SECOND LAW OF THERMODYNAMICS

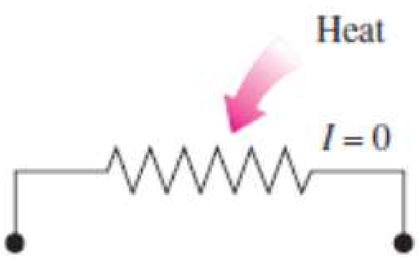
- First law of thermodynamics deals with conservation and conversion of energy. It stipulates that when a thermodynamic process is carried out, energy is neither gained nor lost. Energy only transforms from one form into another and the energy balance is maintained. The law, however, fails to state the condition under which energy conversions are possible. The law presumes that any change of a thermodynamic state can take place in either direction.

- However, this is not true; particularly in the inter-conversion of heat and work. Processes proceed spontaneously in certain directions but not in opposite directions, even though the reversal of processes does not violate the first law.

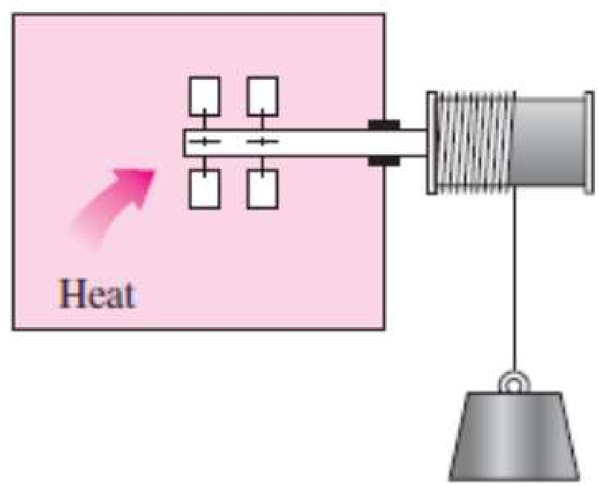
Examples of First law

coffee in a cold room

processes must satisfy both the first and second laws of thermodynamics



Transferring heat to a wire will not generate electricity



Transferring heat to a paddle wheel will not cause it to rotate

Processes occur in a certain direction, and not in the reverse direction

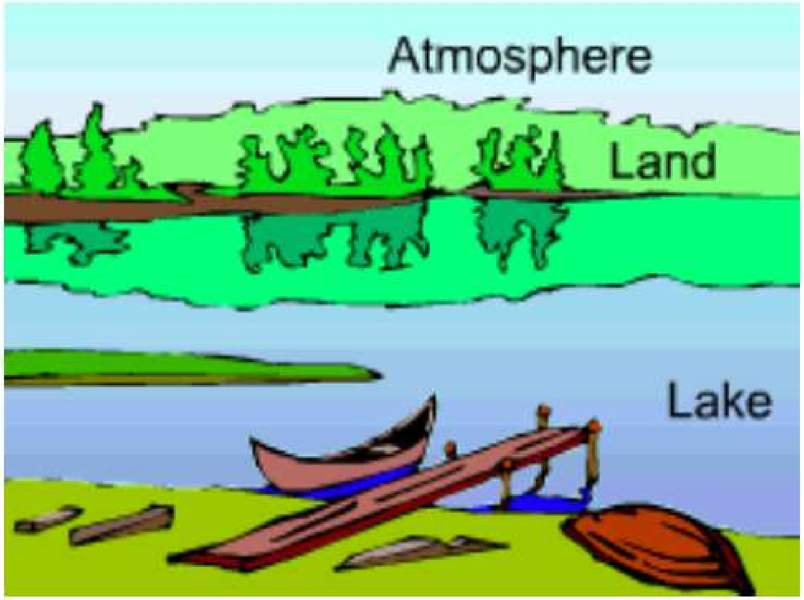
Limitations of First Law of Thermodynamics

- First law does not help to predict whether the certain process is possible or not.
- A spontaneous process can proceed in a particular direction only, but first law does not give information about direction.
- First law not provides sufficient condition for a certain process to take place.
- First law establishes equivalence between the amount of heat used and mechanical work, but does not specify the conditions under which conversion of heat into work is possible, neither the direction in which heat transfer can take place.

Basic Definitions

Thermal Energy Reservoir

- "It is defined as sufficiently large system in stable equilibrium that can supply or absorb finite amount of heat without any change in its temperature."
- A thermal reservoir is thus characterized by its temperature which remains constant.
- In practice, large bodies of water such as oceans, lakes, rivers, and atmospheric air can be considered thermal energy reservoirs.



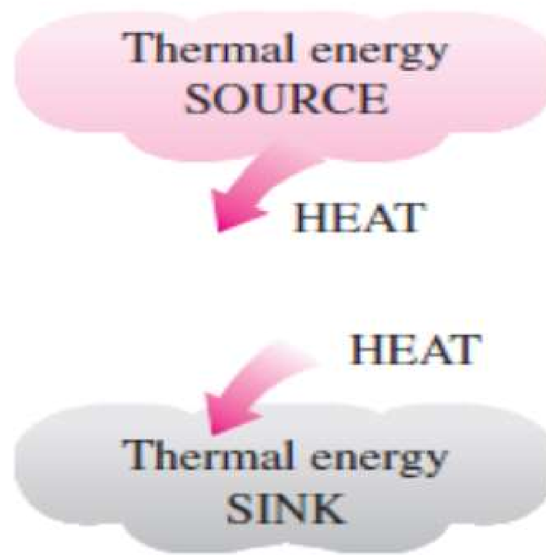
Thermal energy reservoirs

Heat Source

- "It is defined as the thermal reservoir which is at high temperature and supplies heat is called a heat source." i.e. boiler furnace, combustion chamber etc.

Heat Sink

- "It is defined as the thermal reservoir which is at low temperature and to which heat is transferred is called heat sink". i.e. atmospheric air, ocean, rivers etc.



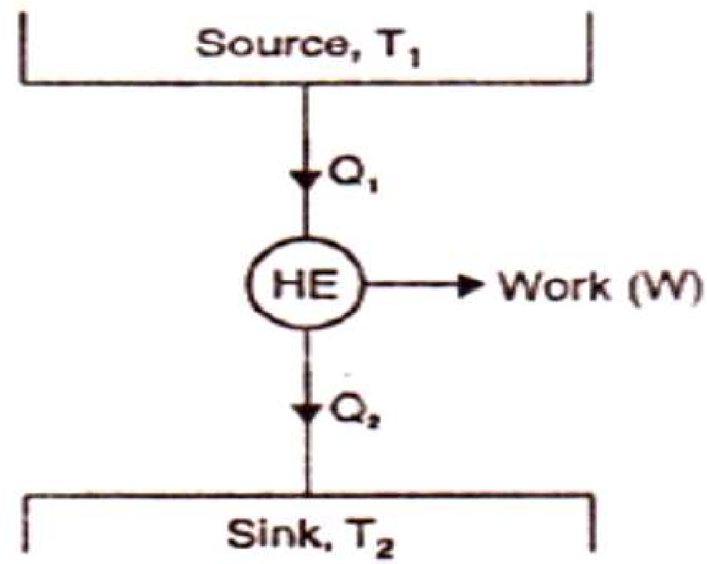
Heat source and Heat sink

Heat Engine

- "It is defined as thermodynamic device used for continuous production of work from heat when operating in a cyclic process is called heat engine".

Characteristics of Heat Engine:

- It receives heat from a high-temperature source at temperature T1 (furnace, nuclear reactor, solar energy etc.)
- It converts the part of this heat to work (mostly in the form of a rotating shaft).
- It rejects the remaining waste heat to a low-temperature sink (the atmosphere, rivers etc.).
- It operates on complete thermodynamic cycle.



Heat engine

Thermal Efficiency of Heat Engine

- "It is defined as the ratio of the desired net work output to the required heat input is called thermal efficiency."
- Thus thermal efficiency of a heat engine can be expressed as,

$$\eta_{th} = \frac{\text{desired work output}}{\text{required heat input}} = \frac{W_{net}}{Q_{in}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

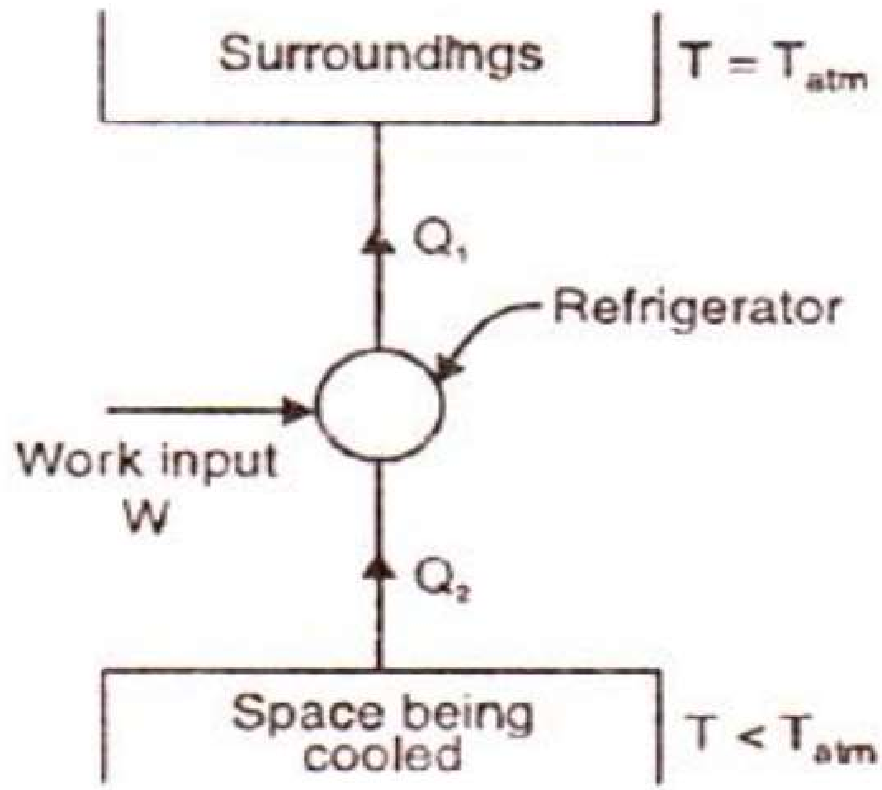
Where Q_1= Heat supplied to system, kJ

Q_2= Heat rejected from system, kJ

W= Net work done by a system, kJ

Refrigerator

- "It is defined as the mechanical device that used for the transfer of heat from a low temperature medium to a high-temperature medium is called refrigerator."
- The objective of a refrigerator is to maintain the refrigerated space at a low temperature by absorbing heat from it and reject to higher-temperature medium.



Coefficient of Performance of Refrigerator

- "The COP of a refrigerator can be expressed as the ratio of refrigerating effect to the work input. "
- Mathematically,

$$COP_R = \frac{\text{desired output}}{\text{required input}} = \frac{\text{refrigerating effect}}{\text{work input}} = \frac{Q_2}{W_{net,in}}$$

  – The conservation of energy principle for a cyclic device requires that,

$$W_{net,in} = Q_1 - Q_2$$

$$COP_R = \frac{Q_2}{Q_1 - Q_2}$$

Heat Pump

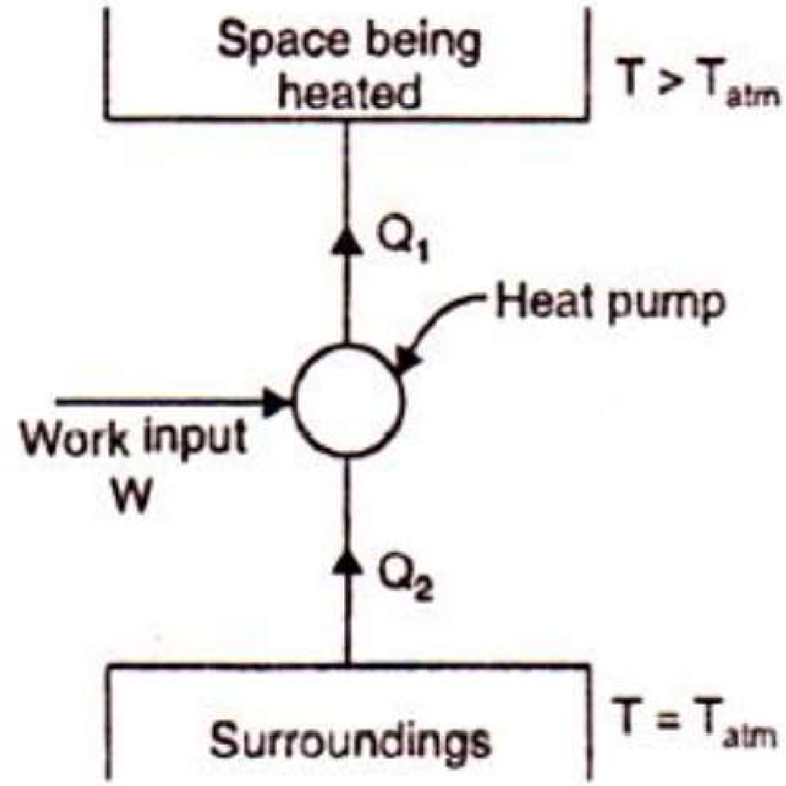
- “It is defined as the mechanical device that transfers heat from a low-temperature medium to a high-temperature is called heat pump.”

- The objective of heat pump is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low-temperature source and reject to higher temperature source.

Coefficient of Performance of Heat Pump

- "The COP of a heat pump can be expressed as the ratio of heating effect to the work input".
- Mathematically,

$$COP_{HP} = \frac{\text{desired output}}{\text{required input}} = \frac{\text{heating effect}}{\text{work input}} = \frac{Q_1}{W_{net,in}}$$



- The conservation of energy principle for a cyclic device requires that,

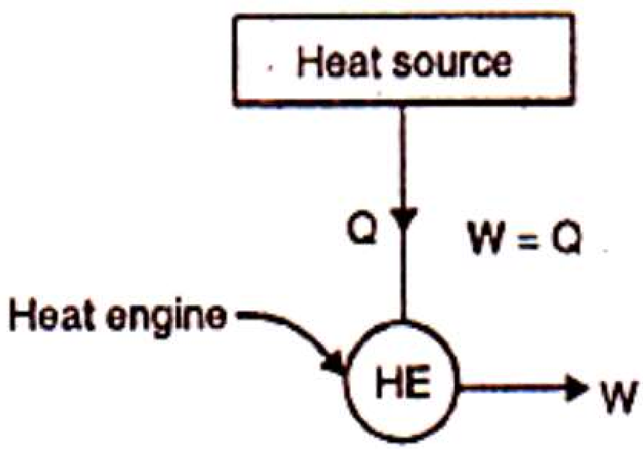
$$W_{net,in} = Q_1 - Q_2$$

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

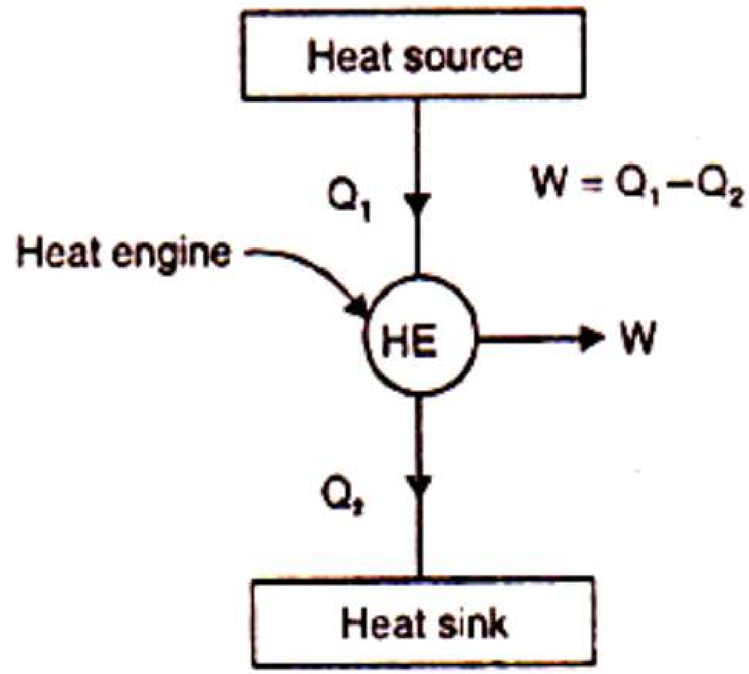
The Statements of Second Law of Thermodynamics

Kelvin–Planck Statement

- "It is impossible to construct a device that operates in thermodynamic cycle produce no effect other than work output and exchange heat with a single reservoir".



