between the two.

Heat: It is defined as the energy transferred, across the boundary of a system because of the temperature difference between the systems and surrounding, without transfer of mass

- It is represented by Q.
- It is expressed in joule (J) or kilojoule (KJ).
- The amount of heat transfer from the state 1 to state 2 is designated as Q_{1-2} .
- Heat transfer per unit mass of a system is denoted by q

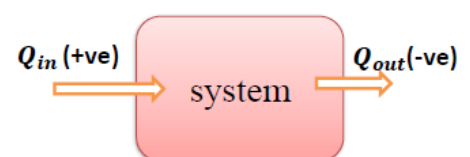
Expressed as $q = \frac{Q}{m}$ ($\frac{kJ}{kg}$)

Heat interaction:

- The transfer of heat into a system is known as heat addition or heat supply.
- The transfer of heat from the system is known as heat rejection.
- It is recognized as it crosses the system boundary

Sign convection for heat:

- Heat supply is consider positive(+ve)
- Heat rejection is consider negative(-ve)



Work: It is defined as the energy transferred, across the boundary of a system because of potential difference (like pressure, velocity, voltage etc.) other than temperature difference, without transfer of mass.

- A moving piston, a rotating shaft, a rising weight are all associated with work interaction.
- It is denoted by W .
- It is also measured in J, KJ.

Sign convention for work:

- Work done produce /work done is positive
- Work consumption is negative

1.8 Similarity between heat and work:

- Both are recognized at the boundary of system as they cross it, Heat and work are boundary phenomenon.
- A system may have energy but no heat and work because heat and work are transient phenomenon
- Both are path function
- Both are associated with a process
- Both are inexact differentiation.
- Heat and work transfer represented by, ∂Q & ∂W respectively.

Dissimilarity between heat and work:

- Heat is a low grade energy and work is a high grade energy
- The entire quantity of work can be converted into heat or any other form of energy.
- While conversion of entire quantity of heat into work is not possible.

1.9 Mechanical Equivalent of Heat

- It was established by joule that heat and mechanical energies are mutually convertible.
- He established ,experimentally that there is a numerical relationship between the unit of heat and work
- The relation id denoted by **J** and is known as joule's equivalent or mechanical equivalent of heat.

1.10 Work transfer, Displacement work:

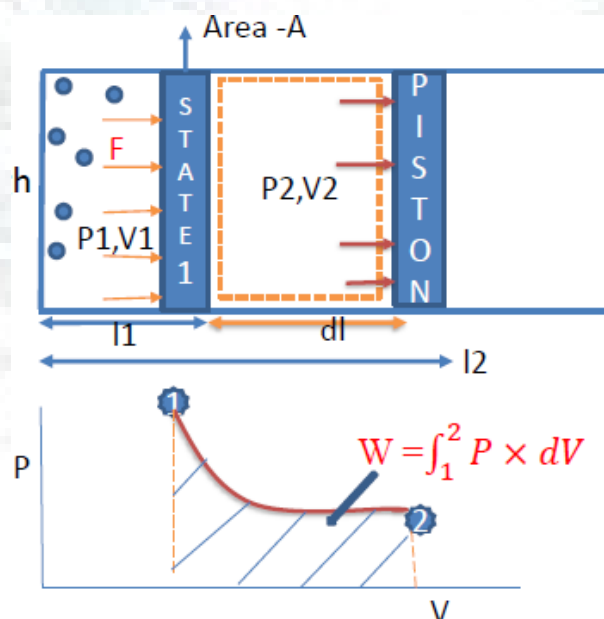
Displacement work or moving boundary work:

Consider a certain amount of gas taken in a cylinder enclosed by piston as shown in fig. below

Let the gas pressure is P and volume is V

And piston cross section area is A

- If the piston is allowed to move through a distance dl in quasi-static manner as the force applied on piston is
- The differential work transfer through a displacement of dl during this process



$$\delta w = F \times dl = P \times A \times dl$$

$$(\because P = \frac{F}{A} \rightarrow F = P \times A)$$

$$\delta w = P \times dV \quad (\because A \times dl = dV)$$



The total boundary work can be obtained by adding all differential work from the initial state 1 to final state 2 as

$$W = \int_1^2 P \times dV \quad (\text{KJ})$$

- Work transfer during a process is equal to area under curve P-V diagram

$$W = \int_1^2 P \times dV \quad (\text{KJ})$$

- Only applied to non-flow system

Problem related to pressure

Convert 1mm of Hg in N/m^2 ?

$$1\text{mm} = 0.001\text{m}$$

$$\begin{aligned} \text{We know that pressure } P &= \rho_{\text{Hg}} \times g \times h \\ &= 13600 \times 9.81 \times 0.001 = 133.416 \text{ N/m}^2 \end{aligned}$$

Convert 1m of water in N/m^2 ?

Q1. A vacuum recorded in the condenser of a steam power plant is 740 mm of Hg. Find the absolute pressure in the condenser in Pascal. The barometric reading is 760 mm of Hg. (Given 1mm of Hg= 133.4 N/m^2)[2019W]

Data given:

$$P_{\text{vacuum}} = 740 \text{ mm of Hg} = 740 \times 133.4 = 98,716 \text{ N/m}^2 = 98,716 \text{ pa}$$

We know that barometer read atmospheric pressure

$$P_{\text{Atmosphere}} = 760 \text{ mm of Hg} = 760 \times 133.4 = 101,384 \text{ N/m}^2 = 101,384 \text{ pa}$$

Solution:

- We know that $P_{\text{absolute}} = P_{\text{atmospheric}} - P_{\text{vacuum}}$

$$P_{\text{absolute}} = 101,384 - 98,716 = 2,668 \text{ pa (Ans.)}$$

Q2. The pressure of steam inside the boiler, as measured by pressure gauge, is 1N/mm^2 . The barometric pressure of the atmosphere is 765mm of mercury. Find the absolute pressure of steam in N/mm^2 , N/m^2 , kPa and bar.

Q3. In the condenser of a steam power plant, the vacuum recorded as 700 mm of Hg. If the barometer reading is 760 mm of Hg. Find, the absolute pressure in the condenser in N/m^2 , Kpa and bar.

Problem related to Displacement work

1. A fluid system undergoes a non-flow frictionless process. The pressure and volume are related as $P = 5/V + 1.5$ Where P is in bar and V is in m^3 , During the process the volume changes from 0.15m^3 to 0.05m^3 . Calculate the work done by the fluid.

Data given:

$$P = 5/V + 1.5, V_1 = 0.15\text{m}^3, V_2 = 0.05\text{m}^3$$

Solution:

For non-flow process Work done = $W = \int_1^2 P \times dV$ (KJ)

In place of P put $P = 5/V + 1.5$

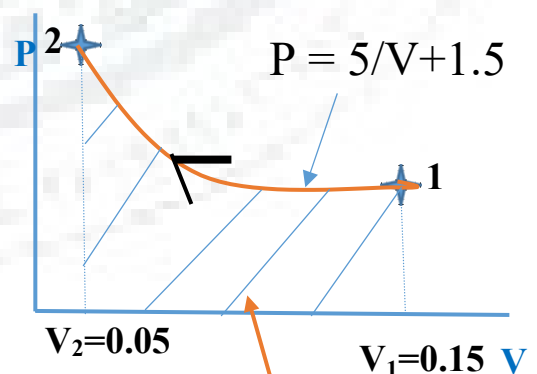
$$W_{1-2} = \int_1^2 P \times dV = \int_1^2 (5/V + 1.5) \times dV$$

$$= \int_1^2 (5/V \times dV + 1.5 \times dV)$$

$$= \int_1^2 \left(\frac{5}{V} \times dV\right) + \int_1^2 (1.5 \times dV)$$

$$= 5 \int_1^2 \left(\frac{1}{V} \times dV\right) + 1.5 \int_1^2 dV$$

$$= 5 \times [\ln V]_1^2 + 1.5 \times [V]_1^2$$



Area under P-V diagram give work done W_{1-2}

$$=5 \times [V_2 - \ln V_1] + 1.5 \times [V_2 - V_1]$$



$$= 5 \times \left[\frac{V_2}{V_1} \right] + 1.5 \times \left[\frac{V_2}{2} - \frac{V_1}{2} \right]$$

Put the value of V_1 & V_2

$$= 5 \times \left[\frac{0.05}{0.15} \right] + 1.5 \times [0.05 - 0.15]$$

$$= -5.643 \text{ bar} \times \text{m}^3$$

$$= -5.643 \times 10^5 \text{ Pa} \times \text{m}^3$$

$$1 \text{ bar} = 10^5 \text{ Pa}$$

$$= -5.643 \times 10^5 \frac{\text{N}}{\text{m}^2} \times \text{m}^3$$

$$1 \text{ Pa} = 1 \frac{\text{N}}{\text{m}^2}$$

$$= -5.643 \times 10^5 \text{ N} \times \text{m}$$

$$\text{N} \times \text{m} = \text{Joule}$$

$$= -5.643 \times 10^5 \text{ J}$$

2. During a non-flow reversible process, a gas enclosed in a cylinder-piston assembly expands from 2m^3 to 4m^3 . The pressure-volume correlation is given by $P=V^2+6/V$, when P is in bar. Determine the work done by the system (gas).

Data Given:

$$V_1 = 2\text{m}^3, V_2 = 4\text{m}^3, P = V^2 + 6/V$$

$$\text{For non-flow process Work done} = W = \int_1^2 P \times dV \quad (\text{KJ})$$

$$W_{1-2} = \int_1^2 (V^2 + 6/V) \times dV$$

$$W_{1-2} = \int_1^2 (V^2 \times dV + 6/V \times dV)$$

$$= \int_1^2 V^2 \times dV + \int_1^2 6/V \times dV = \int_1^2 V^2 \times dV + \int_1^2 \left(\frac{6}{V} \times dV \right)$$

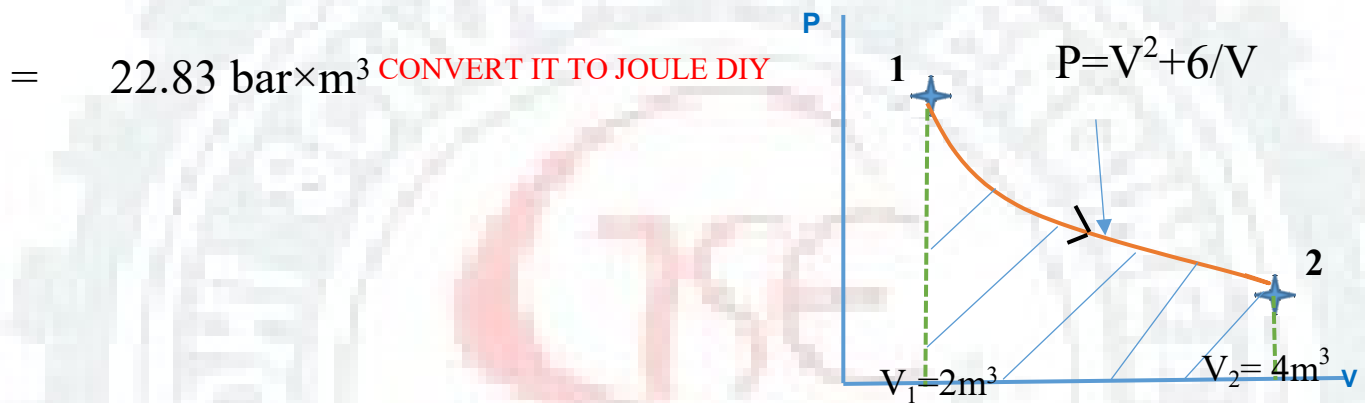
$$= \left[\frac{V^3}{3} \right]_1^2 + 6 \times [\ln V]_1^2 = \frac{1}{3} \times (V_2^3 - V_1^3) + 6 \times \left[\ln \frac{V_2}{V_1} \right]$$

$$= \frac{1}{3} \times (4^3 - 2^3) + 6 \times \left[\ln \frac{4}{2} \right] = \frac{1}{3} \times (64 - 8) + 6 \times [\ln 2]$$

Put the value of $V_1 = 2\text{m}^3$, $V_2 = 4\text{m}^3$

$$= \frac{1}{3} \times (4^3 - 2^3) + 6 \times \left[\ln \frac{4}{2} \right] = \frac{1}{3} \times (64 - 8) + 6 \times [\ln 2]$$

$$= 18.67 + 4.16$$



3. In a reversible non-flow process the work is done by a substance in accordance with $V = 2.80/P \text{ m}^3$, Where P is the pressure in bar .Find work done on or by system as pressure increases from 0.7bar to 7 bar.

DIY- Do It Yourself

Branch: Mechanical

Semester: 3rd Sem

Subject: Engineering Material

Chapter: 2

Topic: Thermal engineering - I

Faculty: SIBASISH SAHU

CHAPTER-2

2. Laws of Thermodynamics

2.1 State & explain Zeroth law of thermodynamics.

2.2 State & explain First law of thermodynamics.

2.3 Limitations of First law of thermodynamics

2.4 Application of First law of Thermodynamics (steady flow energy equation and its application to turbine and compressor)

2.4 Second law of thermodynamics (Clausius & Kelvin Plank statements).

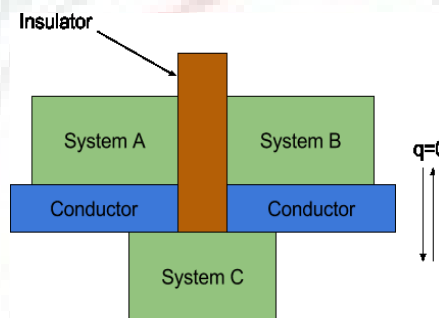
2.5 Application of second law in heat engine, heat pump, refrigerator & determination of Efficiencies & C.O.P (solve simple numerical)

2.1 State & explain Zeroth law of thermodynamics

Statement: The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other.

Explanation:

- Considering three systems. A, B, and C that initially are not in thermal equilibrium. We separate systems A and B with an adiabatic wall(ideal insulating material),
- We let system C interact with both systems A and B.



- We wait until thermal equilibrium is reached; then A and B are each in thermal equilibrium with C.
- Also they are in thermal equilibrium with each other.

Flow & Non flow process:

Flow process:

- Processes undergone by a fluid in open system are called flow process
- So in flow process, there is continuous flow of fluid from one region to another region

Non-flow process:

- Processes undergone by a fluid in closed system are called non-flow processes.
- So in non-flow process, there is no mass interaction between

system and surrounding.

2.2 State & explain First law of thermodynamics

This law may be stated as follows:

- a) First law of thermodynamics for cycle



Statement:

- When a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the network transfer.
- In the other word, cyclic integral of heat transfer is equal to cyclic integral of work transfer.

Mathematically

$$\oint \delta Q = \oint \delta W$$

Where

$\oint \delta Q$ = net heat transfer during the cycle

$\oint \delta W$ = network transfer during the cycle

\oint - stands for cyclic integral

Explanation:

- Let a system undergo cyclic Process along 1-2-1
- where 1-2 & 2-1 are processes
- Also let

Q_1 - Heat added to the system along 1-2

Q_2 - Heat rejected from the system along 2-1

W_1 - Work done by the system along 1-2

W_2 - Work done on the system along 2-1

According to 1st law of thermodynamic undergone a cycle

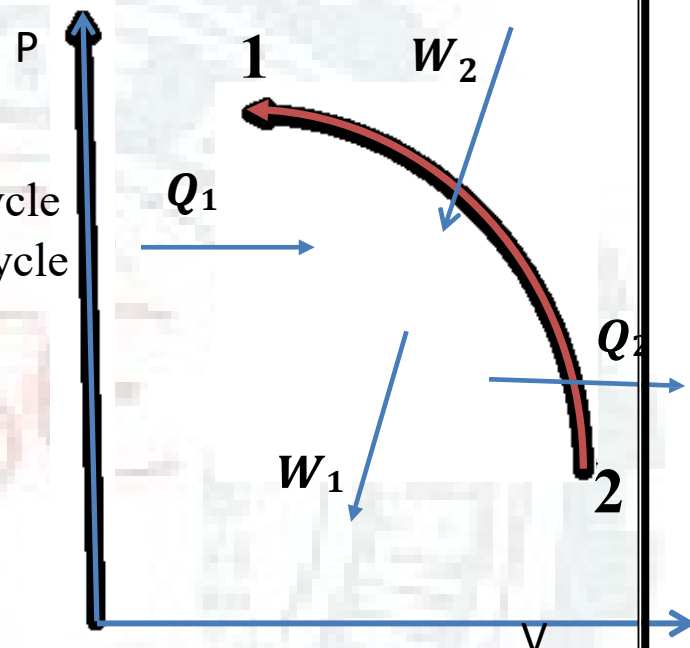
Net heat transfer (Q_{net}) = Net work done (W_{net})

For cycle 1-2-1

$$Q_{net} = Q_1 + (-Q_2) = Q_1 - Q_2$$

$$W_{net} = W_1 + (-W_2) = W_1 - W_2$$

$$Q_1 - Q_2 = W_1 - W_2$$



First law of thermodynamics for process

b) The energy can neither be created nor destroyed though it can be transformed from one form to another.

I. whenever heat is absorbed by a system it goes to increase its energy plus do some external work (P dv work)

I.e. $Q=dE+W$ For flow process (mass in and out)

In differential form $\delta Q= dE+\delta W$

Where Q= energy entering a system causing an increasing in the system total energy by dE .

W= producing some external work $\int P dv$

Where

$dE =$ change in flow energy+ change in(K.E)+change in(P.E)+change in internal energy

II. When system is stationary, the effect of gravity is neglected and there is no flow of the mass into or out of the system

Then PE=0, KE=0 and change in flow work (Pv) =0

Such a case

$dE =$ change ⁰ in flow energy+ change ⁰ in(K.E)+change in(P.E)+change in internal energy

$$dE = dU$$

Then

$Q=dU+W$ For non-flow process

$dU =$ Change in internal energy

In differential form it becomes

$$\delta Q = dU + \delta W$$

For a change of state from 1 to 2

$$\text{We have } Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

2.3 Limitations of First law of thermodynamics

1. It does not explain the direction of processes means no given direction of flow of heat.
2. It does not differentiate between heat and work. All work can be converted into heat but all heat cannot be converted into work.

2.4 Application of First law of Thermodynamics (steady flow energy equation and its application to turbine and compressor)

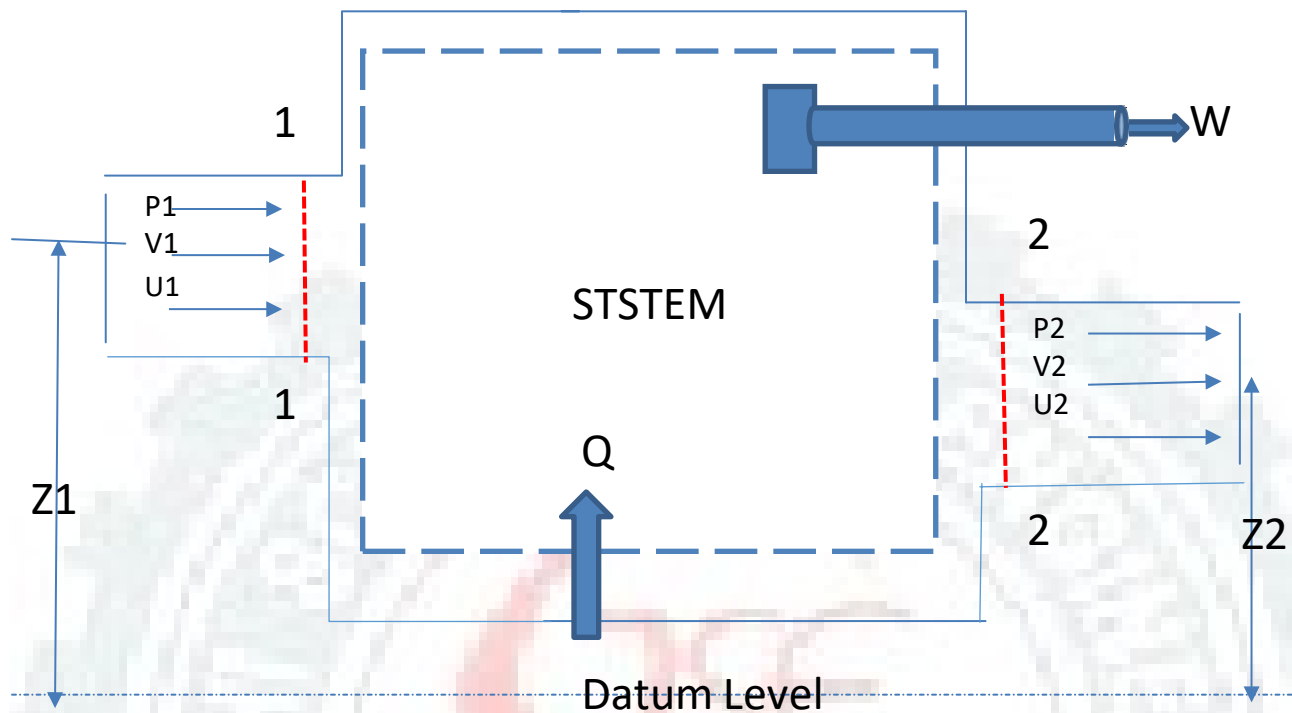
Steady flow energy equation

According to first law of thermodynamics the total energy, entering a system must be equal to total energy leaving, for unit mass.

Assumptions:

The following assumptions are made in the system analysis:

- (i) The mass flow through the system remains constant.
- (ii) Fluid is uniform in composition.
- (iii) The only interaction between the system and surroundings are work and heat.
- (iv) The state of fluid at any point remains constant with time.
- (v) In the analysis only potential, kinetic, and internal and flow energies are considered.



- The above fig shows a steady flow system
- The control volume is shown by means of dotted lines.
- At section 1-1, the working fluid enters the control volume. Various form of energy possessed by it are shown
- Similarly the working fluid leaving the control volume at section 2-2.
- As mass of fluid entering =mass of fluid leaving the system ($m_1=m_2=m$)
- The energy of an **element at inlet** is given by $m \left\{ u_1 + \frac{V_1^2}{2} + g Z_1 + \text{flow work} \left(\frac{P_1}{\rho} \right) \right\}$
- The energy of an **element at outlet** is given by $m \left\{ u_2 + \frac{V_2^2}{2} + g Z_2 + \text{flow work} \left(\frac{P_2}{\rho} \right) \right\}$

- now steady flow energy equation

Energy in all form entering the system = Energy in all form leaving

- Now writing energy balance for system

$$(PE_1 + KE_1 + u_1 + P_1P_1) + Q = (PE_2 + KE_2 + u_2 + P_2P_2) + W$$

- $u_1 + P_1P_1 = h_1$, $u_2 + P_2P_2 = h_2$ & $m_1 = m_2 = m$

So the above equation may be written as

$$(gZ_1 + \frac{1}{2}v_1^2 + P_1P_1) + Q = m(gZ_2 + \frac{1}{2}v_2^2 + P_2P_2) + W$$

$$(gZ_1 + \frac{1}{2}v_1^2 + h_1) + Q = m(gZ_2 + \frac{1}{2}v_2^2 + h_2) + W \text{--- Steady flow energy equation (SFEE)}$$

Steady flow energy equation per unit mass

$$gZ_1 + \frac{v_1^2}{2} + h_1 + q = gZ_2 + \frac{v_2^2}{2} + h_2 + w$$

Where

P_1P_1 , P_2P_2 - Flow work at entering and leaving

$\frac{1}{2}v_1^2$, $\frac{1}{2}v_2^2$ - kinetic energy at entering and leaving

gZ_1 , gZ_2 - potential energy at entering and leaving

u_1 , u_2 - Internal energy at entering and leaving per unit mass

h_1 , h_2 - Enthalpy at inlet and outlet

Q - Heat transfer in (kJ)

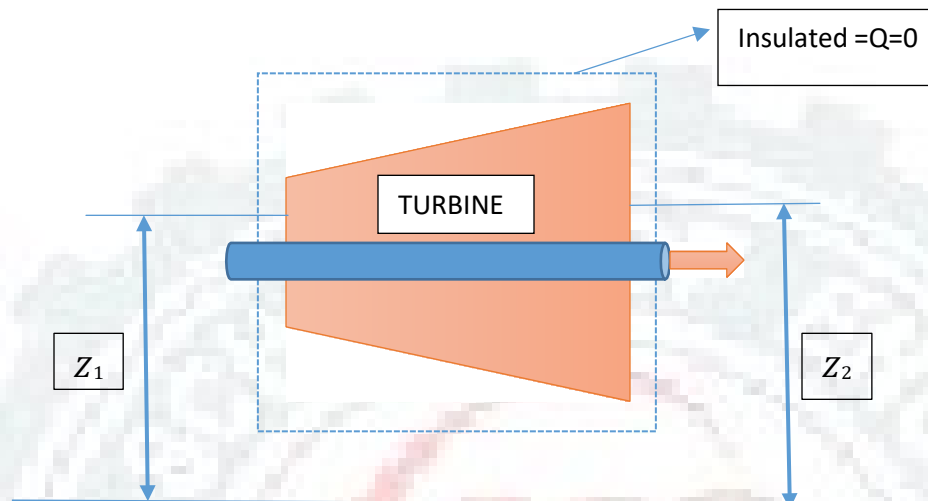
W - Work done (kJ)

q - Heat transfer per unit mass in (kJ/kg)

w - work done per unit mass (kJ/kg)

Steady-flow devices:

Turbine:



- It is a device in which high temperature and high-pressure fluid is expanded to low pressure and temperature resulting generation of positive work at turbine shaft.
 - Turbine is work-producing device.
 - Turbine using gas as working fluid as gas turbine and using water as working fluid as water turbine & using steam i.e. steam turbine.
 - Since turbine is well insulated $Q=0$.
 - The work output = shaft work = W .
 - The steam velocity at the turbine inlet \approx the steam velocity at outlet.
- i.e. $V_1 \approx V_2$
- The turbine is positioned horizontally so $Z_1 = Z_2$.
 - Therefore applying steady flow energy equation (SFEE) to the control volume of steam turbine

$$(gZ_1 + \frac{V_1^2}{2} + h_1) + Q = m(gZ_2 + \frac{V_2^2}{2} + h_2) + W$$

$$W = \{g(Z_1 - Z_2) + (\frac{V_1^2}{2} - \frac{V_2^2}{2}) + (h_1 - h_2)\} + 0$$

$W = (h_1 - h_2)$ SFEE for turbine

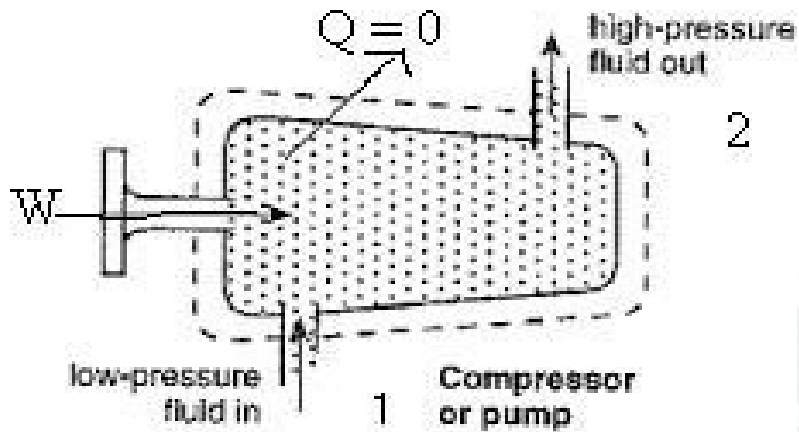
Where m - Mass of the working fluid

h_1 - Specific enthalpy at inlet in KJ/Kg

h_2 - Specific enthalpy at outlet in KJ/Kg

Compressor:

- Compressor is defined as one mechanical device, which is used for increasing the pressure of fluid by securing the work energy from the surrounding.
- Work energy will be supplied to the system i.e. compressor from surrounding with the help of a rotating shaft.
- Let us see here the following figure of compressor, where low pressure fluid enters at inlet1 and high-pressure fluid leaves the compressor at its outlet section i.e. 2.
- Since Compressor is well insulated $Q=0$.
- The work absorbing =shaft work= $(-W)$
- $V_1 \approx V_2$
- $Z_1 = Z_2$ (compressor placed horizontally)



- Therefore applying steady flow energy equation (SFEE) to the control volume of steam turbine

$$m(gZ_1 + \frac{V_1^2}{2} + h_1) + Q = m(gZ_2 + \frac{V_2^2}{2} + h_2) + (-W)$$

$$W = \left\{ g(Z_2 - Z_1) + \left(\frac{V_2^2}{2} - \frac{V_1^2}{2} \right) + (h_2 - h_1) \right\} - Q$$

By applying conditions

$$W = \left\{ g(Z_2 - Z_1) + \left(\frac{V_2^2}{2} - \frac{V_1^2}{2} \right) + (h_2 - h_1) \right\} - 0$$

$W = m(h_2 - h_1)$SFEE for compressor

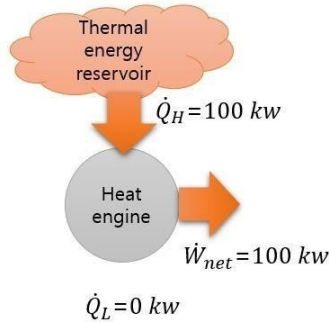
Where m - Mass of the working fluid

h_1 - Specific enthalpy at inlet in KJ/Kg

h_2 - Specific enthalpy at outlet in KJ/Kg

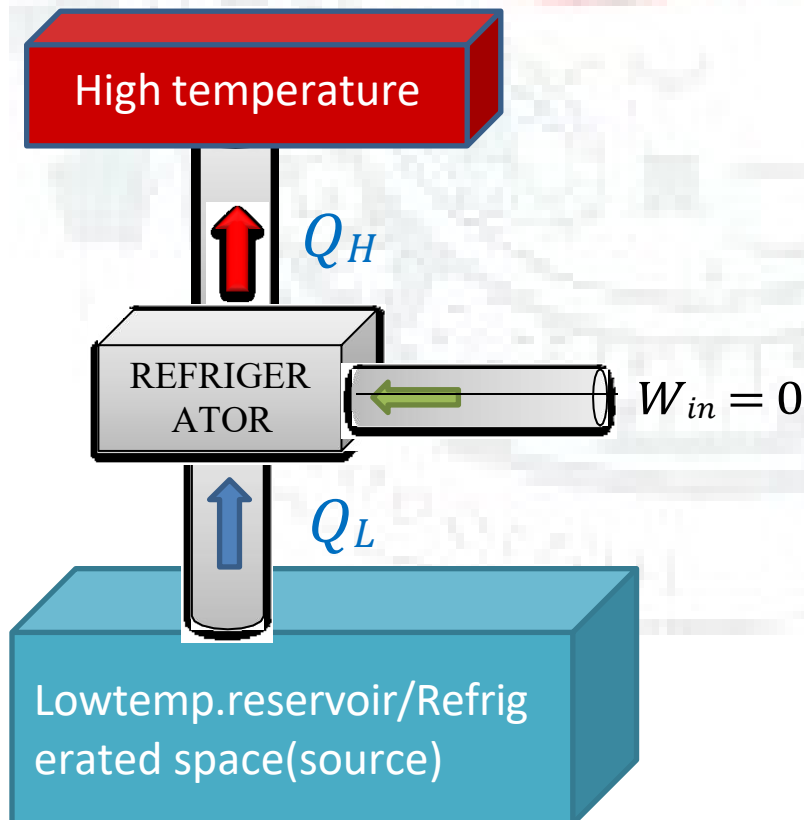
2.4 Second law of thermodynamics

Kelvin Plank statements: It is impossible for any device that operate on a cycle receive heat from single reservoir and produce net amount of work



Claucius statements:

It is impossible to construct a device that operate in a cycle which extract heat from a low temperature reservoir and supplies to a high temperature reservoir without any external agency



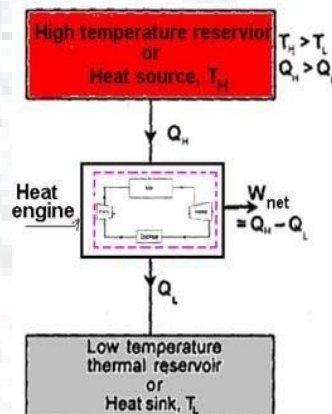
- A thermal reservoir or simply a reservoir is a special kind of system that always remains at constant temperature even though energy is added or removed by heat transfer.
- Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be known as a reservoir (e.g. the air in a room, the earth's atmosphere, large bodies of water (lakes, oceans), so on).

Source: A High temperature reservoir that supplies energy in the form of heat to the system.

Sink : A low temperature reservoir that absorbs energy in the form of heat from the system.

Heat engine:

- Heat engine is a device, which convert thermal energy into mechanical work.
- A heat engine is a device, which operated in a cycle .It, receives the heat energy from a high temperature reservoir, convert part of heat energy into work& remaining heat is rejected to low temperature reservoir.



Working of heat engine

1. Heat engine receive heat (Q_H) from a high temperature source (T_H).
2. They convert part of this heat to work (W_{net}) (Usually in the form of a rotating shaft)
3. They reject the remaining waste heat (Q_L) to a low-temperature sink (T) (the atmosphere, rivers, etc.
4. They operate on a cycle

Thermal efficiency:

- It is the performance measuring parameter of heat engine.
- In general, it is defined as ratio of **desired output to the energy input**.
- It is denoted by η_{thermal} .

Thermal efficiency for heat engine:

For a heat engine desired output is - W_{net}

Energy input is heat supplied - Q_H

$$\eta_{\text{thermal}} = \frac{\text{Desired out put}}{\text{Energy input}}$$
$$\eta_{\text{thermal}} = \frac{\text{Net workdone}}{\text{Heat supplied}} = \frac{W_{net}}{Q_H}$$

Applying first law of thermodynamics

- For a cyclic process **net work done = net heat transfer**
- For a heat engine **net heat transfer = $Q_H - Q_L$**

i.e. $W_{net} = Q_H - Q_L$

$$\eta_{\text{thermal) heat engine}} = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Where W_{net} - net work out put in KJ

Q_H - Heat supplied in KJ

Q_L - Heat rejected in KJ

From thermodynamics temperature scale:

The Absolute or Kelvin Temperature Scale on the Kelvin scale, the temperature ratio of two reservoirs is equal to the ratio of heat transfer between a reversible heat engine and the reservoirs.

$$Q_H = f(T_H), Q_L = f(T)$$

$$\frac{T_H}{T_L} = \left(\frac{Q_H}{Q_L}\right) \text{ reversible}$$

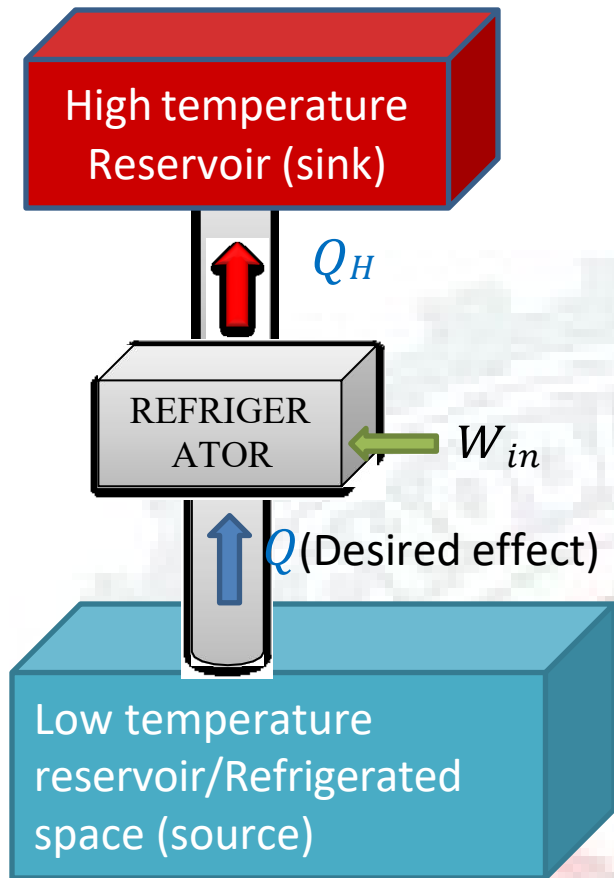
$$\eta_{\text{thermal heat engine}} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

Refrigerator

- A refrigerator is a device, operating in a cycle that maintains a body at lower temperature than its surrounding.
- A refrigerator extracts heat continuously from a refrigerated space, and thus it is maintained at a lower temperature than its surrounding
- The working fluid in the refrigerator is called the refrigerant.

Working of refrigerator:

1. Amount of Q_L is removed from the refrigerated space at temperature T .
2. The work input to the compressor is W_{in}
3. The heat rejected at the condenser is Q_H



COEFFICIENT OF PERFORMANCE (COP):

The performance of a refrigerator is measured in terms of the coefficient of performance (COP).

- It is defined as the ratio of the desired output (Refrigerating effect) to the energy (work) input

Cop for refrigerator:

- $(COP)_R = \frac{\text{Refrigerating effect}}{\text{Work input}} = \frac{Q_L}{W_{in}}$
- Heat energy balance for a cyclic device the work input W_{in} can be expressed as $W_{in} = Q_H - Q_L$

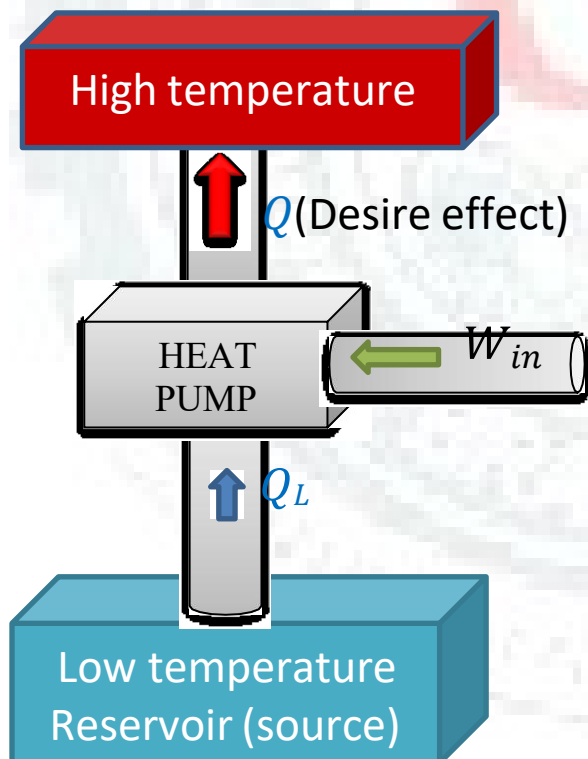
$$(COP)_R = \frac{Q_L}{W_{in}} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

Heat pump:

- A heat pump is a device, operating in a cycle that maintains a space at a higher temperature than its surrounding.
- The heat pump supplies heat continuously to the controlled space and thus maintained at a higher temperature than its surrounding.

The refrigerator and heat pump are operation on the same thermodynamic cycle.

1. Let an amount of heat Q_L be absorbed from the low temperature region
2. W_{in} be the work input.
3. The heat supplied Q_H to the room is the desired output.



$$(\text{COP})_{HP} = \frac{\text{Refrigerating effect}}{\text{Work input}} = \frac{Q_H}{W_{in}}$$

- Heat energy balance for a cyclic device the work input W_{in} can be expressed as $W_{in}=Q_H-Q_L$

$$(\text{COP})_{HP} = \frac{Q_H}{W_{in}} = \frac{Q_H}{Q_H-Q_L} = \frac{T_H}{T_H-T_L}$$

Relationship between heat pump and refrigeration:

- $(\text{COP})_R + 1 = (\text{COP})_{HP}$

$$(\text{COP})_R = \frac{Q_L}{W_{in}} + 1 = \frac{Q_L + Q_H - Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

Note: cop of heat pump is more than cop of refrigerator

Q1. A heat engine, one heat pump and a refrigerator are embedded between two heat reservoirs – one at 600K while the other at 300K. Determine, i) the efficiency of heat engine. ii) The cop of heat pump.

Data Given:

$$T_H = 600\text{K}, T_L = 300\text{K}$$

For Heat engine

$$\eta_{\text{thermal heat engine}} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{600} = 1 - \frac{1}{2} = 0.5$$

For heat pump

$$(\text{COP})_{HP} = \frac{T_H}{T_H - T_L} = \frac{600}{600 - 300} = \frac{600}{300} = 2$$

For Refrigerator

$$(\text{COP})_R = \frac{T_L}{T_H - T_L} = \frac{300}{600 - 300} = \frac{300}{300} = 1$$

Q2. A heat engine, one heat pump and a refrigerator receive 500 kJ of heat each. but they reject 250 kJ, 600kJ and 700kJ of heat respectively. Determine

- a) The efficiency of the heat engine.
- b) The COP of the heat pump.
- c) The COP of the refrigerator.

Data Given:

Heat Engine:

$$\eta_{\text{thermal heat engine}} = 1 - \frac{Q_L}{Q_H}$$

$$= 1 - \frac{250}{500}$$

$$= 1 - \frac{1}{2} = 0.5$$

For heat pump

$$(\text{COP})_{HP} = \frac{Q_H}{Q_H - Q_L}$$

$$= \frac{600}{600 - 500}$$

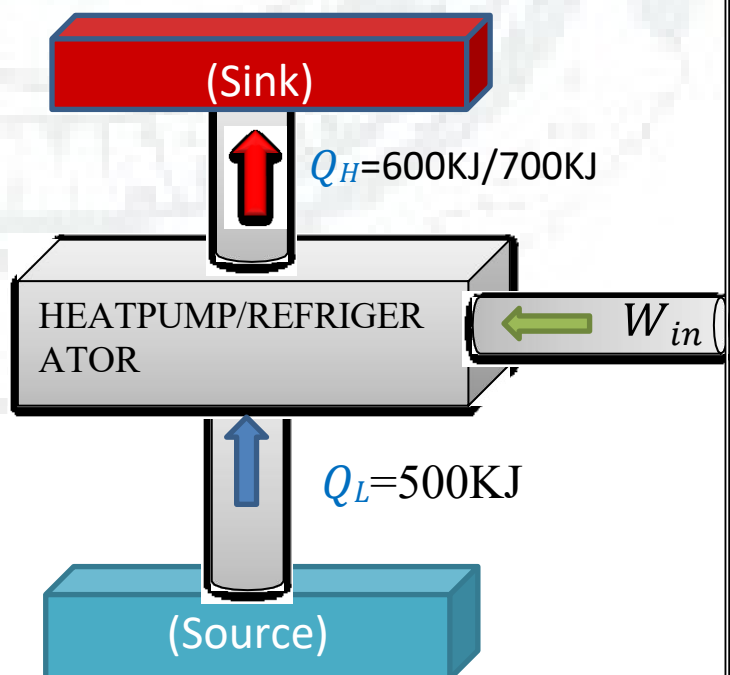
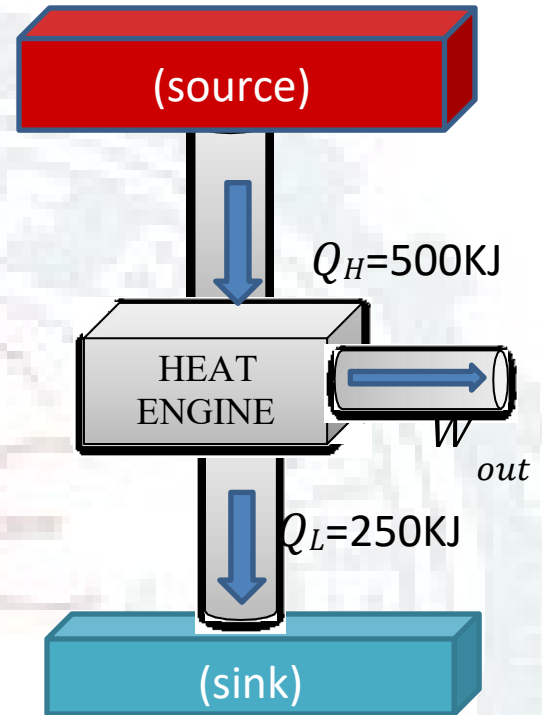
$$= \frac{600}{100} = 6$$

For Refrigerator

$$(\text{COP})_R = \frac{Q_L}{Q_H - Q_L}$$

$$= \frac{500}{700 - 500}$$

$$= \frac{500}{200} = 2.5$$



Q3. A reversible heat engine operates with two environments. In the first, it draws 10000kW from a source at 400°C and in the second it draws 23,000kW from the source at 100°C. In both the operation the engine rejects heat to a thermal sink of 24°C. Determine the operation in which the engine delivers more power. [2019s]

Data Given: Case-1

$$T_H = 400^\circ\text{C} = 400 + 273 = 673\text{K}$$

$$T_L = 24^\circ\text{C} = 24 + 273 = 297\text{K}$$

$$Q_H = 10000\text{KW}$$

$$\eta_{\text{thermal}} = \frac{\text{Net workdone}}{\text{Heat supplied}} = \frac{W_{\text{net}}}{Q_H} =$$

$$\eta_{\text{thermal) heat engine}} = 1 - \frac{Q_L}{Q_H}$$

$$= 1 - \frac{T_L}{T_H} = 1 - \frac{297}{673} = 0.59$$

$$\eta_{\text{thermal}} = \frac{W_{\text{net}}}{Q_H}$$

$$0.59 = \frac{W_{\text{net}}}{10000} = W_{\text{net}} = 10000 \times 0.59 = 5,900\text{KW}$$

Case -2

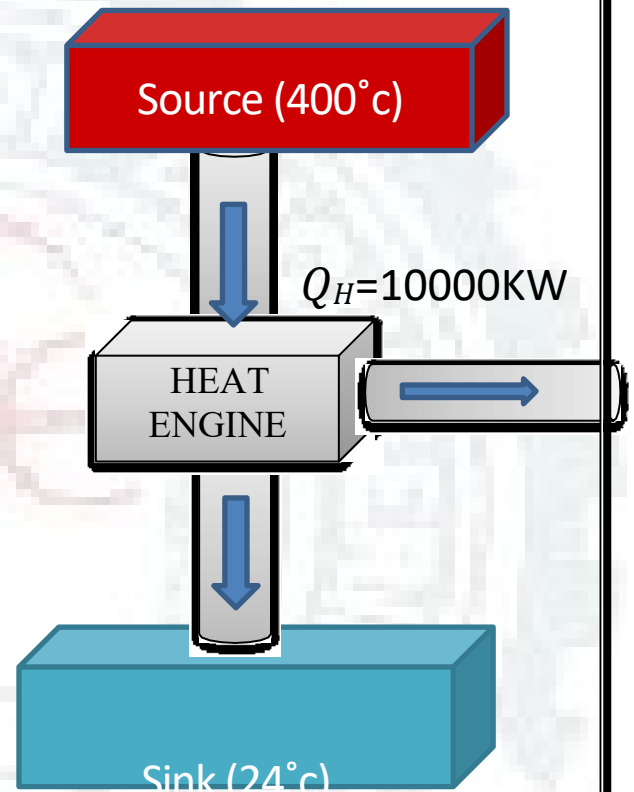
$$T_H = 100^\circ\text{C} = 100 + 273 = 373\text{K}$$

$$T_L = 24^\circ\text{C} = 24 + 273 = 297\text{K}$$

$$Q_H = 23,000\text{KW}$$

$$\eta_{\text{thermal) heat engine}} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} = 1 - \frac{297}{373} = 0.203$$

$$\eta_{\text{thermal}} = \frac{W_{\text{net}}}{Q_H}$$



$$0.203 = \frac{W_{net}}{23000} = W_{net} = 23000 \times 0.203 = 4,669 \text{KW}$$

Case 1 engine deliver more power than case 2 i.e. 5,900Kw

Q4. A cyclic heat engine operates between a source temperature of 800°C and a sink temperature of 30°C . What is the least rate of heat rejection per KW net output of the engine?