(a) Impossible



(b) Possible

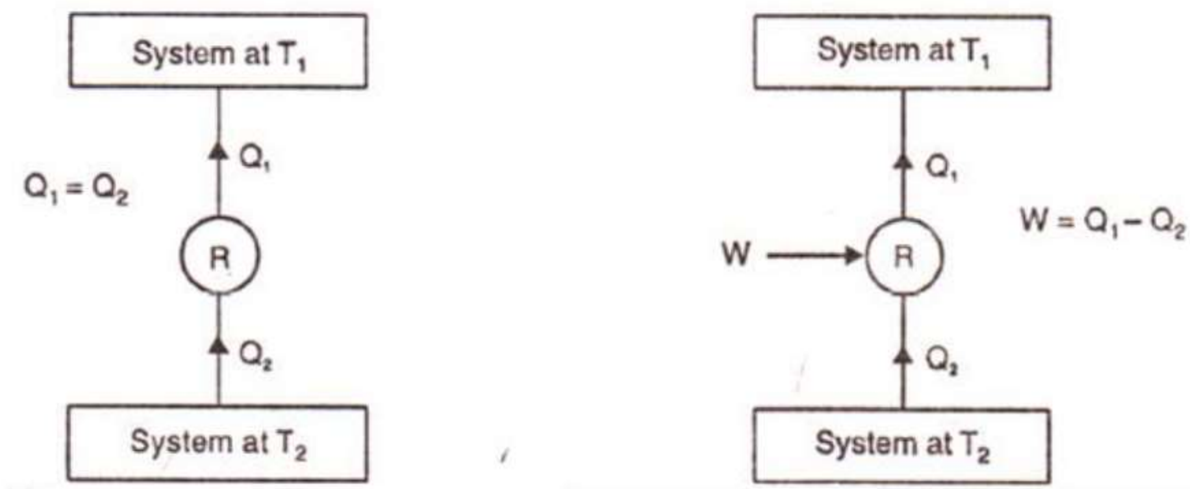
Schematic representation of heat engine accordance with Kelvin–Planck statement

Clausius Statement

- "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature reservoir to a higher temperature reservoir."

OR

- "It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body."



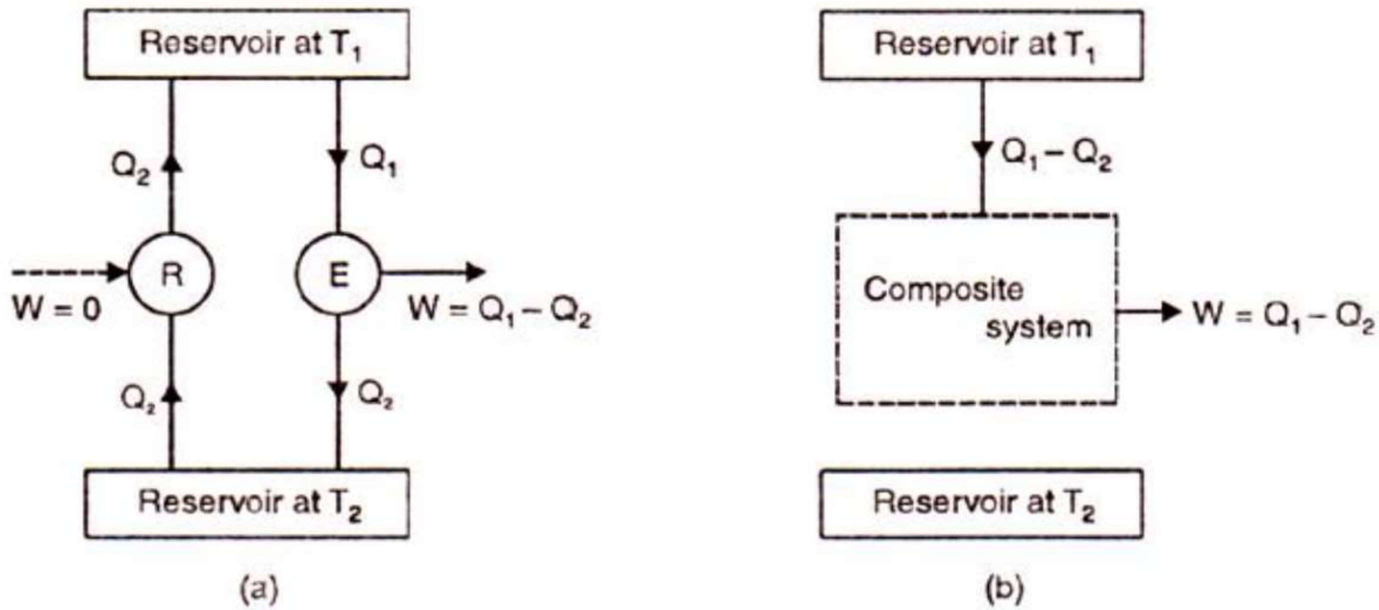
(a) Impossible *(b) Possible*

Schematic representation of refrigerator accordance with the Clausius statement

Equivalency of the Two Statements

Violation of Clausius statement leading to violation of Kelvin-Planck statement.

- As shown in Fig. (a) a refrigerator R that operates in a cycle and transfers Q_2 amount of heat from low temperature reservoir at T_2 to a high temperature reservoir at T_1 without any work input. This is in violation of the Clausius statement.



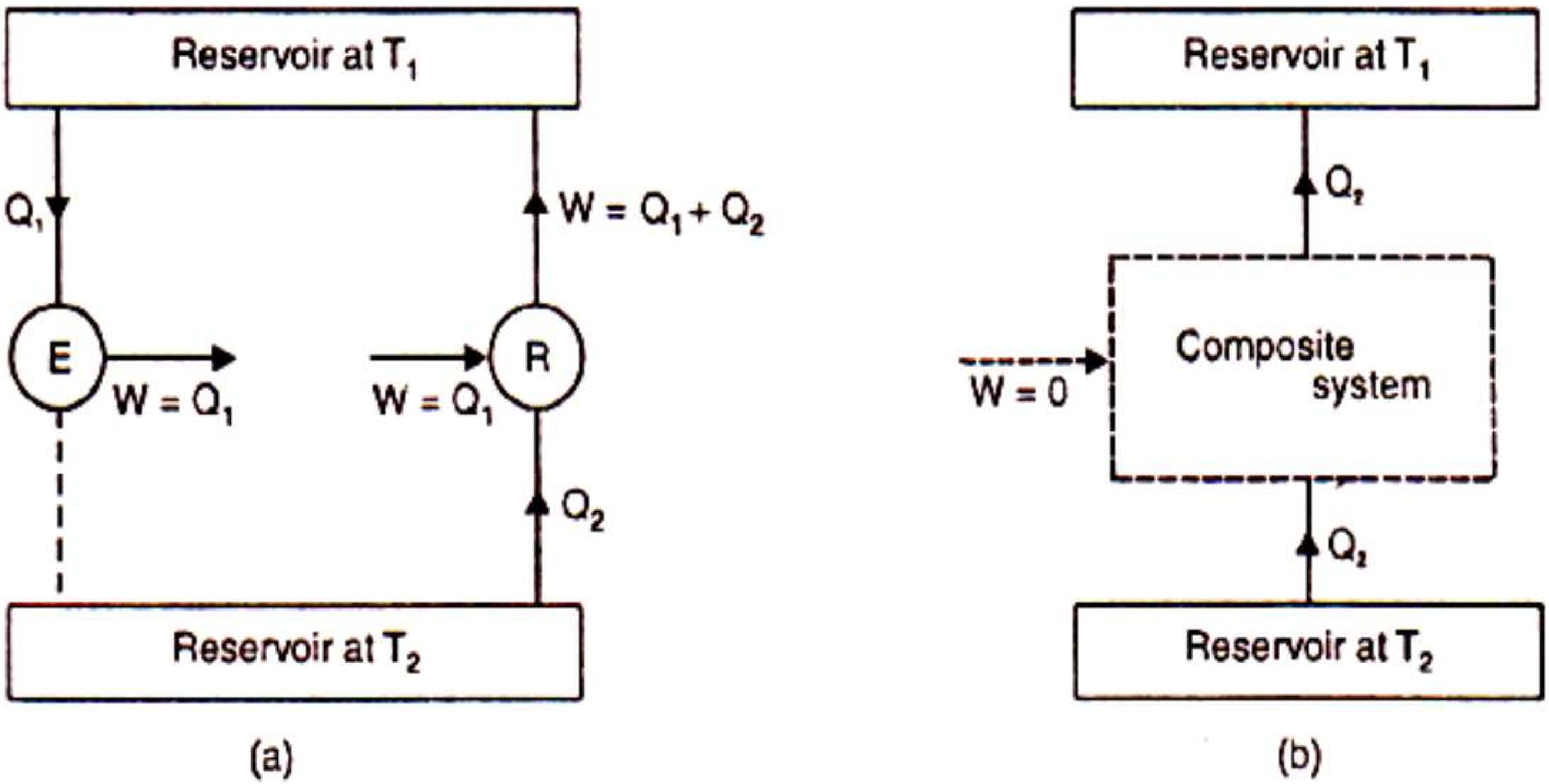
Proof of the violation of the Clausius statement leads to the violation of the Kelvin–Planck statement

- Along with this heat engine E , that also operates in a cycle, takes Q1 amount of heat from the high temperature reservoir, delivers $Q_1 - Q_2$ amount of work to the surroundings and rejects the remaining Q_2 amount of heat to the low temperature reservoir.
- As shown in Fig. (b) the composite system constitutes a device that receives $Q_1 - Q_2$ amount of heat from the high temperature reservoir and converts it completely into an equivalent amount of work $W = Q_1 - Q_2$ without rejecting any heat to the low temperature reservoir. This is violation of the Kelvin-Planck statement.

Violation of Kelvin-Planck statement leading to violation of Clausius statement.

- As shown in Fig. (a) an engine E which operates from a single heat reservoir at temperature T_1 . It receives Q_1 amount of heat from this reservoir and converts it completely into an equivalent amount of work $W=Q_1$ without rejecting any heat to the low temperature reservoir at T_2 . This is violation of the Kelvin-Planck statement.
- Along with this the refrigerator R which extracts Q_2 amount of heat from the low temperature reservoir, is supplied with Q_1 amount of work from an external agency (surroundings) and supplies $Q_1 + Q_2$ units of heat to the high temperature reservoir.

- As shown in Fig. (b) the work and heat interactions for the refrigerator and heat engine when coupled together. The output of the engine is utilized to drive the refrigerator.



Proof of the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement

- This composite system constitutes a device which transfers heat from the low temperature reservoir to the high temperature reservoir without any work input. This is in violation of the Clausius statement. Thus violation of Kelvin-Planck statement leads to violation of Clausius statement also.
- Therefore, the Clausius and the Kelvin–Planck statements are two equivalent expressions of the second law of thermodynamics.

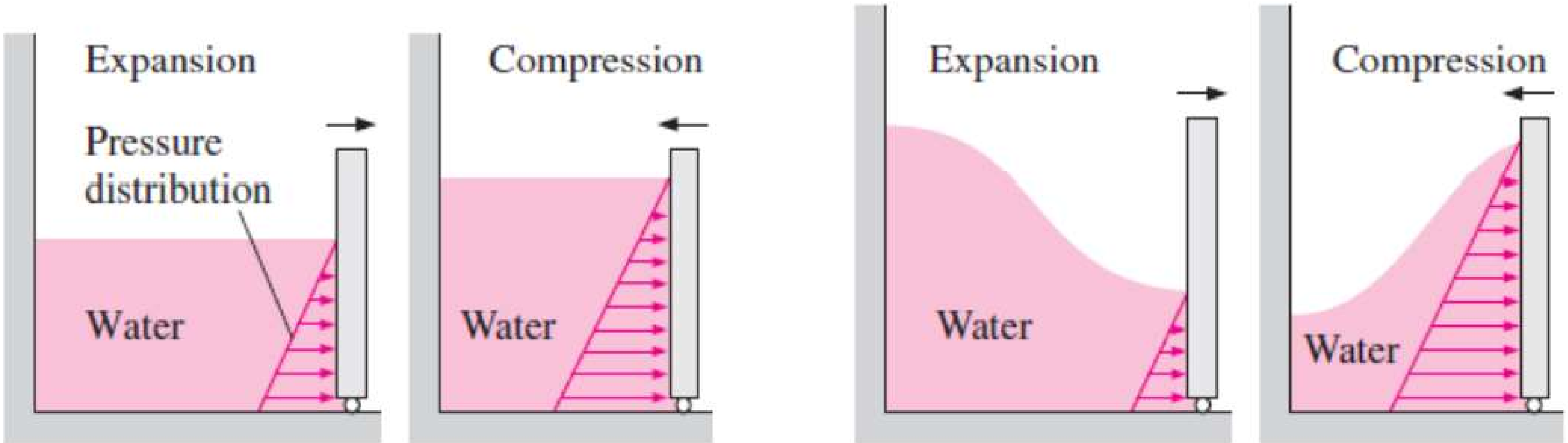
Reversible and Irreversible Process

Reversible Process

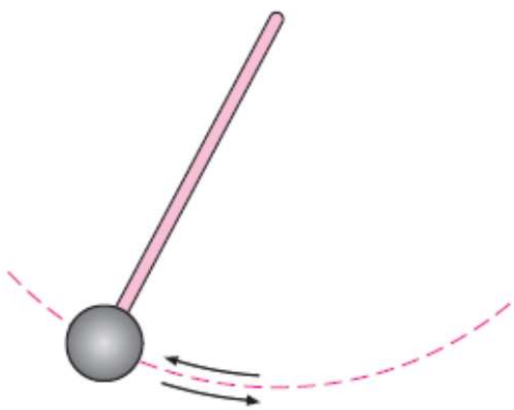
- Definition: “A reversible process is defined as a process that can be reversed without leaving any trace on the surroundings and both the system and the surroundings are restored to their respective initial states by reversing the direction of the process”.

Irreversible Process

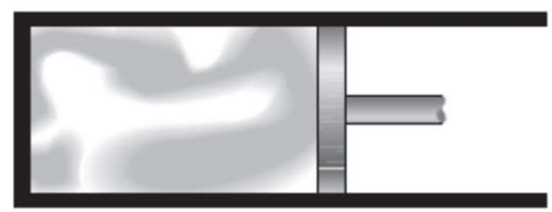
- Definition: “An irreversible process is defined as a process that can be reversed with permanent leaving any trace on the surroundings and both the system and the surroundings are not restored to their respective initial states by reversing the direction of the process”.



(*a*) Slow (reversible) process (*b*) Fast (irreversible) process



(*a*) Frictionless pendulum



(*b*) Quasi-equilibrium expansion and compression of a gas

Reversible processes deliver the most and consume the least work

Reversible Process

Conditions of Reversible Process

- The process must proceed in a series of equilibrium states.
- Heat transfer should not take place with finite temperature difference.
- The process should be quasi-static and it should proceed at infinitely slow speed.
- The process should not involve friction of any kind (mechanical and intermolecular)

Salient Features of Reversible Process

- It is quasi-static process which can be carried out in the reverse direction along the same path. It can be proceed in either direction without violating the second law of thermodynamics.
- The energy transfer as heat and work during the forward process should be identically equal to energy transfer as heat and work during the reversal of the process.
- It is possible only if the net heat and net work exchange between the system and the surroundings is zero for the combined (original and reverse) process or it leaves no trace or evidence of its occurrence in the system and surroundings.

Salient Features of Reversible Process

- Reversible processes can be viewed as theoretical limits for the corresponding irreversible ones.
- The more closely we approximate a reversible process, the more work delivered by a work-producing device or the less work required by a work-consuming device.
- It leads to the definition of the second law efficiency for actual processes, which is the degree of approximation to the corresponding reversible processes. This enables us to compare the performance of different devices that are designed to do the same task on the basis of their efficiencies.
- It is idealized process actually do not occur in nature.
- There should be no free or unrestricted expansion and no mixing of the fluids.
- Work done during reversible process is represented by area under process curve on p-v diagram, and is equal to $\int_1^2 p\,dv$

Some Notable Examples of ideal reversible processes are:

1. Motion without friction.
2. Frictionless adiabatic and isothermal expansion or compression.
3. Restricted and controlled expansion or compression.
4. Elastic stretching of a solid.
5. Restrained discharge of the battery.
6. Electric circuit with zero resistance.
7. Polarisation, magnetisation effects and electrolysis.
8. Condensation and boiling of liquids.

Irreversible Process

- These processes that occurred in a certain direction, once having taken place, these processes cannot reverse themselves spontaneously and restore the system to its initial state.
- For example, once a cup of hot coffee cools, it will not heat up by retrieving the heat it lost from the surroundings. If it could, the surroundings, as well as the system (coffee), would be restored to their original condition, and this would be a reversible process.
- It should be pointed out that a system can be restored to its initial state following a process, regardless of whether the process is reversible or irreversible. But for reversible processes, this restoration is made without leaving any net change on the surroundings, whereas for irreversible processes, the surroundings usually do some work on the system and therefore does not return to their original state.

Salient Features of Irreversible Process

1. It can be carried out in one direction.
2. It occurs at a finite rate.
3. It cannot be reversed without permanent change in surroundings.
4. The system is in never in equilibrium state at any instant during an irreversible process.

Some Notable Examples of an irreversible process are:

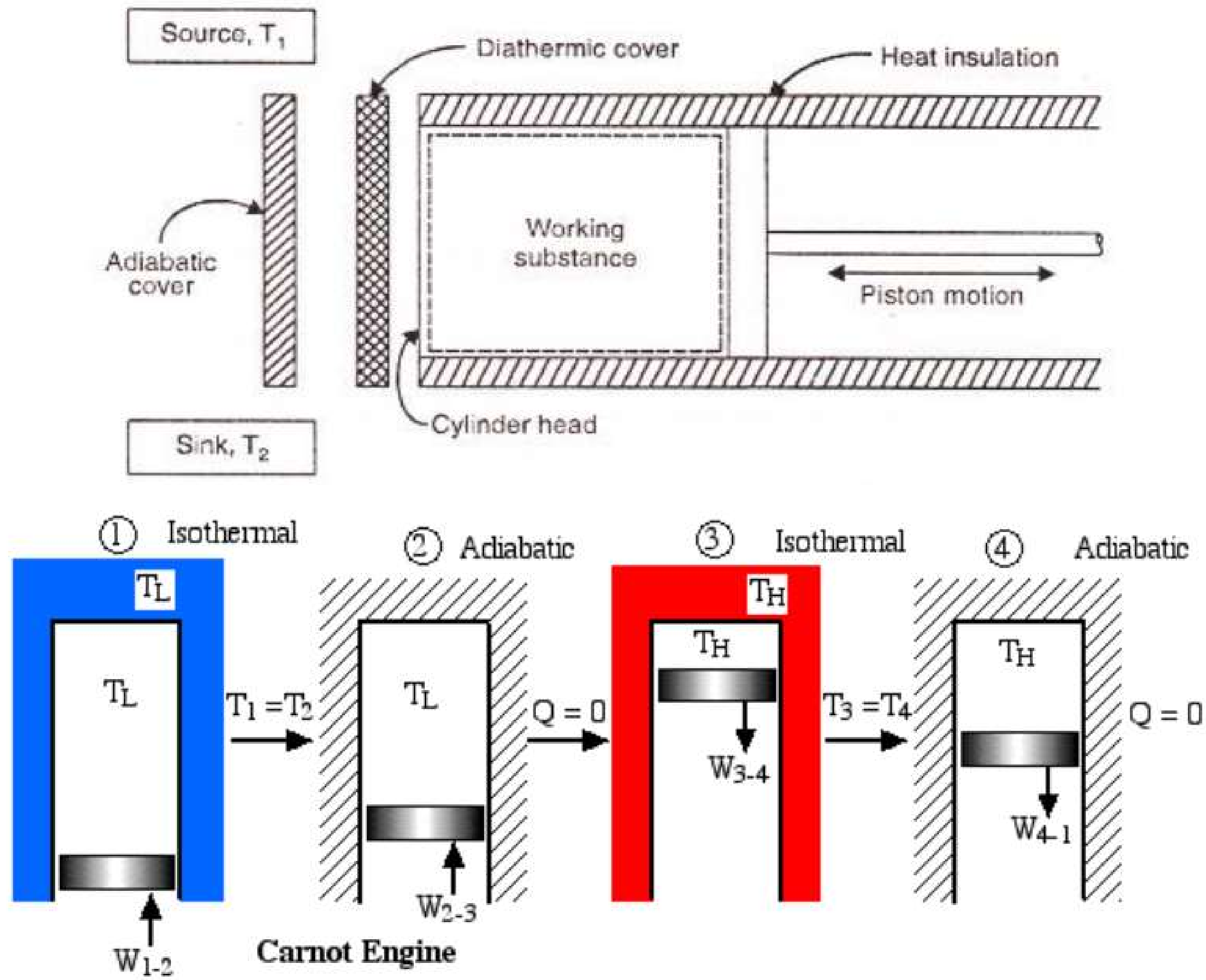
1. Spontaneous chemical reaction.
2. Viscous flow, fluid flow with friction.
3. Inelastic deformation and hysteresis effects.
4. Electric circuit with resistance.
5. Diffusion of gases, mixing of dissimilar gases.
6. Heat transfer takes place with finite temperature difference.
7. Free expansion and throttling process.
8. Friction—sliding friction as well as friction in the flow of fluids

The Carnot Cycle (Carnot Heat engine)

Assumptions for Carnot cycle

1. The piston moving in a cylinder does not develop any friction during motion.
2. The walls of piston and cylinder are considered as perfect insulators of heat.
3. The cylinder head is so arranged that it can be a perfect heat conductor or perfect heat insulator.
4. The transfer of heat does not affect the temperature of source or sink.
5. Working medium is a perfect gas and has constant specific heat.
6. Compression and expansion are reversible.

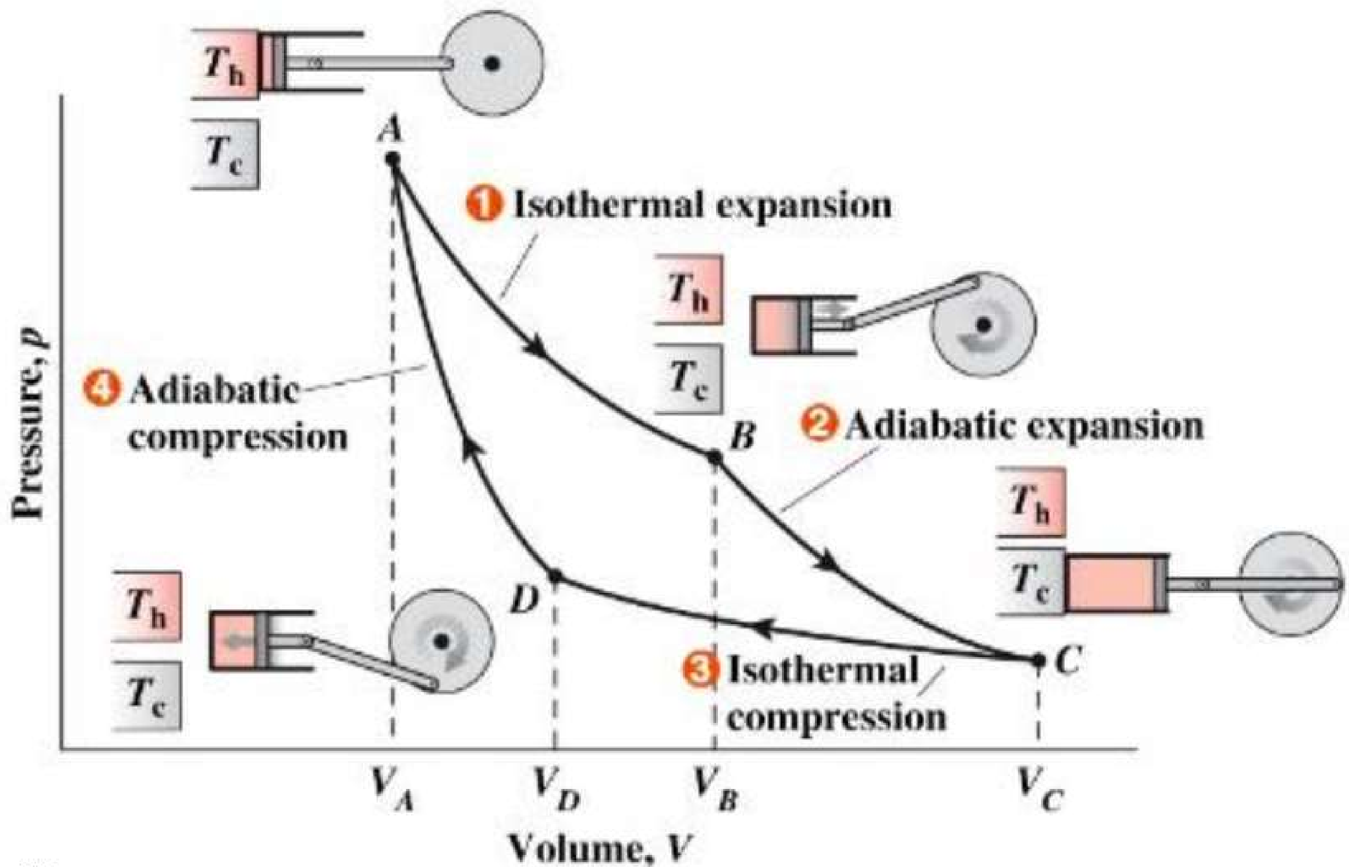
- The Carnot cycle is composed of four reversible processes—two isothermal and two adiabatic.
- Consider a closed system that consists of a gas contained in an adiabatic piston–cylinder device, as shown in Fig. the insulation of the cylinder head is such that it may be removed to bring the cylinder into contact with reservoirs to provide heat transfer.



Carnot cycle

- **Reversible Isothermal Expansion (process 1-2, T_H = constant):** In this process, high temperature energy source is put contact with cylinder cover and Q_1 amount heat is supplied while the gas expands isothermally at temperature T_H . The amount of heat transferred to the gas during this process is given by,

$$Q_1 = W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1} = mRT_H \ln \frac{V_2}{V_1}$$



P-v diagram of the Carnot cycle

- **Reversible Adiabatic Expansion (process 2-3)**: In this process the adiabatic cover is put contact on the cylinder head, and the gas is expanded adiabatically, thus the temperature decreases from T_H to T_L
- **Reversible Isothermal Compression (process 3-4, T_L = constant):** In this process, low temperature energy sink is put contact with cylinder head cover and Q_2 amount of heat is rejected while the gas compressed isothermally at temperature T_L The amount of total heat transferred from the gas during this process is given by,

$$Q_2 = W_{3-4} = P_3 V_3 \ln \frac{V_3}{V_4} = mRT_L \ln \frac{V_3}{V_4}$$

- **Reversible Adiabatic Compression (process 4-1):** In this process the adiabatic cover is put contact on the cylinder head, and the gas is compressed adiabatically, thus temperature increases from T_L to T_H and returns to its initial state 1 to complete the cycle.
- Thermal efficiency of Carnot cycle is given by,

$$\eta_{th} = \frac{W_{net}}{Q_1}$$

- As there is not heat interaction along the reversible adiabatic processes 2-3 and 4-1, and application of first law of thermodynamics for the complete cycle gives,

$$\delta W = \delta Q$$

$$W_{net} = Q_1 - Q_2 = mRT_H \ln\frac{V_2}{V_1} - mRT_L \ln\frac{V_3}{V_4}$$

– Substituting the values of W_{net} in above equation we get,

$$\eta_{th,Carnot} = \frac{mRT_H \ln\frac{V_2}{V_1} - mRT_L \ln\frac{V_3}{V_4}}{mRT_H \ln\frac{V_2}{V_1}}$$

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}\frac{\ln\frac{V_3}{V_4}}{\ln\frac{V_2}{V_1}}$$

– For the adiabatic expansion and compression process 2-3 and 4-1,

$$\frac{T_2}{T_3} = \frac{T_H}{T_L} = \left(\frac{V_3}{V_2}\right)^{\gamma-1} \; and \; \frac{T_1}{T_4} = \frac{T_H}{T_L} = \left(\frac{V_4}{V_1}\right)^{\gamma-1}$$

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

$$\left(\frac{V_3}{V_2}\right) = \left(\frac{V_4}{V_1}\right) or \left(\frac{V_3}{V_4}\right) = \left(\frac{V_2}{V_1}\right)$$

– Substitute the values in above equation, we get,

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

Conclusions from Carnot heat engine are:

1. The efficiency is independent of the working fluid and depends upon the temperature of source and sink. Being a reversible cycle, the Carnot cycle is the most efficient cycle operating between two specified temperature limits.
2. If $T_L = 0$ the engine will have an efficiency of 100%. However that means absence of heat sink which is violation of Kelvin-Plank statement of the second law.
3. The efficiency is directly proportional with the Temperature difference $T_H - T_L$ between the source and sink. Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system. If $T_H = T_L$, no work will be done and efficiency will be zero.

- Even though the Carnot cycle cannot be achieved in reality, the efficiency of actual cycles can be improved by attempting to approximate the Carnot cycle more closely.

The Carnot cycle is impracticable because of the following reasons:

- All the four processes have to be reversible. This necessitates that working fluid must have no internal friction between the fluid particle and no mechanical friction between the piston and cylinder wall. It is impossible to perform a frictionless process.
- The heat absorption and rejection take place with infinitesimal temperature difference. Accordingly the rate of energy transfer will be very low and the engine will deliver only infinitesimal power. It is impossible to transfer the heat without temperature potential.
- Isothermal process can be achieved only if the piston moves very slowly to allow heat transfer so that the temperature remains constant. Also Reversible isothermal heat transfer is very difficult to achieve in reality because it would require very large heat exchangers and it would take a very long time (a power cycle in a typical engine is completed in a fraction of a second). Therefore, it is not practical to build an engine that would operate on a cycle that closely approximates the Carnot cycle.

The Carnot cycle is impracticable because of the following reasons:

- Adiabatic process can be achieved only if the piston moves as fast as possible so that the heat transfer is negligible due to very short time available. The isothermal and adiabatic processes take place during the same stroke therefore the piston has to move very slowly for part of the stroke and it has to move very fast during remaining stroke. This variation of motion of the piston during the same stroke is not possible.

- The source and sink temperatures that can be used in practice are not without limits, however. The highest temperature in the cycle is limited by the maximum temperature that the components of the heat engine, such as the piston or the turbine blades, can withstand. The lowest temperature is limited by the temperature of the cooling medium utilized in the cycle such as a lake, a river, or the atmospheric air.

- There is insignificant difference in the slopes of isothermal and adiabatic lines. Consequently the p-v plot is greatly extended both in horizontal and vertical directions. The cylinder involves great pressure and volumes, and thus becomes bulky and heavy.

ENTROPY

- The entropy is a thermodynamics property of a working substance and serves as a valuable tool in the second law analysis of engineering devices. We know that all heal is not equally valuable for converting into work.
- Entropy is a function of a quantity of heat which shows the possibility of conversion of that heat into work.
- The increase in entropy is lower when heat is added at a high temperature and the increase in entropy is higher when heat is added at a low temperature.
- The maximum entropy means, there is minimum availability for conversion into work and the minimum entropy means, there is maximum availability for conversion into work.

Characteristics of Entropy

The characteristics of entropy in a summarised form are given below :

- Entropy is property of system.
- For reversible process between state 1 and 2, the change in entropy is given by,

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

- The change in entropy for the system may be positive, negative or zero (depending on the heat absorption, rejection or absence)
- Entropy is point function, independent on path of the process.
- For a reversible process, the change in entropy for the surrounding is equal in magnitude but opposite in sign to the change in entropy for the system.so total or net change for system plus surrounding is equal to zero.
- The increase of entropy during the process is a measure of the loss of availability of the energy of the system.
- The entropy of a pure substance approaches zero at the absolute zero temperature.
- From the molecular point of view, entropy can .also be considered to be a measure of microscopic disorder.
- The entropy is a measure the lack of information about a system.

- The entropy of system is changed due to main three causes

a) Heat transfer - heat transfer to system increases the entropy of system, and heat transfer from system decreases the entropy of that system
b) Mass flow
c) Irreversibilities - such as friction, heat transfer due to finite temperature difference and fast expansion or compression.