Data Given:

$$T_H = 800^{\circ}\text{C} = 800 + 273 = 1073 \text{K}$$

$$T_L = 30^{\circ}\text{C} = 30 + 273 = 300 \text{K}$$

$$W_{out} = 1 \text{KW}$$

$$\eta_{\text{thermal}} = \frac{\text{Net workdone}}{\text{Heat supplied}} = \frac{W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

$$1 - \frac{T_L}{T_H} = 1 - \frac{300}{1073} = 0.72 = 72\%$$

$$\eta_{\text{thermal}} = \frac{W_{net}}{Q_H}$$

$$= Q_H = \frac{W_{net}}{\eta_{\text{thermal}}} = \frac{1 \times 10^3}{0.72} = 1388.89 \text{W}$$

$$= W_{net} = Q_H - Q_L$$

$$= Q_L = Q_H - W_{net}$$

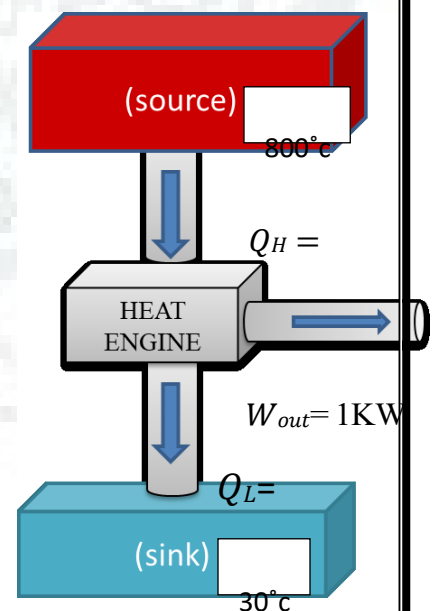
$$= 1388.89 - 1000$$

$$= 388.89 \text{W}$$

$$= 0.39 \text{KW}$$

Least rate of heat rejection per kW net output is

$$\frac{Q_L}{W_{net}} = \frac{388.89}{1000} = 0.39 \text{KW}$$



Q5. A domestic food freezer maintains a temperature of -15°C . The ambient temperature is 30°C . The heat leaks into the freezer at 1.75KJ/S . What is the minimum power necessary to pump this heat out?

Data Given

$$T_H = 30^{\circ}\text{C} = 30 + 273 = 303\text{K}$$

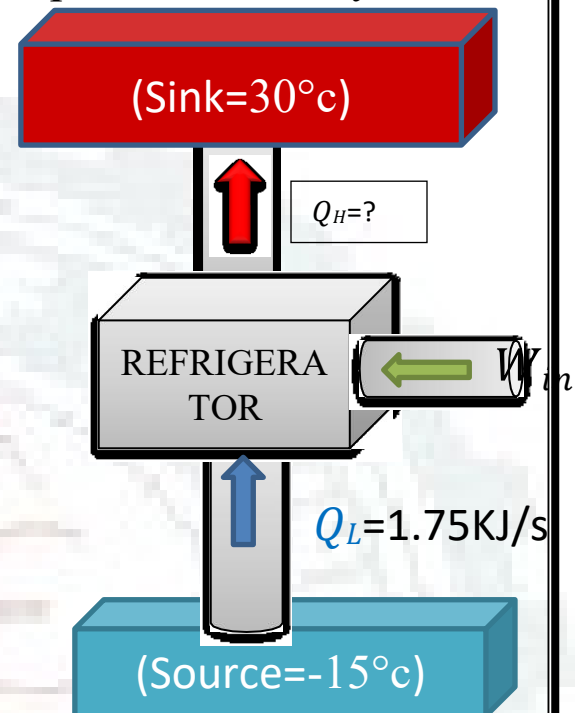
$$T_L = -15^{\circ}\text{C} = -15 + 273 = 258\text{K}$$

$$Q_L = 1.75\text{KJ/s}$$

$$(\text{COP})_R = \frac{T_L}{T_H - T_L} = \frac{258}{303 - 258} = 5.73$$

$$(\text{COP})_R = \frac{Q_L}{Q_H - Q_L} \Rightarrow Q_H - Q_L = \frac{Q_L}{(\text{COP})_R}$$

$$= Q_H = \frac{Q_L}{(\text{COP})_R} + Q_L = \frac{1.75}{5.73} + 1.73 = 2.03$$



Q6. In a non-flow process, the pressure and volume are related by $P = V^2 + 10/V$. Where P is in bar and V is in m^3 , during the process, the volume changes from 1.5m^3 to 4.5m^3 . The total heat added during the process is 8000KJ . Determine the change in internal energy. [2007]

Data Given:

$$P = V^2 + 10/V, V_1 = 1.5\text{m}^3, V_2 = 4.5\text{m}^3$$

$$Q = 8000\text{KJ}, du = ?$$

Solution:

$$W = \int_1^2 P \times dV = \int_1^2 (V^2 + 10/V) \times dV = \int_1^2 (V^2 + 10/V) \times dV$$

$$= \int_1^2 (V^2 \times dV + 10/V \times dV) = \int_1^2 (V^2 \times dV) + \int_1^2 (10/V \times dV)$$

$$\begin{aligned}
&= \frac{1}{3} \times (V_2^3 - V_1^3) + 10 \times [nV_2 - \ln V_2] \\
&= \frac{1}{3} \times (4.5^3 - 1.5^3) + 10 \times [n4.5 - \ln 1.5] \\
&= 29.25 - 10.98 = 18.27 \text{ bar} \times \text{m}^3 \\
&= 18.27 \times 10^5 \text{ Pa} \times \text{m}^3 \qquad 1 \text{ bar} = 10^5 \text{ Pa} \\
&= 18.27 \times 10^5 \text{ N} \times \text{m} \qquad 1 \text{ Pa} = 1 \frac{\text{N}}{\text{m}^2} \\
&= 18.27 \times 10^5 \text{ J} \qquad \text{N} \times \text{m} = \text{Joule} \\
&= \frac{18.27 \times 10^5}{10^3} = 18.27 \times 10^2 \text{ KJ} = 1827 \text{ KJ}
\end{aligned}$$

For non-flow process

$$\begin{aligned}
Q &= dU + W \\
= dU &= Q - W = 8000 - 1827 = \mathbf{6173 \text{ KJ}}
\end{aligned}$$

Q7. A reversible heat engine operates between two reservoirs at temperature of 600°C and 40°C. The engine drives a reversible refrigerator, which operates between reservoirs at temperature of 40°C and -20°C. The heat transfer to the engine is 2MJ and the network output of the combined engine and refrigerator plant is 360kJ. Find the heat transfer to the refrigerant and the net heat transfer to the reservoir at 40°C. Also find these values if the efficiency of the heat engine and cop of the refrigerator are each 40% of their maximum possible values.

Data Given:

Branch: Mechanical

Semester: 3rd Sem

Subject: Engineering Material

Chapter: 3

Topic: Thermal engineering - I

Faculty: SIBASISH SAHU

Content

3. Properties Processes of perfect gas

- 3.1 Laws of perfect gas:
 - Boyle's law, Charle's law, Avogadro's law, Dalton's law of partial pressure, Guy lussac law, General gas equation, characteristic gas constant, Universal gas constant.
- 3.2 Explain specific heat of gas (C_p and C_v)
- 3.3 Relation between C_p & C_v .
- 3.4 Enthalpy of a gas.
- 3.5 Work done during a non- flow process.
- 3.6 Application of first law of thermodynamics to various non flow process (Isothermal, Isobaric, Isentropic and polytrophic process)
- 3.6 Solve simple problems on above.
- 3.7 Free expansion & throttling process.

3.1 Laws of perfect gas

Ideal Gas:

A gas can be modeled as an ideal gas when it has the following features:
Ideal gas has following features:

1. It has no intermolecular force of attraction or repulsion.
2. It doesn't change its phase during a thermodynamic process.
3. It obeys all gas law.
4. A perfect gas has constant specific heats.

Real Gas:

A real gas obviously does not obey the perfect gas equation because, the molecules have a finite size (however small it may be) and they do exert forces among each other.

the real gases describe by the van der Waal's equation

$$(P + a/v^2)(v-b)=RT$$

.

When can a gas be treated as a perfect gas?

- A) At low pressures and temperatures far from critical point.
- B) At low densities.

Boyle's Law:

It states that when a given mass of gas undergoes a process at constant temperature, its volume is inversely proportional to absolute pressure

i.e. $P \propto \frac{1}{V}$

$\rightarrow PV = C$

Where P=absolute pressure

V = Volume of given mass of gas

C= constant proportionality

• If a gas change its state from 1 to 2 without any change in its Temperature then

$P_1V_1 = c, P_2V_2 = c$

$P_1V_1 = P_2V_2$

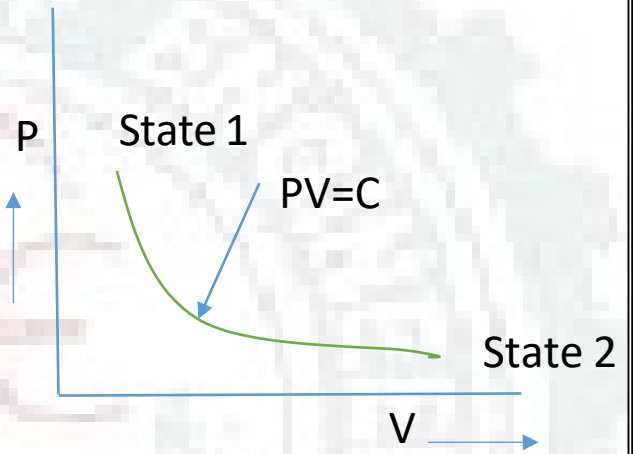
Charles's Law

It states that when a given mass of gas undergoes a process at constant pressure, its volume is proportional to absolute temperature

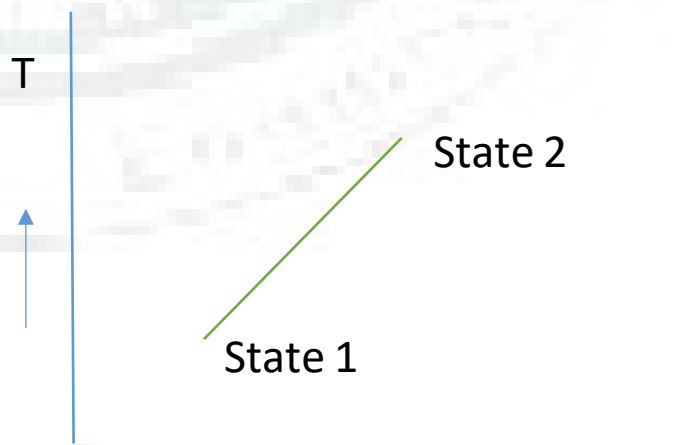
Mathematically

$\rightarrow \frac{V}{T} = C$

If a gas change its state from 1 to 2 without any change in its Pressure then



$P \propto T$



$v \rightarrow$



$$\rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Gay-Lussac Law:

It states that the absolute pressure of an ideal gas varies directly with absolute temperature, if the volume of a gas is constant during the process.

Mathematically

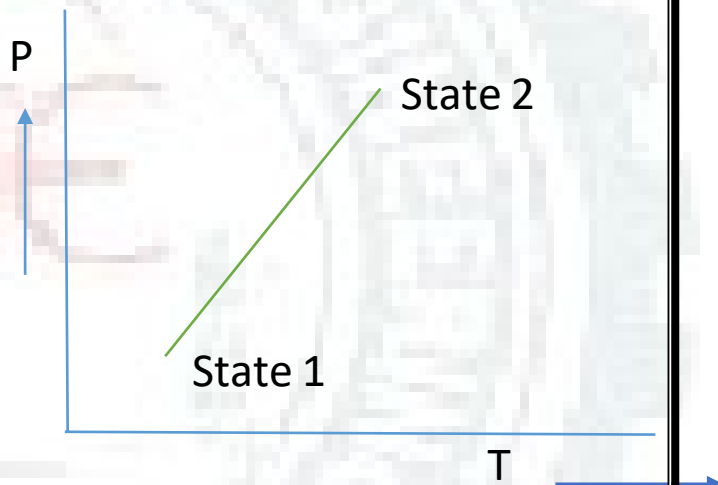
$P \propto T$

$$\frac{P}{T} = C$$

→ If a gas changes its state from 1 to 2 without any change in its

Pressure then

$$\rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2}$$



Dalton's law of partial pressure:

It states that the sum of partial pressures of individual components of a gas mixture is the total pressure of the system.

Mathematically

$$P = P_A + P_B + P_C + \dots$$

Where P is total pressure

P_A, P_B, P_C - Partial pressures of individual components A, B & C respectively

Avogadro's law:

It states that the molecular mass of all perfect gases occupies the same volume under identical conditions of pressure and temperature.

- Avogadro's equipment shows that the average volume for one K-mol (kg-mole) for any perfect gas is 22.413 m^3 at standard atmospheric pressure (1.01325 bar) and 0°C (NTP condition)

$$V = \frac{M \times R \times T}{P} = \frac{R_U \times T}{P} = \frac{8.31447 \times 273.15}{101.325} = 22.413 \text{ m}^3 / \text{K-mol}$$

General gas equation:

If any thermodynamic system of an ideal gas, the pressure, temperature and specific volume vary simultaneously on the basis of these characteristics an equation is derived with the help of Boyle's and Charles's law as General gas equation

Boyle's law $v \propto \frac{1}{P}$ when $T=C$

Charles's law $P \propto T$ when $P=C$

If we combine both the relations we get

$$P \propto \frac{T}{P}$$

$$\rightarrow PP = CT$$

$$\rightarrow \frac{PP}{T} = C \text{ (General gas equation)}$$

For an ideal gas under going process from state 1 to state 2 then

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} = \dots = \text{constant}$$

Characteristic gas equation of a gas:

If any thermodynamic system of an ideal gas, the pressure, temperature and specific volume vary simultaneously. On the basis of these characteristics an equation is derived with the help of Boyle's and Charles's law

Boyle's law $P \propto \frac{1}{v}$ when $T=C$

Charles's law $v \propto T$ when $P=C$

If we combine both the relations we get

$P \propto \frac{T}{v}$ When both P and T vary

$$\rightarrow Pv = RT$$

$$\rightarrow v = \frac{RT}{P}$$

$$\rightarrow Pv = RT$$

Where R is the constant of proportionality and is called specific gas constant or characteristic gas equation

P - is the absolute pressure

v - is the specific volume

T - is the absolute temperature

$$\rightarrow Pv = RT$$

$$\rightarrow \frac{Pv}{m} = RT$$

$\rightarrow PV = mR$ (known as characteristic gas equation or ideal gas equation)

Where P-is the absolute pressure in Pascal

V-is the volume in m^3

m-mass in kg

T- is the absolute temperature in Kelvin

Universal Gas constant (R_U):

When the molecular mass of any gas (M) is multiplied by its specific gas constant (R)

→ It is observed that the product(MR) is always same for all gases

→ This product is called universal gas constant and it is denoted by R_U

$$\rightarrow R_U = MR$$

$$\rightarrow R_U = 8.31447 \text{ KJ/ K-mol .K}$$

Characteristic gas constant (R) :

Constant of proportionality called the specific gas constant

- Its value different for different gas
- Unit of R- KJ/Kg.K
- $R = \frac{R_U}{M}$

For air gas constant is- 0.287KJ/Kg.K

Specific heat:

- It is defined as amount of heat energy required to rise the temperature of the unit mass of a substance by one degree.
- It is denoted by C .
- It is expressed in $\frac{kJ}{kg \times k}$ or $\frac{kJ}{kg \times ^\circ C}$.
- Since heat transfer is a path function the specific heat also become path function.
- Heat required(δQ) = $mcdT$

Specific heat depending upon the process adopted for heating the gases and vapors.

1. Specific heat at constant pressure(C_p)
2. Specific heat at constant volume (C_v)

Specific heat at constant pressure(C_p):

It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree ,When it is heated at constant pressure.

- It is denoted by C_p
- $Q_{1-2} = m \times C_p \times (T_2 - T_1)$ (KJ)

Specific heat at constant volume (C_v):

It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree ,When it is heated at constant volume.

- It is denoted by C_v
- $Q_{1-2} = m \times C_v \times (T_2 - T_1)$ (KJ)
- These specific heats are properties of the gas and both vary with pressure and temperature.

For an ideal gas they are assumed constant

For air $C_p = 1.005 \frac{kJ}{kg \times K}$

$C_v = 0.718 \frac{kJ}{kg \times K}$

- The relationship between C_p & C_v for an ideal gas can be obtained by differentiating the enthalpy relation equation .

$h = u + Pv$

Differentiating both side

$dh = du + pdv$ equation (1)

we know

$PV = mRT$

$P \frac{V}{m} = RT$

$Pv = RT$

$Pdv = RdT$

Relation between C_p & C_v .