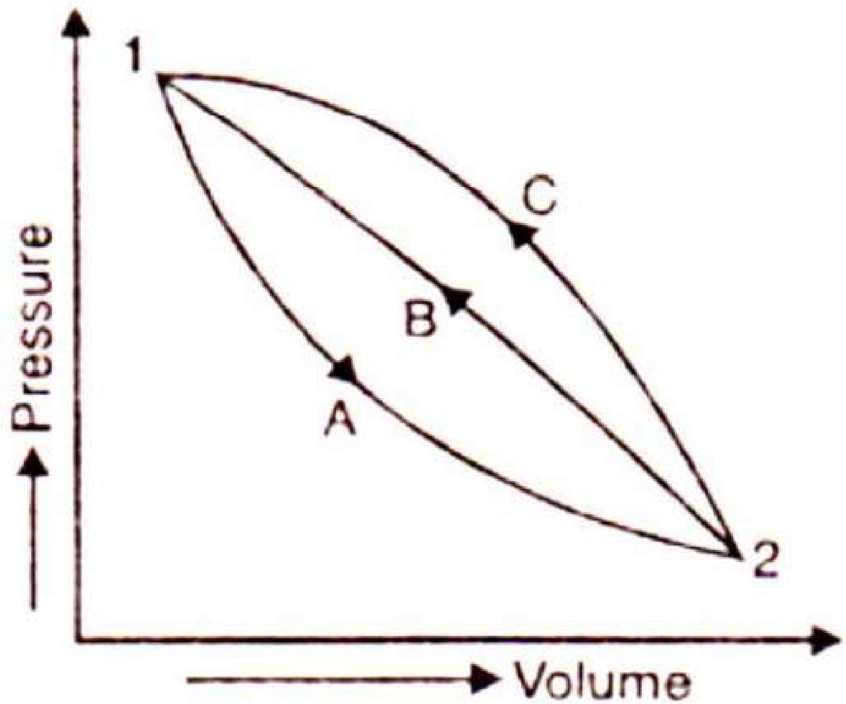
Clausius Theorem

- The cyclic integration of $\frac{\delta Q}{T}$ is equal to zero.
- For any reversible process ,

$$\oint \frac{\delta Q}{T} = 0$$

Entropy is a Property

- Let us consider a system undergoing a reversible process from state 1 to state 2 along path A and then from state 2 to the original state 1 along path B as shown in Fig. Applying the Clausius theorem to this reversible cyclic process, we have



$$\oint \frac{\delta Q}{T} = 0$$

– Hence when the system passes through the cycle 1-A-2-B-1, we have

$$\int_{1}^{2}{}_{(A)}\frac{\delta Q}{T}+\int_{2}^{1}{}_{(B)}\frac{\delta Q}{T}=0$$

– Now consider another reversible cycle in which the system changes from state 1 to state 2 along path A, but returns from state 2 to the original state 1 along a different path C. For this reversible cyclic process, we have

$$\int_{1}^{2}{}_{(A)}\frac{\delta Q}{T}+\int_{2}^{1}{}_{(C)}\frac{\delta Q}{T}=0$$

– From above equation we have,

$$\int_{1}^{2}{}_{(B)}\frac{\delta Q}{T}=\int_{2}^{1}{}_{(C)}\frac{\delta Q}{T}$$

– Above equation indicates that no restriction is imposed on paths, except that they must be reversible, the quantity $\frac{\delta Q}{T}$ is a function of the initial and final states of the system and is independent of the path of the process. Hence it represents a property of the system

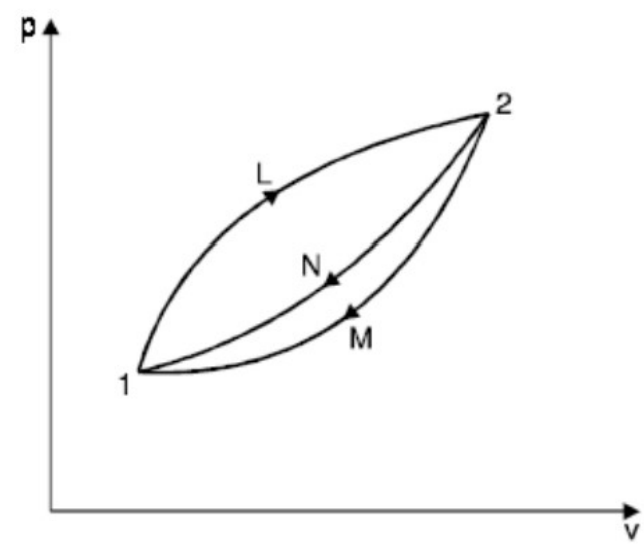
Applications of entropy principle

- Mixing of two fluid
- Heat transfer through a finite temperature difference
- Maximum work obtained from two finite bodies
- Minimum work required for refrigerator operates between two finite bodies
- Isothermal dissipation of work
- Adiabatic dissipation of work

Change of Entropy in a Reversible Process

- Let,
- S1 = Entropy at the initial state 1, and
- S2 = Entropy at the final state 2.
- Then, the change in entropy of a system, as it undergoes a change from state 1 to 2, becomes,

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



- Lastly, if the two equilibrium states 1 and 2 are infinitesimal near to each other, the integral sign may be omitted and S2 – S1 becomes equal to dS.
- Hence equation may be written as

$$dS = \int_1^2 \left(\frac{\delta Q}{T}\right)$$

- Where dS is an exact differential.
- Thus, from equation, we find that the change of entropy in a reversible process is equal to δQ/T. This is the mathematical formulation of the second law of thermodynamics.
- Equation indicates that when an inexact differential δQ is divided by an integrating factor T during a reversible process, it becomes an exact differential.

Clausius Inequality

- When a system undergoes a complete cyclic process, the integral of $\frac{\delta Q}{T}$ around the cycle is less than zero or equal to zero.
- Mathematically,

$$\oint \left(\frac{\delta Q}{T}\right) \leq 0$$

- Consider a reversible engine R and irreversible engine I working between two thermal reservoir at temperature T_H and T_L.
- Efficiency of reversible engine,

$$\eta_R = 1 - \frac{\delta Q_L}{\delta Q_H} = 1 - \frac{T_L}{T_H}$$

- Efficiency of irreversible engine,

$$\eta_I = 1 - \frac{\delta Q_L}{\delta Q_H} \neq 1 - \frac{T_L}{T_H}$$

- We know that efficiency of reversible engine is more than irreversible engine under same temperature limit.

$$\therefore \eta_R > \eta_I$$

$$\therefore \left(1-\frac{\delta Q_L}{\delta Q_H}\right)_R > \left(1-\frac{\delta Q_L}{\delta Q_H}\right)_I$$

$$\therefore \left(1-\frac{T_L}{T_H}\right)_R > \left(1-\frac{\delta Q_L}{\delta Q_H}\right)_I$$

$$\therefore \left(\frac{T_L}{T_H}\right) < \left(\frac{\delta Q_L}{\delta Q_H}\right)_I$$

$$\therefore \left(\frac{\delta Q_H}{T_H}\right) < \left(\frac{\delta Q_L}{T_L}\right)$$

$$\therefore \left(\frac{\delta Q_H}{T_H}\right) - \left(\frac{\delta Q_L}{T_L}\right) < 0$$

- We know heat added should be positive and heat rejected should be negative.

$$\therefore \left(\frac{\delta Q_H}{T_H}\right) - \left(\frac{-\delta Q_L}{T_L}\right) < 0$$

$$\therefore \left(\frac{\delta Q_H}{T_H}\right) + \left(\frac{\delta Q_L}{T_L}\right) < 0$$

- Considering complete original irreversible cycle,

$$\therefore \left[\left(\frac{\delta Q_{H1}}{T_{H1}}\right) + \left(\frac{\delta Q_{L1}}{T_{L1}}\right) + \left(\frac{\delta Q_{H2}}{T_{H2}}\right) + \left(\frac{\delta Q_{L2}}{T_{L2}}\right)\right] + \cdots < 0$$

$$\oint \left(\frac{\delta Q}{T}\right)_I < 0$$

- According to Clausius theorem $\oint(\delta Q/T)=0$ for reversible cycle. combing results for reversible and irreversible cycle,

$$\oint\left(\frac{\delta Q}{T}\right) \leq 0$$

- This expression known as Clausius inequality.

$$\oint\left(\frac{\delta Q}{T}\right)_{Reversible} = 0$$

$$\oint\left(\frac{\delta Q}{T}\right)_{Irreversible} < 0$$

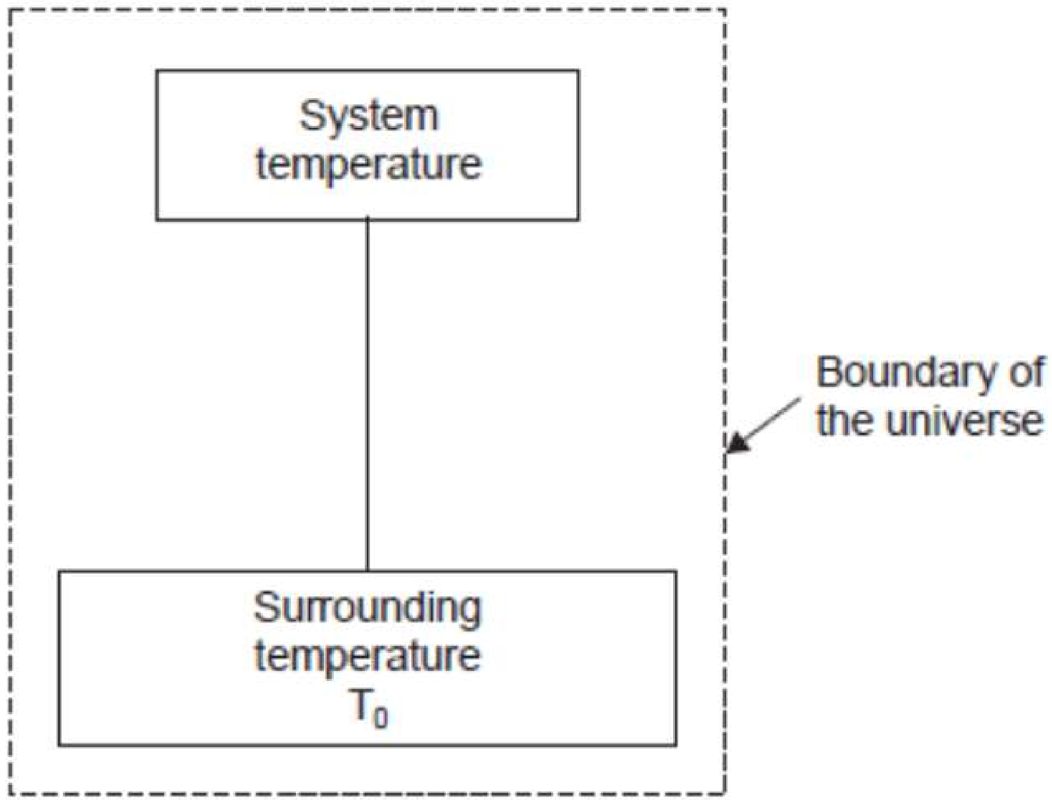
$$\oint\left(\frac{\delta Q}{T}\right)_{Impossible} > 0$$

Principle of increase of entropy or change in entropy of the universe

- The entropy of an isolated system during a process always increases or in the limiting case of reversible process remains constant.
- Mathematically,

$$\Delta S_{isolated} \geq 0$$

– Now, consider any system and its surrounding within a single boundary as shown in fig. The combination of system and surrounding within a single boundary is called the universe.



Entropy change of universe

- Applying the principle of increase in entropy.

$$dS_{Universe} \geq 0$$

Where,

$$dS_{Universe} = dS_{System} + dS_{Surrounding}$$

- In the combined closed system, the heat δQ transferred from the system to surrounding.

- For reversible process,

$$dS_{system} = \frac{-\delta Q}{T_{Sys}}$$

$$dS_{surr} = \frac{\delta Q}{T_{Surr}}$$

- Total change in entropy for the combined system,

$$dS_{system} + dS_{surr} = \delta Q \left(\frac{-1}{T_{sys}} + \frac{1}{T_{surr}} \right)$$

$$\therefore dS_{Universe} = \delta Q \left(\frac{1}{T_{surr}} - \frac{1}{T_{sys}} \right)$$

- But, $T_{sys} > T_{Surr}$, $\therefore \delta Q \left(\frac{1}{T_{surr}} - \frac{1}{T_{sys}} \right) > 0$

$$\therefore dS_{Universe} \geq 0$$

- Above equation states that the process involving the integration of a system and the surroundings, net entropy of universe increases or remains constant.
- Since all natural processes are irreversible, the entropy is increasing continuously. The entropy becomes maximum value when the system reaches a stable equilibrium state from non-equilibrium state.

Internal Combustion Engine

- Heat Engine is a machine which converts heat energy supplied to it into mechanical work.
- Heat energy is supplied to the engine by burning the fuel.

Classification of Heat Engines

•**Internal Combustion Engines (IC Engines)**

• In IC engines, combustion of fuel takes place inside the engine cylinder.

Examples: Diesel Engines, Petrol Engines, Gas engines.

•**External Combustion Engines (EC Engines)**

• In EC engines, combustion of fuel takes place outside the working cylinder.

Examples: Steam Engines and Steam turbines

Classification of Heat Engines

- IC Engines are classified into,

(1) Cycle of operation (No of Strokes per cycle

- Two Stroke cycle Engines
- Four Stroke Cycle Engines

(2) **Thermodynamic Cycle or Method of Heat addition:**

- Otto Cycle Engines (Combustion at constant volume)
- Diesel Cycle Engines (Combustion at constant Pressure)
- Semi Diesel Engines (Dual Combustion Engines)

(3) Types of Fuel Used :

- **Petrol Engines**
- **Diesel Engines**
- **Gas Engines**

(4) Ignition Method :

- **Spark Ignition (SI)**
- **Compression Ignition (CI)**

(5) Cooling System:

- Air cooled Engines
- Water Cooled Engines

(6) Valves Location :

- L head (Side valve) engine
- T Head (Side valve) engine
- I head (over head valve) engine
- F head (over head inlet and side exhaust) engine

I.C ENGINE TERMINOLGOGY

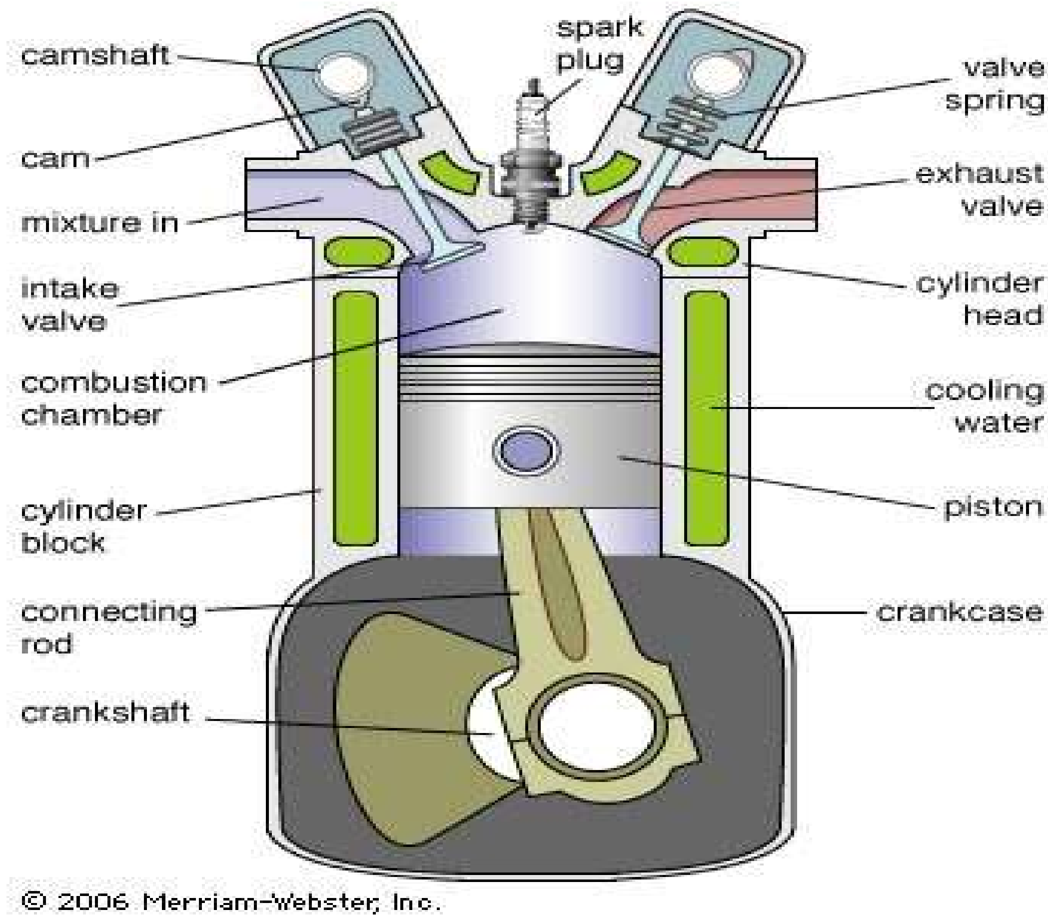
- **The standard terms used in I.C Engines are**

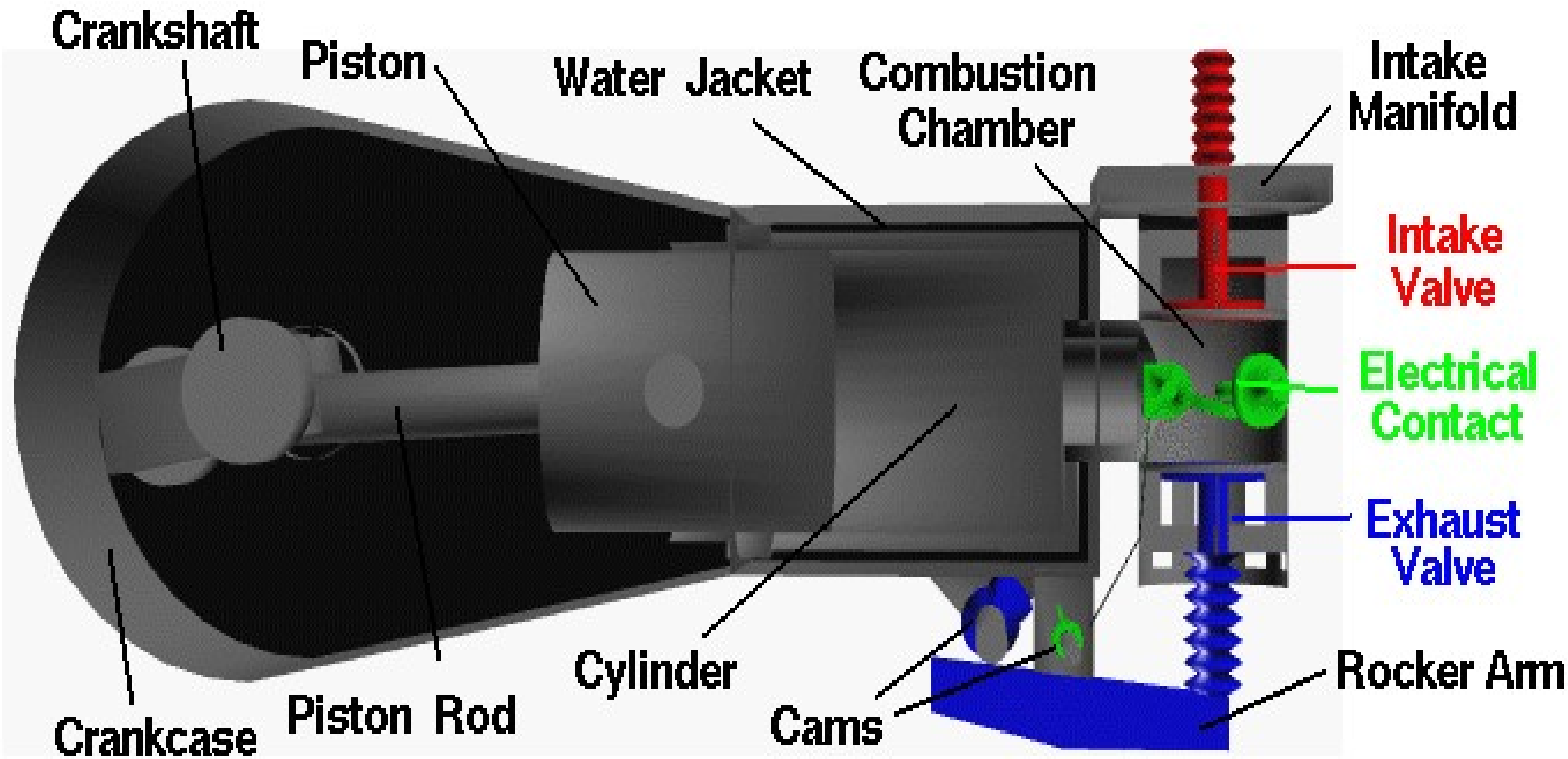
1. **Bore**: Inside diameter of the cylinder is termed as Bore.
2. **Top Dead Center (TDC):** The extreme position reached by the piston at the top of the cylinder in the vertical engine is called Top Dead center.
3. **Bottom Dead Center (BDC):** The extreme position reached by the piston at the Bottom of the cylinder in the vertical engine is called Bottom Dead center.

4. **Stroke:** The nominal distance travelled by the piston in the cylinder between the extreme upper and lower positions of the piston (TDC &BDC) is termed as stroke.
5. **Compression ratio (r):** It is the ratio of Maximum cylinder volume to the Clearance volume.
6. **Cylinder volume (v):** It is the sum of swept volume and the Clearance volume.
   - $V = Vs + Vc$

7. **Swept volume (Vs):** It is the volume of space generated by the movement of piston from one dead center to another dead center.
8. **Clearance Volume(Vc):** It is the space in the cylinder, when the piston is at Top Dead Center

Engine Components




Crankshaft
Piston
Water Jacket
Combustion
Chamber
Intake
Manifold
Intake
Valve
Electrical
Contact
Exhaust
Valve
Rocker Arm
Cams
Cylinder
Piston Rod
Crankcase

Internal combustion Engine Components:

- I.C. Engine components shown in figure1 and figure2 are defined as follows:
- **Block :** Body of the engine containing cylinders, made of cast iron or aluminium.
- **Cylinder :** The circular cylinders in the engine block in which the pistons reciprocate back and forth.
- **Head :** The piece which closes the end of the cylinders, usually containing part of the clearance volume of the combustion chamber.
- **Combustion chamber:** The end of the cylinder between the head and the piston face where combustion occurs.
  - The size of combustion chamber continuously changes from minimum volume when the piston is at TDC to a maximum volume when the piston at BDC.

- **Crankshaft :** Rotating shaft through which engine work output is supplied to external systems.
  - The crankshaft is connected to the engine block with the main bearings.
  - It is rotated by the reciprocating pistons through the connecting rods connected to the crankshaft, offset from the axis of rotation. This offset is sometimes called crank throw or crank radius.
- **Connecting rod :** Rod connecting the piston with the rotating crankshaft, usually made of steel or alloy forging in most engines but may be aluminum in some small engines.
- **Piston rings:** Metal rings that fit into circumferential grooves around the piston and form a sliding surface against the cylinder walls.

- Camshaft : Rotating shaft used to push open valves at the proper time in the engine cycle, either directly or through mechanical or hydraulic linkage (push rods, rocker arms, tappets) .
- Push rods : The mechanical linkage between the camshaft and valves on overhead valve engines with the camshaft in the crankcase.
- Crankcase : Part of the engine block surrounding the crankshaft.
  - In many engines the oil pan makes up part of the crankcase housing.
- Exhaust manifold : Piping system which carries exhaust gases away from the engine cylinders, usually made of cast iron .

- Intake manifold :Piping system which delivers incoming air to the cylinders, usually made of cast metal, plastic, or composite material.
  - In most SI engines, fuel is added to the air in the intake manifold system either by fuel injectors or with a carburetor.
  - The individual pipe to a single cylinder is called runner.
- Carburetor : A device which meters the proper amount of fuel into the air flow by means of pressure differential.
  - For many decades it was the basic fuel metering system on all automobile (and other) engines.
- Spark plug : Electrical device used to initiate combustion in an SI engine by creating high voltage discharge across an electrode gap.

Petrol Engines

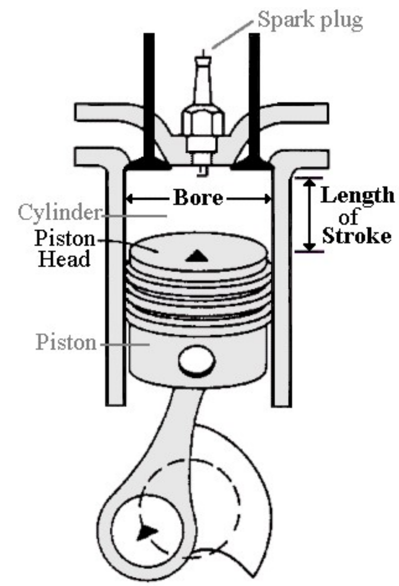
Classification of Petrol Engines

- **Two Stroke cycle Petrol Engines**
- **Four Stroke cycle petrol Engines**

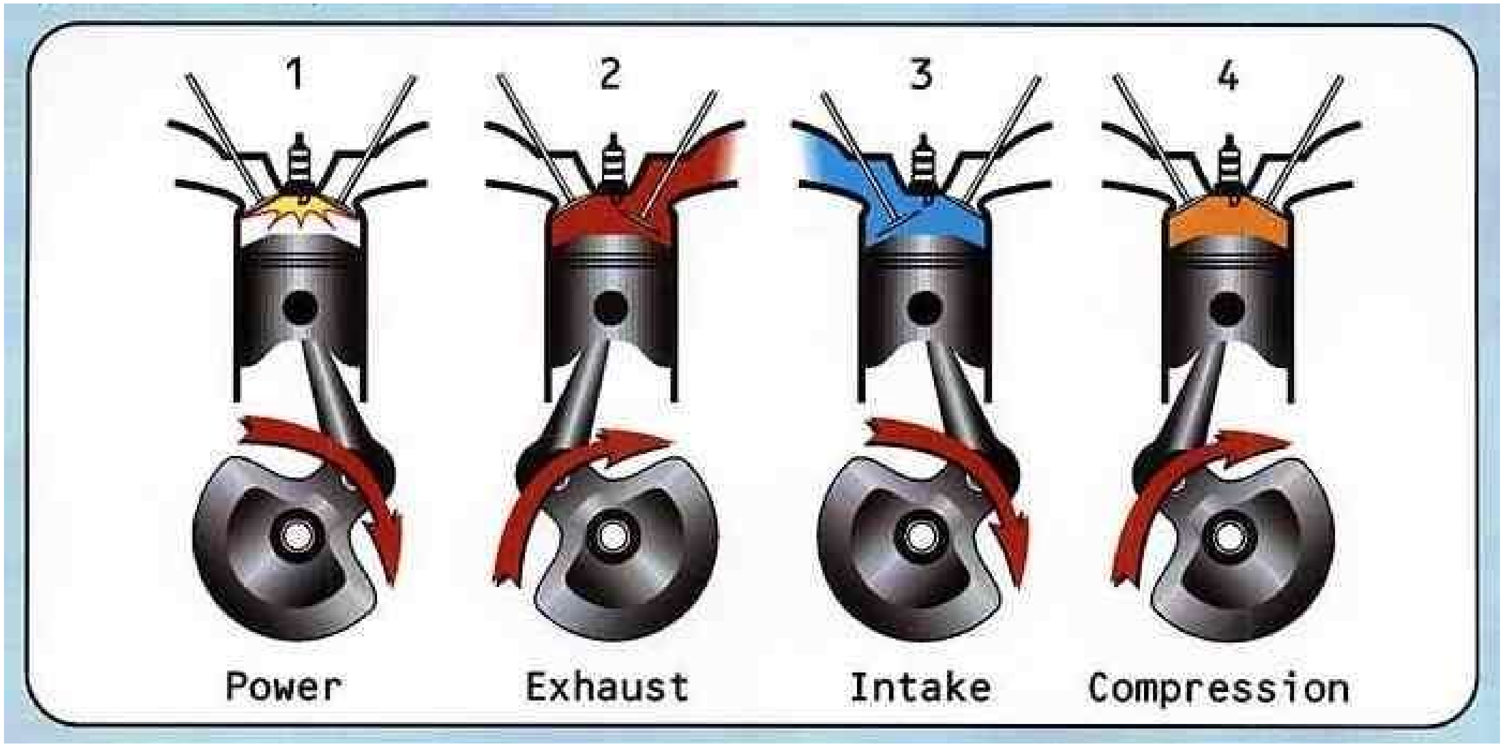
Four stroke cycle Petrol Engines

Construction :

- A piston reciprocates inside the cylinder
- The piston is connected to the crank shaft by means of a connecting rod and crank.
- The inlet and exhaust valves are Mounted on the cylinder head.
- A spark is provided on the cylinder Head.
- The fuel used is petrol



Four Stroke Petrol Engine- Working



Four Stroke Petrol Engine - Working

(a) Suction Stroke (First Stroke of the Engine)

- Piston moves down from TDC to BDC
- Inlet valve is opened and the exhaust valve is closed.
- Pressure inside the cylinder is reduced below the atmospheric pressure.
- The mixture of air fuel is sucked into the cylinder through the inlet valve

(b) Compression Stroke : (Second Stroke of the piston)

- Piston moves up from BDC to TDC
- Both inlet and exhaust valves are closed.
- The air fuel mixture in the cylinder is compressed.

Four Stroke Petrol Engine - Working

(c) Working or Power or Expansion Stroke: (Third Stroke of the Engine)

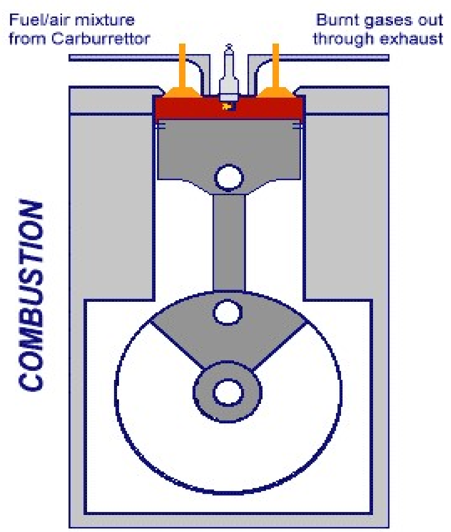
- The burning gases expand rapidly. They exert an impulse (thrust or force) on the piston. The piston is pushed from TDC to BDC
- This movement of the piston is converted into rotary motion of the crankshaft through connecting rod.
- Both inlet and exhaust valves are closed.

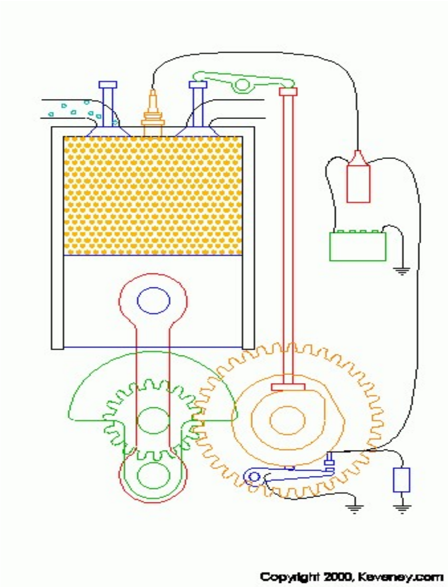
(d) Exhaust Stroke (Fourth stroke of the piston)

- Piston moves upward from BDC
- Exhaust valve is opened and the inlet valve is closed.
- The burnt gases are forced out to the atmosphere through the exhaust valve (Some of the burnt gases stay in the clearance volume of the cylinder)
- The exhaust valve closes shortly after TDC
- The inlet valve opens slightly before TDC and the cylinder is ready to receive fresh charge to start a new cycle.

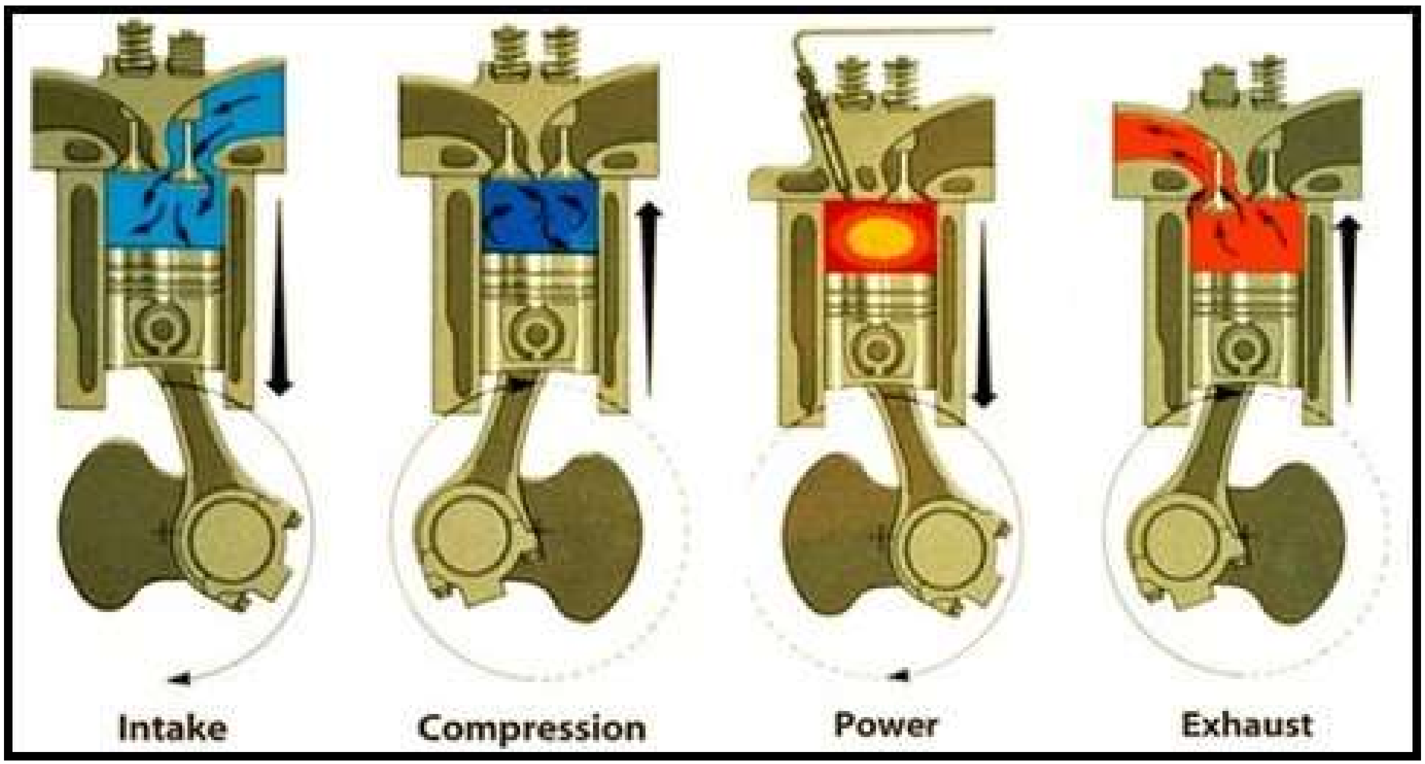
Four Stroke Petrol Engine - Working

- Compression ratio varies from 5 to 8
- The pressure at the end of compression is about 6 to 12 bar.
- The temperature at the end of the compression reaches 250^{o} C to 350^{o} C





Four Stroke Diesel Engine - Working



Four Stroke Diesel Engine - Working

(a) Suction Stroke (First Stroke of the piston)

- Piston moves from TDC to BDC
- Inlet valve is opened and the exhaust valve is closed.
- The pressure inside the cylinder is reduced below the atmospheric pressure.
- Fresh air from the atmosphere is sucked into the engine cylinder through air cleaner and inlet valve.