Put the value in equation

- $dh = du + R dT$
- Replacing $dh = C_p \times dT$, $du = C_v \times dT$

- $C_P dT = C_V dT + R dT$
- $C_P dT = dT (C_V + R)$
- $C_P = C_V + R$
- $C_P - C_V = R(\text{KJ/Kg})$
- The ratio of the specific heat is defined as
- $\gamma = \frac{C_P}{C_V}$

Work done during a non- flow process

The non-flow processes are

1. Isobaric process – constant pressure process
2. Isochoric process – Constant volume process
3. Isothermal process – constant temperature process
4. Polytrophic process
5. Reversible adiabatic process- isentropic process

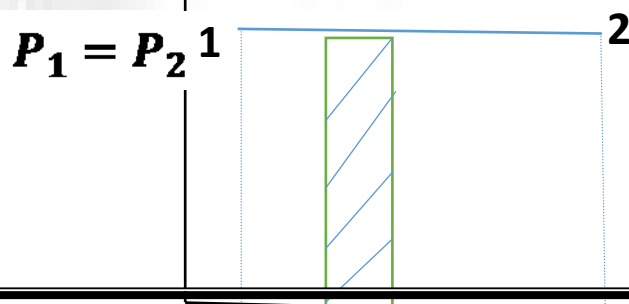
Work done during non-flow process can be calculated by using formula $W_{1-2} = \int_1^2 P \times dV$

Work done for Isobaric process or constant pressure process

We know that $\delta W = PdV$ or $W = \int P \times dV$

work done for process 1-2

$$W_{1-2} = \int_1^2 P \times dV$$



$V \quad dV$



AS $P=C$

$$W_{1-2} = P \int_1^2 dV$$

$$= P [V]_1^2 = P \times (V_2 - V_1)$$

$$W_{1-2} = P (V_2 - V_1)$$

As we know $PV = m RT$,

$$\text{Then } P_1V_1 = m RT_1 \text{ \& } P_2V_2 = m RT_2$$

Then

$$W_{1-2} = P (V_2 - V_1) = (P_2V_2 - P_1V_1)$$

$$= m RT_2 - m RT_1$$

$$W_{1-2} = m R (T_2 - T_1)$$

2. Work done for Isochoric process or Constant volume process

For constant - volume process

$$V_1 = V_2 \quad \text{so } \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Work done during the process:

$$W = \int P \times dV$$

For a process 1-2

$$W_{1-2} = \int_1^2 P \times dV$$

$dV = 0$ (Constant Volume Process)

$$W_{1-2} = 0$$

3. Work done for Isothermal process or constant temperature process

isothermal process follow the law $PV = C$

$$W_{1-2} = \int_1^2 P \times dV$$

$$\text{As } PV = C$$

Then for process 1-2 $P_1V_1 = P_2V_2 = C$

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

$$P = \frac{C}{V}$$

$$W_{1-2} = \int_1^2 \frac{C}{V} \times dV$$

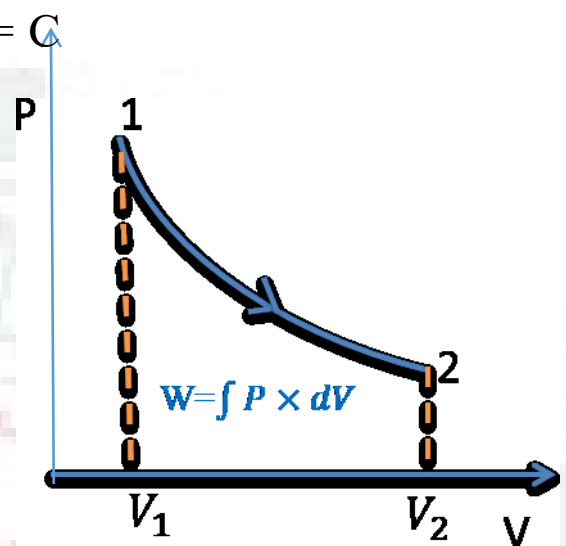
$$= C \int_1^2 \frac{1}{V} \times dV = C [\ln V]_1^2$$

$$= C [\ln V_2 - \ln V_1]$$

$$= C \left(\ln \frac{V_2}{V_1} \right) = P_1 V_1 \left(\ln \frac{V_2}{V_1} \right)$$

$$= m R T_1 \left(\ln \frac{V_2}{V_1} \right)$$

$$= m R \frac{P_1}{T_1} \left(\ln \frac{V_2}{V_1} \right)$$

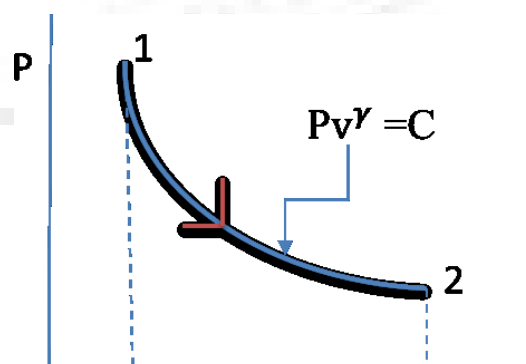


Work done for Reversible adiabatic or Isentropic process

For an isentropic process

$$PV^\gamma = C$$

For process 1-2



$$P_1 V_1^\gamma = P_2 V_2^\gamma = C$$

$$W_{1-2} = \int_1^2 P \times dV$$

$$P V^\gamma = C \text{ or } P = \frac{C}{V^\gamma}$$

$$\begin{aligned} = W_{1-2} &= \int_1^2 P \times dV = \int_1^2 \frac{C}{V^\gamma} \times dV \\ &= C \int_1^2 \frac{1}{V^\gamma} \times dV = C \int_1^2 V^{-\gamma} \times dV \end{aligned}$$

$$\begin{aligned} &C \times \left[\frac{V^{-\gamma+1}}{-\gamma+1} \right]_1^2 \\ &= C \times \left(\frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1} \right) \\ &= \frac{c \times V_2^{-\gamma+1} - c \times V_1^{-\gamma+1}}{-\gamma+1} \end{aligned}$$

Substituting for c as $P_1 V_1^\gamma$ and $P_2 V_2^\gamma$

$$\begin{aligned} &= \frac{P_2 V_2^\gamma \times V_2^{-\gamma+1} - P_1 V_1^\gamma \times V_1^{-\gamma+1}}{-\gamma+1} \\ &= \frac{P_2 \times V_2^\gamma \times V_2^{-\gamma} \times V_2^1 - P_1 \times V_1^\gamma \times V_1^{-\gamma} \times V_1^1}{-\gamma+1} \end{aligned}$$

$$W = \frac{P_2 V_2 - P_1 V_1}{-\gamma+1}$$

$$W = \frac{P_2 V_2 - P_1 V_1}{1-\gamma} = \frac{mRT_2 - mRT_1}{1-\gamma} = \frac{m(T_2 - T_1)}{1-\gamma}$$

Work done for Polytropic process

For an polytropic process

$$P V^n = C$$

For process 1-2

$$P_1 V_1^n = P_2 V_2^n$$

$$W_{1-2} = \int_1^2 P \times dV$$

$$P V^n = C \text{ or } P = \frac{C}{V^n}$$

$$= W_{1-2} = \int_1^2 P \times dV = \int_1^2 \frac{C}{V^n} \times dV$$

$$= C \int_1^2 \frac{1}{V^n} \times dV = C \int_1^2 V^{-n} \times dV$$

$$C \times \left[\frac{V^{-n+1}}{-n+1} \right]_1^2$$

$$= C \times \left(\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} \right)$$

$$= \frac{c \times V_2^{-n+1} - c \times V_1^{-n+1}}{-n+1}$$

Substituting for c as $P_1 V_1^n$ and $P_2 V_2^n$

$$= \frac{P_2 V_2^n \times V_2^{-n+1} - P_1 V_1^n \times V_1^{-n+1}}{-n+1}$$

$$= \frac{P_2 \times V_2^n \times V_2^{-n} \times V_2^1 - P_1 \times V_1^n \times V_1^{-n} \times V_1^1}{-n+1}$$

$$W = \frac{P_2 V_2 - P_1 V_1}{-n+1}$$

$$W = \frac{P_2 V_2 - P_1 V_1}{1-n} = \frac{mRT_2 - mRT_1}{1-n} = \frac{m(T_2 - T_1)}{1-n}$$

Application of first law of thermodynamics to various non flow process

1. Isobaric or constant pressure process:

Definition: If any system undergo a process in such a way that the pressure of the gas remain constant is called constant pressure process.

- When a gas expand or in compressed under constant pressure, it follows Charles's law.
- Where pressure(P) is constant, but temperature(T) and volume(V) varies
- P-V diagram for constant pressure process :

At constant pressure if we add

heat to a system is called

Constant pressure heating or expansion

As volume and temperature increases

At constant pressure if system

reject heat is called constant pressure

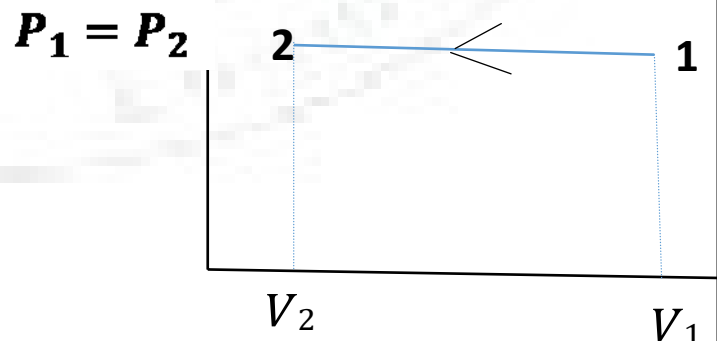
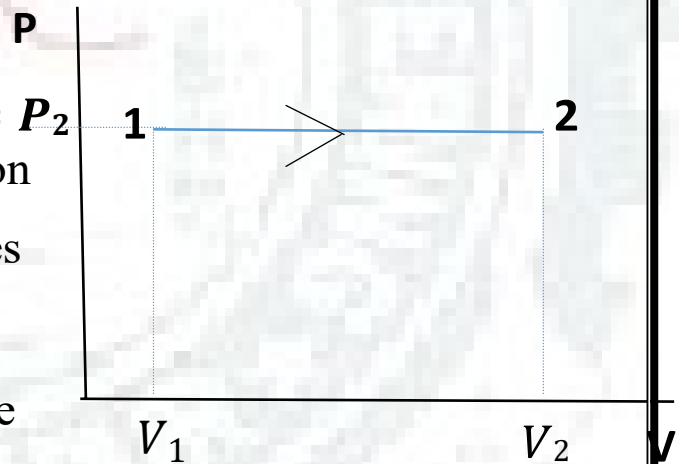
Cooling as volume and

temperature decreases

Property relation:

$$\text{General gas equation } = \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\text{AS } P_1 = P_2 \quad \text{Then } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$



Work done:

$$W_{1-2} = P (V_2 - V_1)$$

$$W_{1-2} = m R (T_2 - T_1)$$

Change in internal energy:

$$dU = m C_V dT = m C_V (T_2 - T_1) \text{ KJ}$$

Heat transfer:

$$\begin{aligned} \delta Q &= m C_P dT \\ = Q &= \int_1^2 m C_P dT \end{aligned}$$

Property relation:

$$\text{General gas equation } = \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\text{AS } P_1 = P_2 \quad \text{Then } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Work done :

$$W_{1-2} = P (V_2 - V_1)$$

$$W_{1-2} = m R (T_2 - T_1)$$

Change in internal energy:

$$dU = m C_V dT = m C_V (T_2 - T_1) \text{ KJ}$$

Heat transfer:

$$\begin{aligned} \delta Q &= m C_P dT \\ = Q &= \int_1^2 m C_P dT \end{aligned}$$

$$Q = m \int_{T_1}^{T_2} c_p dT = m c_p \left[T \right]_{T_1}^{T_2} = m c_p (T_2 - T_1)$$

$$Q = m c_p (T_2 - T_1) \text{ KJ}$$

$$q = (Q/m) = c_p (T_2 - T_1) \text{ KJ/kg}$$

Change in enthalpy for a process

$$dH = m c_p (T_2 - T_1) \text{ KJ}$$

Note: For a non flow constant pressure process

Change in enthalpy (dH) = change in heat transfer (δQ)

Change in entropy:

$$dS = \frac{\delta Q}{T}$$

For process 1-2

$$dS = \int_1^2 \frac{\delta Q}{T} = \int_1^2 \frac{m c_p dT}{T}$$

$$= m c_p \times \int_1^2 \frac{dT}{T}$$

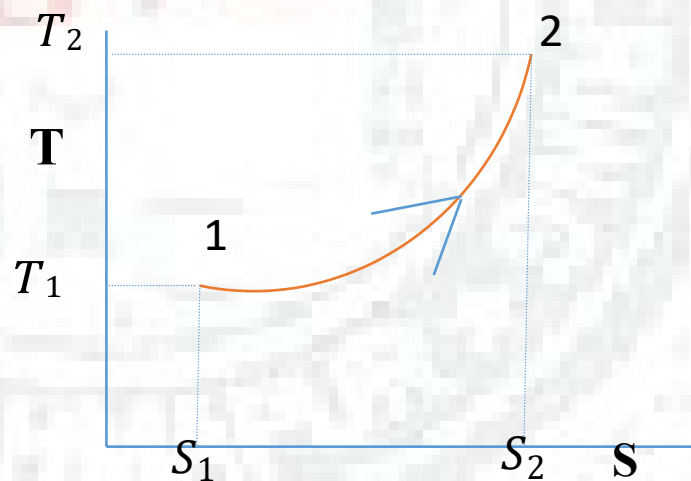
$$= m c_p \times [\ln T]_1^2$$

$$= m c_p \times [\ln T_2 - \ln T_1]$$

$$= m c_p \times \left[\ln \left(\frac{T_2}{T_1} \right) \right]$$

$$dS = m c_p \ln \left(\frac{T_2}{T_1} \right) \text{ kJ/k}$$

$$S_2 - S_1 = m c_p \ln \left(\frac{T_2}{T_1} \right) \text{ kJ/k}$$



Constant Volume process:

If any system of gas undergoes a process in such a way that during the process the volume of the system remains constant the process is called Isobaric process.

Property relation:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

For constant - volume process

$$V_1 = V_2 \quad \text{so} \quad \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Work done during the process:

$$dV = 0 \quad (\text{Constant Volume Process})$$

$$W_{1-2} = 0$$

Change in internal energy

$$dU = m C (T_2 - T_1)$$

$$du = \left(\frac{dU}{m} \right) = C_V (T_2 - T_1)$$

Heat Transfer

$$Q = m C_V \int_1^2 dT = m C_V (T_2 - T_1) = dU$$

$$Q = dU$$

Change in enthalpy $dH = m C (T_2$

$$- T_1) \text{kJ}$$

$$dh = (dH)_P = C_P (T_2 - T_1) \text{ KJ/kg}$$

Change in entropy:

$$dS = \frac{\delta Q}{T}$$

$$\begin{aligned} \text{For process 1-2 } dS &= \int_1^2 \frac{\delta Q}{T} = \int_1^2 \frac{m C_V dT}{T} = m C_V \times \int_1^2 \frac{dT}{T} \\ &= m C_V \times [\ln T]_1^2 = m C_V \times [\ln T_2 - \ln T_1] = m C_V \times \left[\ln \left(\frac{T_2}{T_1} \right) \right] \\ dS &= m C_V \ln \left(\frac{T_2}{T_1} \right) \text{ (kJ/k)} \end{aligned}$$

Isothermal Process or constant temp. Process

If a system undergoes a process in such a way that during the process the temperature of the system remain constant such a process is called an isothermal process or constant temperature process.

2. Property Relation

$$\text{General gas equation } = \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

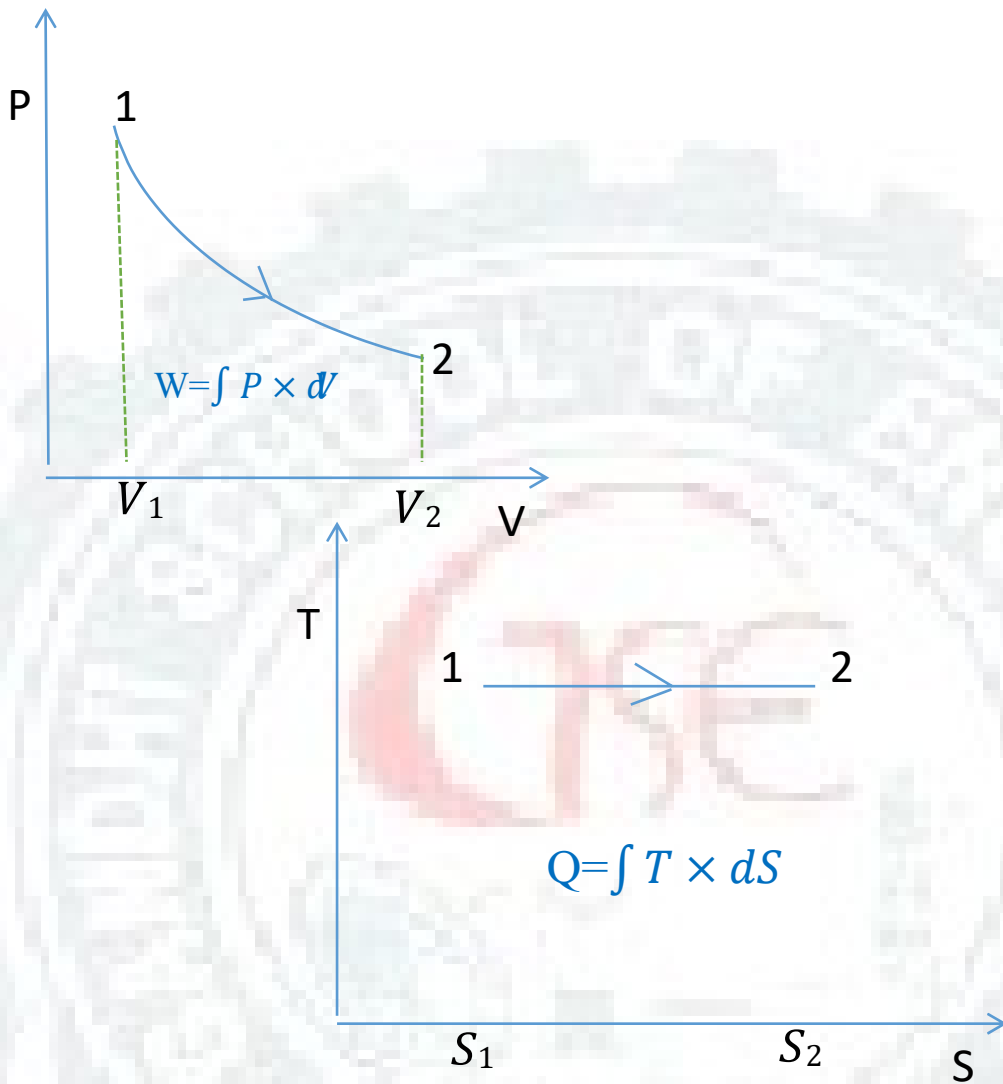
$$\text{AS } T_1 = T_2$$

$$\text{Then } P_1 V_1 = P_2 V_2$$

i.e. $PV = C$ It is a equation of hyperbola

Hence process may b hyperbolic process

P-V & T-S diagram



Isothermal expansion 1-2

Work done

$$\begin{aligned}
 W_{1-2} &= \int_1^2 P \times dV \\
 &= P_1 V_1 \left(\ln \frac{V_2}{V_1} \right) \\
 &= m R T_1 \left(\ln \frac{V_2}{V_1} \right)
 \end{aligned}$$

$$= m R T_1 \ln \frac{P_1}{P_2}$$

Change in internal energy:

$$dU = m C_V dT = m C_V (T_2 - T_1) \text{ KJ}$$

$$\text{AS } T_1 = T_2$$

$$dU=0$$

Heat transfer:

$$Q = du + W$$

Though $dU=0$

$$Q = W = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right) \\ = m R \ln \left(\frac{P_1}{P_2} \right)$$

During isothermal process heat transfer = work transfer

Change in enthalpy $dH = mC(T_2 - T_1) \text{ kJ}$

$$dh = \left(\frac{dH}{m} \right) = C (T_2 - T_1) \text{ KJ/kg}$$

$$dh = 0 \quad (\text{as } T_1 = T_2)$$

Change in entropy

$$dS = \frac{\delta Q}{T}$$

$$\text{For process 1-2 } dS = \int_1^2 \frac{\delta Q}{T} = \int_1^2 \frac{\delta W}{T}$$

$$\int_1^2 \frac{P dV}{T} =$$

$$\text{AS } PV = mRT, \left(\frac{P}{T} = \frac{mR}{V} \right)$$

$$= \int_1^2 \frac{mR}{V} dV = mR \times \int_1^2 \frac{1}{V} dV$$

$$= mR \times [\ln V]_1^2 = mR \times [\ln V_2 - \ln V_1] = mR \times \left[\ln \left(\frac{V_2}{V_1} \right) \right]$$

$$dS = m R \ln \left(\frac{V_2}{V_1} \right) \text{ (kJ/k)}$$

Reversible adiabatic or Isentropic process

If any process of expansion or compression is carried out without exchange of heat between system and surrounding i.e. operation in an insulated system process is called adiabatic process.

- When an adiabatic processes is reversible then this process is called Isentropic or constant entropy process.

Law of an isentropic process:

For unit mass of a system the energy equation for a non-flow process is expressed as

$$\delta Q = dU + \delta W$$

$$\delta q = du + \delta w$$

For adiabatic process

$$0 = du + \delta w$$

$$du + \delta w = 0$$

$$C_V dT + P dv = 0 \dots \dots \dots \text{eqn 1}$$

For unit mass of an ideal gas the characteristic gas equation

$$PV = mRT$$

$$P \frac{V}{m} = RT$$

$$Pv = RT$$

Differentiate both side we get

$$d(Pv) = d(RT)$$

$$= Pdv + v dP = R dT$$

$$dT = \frac{Pdv + v dP}{R}$$

- Substituting dT in equation 1 we have

$$C_V dT + P dv = 0$$

$$C_V \frac{Pdv + v dP}{R} + P dv = 0$$

$$= C_V (Pdv + v dP) + R \times P dv = 0$$

$$\text{Using } R = C_P - C_V$$

$$= C_V Pdv + C_V v dP + R \times P dv = 0$$

$$= C_V Pdv + C_V v dP + (C_P - C_V) \times P dv = 0$$

$$= C_V Pdv + C_V v dP + C_P P dv - C_V P dv = 0$$

$$= C_V v dP + C_P P dv = 0$$

Dividing both sides by $(C_V v P)$ we get

$$= C_V v dP + C_P P dv = 0$$

$$= \frac{C_V v dP}{C_V v P} + \frac{C_P P dv}{C_V v P} = 0$$

$$= \frac{dP}{P} + \frac{C_P dv}{C_V v} = 0$$

$$= \frac{dP}{P} + \frac{C_P}{C_V} \times \frac{dv}{v} = 0$$

$$= \frac{dP}{P} + \gamma \times \frac{dv}{v} = 0$$

Integrating above equation we get

$$= \int \frac{dP}{P} + \gamma \int \frac{dv}{v} = 0$$

$$= \log_e P + \gamma \log_e v = \log_e C$$

Taking antilog on both sides we get

$$P v^\gamma = C$$

Relation between P, V & T:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$= \frac{T_2}{T_1} = \frac{P_2 V_2}{P_1 V_1} \dots \dots \dots \text{equation 1}$$

For an isentropic process

$$P v^\gamma = C$$

For process 1-2

$$1. \frac{P_1 V_1^\gamma}{1} = \frac{P_2 V_2^\gamma}{2}$$

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

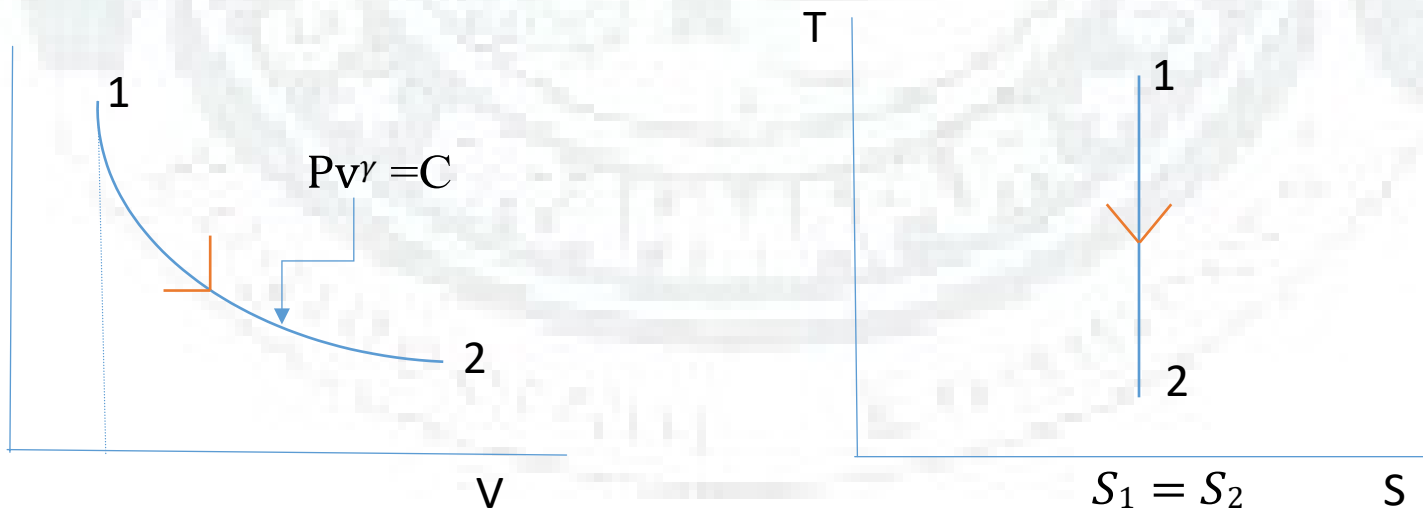
Put the value of $\frac{P_2}{P_1}$ in equation 1

$$\begin{aligned} \frac{T_2}{T_1} &= \frac{V_2}{V_1} \times \left(\frac{V_2}{V_1}\right)^{-\gamma} = \left(\frac{V_2}{V_1}\right)^{1-\gamma} \\ &= \frac{V_2}{V_1} \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \dots \dots \dots \text{equation 2} \end{aligned}$$

substituting eq.2 in eq.1

$$\begin{aligned} \frac{T_2}{T_1} &= \frac{P_2}{P_1} \times \frac{V_2}{V_1} \\ \frac{T_2}{T_1} &= \frac{P_2}{P_1} \times \left(\frac{P_2}{P_1}\right)^{-\frac{1}{\gamma}} = \left(\frac{P_2}{P_1}\right)^{1-\frac{1}{\gamma}} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \end{aligned}$$

P-V & T-S diagram



Reversible adiabatic or isentropic expansion

Work done during the process

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

$$W = \frac{P_2V_2 - P_1V_1}{1 - \gamma} = \frac{mRT_2 - mRT_1}{1 - \gamma} = \frac{m(T_2 - T_1)}{1 - \gamma}$$

$$W = \frac{-(P_2V_2 - P_1V_1)}{-(1 - \gamma)} = \frac{-P_2V_2 + P_1V_1}{-1 + \gamma} = \frac{P_1V_1 - P_2V_2}{\gamma - 1}$$

If we put $C_p - C_v = R$ and $\gamma = \frac{C_p}{C_v}$

$$= C_p = \gamma C_v$$

$$= \gamma C_v - C_v = R$$

$$= C(\gamma - 1) = R$$

$$= C_v = \frac{R}{(\gamma - 1)}$$

$$= W = \frac{m(T_2 - T_1)}{1 - \gamma} = \frac{-mR(T_2 - T_1)}{-(1 - \gamma)} = \frac{-mR(T_2 - T_1)}{\gamma - 1} = -mC_v(T_2 - T_1)$$

$$W = -mC(T_2 - T_1)$$

Change in internal energy

$$dU = mC_v(T_2 - T_1)$$

$$dU = -W_{1-2}$$

Heat transfer

During an adiabatic process the heat transferred is zero

$$Q_{1-2} = 0$$

Change in enthalpy

$$dH = mC_p(T_2 - T_1)$$

Change in entropy

$$dS = \frac{\delta Q}{T} = 0 \quad (\text{as } \delta Q = 0)$$

Polytropic Process

$$P V^n = C$$

$$P_1 V_1^n = P_2 V_2^n$$

Determination of polytropic index

$$n = \frac{\ln(P_2/P_1)}{\ln(V_1/V_2)}$$

Relation between P, V & T

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n = \left(\frac{V_2}{V_1}\right)^{-n}$$

$$T_2 = V_2^{1-n}$$

$$T_1 = \left(\frac{V_1}{V_2}\right)^n$$

$$\frac{V_2}{V_1} = \left(\frac{P_2}{P_1}\right)^{\frac{-1}{n}}$$

$$T_2 = \frac{P_2^{\frac{n-1}{n}}}{P_1^{\frac{n-1}{n}}}$$

Work done

$$W = \frac{P_2 V_2 - P_1 V_1}{1-n} = \frac{m(T_2 - T_1)}{1-n}$$

$$= \frac{P_1 V_1 - P_2 V_2}{n-1} = \frac{m(T_1 - T_2)}{n-1}$$

Change in internal energy

$$dU = mC(T_2 - T_1)$$

Change in enthalpy

$$dH = mC_P(T_2 - T_1)$$

Heat Transfer

$$Q = dU + W$$

$$= mC_V(T_2 - T_1) + \frac{mR(T_1 - T_2)}{1-n}$$

$$= m(T_2 - T_1) \left(C_V + \frac{R}{1-n} \right)$$

$$= m(T_2 - T_1) \left(C_V + \frac{C_P - C_V}{1-n} \right)$$

$$= m(T_2 - T_1) \left(\frac{C(1-n) + C_P - C_V}{1-n} \right)$$

$$= m(T_2 - T_1) \left(\frac{C_V - C_V n + C_P - C_V}{1-n} \right)$$

$$= m(T_2 - T_1) \left(\frac{C_V - C_V n + C_P - C_V}{1-n} \right)$$

$$= m(T_2 - T_1) \left(\frac{-C_V n + C_P}{1-n} \right)$$

$$= m(T_2 - T_1) \left(\frac{C_P - C_V n}{1-n} \right)$$

$$Q = mC_n (T_2 - T_1) \quad \left(C_n = \frac{C_P - C_V n}{1-n} \right)$$

$$Q = mC_n dT$$

$$Q = m \frac{C_P - C_V n}{1-n} (T_2 - T_1)$$

$$\begin{aligned}
&= m \frac{C_V \left(\frac{C_P}{C_V} - n \right)}{1-n} (T_2 - T_1) \\
&= m \frac{C(\gamma-n)}{1-n} (T_2 - T_1) \\
&= \frac{(\gamma-n)}{1-n} m C_V (T_2 - T_1) \\
&= \frac{(\gamma-n)}{1-n} m \frac{R}{(\gamma-1)} (T_2 - T_1) \\
&= \frac{(\gamma-n) m R (T_2 - T_1)}{(\gamma-1) (1-n)}
\end{aligned}$$

$$Q = \frac{(\gamma-n)}{(\gamma-1)} \times \text{Polytropic work transfer}$$

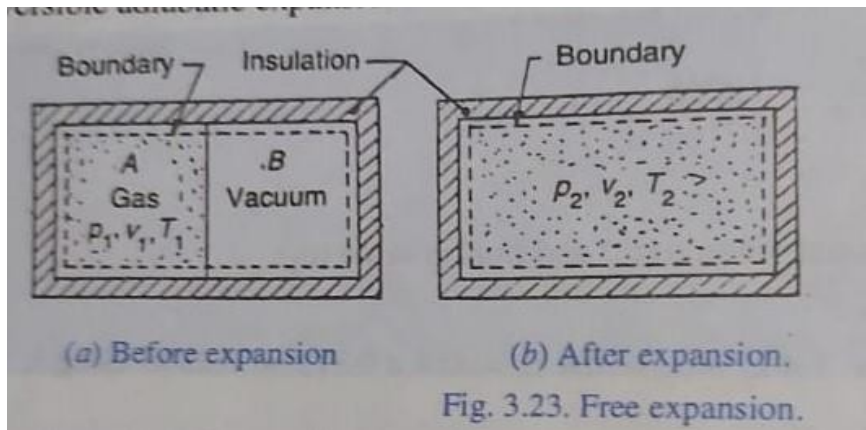
Change in entropy:

$$dS = \frac{\delta Q}{T}$$

$$\begin{aligned}
S_2 - S_1 &= \int_1^2 \frac{\delta Q}{T} = \int_1^2 \frac{m C_n dT}{T} = m C_n \int_1^2 \frac{dT}{T} \\
&= m C_n \left[\ln T \right]_1^2 = m C_n \left(\ln T_2 - \ln T_1 \right) = m C_n \ln \left(\frac{T_2}{T_1} \right) \\
S_2 - S_1 &= m C_n \ln \left(\frac{T_2}{T_1} \right)
\end{aligned}$$

Free expansion process:

The free expansion process is an irreversible non-flow process. A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum chamber through an orifice of large dimension.



- Since there is no expansion of boundary of the system, because it is rigid, therefore no work is done.

- Thus, for a free expansion process
 $Q_{1-2} = 0$ (Boundary insulated)
 $W_{1-2} = 0$ and $dU = 0$

The following point may be noted:

1. Since the system is perfectly so that no heat transfer takes place (i.e. $Q_{1-2} = 0$) Therefore the expansion of gas may be called as an adiabatic expansion
2. Since the free expansion of the gas takes place suddenly, therefore the intermediate states will not be in equilibrium state. Thus the process is irreversible and the expansion is, therefore known as irreversible expansion
3. According to the first law of thermodynamics

$$Q_{1-2} = W_{1-2} + dU$$

though $Q_{1-2}=0$ & $w_{1-2} =0$

Then $dU =0$ or $U_2 - U_1 =0$

$$U_2=U_1$$

Free expansion process is also known as a constant internal energy process

4.

We know that change in internal energy

$$dU= mC_v dT$$

Since $dU=0$ therefore $dT =0$ or $(T_2 - T_1) =0$ or $T_2 = T_1$

Temperature of the system remain constant

5. Change in enthalpy $dH= mC_p dT$

Since $dT=0$ therefore $dH=0$ or $H_2 = H_1$

Thus the free expansion process may also be called as constant enthalpy process.

Throttling process:

The throttling process is an is an irreversible steady flow expansion process in which a perfect gas is expanded through an orifice of minute dimension such as narrow throat or a slightly opened valve as shown

Branch: Mechanical

Semester: 3rd Sem

Subject: Engineering Material

Chapter: 4

Topic: Thermal engineering - I

Faculty: SIBASISH SAHU

Content

4.1 Explain & classify I.C engine.

4.2 Terminology of I.C Engine such as bore, dead centers, stroke volume, piston speed & RPM.

4.3 Explain the working principle of 2-stroke & 4-stroke engine C.I & S.I engine.

4.4 Differentiate between 2-stroke & 4-stroke engine C.I & S.I engine

HEAT ENGINE:

- A **heat engine** is a system that converts **heat** or **thermal energy** to **mechanical work**.

TYPE OF ENGINE:

- Heat engine classification can be done into two types.

They are:

- 1) External Combustion Engine (EC Engine)
- 2) Internal Combustion Engine (IC Engine)

EC ENGINE:

- External combustion engines are those in which combustion takes place outside the engines.
- Heat produced during external combustion is used for inducing useful mechanical motion in the cylinder of the engine.

Ex: *Steam Engine, Steam Turbine, Closed cycle gas turbine*

IC ENGINE:

- IC engines are those in which combustion takes place within the engine.
- Chemical energy of the fuel is converted to thermal energy and thermal energy is *converted* to mechanical energy.
- Ex: *Gasoline Engine, Diesel Engine, Wankel Engine, Open cycle Gas Turbine*

Classification of I.C engine

1. According to No. of Strokes per cycle
 - a) Four Stroke Engine
 - b) Two Stroke Engine
2. According to Types of Fuel Used
 - a) Petrol or Gasoline Engine
 - b) Diesel Engine
 - c) Gas Engine
 - d) Bi-Fuel Engine
3. According to Nature of Thermodynamic Cycle
 - a) Otto Cycle Engine
 - b) Diesel Cycle Engine
 - c) Dual Combustion Cycle Engine
4. According to Method of Ignition
 - a) Spark Ignition (SI) Engine

- b) Compression Ignition (CI) Engine
5. According to No of Cylinders
- a) Single Cylinder Engine
 - b) Multi Cylinder Engine
6. According to Arrangement of Cylinders
- a) Horizontal Engine
 - b) Vertical Engine
 - c) V – Type Engine
 - d) Radial Engine
 - e) Inline Engine
 - f) Opposed Cylinder Engine
 - g) Opposed Piston Engine
7. According to Cooling System
- a) Air Cooled Engine
 - b) Water Cooled Engine
8. According to Lubrication System
- a) Wet Sump Lubrication System
 - b) Dry Sump Lubrication System
9. According to Speed of the Engine
- a) Slow Speed Engine
 - b) Medium Speed Engine
 - c) High Speed Engine
10. According to Location of Valves
- a) Over Head Valve Engine
 - b) Side Valve Engine

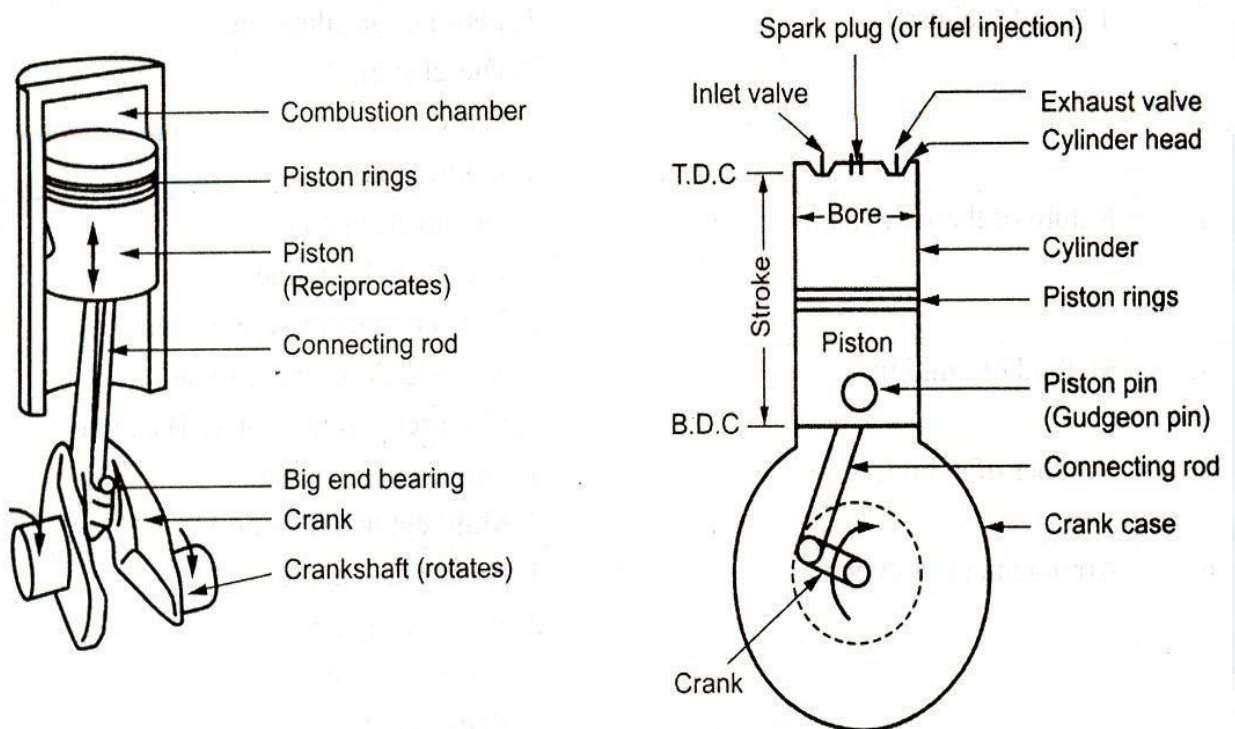
COMPONENTS OF IC ENGINE:

1. Cylinder Block:

- It is the heart of the engine.
- It consists of three parts.
 - The cylinders in which the piston slides up and down.
 - The ports or openings for valves.
 - The passages (water jackets) for the flow of cooling water.
- **Function:** In the bore of the cylinder, the charge is compressed by piston, ignited and expanded to give power to piston.
- Made from Aluminium alloy and grey cast iron

2. Cylinder Head

- It is fitted on the top of the cylinder.
- It has inlet valve, exhaust valve and the spark plug or fuel injector.
- Function: Through inlet valve fresh charge is admitted and through exhaust valve burnt gases are sent out



3. Piston:

- It is the main active part of the engine.
- It is cylindrical in construction and slides up and down inside the cylinder.
- It has piston rings to provide good seal between the cylinder wall and the piston.

Function:

- (i) To compress the fresh charge during the compression stroke.
- (ii) To transmit the force exerted due to combustion of the charge to the connecting rod finally to the crankshaft during the power stroke.



4. Piston Rings:

- Piston rings are fitted into the grooves of the piston to maintain good seal between the piston and the cylinder walls.
- There are two types of pistons rings. Upper rings are called compression rings and the lower rings are called oil rings.

Function:

- Compression rings are used to provide gas tight sealing to prevent leakage of the lubricating oil into the engine cylinder.
- The oil rings, also called as scrapper rings are used to scrap the used lubricating oil into the crank case.



5. Combustion Chamber:

- The space enclosed in the upper part of the cylinder, by the cylinder head and the piston top during the combustion process, is called the **combustion chamber**.
- Combustion chamber is the closed space in which combustion of fuel takes place.

6. Inlet and Exhaust Valves:

- There are two valves in the cylinder of IC engines inlet and exhaust valve.

Function:

- Inlet valve allows the fresh charge into the cylinder.
- Exhaust valve provides passages for the burnt gases to escape from the cylinder.

7. Connecting Rod:

- The connecting rod interconnects the piston to the crankshaft.
- The upper end of the connecting rod is fitted to the piston and lower end to the crankshaft.

Function:

- It transmits the power produced in the cylinder to the crankshaft.
- It converts the reciprocating motion of the piston into rotary motion of the crankshaft.



8. Piston Pin:

- The piston pin is a pin that connects the small end of the connecting rod to the piston. It is also known as gudgeon pin or wristpin.

9. Crank Pin:

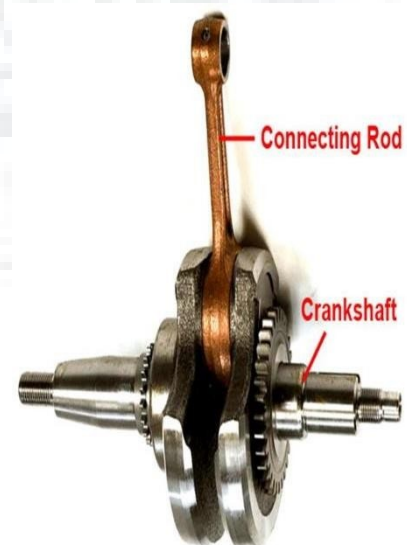
- Crank pin connects the connecting rod big end to the crankshaft

10. Crank and Crankshaft:

- The crank is a lever that is connected to the end of the connecting rod by a pin joint with its other end connected rigidly to a shaft, called crankshaft.
- The crankshaft is the principle rotating part of the engine. The crankshaft is provided with suitable holes to help in the lubrication system.

Function:

- It converts the reciprocating motion of the piston into useful rotary motion of the Output Shaft.



11. Camshaft:

- A camshaft is a shaft on which cams are mounted.
- The camshaft is driven by crankshaft through timing gears.
- This shaft also provides the drive to the ignition system.

Function:

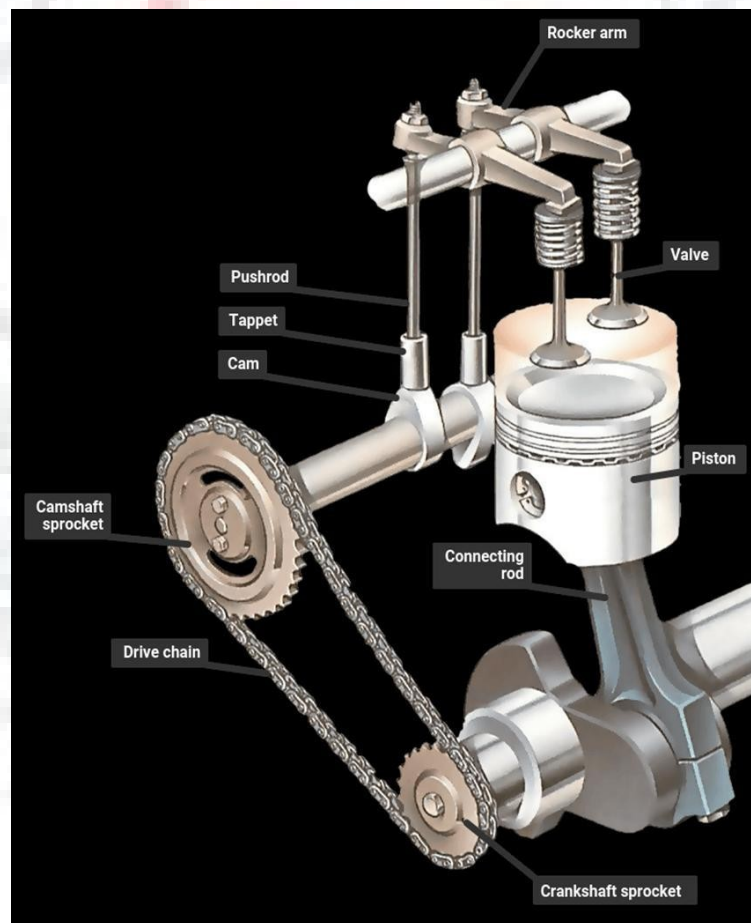
- It is used to operate the intake and exhaust valves through cam follower, push rod and rocker arm

12. Cams:

- Cams are integral parts of the camshaft.

Function:

- Cams are designed in such a way to open the valves at the correct timing and to keep them open for the necessary duration.



13. Flywheel:

- The flywheel is a heavy wheel that is connected to the extreme end of the crankshaft.
- The size of the flywheel depends upon the number of cylinders and the general construction of the engine.

Function:

- The flywheel stores the excess energy during the power stroke of the engine and supply the energy for the movement of the piston during the remaining stroke.
- Thus its function is to maintain Uniform rotation of the crankshaft.

Material:Cast iron.

14. Crankcase:

- It is a cast iron case, which holds the cylinder and the crankshaft.
- It also serves as sump for the lubricating oil.

Material:Cast iron and Aluminium alloy

IC ENGINE TERMINOLOGY

1. Bore:

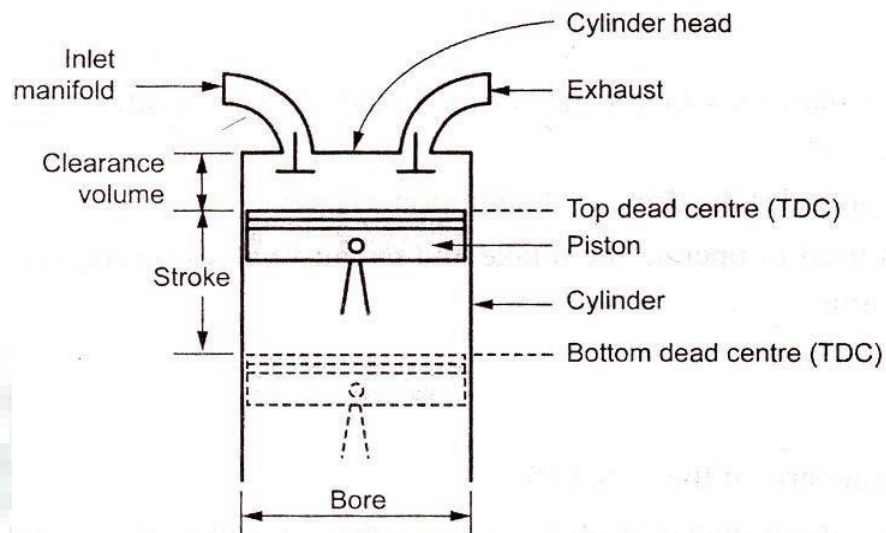
- The nominal inside diameter of the engine cylinder is called bore.