(b) Compression stroke (Second stroke of the piston)

- Piston moves from BDC to TDC
- Both inlet and exhaust valves are closed.
- The air is drawn during suction stroke is compressed to a high pressure and temperature

Four Stroke Diesel Engine - Working

(c) Working or power or expansion stroke (Third stroke of the piston)

- The burning gases (products of combustion) expand rapidly.
- The burning gases push the piston move downward from TDC to BDC
- This movement of piston is converted into rotary motion of the crank shaft through connecting rod.
- Both inlet and exhaust valves are closed.

(d) Exhaust Stroke (Fourth stroke of the piston)

- Piston moves from BDC to TDC
- Exhaust valve is opened the inlet valve is closed.
- The burnt gases are forced out to the atmosphere through the exhaust valve. (some of the burnt gases stay in the clearance volume of the cylinder)
- The exhaust valve closes shortly after TDC
- The inlet valve opens slightly before TDC and the cylinder is ready to receive fresh air to start a new cycle.

Gas Power Cycles

- Terminology Used in Gas Power Cycles

a) Cycle: “A Cycle is defined as a repeated series of operations occurring in a certain order.”

b) Air standard cycle: “The thermodynamics cycle with air as the working fluid is called an air standard cycle.”

c) Compression ratio (r):

$$r = \frac{Total\ cylinder\ volume}{Clearance\ volume}$$

$$r = \frac{V_C + V_S}{V_C}$$

– Higher the compression ratio better will be the performance of an engine.

d) Piston Speed: "The distance travelled by the piston in one minute is called piston speed."

$$Piston\ Speed = \frac{2LN}{60}\frac{m}{sec}$$

e) Mechanical Efficiency: It is defined as the ratio of the brake power and the indicated power. Mechanical efficiency is indicator of losses due to friction.

$$\eta_{mech} = \frac{B.P.}{I.P.}$$

f) Thermal Efficiency: "It is the ratio of work done to heat supplied by fuel."

$$\eta_{th} = \frac{\text{Work output}}{\text{Heat input}} = \frac{Q_1 - Q_2}{Q_1}$$

Where,

Q_1 = Heat addition

Q_2 = Heat rejection

[Assuming no friction & heat losses, so $W = Q_1 - Q_2$]

i. **Indicated thermal efficiency** = Indicated Power/ Heat supplied by fuel

$$\eta_{ith} = \frac{I.P.}{m_f \times CV}$$

Where, m_f = mass of fuel supplied, Kg/sec and CV = calorific value of fuel, J/kg

ii. **Brake thermal efficiency** = Brake Power/ Heat supplied by fuel

$$\eta_{bth} = \frac{B.P.}{m_f \times CV}$$

$$\eta_{mech} = \frac{\eta_{bth}}{\eta_{ith}}$$

g) Air standard efficiency: The efficiency of engine using air as the working medium is known as an "Air standard efficiency" or "Ideal efficiency".

- The actual efficiency of a cycle is always less than the air standard efficiency of that cycle under ideal conditions.
- This is taken into account by introducing a new term "Relative efficiency".

$$\eta_{\text{relative}} = \frac{\text{Actual thermal efficiency}}{\text{Air standard efficiency}}$$

- The analysis of all air standard cycles is based upon the following assumptions.

Assumptions:

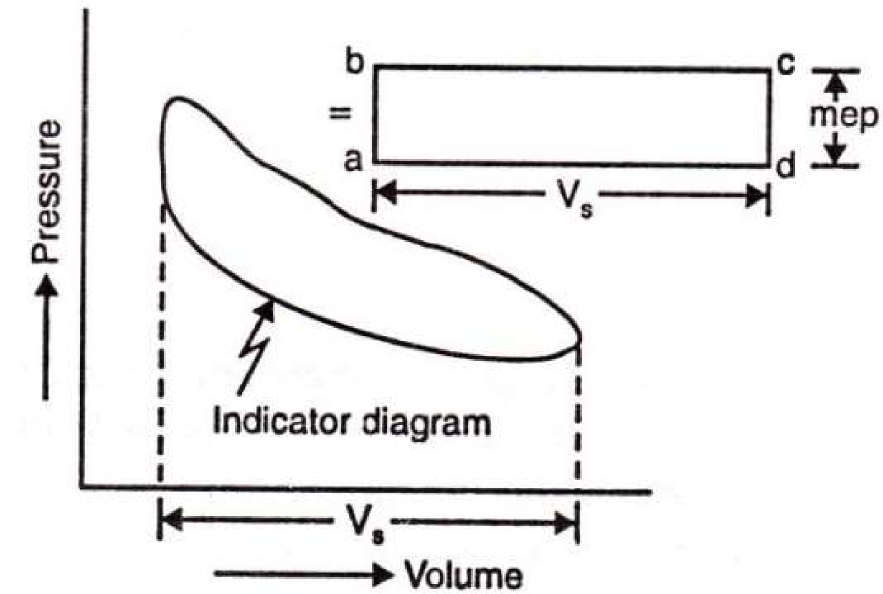
1. The gas in the engine cylinder is a perfect gas i.e. it obeys the gas laws and has constant specific heat.
2. The compression and expansion processes are adiabatic and they take place without internal friction i.e. these processes are Isentropic.
3. No chemical reaction takes place in the cylinder. Heat is supplied or rejected by bringing a hot body or a cold body in contact with cylinder at appropriate points during the process.
4. The engine operates in a closed cycle. The cylinder is filled with constant amount of working medium and the same fluid is used repeatedly.

The approach and concept of ideal air cycle helps to…….

1. Indicate the ultimate performance i.e. to determine the maximum ideal efficiency of a specific thermodynamics cycle.
2. Study qualitatively the influence of different variables on the performance of an actual engine.
3. Evaluate one engine relative to another.

Mean Effective Pressure

- The pressure variation versus volume inside the cylinder of a reciprocating engine is plotted with the help of an engine indicator. The resulting contour is closed one and is referred to as indicator diagram as shown in Fig.
- The area enclosed by the contour is a measure of the work output per cycle from the engine.



Engine Indicator Diagram

- Mean effective pressure is defined as the average pressure acting on the piston which will produce the same output as is done by the varying pressure during a cycle.

Therefore

Area of indicator loop = Area of rectangle abcd

- The height of the rectangle than represents the mean effective pressure.

$$mep = \frac{work\ done\ per\ cycle}{swept\ volume}$$

$$= \frac{Area\ of\ indicator\ loop}{length\ of\ loop}$$

Unit: bar or KN/m^2

- Mean effective pressure is used as a parameter to compare the performance of reciprocating engines of equal size.

- An engine that has a large volume of mep will deliver more net work and will thus perform better.

The Carnot Gas Power Cycle

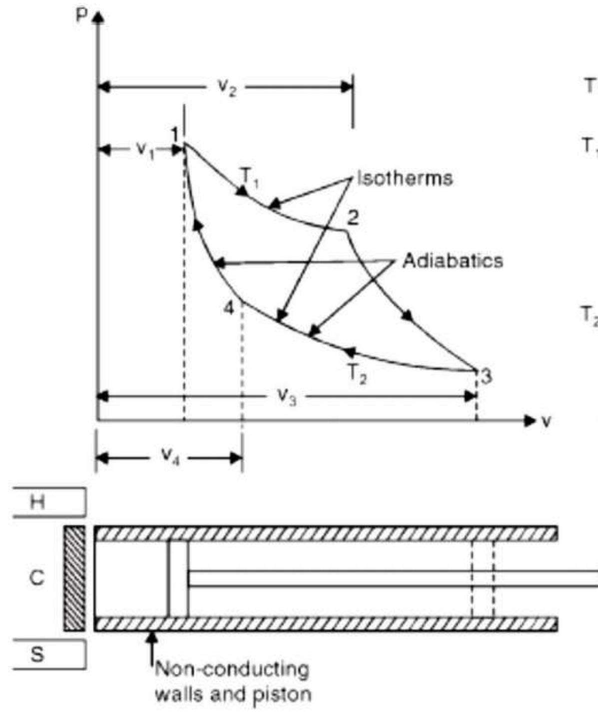
- A Carnot cycle is a hypothetical cycle consisting four different processes: two reversible isothermal processes and two reversible adiabatic (isentropic) processes.
- According to Carnot theorem "No cycle can be more efficient than a reversible cycle operating between the same temperature limits." Assumptions made in the working of the Carnot cycle

a. Working fluid is a perfect gas.

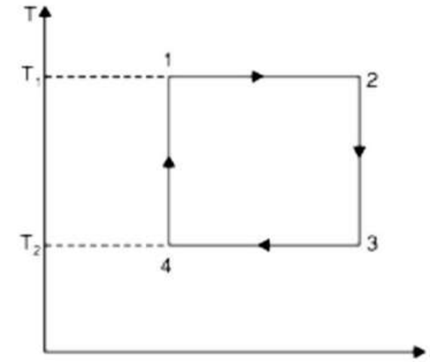
b. Piston cylinder arrangement is weightless and does not produce friction during motion.

c. The walls of cylinder and piston are considered as perfectly insulated. d) Compression and expansion are reversible.

d. The transfer of heat does not change the temperature of sources or sink.



(a) Four stages of the carnot cycle



(b) T-s diagram

Thermal efficiency,

$$\eta = \frac{Work\ done}{Heat\ supplied}$$

$$\therefore \eta = \frac{RT_1 \ln r - RT_2 \ln r}{RT_1 \ln \frac{V_2}{V_1}} = \frac{RT_1 \ln r - RT_2 \ln r}{RT_1 \ln r}$$

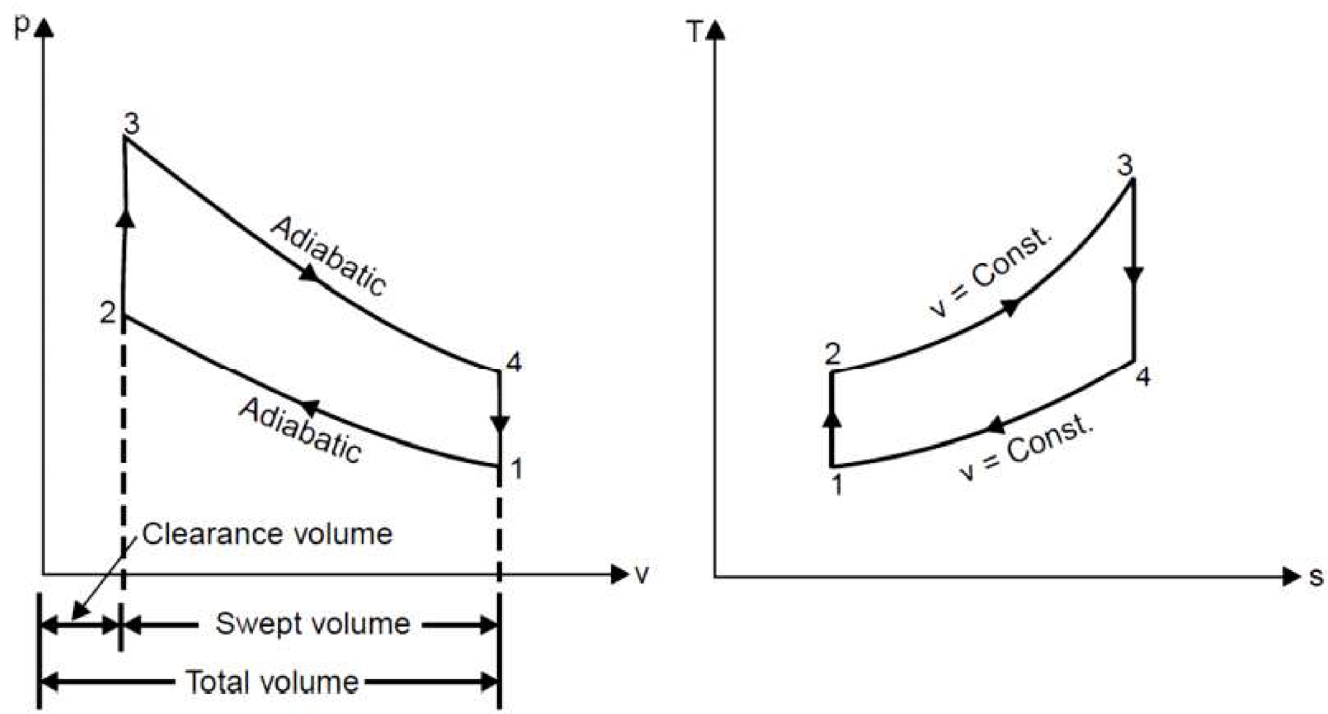
$$\therefore \eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

Limitations of Carnot Gas Cycle:

- The Carnot cycle is hypothetical.
- The thermal efficiency of Carnot cycle depends upon absolute temperature of heat source T1 and heat sink T2 only, and independent of the working substance.
- Practically it is not possible to neglect friction between piston and cylinder. It can be minimized but cannot be eliminated.
- It is impossible to construct cylinder walls which are perfect insulator. Some amount of heat will always be transferred. Hence perfect adiabatic process cannot be achieved.
- The isothermal and adiabatic processes take place during the same stroke. Therefore the piston has to move very slowly for isothermal process and it has to move very fast during remaining stoke for adiabatic process which is practically not possible.
- The output obtained per cycle is very small. This work may not be able to overcome the friction of the reciprocating parts.

The Otto Cycle OR Constant Volume Cycle (Isochoric)

- The cycle was successfully applied by a German scientist Nicolous A. Otto to produce a successful 4 – stroke cycle engine in 1876.
- The thermodynamic cycle is operated with isochoric (constant volume) heat addition and consists of two adiabatic processes and two constant volume changes.



p-V and T-s diagrams of Otto cycle

Adiabatic Compression Process (1 – 2):

- At pt. 1 cylinder is full of air with volume V_1, pressure P_1 and temp. T_1.
- Piston moves from BDC to TDC and an ideal gas (air) is compressed isentropically to state point 2 through compression ratio,

$$r = \frac{V_1}{V_2}$$

Constant Volume Heat Addition Process (2 – 3):

- Heat is added at constant volume from an external heat source.
- The pressure rises and the ratio $r_p \, or \, \alpha = \frac{P_3}{P_2}$ is called expansion ratio or pressure ratio.

Adiabatic Expansion Process (3 – 4):

- The increased high pressure exerts a greater amount of force on the piston and pushes it towards the BDC.
- Expansion of working fluid takes place isentropically and work done by the system.
- The volume ratio $\frac{V_4}{V_3}$ is called isentropic expansion ratio.

Constant Volume Heat Rejection Process (4 – 1):

- Heat is rejected to the external sink at constant volume. This process is so controlled that ultimately the working fluid comes to its initial state 1 and the cycle is repeated.
- Many petrol and gas engines work on a cycle which is a slight modification of the Otto cycle.
- This cycle is called constant volume cycle because the heat is supplied to air at constant volume.

Thermal Efficiency of an Otto Cycle:

- Consider a unit mass of air undergoing a cyclic change.
- **Heat supplied** during the process 2 – 3,

$$q_1 = C_V(T_3 - T_2)$$

- **Heat rejected** during process 4 – 1 ,

$$q_2 = C_V(T_4 - T_1)$$

- **Work done,**

$$\therefore W = q_1 - q_2$$

$$\therefore W = C_V(T_3 - T_2) - C_V(T_4 - T_1)$$

- **Thermal efficiency,**

$$\eta = \frac{Work\ done}{Heat\ supplied} = \frac{W}{q_1}$$

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

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

- For Adiabatic compression process (1 – 2),

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

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

– For Isentropic expansion process (3 – 4),

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

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

$$\therefore T_3 = \mathrm{T}_4\left(\frac{\mathrm{V}_1}{\mathrm{V}_2}\right)^{\gamma-1} \quad (\because\ \mathrm{V}_1 = \mathrm{V}_4\,, \mathrm{V}_2 = \mathrm{V}_3)$$

$$\therefore T_3 = T_4(r)^{\gamma-1}$$

– From equation 7.13, 7.14 & 7.15, we get,

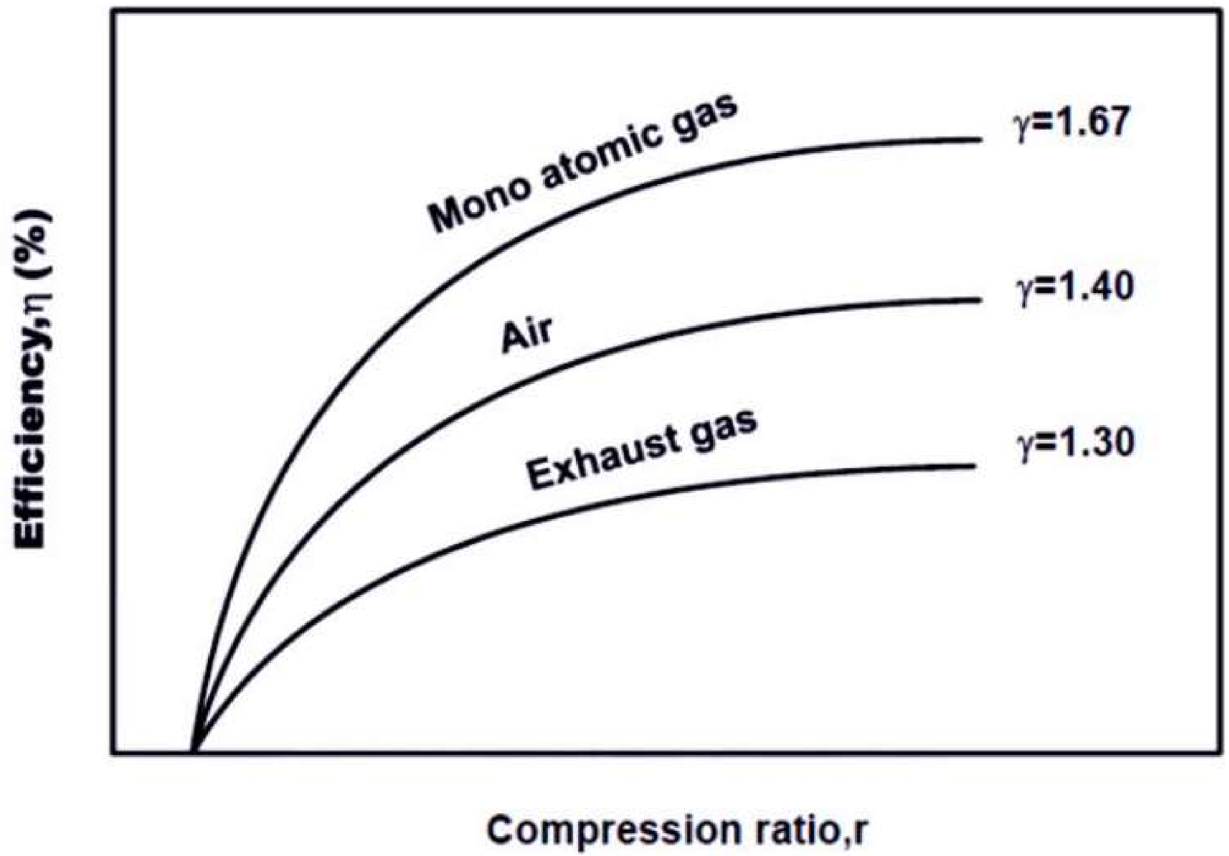
$$\eta_{otto} = 1 - \frac{(T_4 - T_1)}{T_4\, r^{\gamma-1} - T_1\, r^{\gamma-1}}$$

$$\therefore \eta_{otto} = 1 - \frac{(T_4 - T_1)}{r^{\gamma-1}(T_4 - T_1)}$$

$$\therefore \boldsymbol{\eta_{otto} = 1 - \frac{1}{r^{\gamma-1}}}$$

Expression is known as the air standard efficiency of the Otto cycle.

- It is clear from the above expression that efficiency increases with the increase in the value of r (as γ is constant).
- We can have maximum efficiency by increasing r to a considerable extent, but due to practical difficulties its value is limited to 8.
- In actual engines working on Otto cycle, the compression ratio varies from 5 to 8 depending upon the quality of fuel.
- At compression ratios higher than this, the temperature after combustion becomes high and that may lead to spontaneous and uncontrolled combustion of fuel in the cylinder.
- The phenomenon of uncontrolled combustion in petrol engine is called detonation and it leads to poor engine efficiency and in structural damage of engine parts.



Variation of Otto cycle efficiency with compression ratio

Mean effective pressure,

$$mep = \frac{Work\ done\ per\ cy}{swept\ volume}$$

$$= \frac{C_V\,(T_3 - T_2) - C_V(T_4 -}{\frac{R\,T_1}{P_1 r}\,(r-1)}$$

$$= \frac{C_V}{R}\,\frac{P_1 r}{(r-1)}\left[\frac{(T_3 - T_2) - (T_4 - T_1)}{T_1}\right]$$

– For process 1 – 2,

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

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

– Process 2 – 3,

$$\frac{T_3}{T_2} = \frac{P_3}{P_2}(\because\ V_2 = V_3)$$

$$\therefore\ T_3 = T_2\,\alpha \qquad (\alpha = explosion\ pressure\ ratio)$$

$$\therefore\ \boldsymbol{T_3 = T_1\,\alpha\, r^{\gamma-1}}$$

– Process 3 – 4,

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

$$\therefore T_4 = T_1\ \alpha\ r^{\gamma-1}\left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$\therefore T_4 = T_1\ \alpha\ r^{\gamma-1} \times \frac{1}{r^{\gamma-1}}$$

$$\therefore\ \boldsymbol{T_4 = T_1 \cdot \alpha}$$

Substituting all these temperature values in equation We get,

$$mep = \frac{C_V}{R}\frac{P_1\, r}{(r-1)}\left[\frac{(T_1\,\alpha\, r^{\gamma-1} - T_1\, r^{\gamma-1}) - (T_1\,\alpha - T_1)}{T_1}\right]$$

$$\therefore mep = \frac{C_V}{R}\frac{P_1\, r}{(r-1)}\left[\frac{T_1\, r^{\gamma-1}(\alpha-1) - T_1\,(\alpha-1)}{T_1}\right]$$

$$\therefore mep = \frac{C_V}{R}\frac{P_1\, r}{(r-1)}[(r^{\gamma-1}-1)(\alpha-1)]$$

$$\therefore mep = \frac{P_1\, r}{(r-1)(\gamma-1)}[(r^{\gamma-1}-1)(\alpha-1)] ---------(7.20)$$

$$\left(\because \frac{C_V}{R} = \frac{1}{\gamma-1}\right)$$

$$\left[\begin{array}{c} \frac{C_P}{C_V} = \gamma, \\ C_P - C_V = R, \\ C_V\left(\frac{C_P}{C_V} - 1\right) = R, \\ \frac{C_V}{R} = \frac{1}{\gamma-1} \end{array}\right]$$

The Diesel Cycle OR Constant Pressure Cycle (Isobaric)

- This cycle was discovered by a German engineer Dr. Rudolph Diesel. Diesel cycle is also known as constant pressure heat addition cycle.

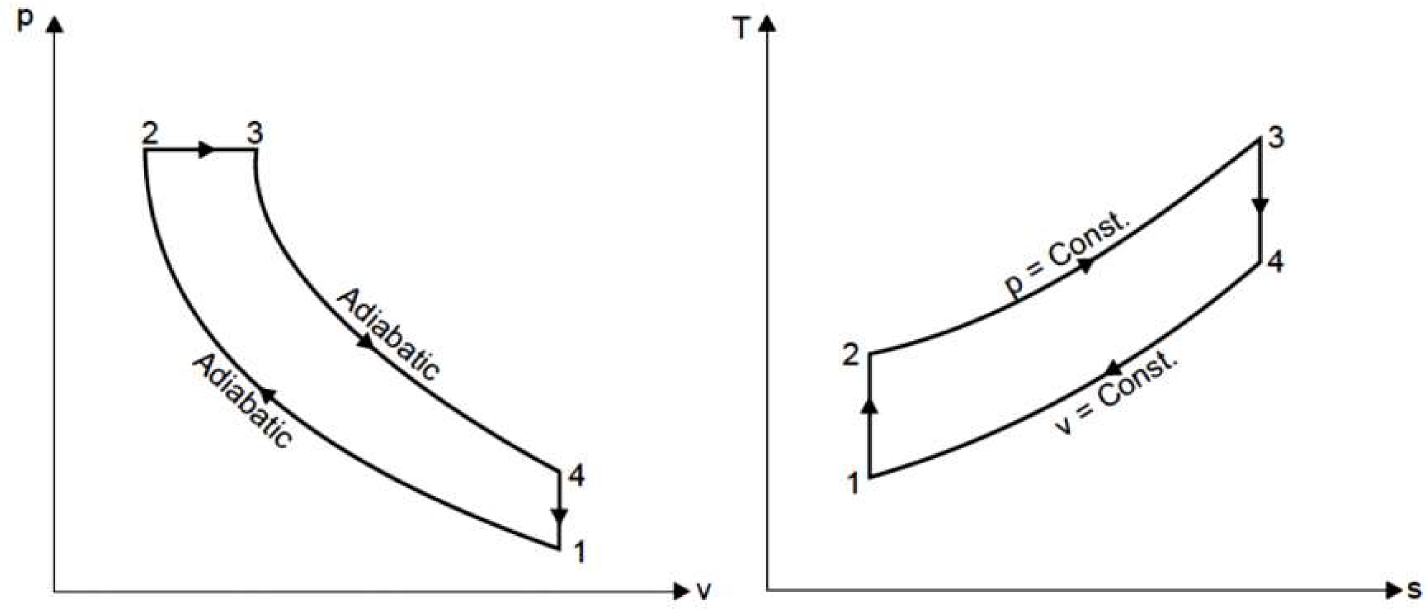


Fig. p-V and T-s diagrams of Diesel cycle

Adiabatic Compression Process (1 – 2):

– Isentropic (Reversible adiabatic) compression with $= \frac{V_1}{V_2}$.

Constant Pressure Heat Addition Process (2 – 3):

– The heat supply is stopped at point 3 which is called the cut – off point and the volume ratio $\rho = \frac{V_3}{V_2}$ is called **cut off ratio** or Isobaric expansion ratio.

Adiabatic Expansion Process (3 – 4):

– Isentropic expansion of air $\frac{V_4}{V_3}$ = isentropic expansion ratio.

Constant Volume Heat Rejection Process (4 – 1):

– In this process heat is rejected at constant volume.

This thermodynamics cycle is called constant pressure cycle because heat is supplied to the air at constant pressure.

Thermal Efficiency for Diesel Cycle:

- Consider unit mass of air.
- **Heat supplied** during process 2 – 3,

$$q_1 = C_P(T_3 - T_2)$$

- **Heat rejected** during process 4 – 1,

$$q_2 = C_V(T_4 - T_1)$$

- **Work done,**

$$W = q_1 - q_2$$

$$W = \mathrm{C_P}(\mathrm{T_3} - \mathrm{T_2}) - \mathrm{C_V}(\mathrm{T_4} - \mathrm{T_1})$$

- **Thermal efficiency,**

$$\eta = \frac{Work\ done}{Heat\ supplied}$$

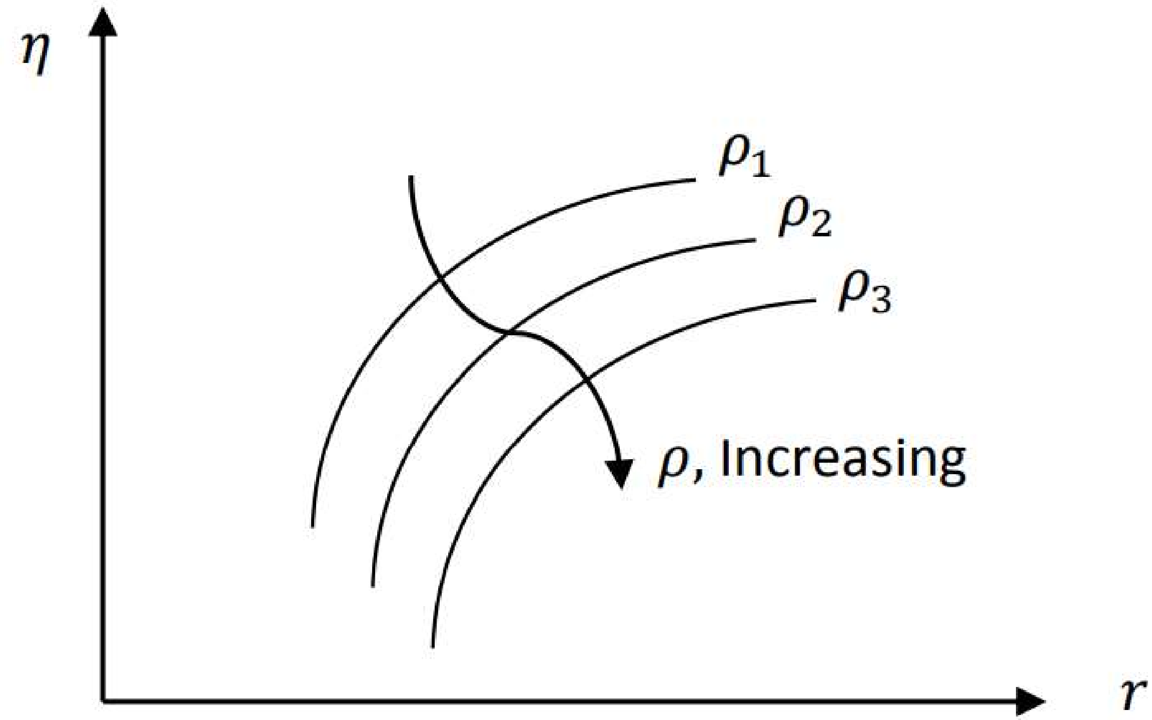
$$\therefore \eta = \frac{C_P(T_3 - T_2) - C_V(T_4 - T_1)}{C_P(T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{C_V}{C_P}\frac{(T_4 - T_1)}{(T_3 - T_2)}$$

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

$$\therefore \boldsymbol{\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{(\rho^{\gamma} - 1)}{\gamma(\rho - 1)}\right]}$$

Apparently the efficiency of diesel cycle depends upon the compression ratio (r) and cutoff ratio (ρ) and hence upon the quantity of heat supplied.



Efficiency of Diesel cycle for various cut-off ratio

- Further,

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

reveals that with an increase in the cut – off ratio (ρ) the value of factor K increases.

That implies that for a diesel engine at constant compression ratio, the efficiency would increase with decrease in ρ and in the limit $\rho \rightarrow 1$, the efficiency would become

$$1 - \frac{1}{r^{\gamma-1}}$$

- Since the factor $K = \frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}$ is always greater than unity, the Diesel cycle is always less efficient than a corresponding Otto cycle having the same compression ratio.

- However Diesel engine operates on much higher compression ratio (14 to 18) compared to those for S.I. Engines operating on Otto cycle.
- High compression ratios for Diesel engines are must not only for high efficiency but also to prevent diesel knock; a phenomenon which leads to uncontrolled and rapid combustion in diesel engines.

Mean Effective Pressure:

- **Net work done** per unit mass of air,

$$W_{net} = C_p (T_3 - T_2) - C_V (T_4 - T_1)$$

- **Swept volume,**

$$Swept\ volume = V_1 - V_2 = V_1\left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1}\left(1 - \frac{1}{r}\right)$$

$$= \frac{RT_1}{P_1 r}(r - 1)$$

- **Mean effective pressure,**

$$mep = \frac{Work\ done\ per\ cycle}{swept\ volume}$$

$$\therefore mep = \frac{C_P (T_3 - T_2) - C_V (T_4 - T_1)}{\frac{R\,T_1}{P_1 r}(r - 1)}$$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{(r-1)}\left[\frac{\gamma(T_3 - T_2) - (T_4 - T_1)}{T_1}\right]$$

- From equation

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

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

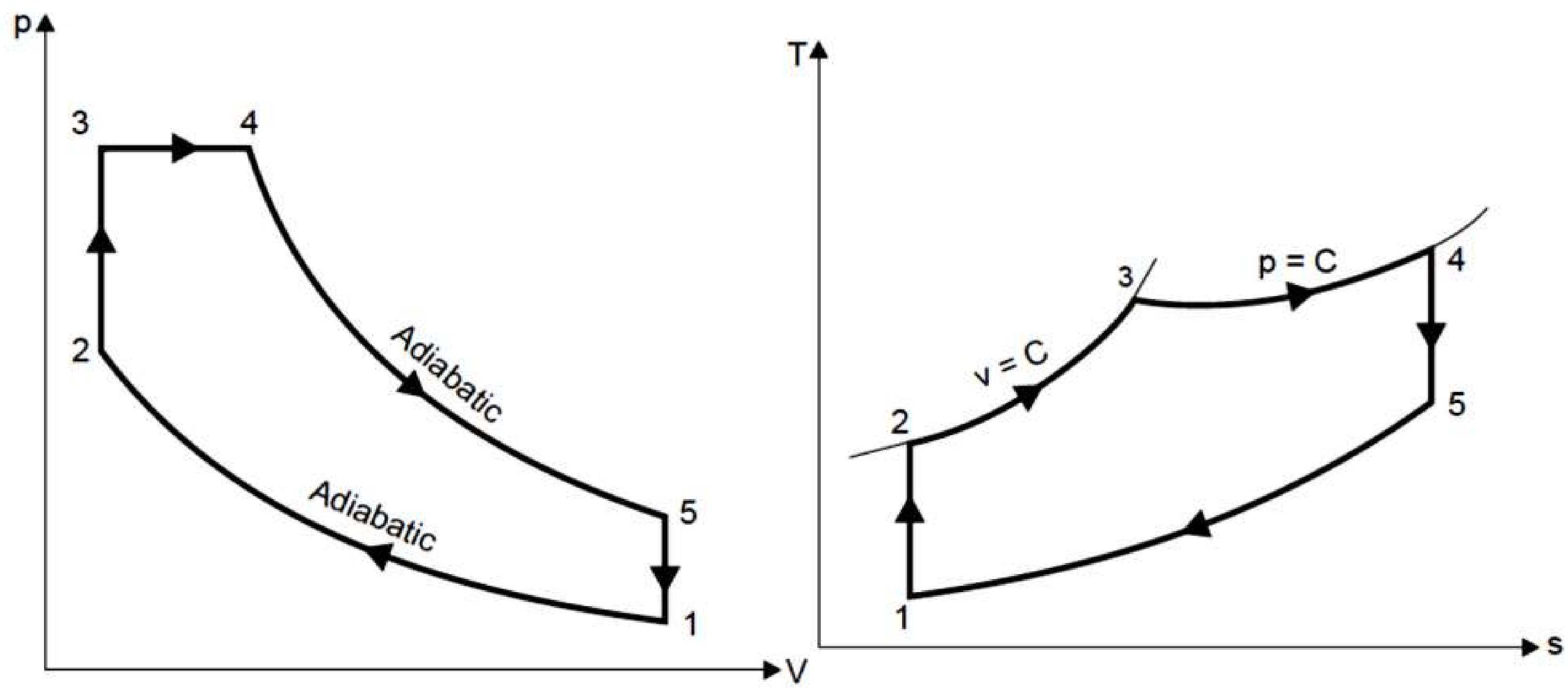
$T_4 = T_1\, \rho^{\gamma}$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{(r-1)}\left[\frac{\gamma(T_1\, r^{\gamma-1}\rho - T_1\, r^{\gamma-1}) - (T_1\, \rho^{\gamma} - T_1)}{T_1}\right]$$

$$\boldsymbol{\therefore mep = \frac{P_1 r}{(\gamma - 1)(r - 1)}[\gamma r^{\gamma-1}(\rho - 1) - (\rho^{\gamma} - 1)]}$$

The Dual Combustion Cycle OR The Limited Pressure Cycle

- This is a cycle in which the addition of heat is partly at constant volume and partly at constant pressure.



p-V and T-s diagrams of Diesel cycle

Adiabatic Compression Process (1 – 2):

– Isentropic (Reversible adiabatic) compression with $= \frac{V_1}{V_2}$.