2. Top Dead Centre (TDC):

- The extreme position of the piston at the top of the cylinder of the vertical engine is called top dead Centre (TDC),

3. Bottom Dead Centre (BDC):

- The extreme position of the piston at the bottom of the cylinder of the vertical engine called bottom dead centre (BDC).



4. Bottom Dead Centre (BDC):

- The extreme position of the piston at the bottom of the cylinder of the vertical engine called bottom dead centre (BDC).
- In case of horizontal engines, it is known as outer dead center (ODC).

5. Stroke:

- The distance travelled by the piston from TDC to BDC is called stroke.
- In other words, the maximum distance travelled by the piston in the cylinder in one direction is known as stroke.
- It is equal to twice the radius of the crank.

6. Clearance Volume (V_c):

- The volume contained in the cylinder above the top of the piston, when the piston is at top dead centre is called the clearance volume.

7. Swept Volume (V_s):

- The volume swept by the piston during one stroke is called the swept volume or piston displacement.
- Swept volume is the volume covered by the piston while moving from TDC to BDC.

- **Swept volume = $V_s = A \times L = \frac{\pi D^2 L}{4}$**

Where;

A = Cross sectional area of the piston in Sq.m,

L = Stroke in m, and

D = Cylinder bore i.e., inner diameter of the cylinder in m.

8. Compression Ratio (r):

- Compression ratio is a ratio of the volume when the piston is at bottom dead centre to the volume when the piston is at top dead centre.

Mathematically,

$$\text{Compression ratio} = \frac{\text{Maximum Cylinder Volume}}{\text{Minimum Cylinder Volume}} =$$
$$= \frac{\text{Swept Volume} + \text{Clearance Volume}}{\text{Clearance Volume}}$$

- The compression ratio varies from 5 : 1 to 10 : 1 for petrol engines and from 12:1 to 22 : 1 for diesel engines.

9. Piston speed

- It is the distance travels by piston in one minute
- If RPM of engine shaft = N
- Length of stroke = L meter
- Then piston speed = $2LN$ meter/min

10. R.P.M :

- **RPM** stands for rotations per minute and is also abbreviated **rpm**
- This is a unit which describes how many times an object completes a cycle in a minute.

TWO STROKE ENGINES

- Two stroke engines perform only two strokes in one complete revolution of the crankshaft.
- Two stroke Cycle engines will theoretically give **twice the power** obtained from a four-stroke cycle engine of similar size.

Construction Details:

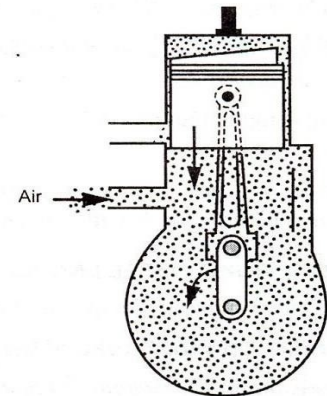
- In 2-stroke petrol engine, the ports are provided for charge inlet and exhaust, which are uncovered and cover by the moving piston.
- The suction port used for inlet of charge into the crankcase .The transfer port used for transfer of charge from the crankcase to the cylinder and exhaust port serves the purpose of discharging the burnt gases from the cylinder.
- The spark plug is located in the cylinder head.
- The **crown of the piston** (i.e., top of the piston) is shaped in such a way to assist in deflecting the fresh charge upwards in the cylinder and help scavenging.
- **Scavenging:** Scavenging is the process of forcing out the burnt exhaust gases from the cylinder by admitting the fresh charge into the cylinder.

Working of 2 –stroke Diesel Engine

1. First Stroke (Upward Stroke of the Piston Compression and Suction:

- During the upward movement of the piston from BDC to TDC, both the transfer and exhaust ports are covered by the piston

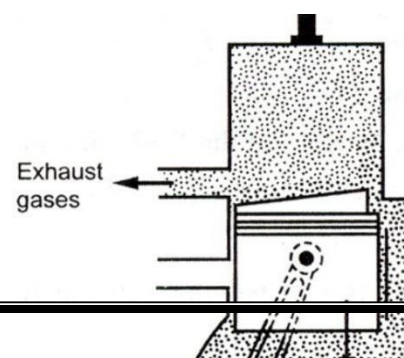
- The air, which is already transferred into the engine cylinder, is compressed by the moving piston. This increases the pressure and temperature of the air.
- The compression process is continued until the piston reaches TDC
-
- At the same time, the inlet port is uncovered by the moving piston and the fresh air enters the crankcase through the inlet port.
 - After the piston almost reaches the TDC, the fuel (diesel) is injected through the fuel injector in the cylinder and the combustion takes place.



(b) Ignition and inductance

2. Second Stroke (Downward Stroke of the Piston): Expansion and Exhaust

- The hot gases during combustion try to expand, forces the piston to move down, thus useful work is obtained.
- When the piston moves down, the air is partially compressed in the crankcase. This compression is known as crankcase compression.
- Nearly at the end of expansion, the exhaust port is uncovered and the combustion products escape to the atmosphere
- Immediately the transfer port is also uncovered and the partially compressed air from the crankcase enters the cylinder through the transfer port.
- The cycle of the operations are then repeated.



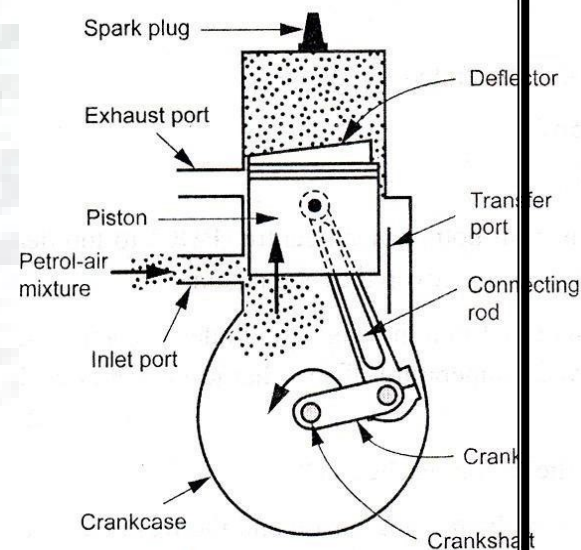
Working of 2 –stroke Petrol Engine

1. First Stroke (Upward Stroke of the Piston)

(a) Compression and Inductance

- During the upward movement of the piston from BDC to TDC, both the transfer and exhaust ports are covered by the piston.
- The petrol air mixture which is already transferred into the engine cylinder is compressed by the moving piston. Thus, the pressure and temperature of the charge increases at the end of compression.
- The compression process is continued until the piston reaches TDC.
- At the same time, the inlet port is uncovered by the moving piston and the fresh petrol air mixture enters the crankcase through the inlet port.

- After the piston almost reaches the TDC, the compressed petrol air mixture is ignited by means of an electric spark produced by a spark plug.
- The admission of fresh charge into the crankcase continues till the piston reaches



(a) Compression and inductance

the TDC.

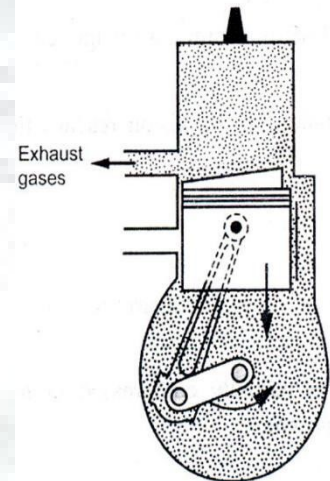
2. Second Stroke (Downward Stroke of the Piston)

(b) Expansion and Crankcase Compression:

- The ignited gases expand and forces the piston to move down, thus useful work is obtained.
- When the piston moves down, the petrol air mixture is partially compressed in the crankcase.

Thus compression is known as crankcase compression.

- Almost at the end of expansion, the exhaust port is uncovered and the combustion products escape to the atmosphere. Immediately, the transfer port is also uncovered and the partially compressed air fuel mixture from the crankcase enters the cylinder through transfer port.
- The crown of the piston is made of a deflected shape, so the fresh air petrol mixture entering the cylinder is deflected upward in the cylinder. Thus the escape of fresh charge along with the exhaust gases is reduced.
- The cycle of operations are then repeated.



(c) Expansion and crankcase compression

FOUR STROKE PETROL ENGINE

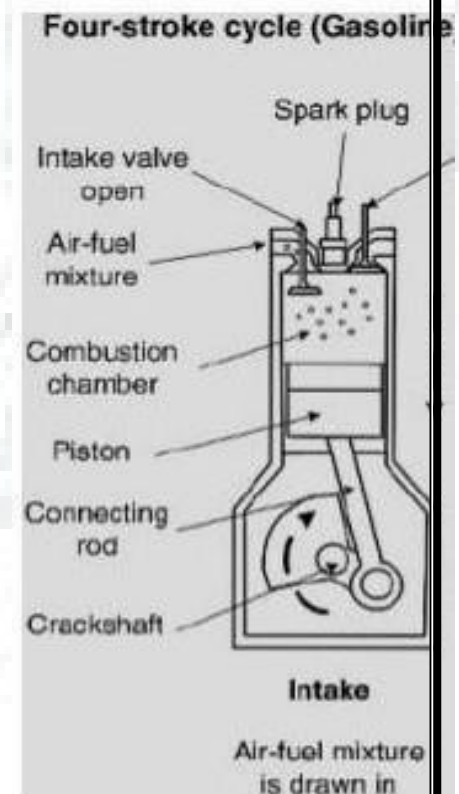
- Petrol engine is also known as Spark Ignition (SI) engine.
- Since ignition occurs due to a spark, petrol engines are called spark ignition (SI) engines.
- A four-stroke engine gives a power stroke in every set of four strokes of the piston or two revolution of the crankshaft.
- The petrol engine operates on theoretical Otto cycle.
- It is also called as constant volume combustion cycle as the combustion takes place at constant volume with increase of pressure.

The cycle of operation of a four-stroke petrol engine consists of the following strokes:

1. Suction or intake stroke,
2. Compression stroke,
3. Expansion or power stroke, and
4. Exhaust stroke.

Suction or intake stroke:

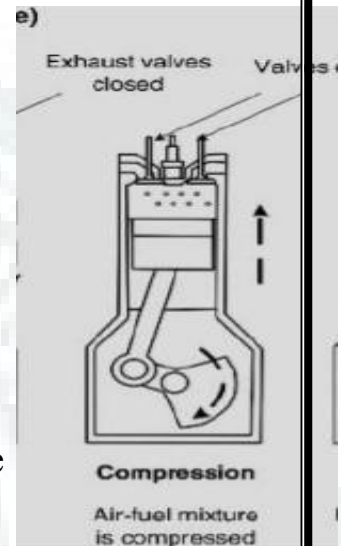
- During this stroke, the piston moves from Top Dead Centre (TDC) to Bottom Dead Centre (BDC) creating a vacuum inside the cylinder.
- During this stroke, the inlet valve is kept opened and the exhaust valve is kept closed.
- The vacuum created inside the cylinder draws the air petrol mixture into the cylinder through the inlet valve.



- It is performed till the piston reaches BDC.
- The above process is known as suction and this stroke is called the suction stroke.

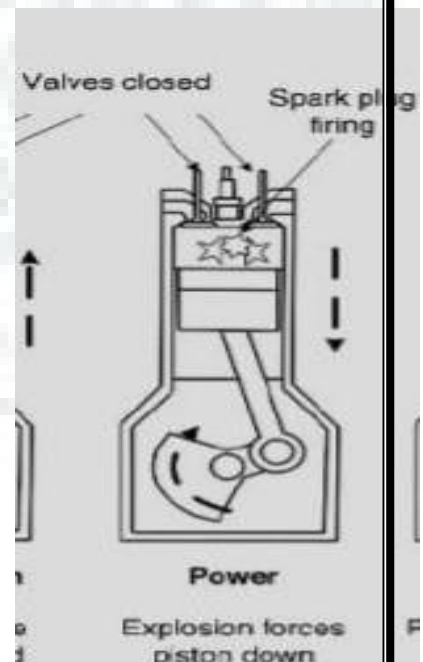
Compression Stroke:

- During this stroke, both the inlet and exhaust valves are closed
- The air petrol mixture is compressed as the piston moves upwards from BDC to TDC.
- As a result of this compression, pressure and temperature of the air fuel mixture or charge is increased.
- Just before the piston reaches the TDC, the air petrol mixture (charge) is ignited by a spark plug; suddenly burning of the air fuel mixture takes place almost instantaneously.



Expansion or Power Stroke or Working Stroke:

- During this stroke, both the inlet and exhaust valves remain closed.
- The high pressure of the products of combustion (hot gases) pushes the piston from TDC to BDC. It is also called as working stroke as work is done by the expansion of hot gases.
- The force above the piston is transmitted to the

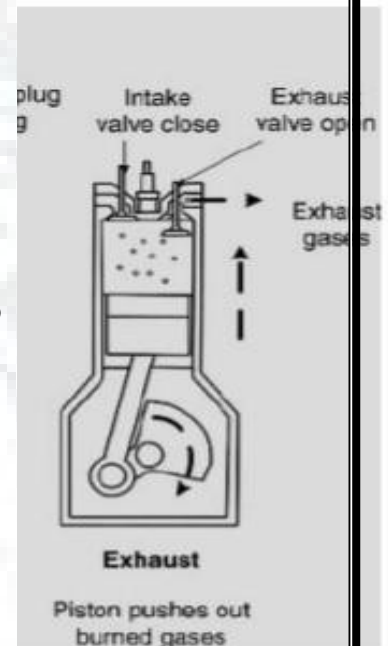


crankshaft through the connecting rod and crank mechanism.

- Excess energy due to the combustion is stored in the flywheel which helps for the operation of three idle strokes

4. Exhaust Stroke:

- At the end of the expansion stroke, the exhaust valve opens and the
- pressure inside falls suddenly. Thus during this stroke, the inlet valve is closed and the exhaust valve is kept opened.
- The upward movement of the piston from BDC to TDC pushes out the products of combustion from the engine cylinder through the exhaust valve into the atmosphere.
- The cycle of operation is then repeated.



FOUR STROKE DIESEL ENGINE

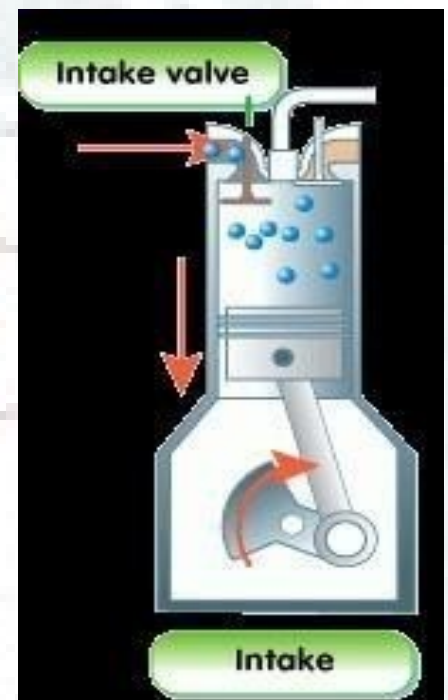
- Diesel engine is also known as **compression ignition (CI) Engine**.
- It is invented by **Rudolf Diesel (1892)**
- The four-stroke diesel engine is similar to four stroke petrol engine except that it operates at a **higher compression ratio (14 to 22)**.
- In a diesel engine, only **air is sucked from the atmosphere** instead of air fuel mixture during the suction stroke.
- In diesel engines, spark plug is not required for igniting the air fuel mixture. Because **the fuel is injected and forms an explosive mixture, which ignites spontaneously under pressure**.
- Diesel engine works on the principle of **diesel cycle**.
- It is also called as **constant pressure combustion cycle** as the combustion of fuel takes place at constant pressure with increase of temperature.
- Since ignition results due to high temperature of compressed air, these are called compression ignition (CI) engines.

The cycle of operation of a four-stroke diesel engine consists of the following strokes:

1. Suction or intake stroke,
2. Compression stroke,
3. Expansion or power stroke, and
4. Exhaust stroke.

1. Suction Stroke:

- During suction stroke, the inlet valve opens and the exhaust valve closes.
- The piston moves from TDC to BDC. This piston movement reduces the pressure inside the cylinder below the atmospheric pressure.
- Due to the pressure difference, the fresh air is sucked into the cylinder through the inlet valve.



2. Compression Stroke:

- During this stroke, both the inlet and exhaust valves are closed.
- The air in the cylinder is compressed as the piston moves upwards from BDC to TDC.
- As a result of this compression, pressure and temperature of the air is increased.
- Just before the piston reaches the TDC, the diesel is injected into the cylinder in the form of a fine spray.
- The fuel gets vaporized and self ignited due



to the heat of compressed air.

- The fuel burns instantaneously at constant pressure.

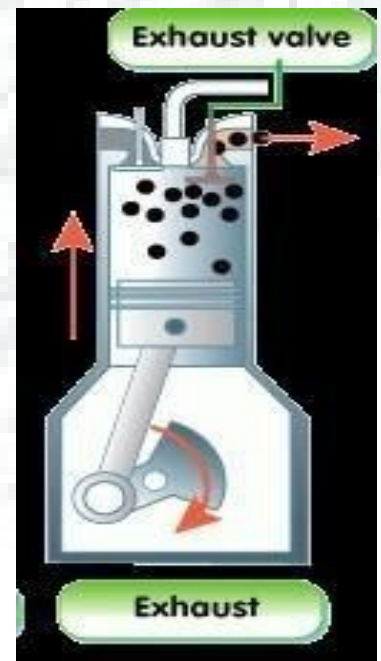
3. Expansion or Power Stroke:

- During this stroke, both inlet and exhaust valves are closed.
- The combustion of fresh fuel injected into the cylinder is due to the high pressure and temperature developed during compression stroke.
- The high pressure of the combustion products due to expansion of charge pushes piston from TDC to BDC. It is also called as working stroke as work is done by the expansion of hot gases.



4. Exhaust Stroke:

- During this stroke, inlet valve is closed and the exhaust valve is opened.
- The piston moves from BDC to TDC. The burnt waste gases are sent out through exhaust valve and the cycle is repeated.



4 STROKE ENGINE	2 STROKE ENGINE
No of Strokes per Cycle is four	No of Strokes per Cycle is two
In 2 Revolutions of Crankshaft there is one power stroke	In 1 Revolutions of Crankshaft there is one power stroke
It has valve, Inlet, Exhaust Valve Operated by cam using Valve – Gear Mechanism	It has port, Inlet, Transfer & Exhaust Port are in Cylinder Walls Piston Movement Covers & Uncovers the Ports
The Torque Fluctuations is High	The Torque Fluctuations is more uniform.
Heavy Flywheel is used due to Non Uniform Torque on the Crankshaft	Lighter Flywheel is enough due to Uniform Torque
Charge is Directly admitted into cylinder during Suction Stroke	Charge is Admitted into the Crankcase and then Transferred to the cylinder
Fuel Consumption is less	Fuel Consumption is more
Mechanical Efficiency is low	Mechanical Efficiency is high
Engine Size is heavy and bulky	Engine Size Compact

PETROL ENGINE	DIESEL ENGINE
Fuel used is Petrol	Fuel used is Diesel
It works on Otto or Constant Volume Cycle	It works on Diesel or Constant Pressure Cycle
Air – Fuel Mixture is used as charged	Air & Fuel is Injectedis used as charged
Fuel Admitted in to the engine cylinder through carburetor	Fuel Admitted in to the engine cylinder through fuel injector
Ignition System is Spark Ignition	Ignition System is Compression Ignition
Compression Ratio is low(6 to 8)	Compression Ratio is High (16 to 18)
Thermal Efficiency is Less due to Low Compression ratio	Thermal Efficiency is More due to High Compression ratio
Starting of Engine is easy	Starting of Engine is difficult
Weight of Engine is lighter	Weight of Engine is heavior
Power Output is less	Power Output is more

1.



Branch: Mechanical

Semester: 3rd Sem

Subject: Engineering Material

Chapter: 5

Topic: Thermal engineering - I

Faculty: SIBASISH SAHU

Course contain

- 5.1 Carnot cycle
- 5.2 Otto cycle.
- 5.3 Diesel cycle.
- 5.4 Dual cycle.
- 5.5 Solve simple numerical.

Introduction

Gas Power Cycle :

- In case of gas power cycle the working fluid is a gas . The gas is normally air or the product of combustion of the fuel and air
- In gas power cycle ,The supply of heat is by means of the combustion of a suitable mixture of air and fuel with in the confines of engine.
- As there is no external source of heat such engines are also known as internal combustion engine.

Carnot engine:

- Carnot engine is an ideal heat engine whose efficiency is maximum.
- In Carnot engine, Carnot cycle is used.
- In Carnot engine, ideal gas is the working substance

Carnot cycle:

- Carnot cycle , also called *reversible cycle* .
- In one complete cycle of operation , there are four different thermodynamic reversible processes are given:
 1. Reversible isothermal expansion
 2. Reversible adiabatic (isentropic) expansion
 3. Reversible isothermal compression, and
 4. Reversible adiabatic (isentropic) compression

Working of a Carnot engine

Reversible isothermal expansion-(1-2, $T_H = \text{constant}$)

- At first, the working substance is kept in contact with the source. The piston of then cylinder is moved outwards.
- The gas expands at constant temperature. The amount of heat(Q_1) is absorbed from the source to make the temperature constant. The volume increases and pressure decreases. This is called **isothermal expansion**

- It is represented by the curve 1-2

2. Reversible Adiabatic expansion : (2-3, $Q=0$, $T_H \Rightarrow T_L$)

- The lower conducting side of the cylinder is kept in contact with the insulating stand. The piston of the cylinder is moved outwards. The gas expands such that no heat enters the system or leaves from it. The volume increases and pressure decreases. The temperature is decreased from T_1 to T_2 .
- This is called adiabatic expansion. It is represented by the curve 2-3 in the indicator diagram.

3. Reversible Isothermal Compression: (3-4, $T_L = \text{constant}$)

- The cylinder is kept in contact with the sink. The piston of the cylinder is moved inwards. The gas is compressed at constant temperature. The excess heat produced (Q_2) will flow to the sink to make the temperature constant. The volume decreases and pressure increases. This is called isothermal compression.
- It is represented by the curve 3-4 in the indicator diagram

4. Reversible Adiabatic compression:(4-1, $Q=0$, $T_L \rightarrow T_H$)

- The cylinder is kept in contact with the insulating stand. The piston of the cylinder is moved inwards. The gas is compressed such that no heat enters the system or leaves from it.
- The volume decreases and pressure increases. The temperature increases from T_2 to T_1 . This is called adiabatic compression. It is
- represented by the curve 4-1 in the indicator diagram.

The Carnot cycle for a gas might occur as visualized below.

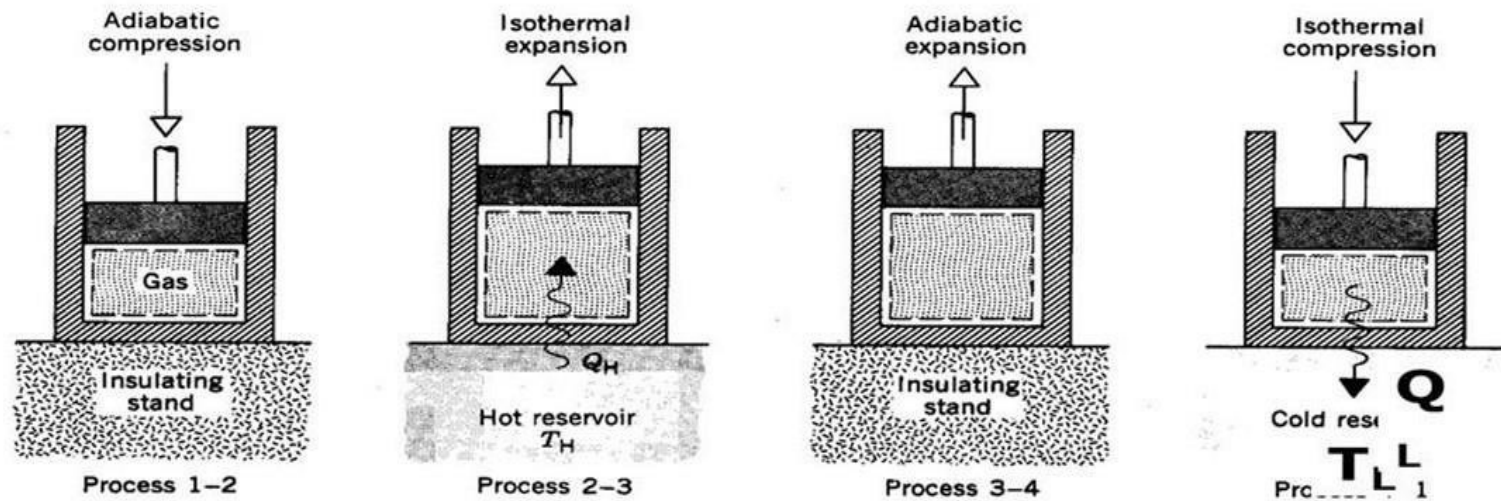
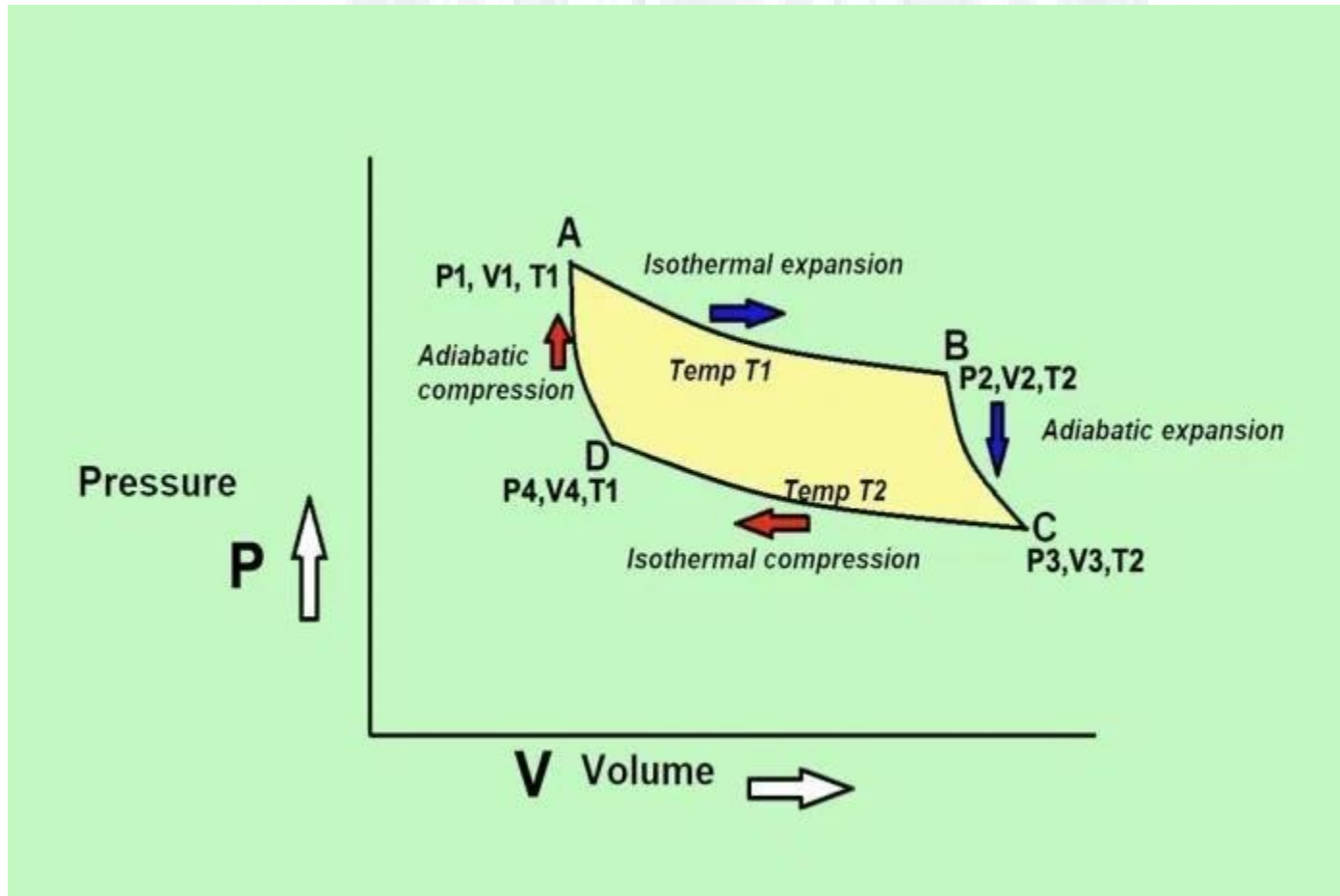
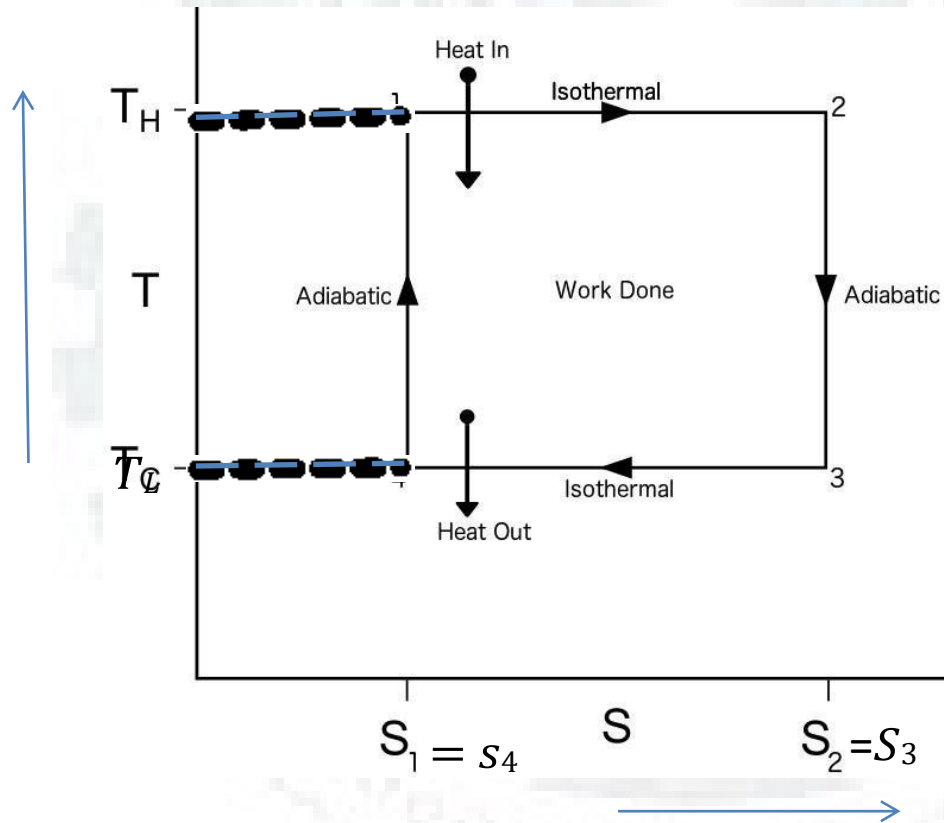


Figure 5.10 Carnot power cycle executed by a gas in a piston-cylinder assembly.

P-V diagram



T-S diagram



Efficiency of Carnot cycle

We have the efficiency of heat engine,

- Efficiency (η) = $\frac{\text{Workdone}}{\text{Heat supplied}} = \frac{W}{Q_H}$

where

W is the work done and

Q_H is the amount of heat absorbed from the source (T_H).

Though it is a cyclic process, then applying first law of thermodynamic for cyclic process

net work done = net heat transfer

$$\square \delta W = \square$$

- Therefore $W = Q_H - Q_L$
- where Q_L is the amount of energy rejected to sink. (T_L)

- Therefore, $\eta = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H}$
- For a Carnot engine, it can be shown that
- $\eta = 1 - (T_L/T_H)$
- where T_H is the temperature of source and T_L that of sink.

From T-S diagram:

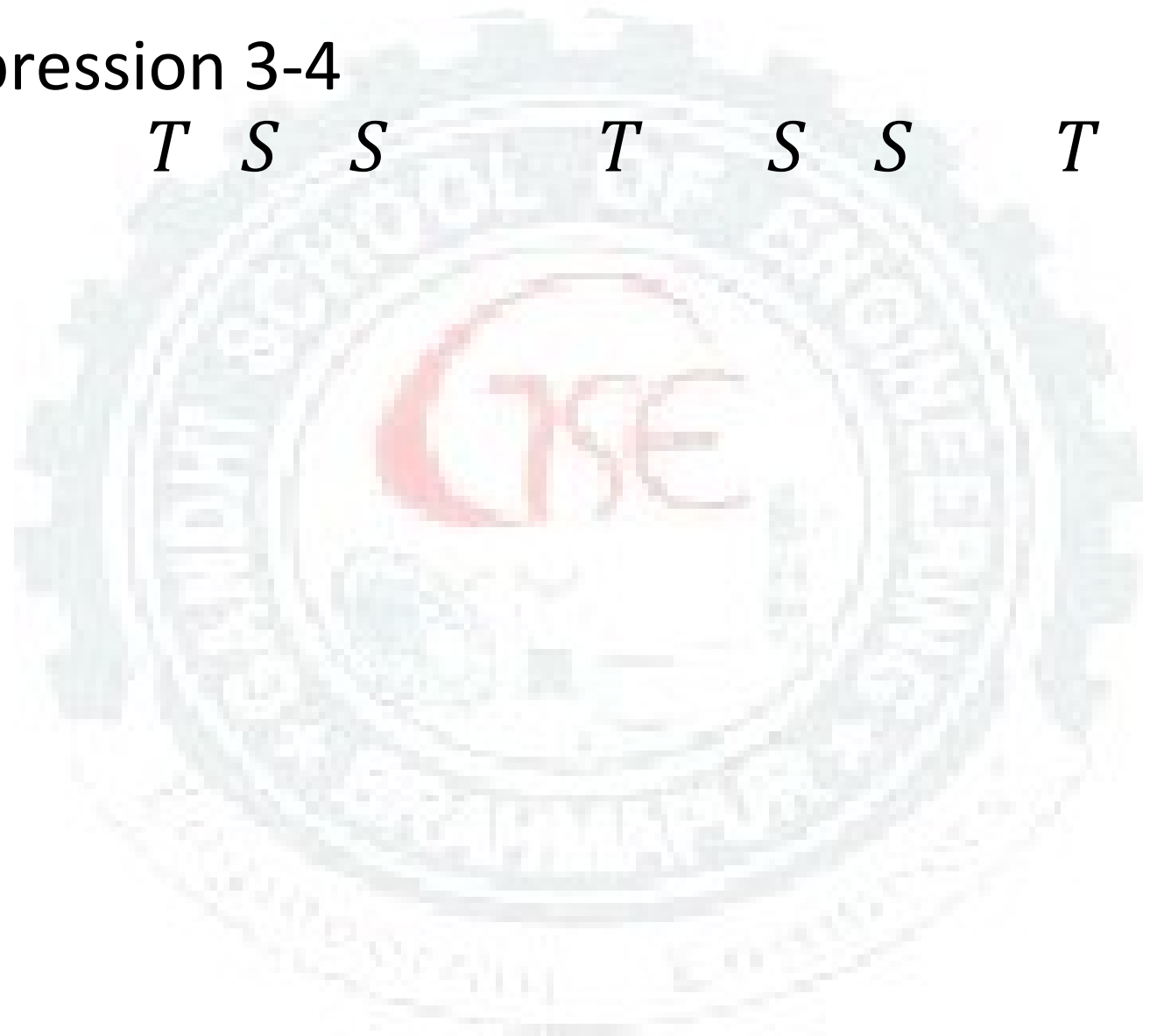
Heat supplied during isothermal process
expansion 1-2

$$Q_{1-2} = T(S_2 - S_1)$$

And heat rejected during isothermal

compression 3-4

Q T S S T S S T S



Efficiency

$$= \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$$

$$\eta = \frac{\text{Workdone}}{\text{Heat supplied}} = \frac{W}{Q_H} = \frac{(S_2 - S_1)(T_H - T_L)}{T(S_2 - S_1)}$$

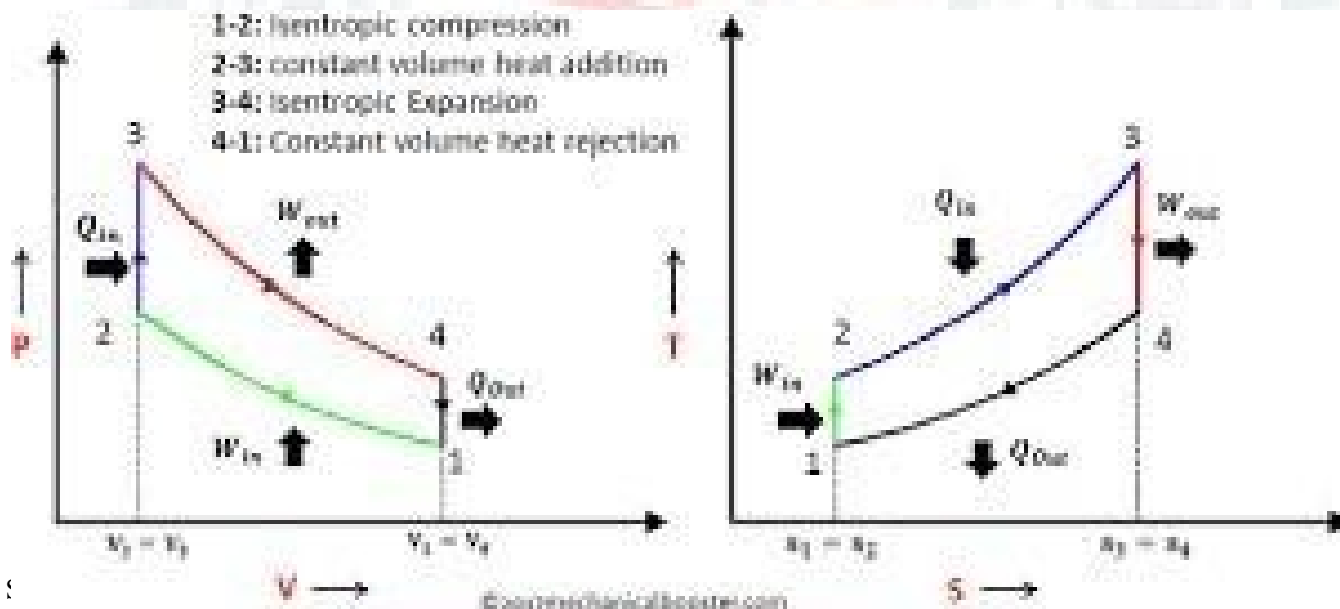
Air standard cycle:

Assumption :

- The working fluid (air) has a constant mass throughout the entire air cycle and air is taken to be ideal.
- The air maintains a constant specific heat capacity throughout the cycle.
- The combustion process is replaced by a heat transfer process from an external heat source.
- The cycle is completed by the heat transfer to the surrounding in contrast to the exhaust and the intake processes of an actual engine.
- All the processes are internally reversible.

Otto cycle:

- The Otto cycle is an ideal air standard cycle for gasoline (petrol) engine, gas engine and high speed engine
- The operation of the Otto cycle is shown in below:



• The air-standard-Otto cycle is the idealized cycle for the spark-ignition internal combustion engines. This cycle is shown above on p-v and T-s diagrams. The Otto cycle 1-2-3-4 consists of following four process:

1. Process 1-2: Reversible adiabatic compression of air & isentropic compression
2. Process 2-3: Heat addition at constant volume.
3. Process 3-4: Reversible adiabatic expansion of air & isentropic expansion
4. Process 4-1: Heat rejection at constant volume

Analysis:

For Otto cycle per unit mass

$$\text{Thermal efficiency} = \eta_{th} = \frac{\text{Net work out}}{\text{Heat supplied}} = \frac{W_{net}}{q_s}$$

Heat supplied $q_{in} = C(T_3 - T_2)$ Heat

reject $q_{out} = C_V(T_4 - T_1)$

Applying 1st law of thermodynamic for cycle

Network done = net heat transfer

$$W_{net} = q_{in} - q_{out} = C(T_3 - T_2) - C_V(T_4 - T_1)$$

$$\eta_{th} = \frac{W_{net}}{q_s} = \frac{C(T_3 - T_2) - C_V(T_4 - T_1)}{C(T_3 - T_2)} = 1 - \frac{C_V(T_4 - T_1)}{C(T_3 - T_2)}$$

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$= 1 - \frac{T_1(T_4 - T_1)}{T_1(T_3 - T_2)}$$

$$= 1 - \frac{T_2(T_4 - T_1)}{T_2(T_3 - T_2)}$$

T_2

.....

.....

...(1)



Considering the isentropic process 1-2

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1}$$

$$\frac{P_1 V_1^\gamma}{P_2 V_2^\gamma}$$

as $PV = mRT$
 $\frac{mRT}{V}$

$$P = \frac{mRT}{V}$$

$$\frac{mRT_1 V_1^\gamma}{V_1} = \frac{mRT_2 V_2^\gamma}{V_2}$$

$$= T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

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

$r = \frac{V_1}{V_2}$ is called compression ratio

For the isentropic process 3-4

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

T_4

V_3

V_2



Equating equation (ii) & (iii) we get

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \text{ or } \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\text{as } \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

If we apply $\frac{T_4}{T_1} = \frac{T_3}{T_2}$ in equation (1)

then equation become

$$\eta_{th} = 1 - \frac{T_1 \left(\frac{T_3}{T_2} - 1 \right)}{T_2 \left(\frac{T_3}{T_2} - 1 \right)} = 1 - \frac{T_1}{T_2}$$

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

$$\text{Then } \eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\frac{T_2}{T_1}} = 1 - \frac{1}{(r)^{\gamma-1}}$$

$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}}$$



- For air the ratio of specific heat γ is assumed to be constant and thus the efficiency of the Otto cycle is the function of compression ratio only.
- The efficiency of the Otto cycle increases with increases in compression ratio.
- practically the compression ratio of petrol engines is restricted to maximum of 9 or 10 due to the phenomenon of knocking at high compression ratios.

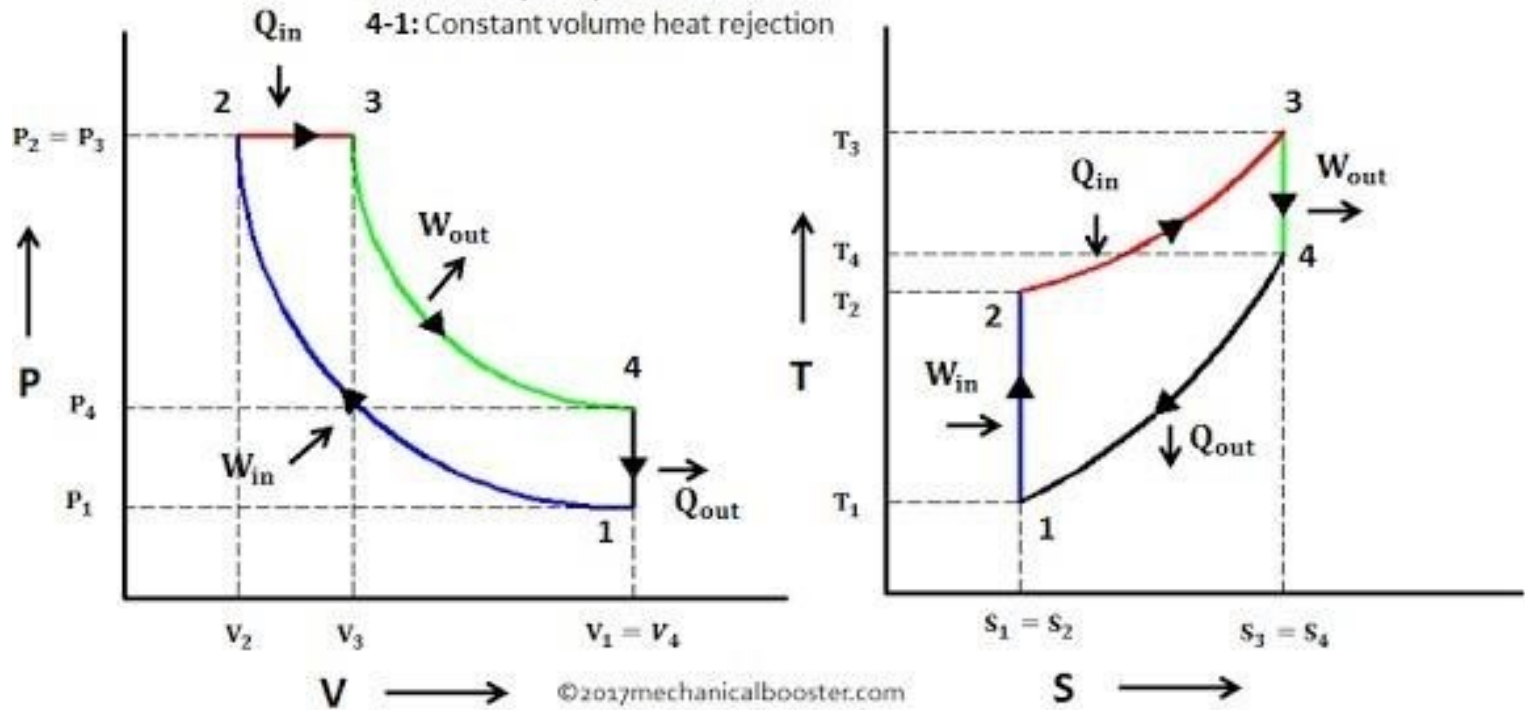
Diesel Cycle:

The Diesel cycle is an ideal cycle for reciprocating compression ignition (CI) engine.

- In a Diesel engine only air is compressed during the compression stroke thus eliminating the possibility of auto-ignition.
- Therefore Diesel engines are designed to operate at a very high compression ratio between 12 and 14

DIESEL CYCLE

- 1-2: Isentropic compression
- 2-3: Constant pressure heat addition
- 3-4: Isentropic expansion
- 4-1: Constant volume heat rejection



The thermodynamic process undergoing cyclic process
 net work done = net heat transfer

$$W_{net} = q_{in} - q_{out}$$

$$\text{Heat supplied } q_{in} = C_P (T_3 - T_2)$$

$$\text{Heat rejected } q_{out} = C_V (T_4 - T_1)$$

$$\begin{aligned} \eta_{th} &= \frac{W_{net}}{q_s} = \frac{C_P (T_3 - T_2) - C_V (T_4 - T_1)}{C_P (T_3 - T_2)} = 1 - \frac{C_V (T_4 - T_1)}{C_P (T_3 - T_2)} \\ &= 1 - \frac{C_V}{C_P} \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{1}{\gamma} \frac{(T_4 - T_1)}{(T_3 - T_2)} \end{aligned}$$

Compression ratio

$$r = \frac{V_1}{V_2} = \frac{\text{Volume before compression}}{\text{Volume after compression}}$$

Cutoff : It is the ratio of volume at where fuel supply is cutoff to the volume at where fuel supply is started

$$\rho = \frac{V_3}{V_2} = \frac{\text{Volume after heat supply}}{\text{Volume after compression}}$$

Expansion ratio

$$r_e = \frac{V_4}{V_3} = \frac{\text{Volume after expansion}}{\text{Volume before expansion}}$$

It can be proved that

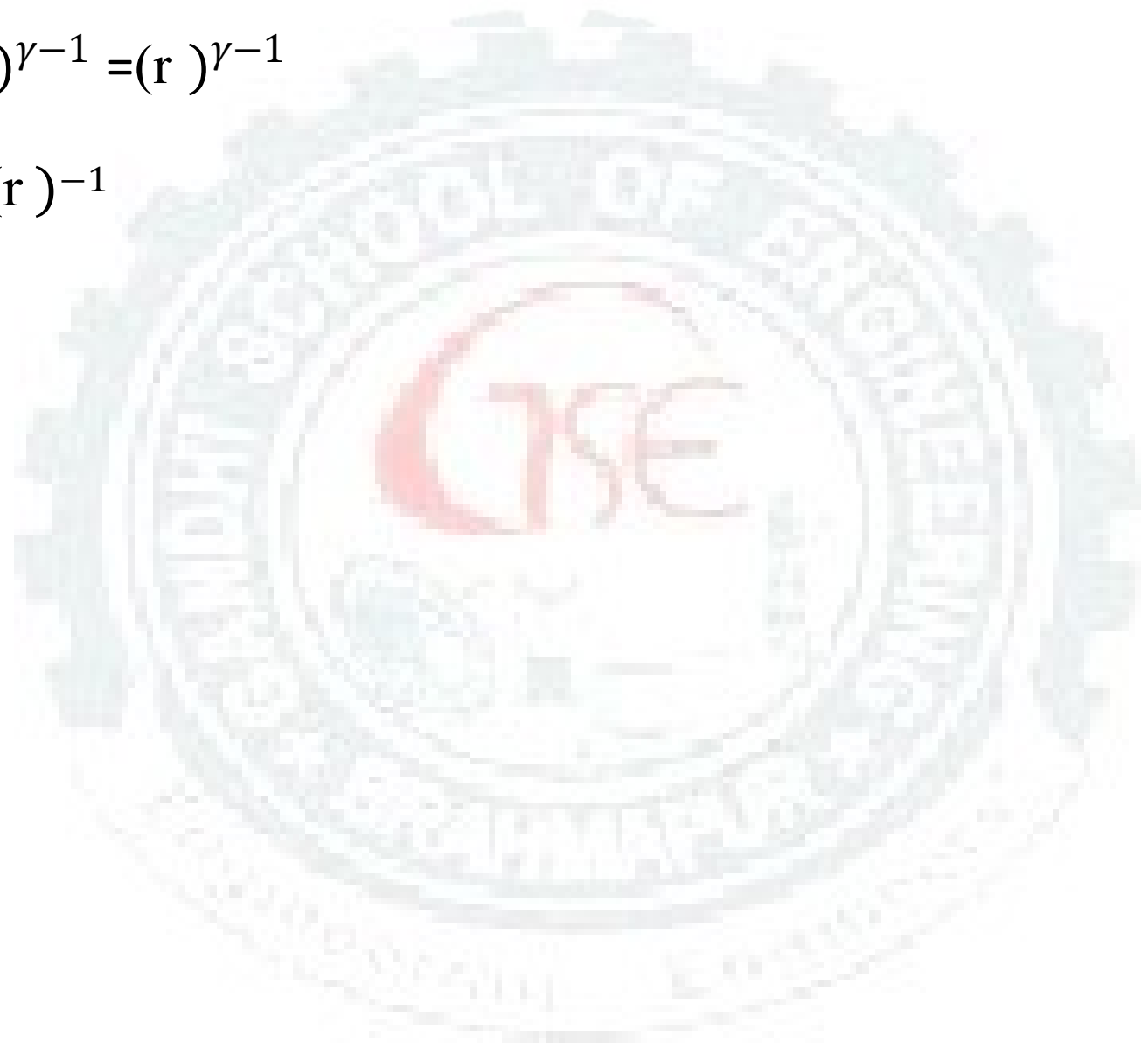
$$r_e = r \times \rho = \frac{V_4}{V_3} \times \frac{V_3}{V_2} = \frac{V_4}{V_2} = r$$

Isentropic process 1-2

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1} = (r)^{\gamma-1}$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1}$$

$$T_2 = T_1 (r)^{\gamma-1}$$



For constant –pressure heat addition process 2-3

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

$$T_3 = \rho T_2 = \rho T_1 (r)^{-1}$$

Isentropic process 3-4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \left(\frac{v_3}{v_1}\right)^{\gamma-1} = \left(\frac{v_3}{\rho v_2} \times \frac{v_2}{v_1}\right)^{\gamma-1} \rho^{\gamma-1}$$

$$T_4 = \rho^{\gamma-1} \left(\frac{v_3}{v_1}\right)^{\gamma-1} \rho T_3 = \rho^{\gamma-1} \left(\frac{v_3}{v_1}\right)^{\gamma-1} \rho T_1 (r)^{-1}$$

$$\frac{T_4}{T_1} = \rho^{\gamma} (r)^{-1} \Rightarrow T_4 = \rho^{\gamma} T_1$$

$$T_4 = \rho^{\gamma} T_1$$

$$\begin{aligned}
 \eta_{Diesel} &= 1 - \frac{(4-T_1)}{\gamma(3-T_2)} \\
 &\quad (\rho^\gamma T_1 - T_1) \\
 &= 1 - \frac{(\rho^\gamma T_1 (r)^{-1} - T_1 (r)^{\gamma-1})}{\gamma T_1 (r)^{-1} (\rho - 1)} \\
 &= 1 - \frac{T_1 (\rho^\gamma - 1)}{\gamma T_1 (r)^{-1} (\rho - 1)} \\
 &= 1 - \frac{(\rho^\gamma - 1)}{\gamma (r)^{-1} (\rho - 1)} \\
 &= 1 - \frac{1}{(r)^{-1}} \times \frac{(\rho^\gamma - 1)}{\gamma (\rho - 1)}
 \end{aligned}$$

Effect of cut off ratio on Diesel cycle efficiency:

Since the cut off ratio ρ is always greater than unity then the quantity

$\frac{1(\rho^\gamma - 1)}{\gamma(\rho - 1)}$ is also greater than unity

Thus $\eta_{Diesel} < \eta_{Otto\ cycle}$ for the same compression ratio

Since Diesel engine employ much higher compressor ratio, thus their thermal efficiency is higher

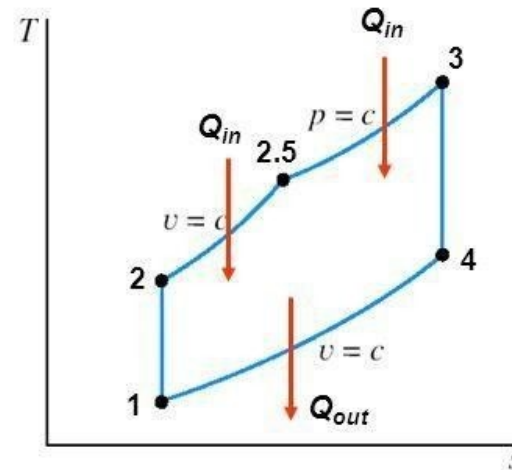
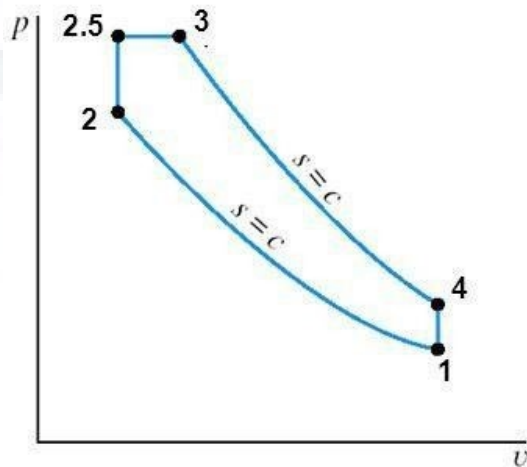
- As cut-off ratio decreases η_{Diesel} cycle increases

DUAL CYCLE:

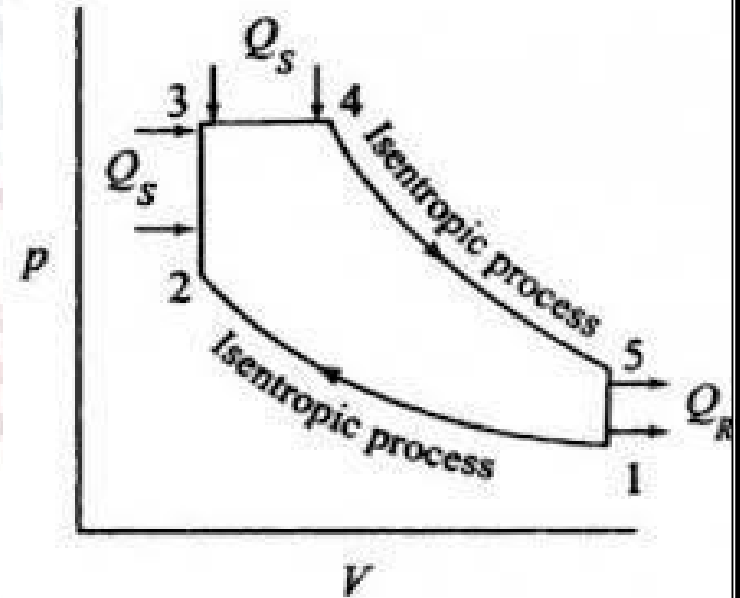
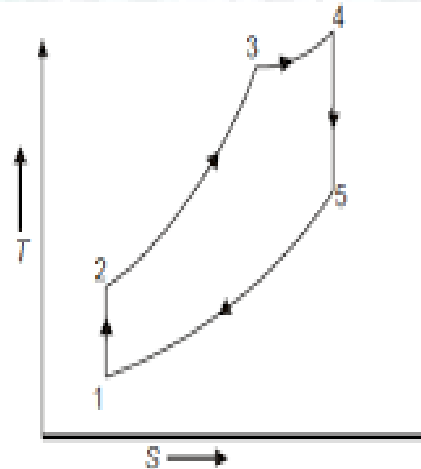
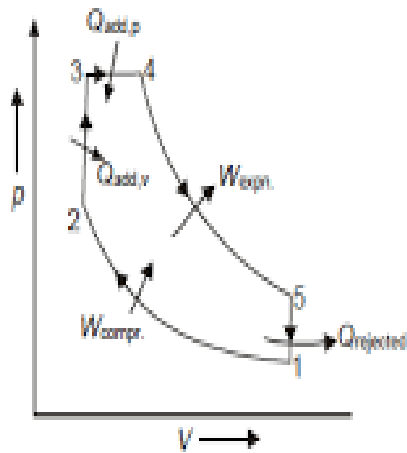
- In Otto cycle the combustion is assumed at constant volume, while in the Diesel cycle, the combustion is at constant pressure.
- In actual diesel cycle, the fuel injection starts before the end of compression stroke and thus a part of heat is added at constant volume and rest at constant pressure showing in fig.
- Such cycle is referred as air standard dual cycle or mixed cycle or limited pressure cycle.

Dual Cycle

- Process 1 → 2 Isentropic compression
- Process 2 → 2.5 Constant volume heat addition
- Process 2.5 → 3 Constant pressure heat addition
- Process 3 → 4 Isentropic expansion
- Process 4 → 1 Constant volume heat rejection



$$\frac{Q_{in}}{m} = (u_{2.5} - u_2) + (h_3 - h_{2.5}) = c_v(T_{2.5} - T_2) + c_p(T_3 - T_{2.5})$$



$$q_{in} = C(T_3 - T_2)$$

$$q_{in} = C(T_4 - T_3)$$

$$q_{in} = C(T_3 - T_2) - C_P(T_4 - T_3)$$

$$q_{out} = C(T_5 - T_1)$$

$$\eta = 1 - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{C(T_5 - T_1)}{C(T_3 - T_2) - C_P(T_4 - T_3)} = 1 - \frac{(T_5 - T_1)}{\frac{C}{C_P}(T_3 - T_2) - (T_4 - T_3)}$$

Cv



Er.SIBASIS

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma (T_4 - T_3)} \dots \dots \dots \text{eq.(1)}$$

• Compression ratio = $r = \frac{V_1}{V_2}$

• Cutoff ratio = $\rho = \frac{V_4}{V_3} = \frac{V_5}{V_3}$

• Expansion ratio $r_e = \frac{V_4}{V_5}$

• Isentropic compression process 1-2

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

$$T_2 = T_1 r^{\gamma-1}$$

Constant volume heat addition process 2-3

$$V_2 = V_3 = V_C$$

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

$$\underline{T_3} = \underline{P_3} = r$$

T_2 P_2 P



Er.SIBASIS

$$T_3 = r_p T_2$$

$$T_3 = r_p T_1 r^{\gamma-1}$$

Constant pressure heat addition process 3-4

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

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

$$T_4 = \rho T_3$$

$$T_4 = \rho r_p T_1 r^{\gamma-1}$$

Isentropic expansion process 4-5

$$\frac{T_5}{T_4} = \left(\frac{V_4}{V_5}\right)^{\gamma-1} = \left(\frac{V_4}{V_1}\right)^{\gamma-1} = \left(\frac{V_4}{V_3} \times \frac{V_3}{V_2} \times \frac{V_2}{V_1}\right)^{\gamma-1}$$

$$= \left(\frac{V_4}{V_3} \times \cancel{\frac{V_3}{V_2}} \times \frac{V_2}{V_1}\right)^{\gamma-1} \quad (\text{as } V_3 = V_2)$$

$$\frac{T_5}{T_4} = \left(\frac{V_4}{V_3} \times \frac{V_2}{V_1} \right)^{\gamma-1} = \left(\frac{\rho}{r} \right)^{\gamma-1}$$

$$T_5 = T_4 \left(\frac{\rho}{r} \right)^{\gamma-1} = \rho r_P T_1 r^{\gamma-1} \left(\frac{\rho}{r} \right)^{\gamma-1} = \rho r_P T_1 \frac{\rho^{\gamma-1}}{r^{\gamma-1}}$$

$$T_5 = \rho^{\gamma} r_P T_1$$

$$T_5 = \rho^{\gamma} r_P T_1$$

Using the value of $T_{2,3}, T_4$ & T_5 in equation 1

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$


$$= 1 - \frac{(\rho^{\gamma} r_P T_1 - T_1)}{(r^{\gamma-1} r_P T_1 - r^{\gamma-1} T_1) + \gamma(r^{\gamma-1} \rho r_P T_1 - r^{\gamma-1} r_P T_1)}$$

$$= 1 - \frac{T_1(\rho^{\gamma} r_P - 1)}{T_1 \times r^{\gamma-1} (r_P - 1) + \gamma \times r^{\gamma-1} \times T_1 (\rho r_P - r_P)}$$

$$\begin{aligned}
&= 1 - \frac{T_1(\rho^\gamma r_P - 1)}{T_1 \times r^{\gamma-1}(r_P - 1) + \gamma \times r^{\gamma-1} \times T_1(\rho r_P - r_P)} \\
&= 1 - \frac{1}{r^{\gamma-1}} \times \frac{(\rho^\gamma r_P - 1)}{(r_P - 1) + \gamma(\rho r_P - r_P)} \\
&= 1 - \frac{1}{r^{\gamma-1}} \times \frac{(\rho^\gamma r_P - 1)}{(r_P - 1) + \gamma r(\rho - 1)} \\
\eta_{Dual} &= 1 - \frac{1}{r^{\gamma-1}} \times \frac{(r_P \rho^\gamma - 1)}{(r_P - 1) + \gamma \times r(\rho - 1)}
\end{aligned}$$



THANK YOU



Branch: Mechanical
Semester: 3rd Sem
Subject: Engineering Material
Chapter: 6
Topic: Thermal engineering - I
Faculty: SIBASISH SAHU

Content

6.1 Define Fuel.

6.2 Types of fuel.

6.3 Application of different types of fuel.

6.4 Heating values of fuel.

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Introduction

Fuel: Fuel are those substance which when burn in the presence of air it's generate heat.

Classification of fuel:

Fuels are classified in 3 types

- i. Solid
- ii. Liquid
- iii. Gas

Solid fuel:

The fuel appear in solid state for e.g. Coal, wood , Charcoal, Anthracite, Bituminous etc.

Liquid fuel:

The fuel appear in liquid state for e.g. Crude oil, Petrol, Diesel, Kerosene etc.

Gaseous fuel:

The fuel appear in gaseous state e.g. Natural gas ,Biogas , Methane ,Ethane etc.

Fuels suitable for fast chemical reaction have to be used in IC engines, they are following types-

Hydrocarbon Fuel

- The fuel which contain hydrogen and carbon are main constituent
- Hydrocarbons fuels derived from the crude petroleum by proper refining process such as thermal and catalytic cracking method, polymerisation, alkylation, isomerisation, reforming and blending

e.g. CH_4

- **Alternative fuels** such as-Alcohols (methanol, ethanol) Natural gas (methane) LPG (propane, butane) Hydrogen
- **Liquid hydrocarbons-** Engine fuels are mainly mixtures of hydrocarbons, with bonds between hydrogen and carbon atoms. During combustion these bonds are broken and new bonds are formed with oxygen atoms, accompanied by the release of chemical energy. Principal products are carbon dioxide and water vapour . Fuels also contain small amounts of S, O₂, N₂, H₂O. The different constituents of crude petroleum which are available in liquid hydrocarbons are- paraffins, naphthenes, naphthenes, olefins, aromatics.

Application of different types of fuel.

Solid Fuel: The common coals used in Indian industry are bituminous and sub-bituminous coal .

Gaseous fuels in common use are liquefied petroleum gases (LPG), Natural gas, producer gas, blast furnace gas, coke oven gas etc. The calorific value of gaseous fuel is expressed in Kilocalories per normal cubic meter (kCal/Nm^3) i.e. at normal temperature (20°C) and pressure (760 mm Hg)

Liquid Fuels are used in i.c engine and also industrial purpose e.g. Petrol Engine, Diesel Engine, etc.

- *Combustion* is the conversion of a substance called a *fuel* into chemical compounds known as *products of combustion* by combination with an *oxidizer*.
- The combustion process is an *exothermic* chemical reaction, i.e., a reaction that releases energy as it occurs. Thus combustion may be represented symbolically by:
- **Fuel + Oxidizer → Products of combustion + Energy**
- Here the fuel and the oxidizer are *reactants*, i.e., the substances present before the reaction takes place. This relation indicates that the reactants produce combustion products and energy. Either the chemical energy released is transferred to the surroundings as it is produced, or it remains in the combustion products in the form of elevated internal energy (temperature), or some combination thereof

- Fuels are evaluated, in part, based on the amount of energy or heat that they release per unit mass or per mole during combustion of the fuel. Such a quantity is known as the fuel's *heat of reaction* or *heating value*.
- Heats of reaction may be measured in a calorimeter, a device in which chemical energy release is determined by transferring the released heat to a surrounding fluid.
- The amount of heat transferred to the fluid in returning the products of combustion to their initial temperature yields the heat of reaction.

Carofic Value:

It is defined as “ the total amount of heat liberated when a unit mass of fuel is burnt completely.

- It is used to identify ‘ the efficiency of a fuel’
- CV can be measured by following units

Kcal/Kg(solid & liquid fuel) or Kcal/m³(Gaseous fuel)

- With fuels containing hydrogen, Two calorific values are distinguished
- Higher & Gross Calorific Value
- Lower & Net Calorific Value

Higher & Gross Calorific Value or Higher Heating value

- It is defined as the total amount of heat liberated , when a unit mass of fuel is burnt completely and the product of combustions are cooled to room temperature
- When a fuel containing hydrogen is burnt, the hydrogen is converted in to steam.
- If the combustion product are cooled to room temperature , the steam get condensed into water & latent heat is evolved
- The latent heat of condensation of steam is also included in gross calorific value
- A good fuel posses HCV

Lower & Net Calorific Value or Lower Heating Value

- It is defined as” the net heat produce , when a unit quantity of fuel is completely burnt and the product of combustion are allowed to escape Under normal working condition ,
- water vapour produced during combustion are not condensed and escape as such along with hot gases
- Hence lesser amount of heat is available, which is called lower or net calorific value.

Quality of I.C engine fuels

Octane number

- It indicates the percentage by volume of isooctane and n-heptane which exhibit the same characteristics of fuel in a standard engine under a set up operating condition
- 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 an octane number 0, iso-octane (C_8H_{18}) has an octane number 100.
- Gasoline has an octane number 93 – 97.

- **cetane number** denotes the ignition delay time (the start of the injection of diesel fuel to the onset of the auto-ignition).
- The cetane number ranks the fuels; the higher the cetane number the faster the auto-ignition.
- Isooctane has a cetane of 15
- diesel has a cetane number about 37 – 56.
- Cetane (C₁₆H₃₄) has a cetane number 100