Constant Volume Heat Addition Process (2 – 3):

– The heat is supplied at constant volume with explosion ratio or pressure ratio $\alpha = \frac{P_3}{P_2}$.

Constant Pressure Heat Addition Process (3 – 4):

– The heat supply is stopped at point 4 which is called the cut – off point and the volume ratio $\rho = \frac{V_4}{V_3}$ is called **cut off ratio**.

Adiabatic Expansion Process (4 – 5):

– Isentropic expansion of air with $\frac{V_5}{V_4}$ = isentropic expansion ratio.

Constant Volume Heat Rejection Process (5 – 1):

– In this process heat is rejected at constant volume.

The high speed Diesel engines work on a cycle which is slight modification of the Dual cycle.

Thermal Efficiency for Dual Cycle:

- Consider unit mass of air undergoing the cyclic change.
- **Heat supplied**,

$$q_1 = q_{2-3} + q_{3-4}$$

$$q_1 = C_V(T_3 - T_2) + C_P(T_4 - T_3)$$

- **Heat rejected** during process 5 – 1,

$$q_2 = C_V(T_5 - T_1)$$

- **Work done,**

$$W = q_1 - q_2$$

$$W = C_V(T_3 - T_2) + C_P(T_4 - T_3) - \mathrm{C_V}(\mathrm{T_5} - \mathrm{T_1})$$

– **Thermal efficiency,**

$$\eta = \frac{Work\ done}{Heat\ supplied}$$

$$\therefore \eta = \frac{C_V(T_3 - T_2) + C_P(T_4 - T_3) - C_V(T_5 - T_1)}{C_V(T_3 - T_2) + C_P(T_4 - T_3)}$$

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

– For adiabatic compression process (1 – 2),

$$r = \frac{V_1}{V_2} ----------(a)$$

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

$$P_2 = P_1 r^{\gamma} ----------(b)$$

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

– For constant volume heat addition process (2 – 3)

$$V_3 = V_2 = \frac{V_1}{r}$$

$$\alpha = \frac{P_3}{P_2} \ (Pressure\ ratio) ---------(d)$$

$$\therefore P_3 = P_2\alpha = P_1 r^\gamma \alpha$$

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

$$= T_2\, \alpha$$

$$\therefore T_3 = T_1\, r^{\gamma-1}\alpha ---------(e)$$

– For constant pressure heat addition process (3 – 4)

$$P_3 = P_4 = P_1 r^\gamma \alpha ---------(f)$$

$$\rho = \frac{V_4}{V_3} \ (Cutoff\ ratio) ---------(g)$$

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

$$\therefore\ T_4 = T_3\,\rho$$

$$\therefore\ T_4 = T_1\,r^{\gamma-1}\rho\alpha \text{ ---------}(h)$$

- For adiabatic expansion process (4 – 5),

$$P_4V_4^{\gamma} = P_5V_5^{\gamma}$$

$$P_5 = P_4(V_4/V_5)^{\gamma} = P_3(V_4/V_1)^{\gamma} \qquad (\because V_1 = V_5\ \&\ P_3 = P_4)$$

$$P_5 = P_3\left(\frac{V_4}{V_1}\frac{V_3}{V_3}\right)^{\gamma} = P_3\left(\frac{V_4}{V_1}\frac{V_2}{V_3}\right)^{\gamma} \qquad (\because V_3 = V_2)$$

$$\therefore\ P_5 = P_3\left(\frac{V_4/V_3}{V_1/V_2}\right)^{\gamma} = P_3(\rho/r)^{\gamma} \text{ ---------}(i)$$

And

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

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

$$\therefore\ T_5 = \frac{T_1\,r^{\gamma-1}\,\rho\alpha\,\rho^{\gamma-1}}{r^{\gamma-1}}$$

$$\therefore\ T_5 = T_1\,\alpha\,\rho^{\gamma} \text{ ---------}(j)$$

From equation

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

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

$$\therefore \eta = 1 - \frac{(\rho^{\gamma}\alpha - 1)}{[r^{\gamma-1}\{(\alpha - 1\alpha) + \gamma\alpha(\rho - 1)\}]}$$

$$\therefore \boldsymbol{\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{(\alpha\rho^{\gamma} - 1)}{(\alpha - 1) + \gamma\alpha(\rho - 1)}\right]}$$

- It can be seen from the equation that the thermal efficiency of a Dual cycle can be increased by supplying a greater portion of heat at constant volume (high value of α) and smaller portion at constant pressure (low value of ρ).
- In the actual high speed Diesel engines operating on this cycle, it is achieved by early fuel injection and an early cut-off.
- It is to be noted that Otto and Diesel cycles are special cases of the Dual cycle.
- If $\rho = 1$ $(V_3 = V_4)$

  Hence, there is no addition of heat at constant pressure. Consequently the entire heat is supplied at constant volume and the cycle becomes the Otto cycle.

By substituting $\rho = 1$ in equation we get,

$$\eta = 1 - \frac{1}{r^{(\gamma-1)}} = Efficiency\ of\ Otto\ cycle$$

– Similarly if $\alpha = 1$, the heat addition is only at constant pressure and cycle becomes Diesel cycle.

By substituting $\alpha = 1$ in equation we get,

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{(\rho^{\gamma} - 1)}{\gamma(\rho - 1)}\right] = Efficiency\ of\ Diesel\ cycle$$

Mean Effective Pressure:

- **Net work done** per unit mass of air,

$$W_{net} = C_V(T_3 - T_2) + C_p(T_4 - T_3) - C_V(T_5 - T_1)$$

- **Swept volume,**

$$Swept\ volume = V_1 - V_2 = V_1\left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1}\left(1 - \frac{1}{r}\right)$$

$$= \frac{RT_1}{P_1 r}(r - 1)$$

- **Mean effective pressure,**

$$mep = \frac{Work\ done\ per\ cycle}{swept\ volume}$$

$$\therefore mep = \frac{C_V(T_3 - T_2) + C_p(T_4 - T_3) - C_V(T_5 - T_1)}{\frac{R\,T_1}{P_1 r}(r - 1)}$$

$$\therefore mep = \frac{C_V}{R}\,\frac{P_1 r}{(r-1)}\left[\frac{(T_3 - T_2) + \gamma(T_4 - T_3) - (T_5 - T_1)}{T_1}\right]$$

- From equation (c), (e), (h) and (j),

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

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

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

$$T_5 = T_1\, \alpha\, \rho^{\gamma}$$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{(r-1)}\left[\frac{\gamma(T_1\, r^{\gamma-1}\alpha - T_1\, r^{\gamma-1}) + \gamma(T_1\, r^{\gamma-1}\alpha\rho - T_1\, r^{\gamma-1}\alpha) - (T_1\, \alpha\rho^{\gamma} - T_1)}{T_1}\right]$$

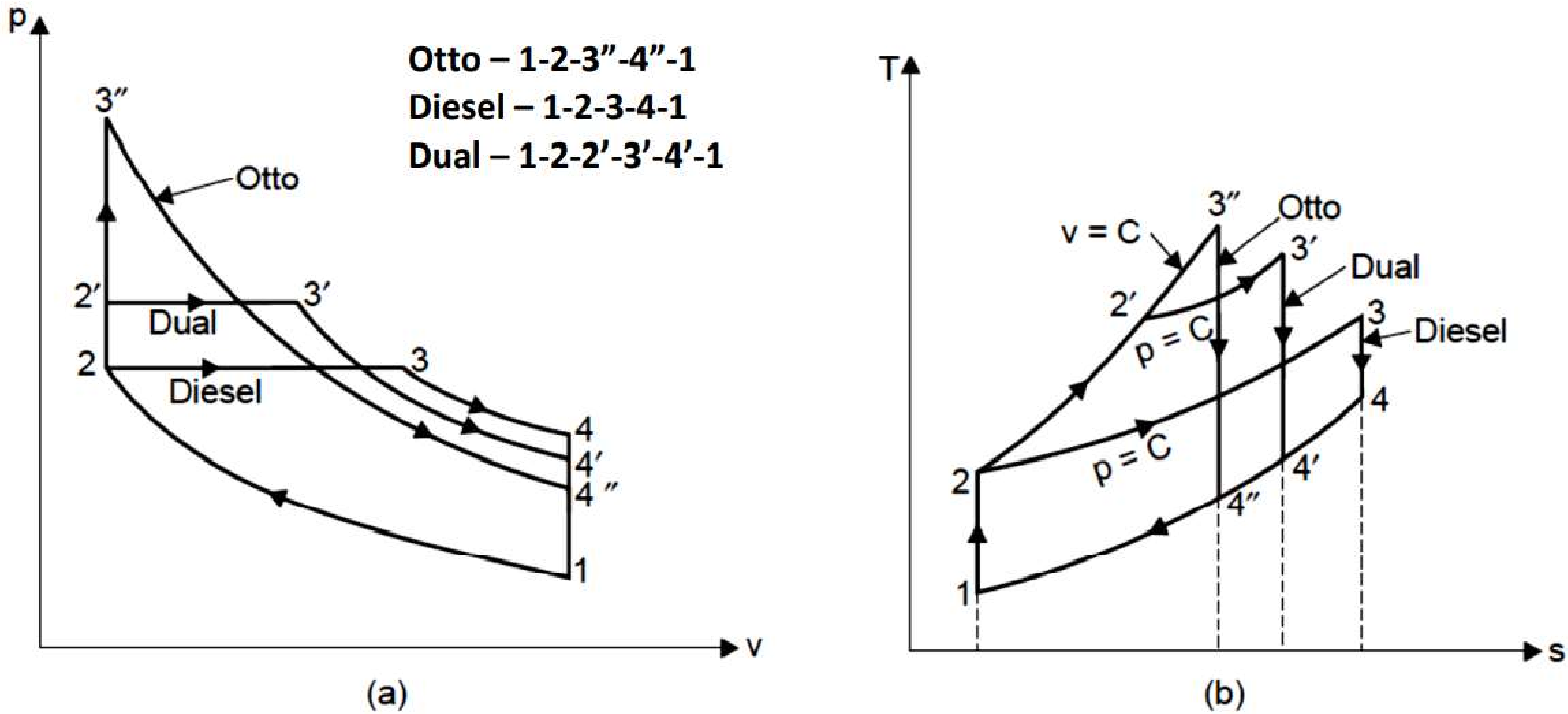
$$\boldsymbol{\therefore mep = \frac{P_1 r}{(\gamma-1)(r-1)}[(\alpha - 1)r^{\gamma-1} + \gamma\alpha r^{\gamma-1}(\rho - 1) - (\alpha\rho^{\gamma} - 1)]}$$

Comparison of Otto, Diesel and Dual Cycles

Following are the important variable factors which are used as a basis for comparison of the cycles:

- Compression ratio
- Maximum pressure
- Heat supplied
- Heat rejected
- Net work.

A. For the Same Compression Ratio and the Same Heat Input



(a) P-V diagram and (b) T-S diagram

- We know that,

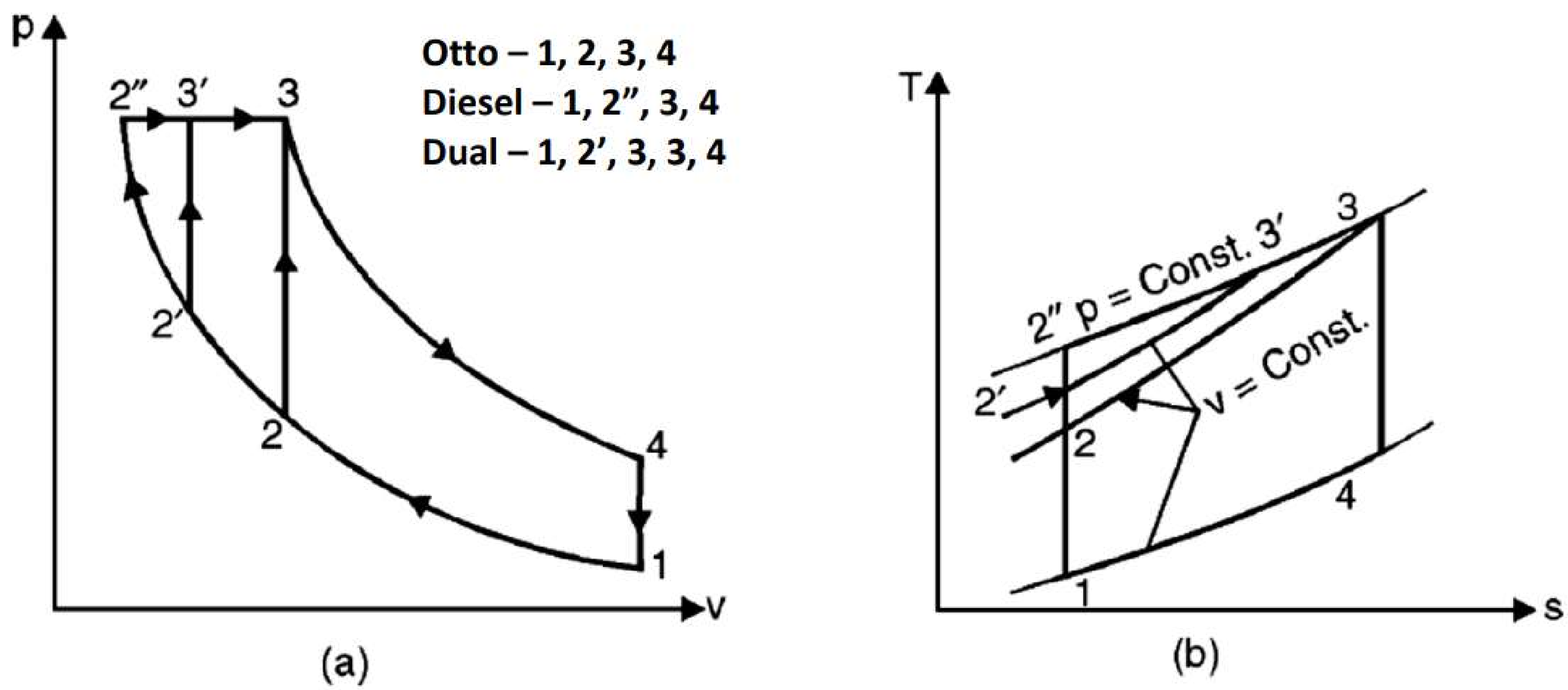
$$\eta = 1 - \frac{Heat\ Rejected}{Heat\ Supplied} = 1 - \frac{q_2}{q_1}$$

- The quantity of heat rejected from each cycle is represented by the appropriate area under the line 4 – 1 on the T – S diagram.
- From equation it is clear that the cycle which has the least heat rejected will have the highest efficiency.

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

B. Same Maximum Pressure and Temperature

- When pressure is the limiting factor in engine design, it becomes necessary to compare the air standard cycles on the basis of same maximum pressure & temperature.



(a) P-V diagram and (b) T-S diagram

- Here the Otto cycle must be limited to low compression ratio to fulfill the condition that point 3 (same maximum pressure & temperature) is to be a common state for all the three cycles.
- From Fig. it is clear that the heat rejected is same for all the three cycles. Hence with the same heat rejected, the cycle with greater heat addition is more efficient.
- We know that,

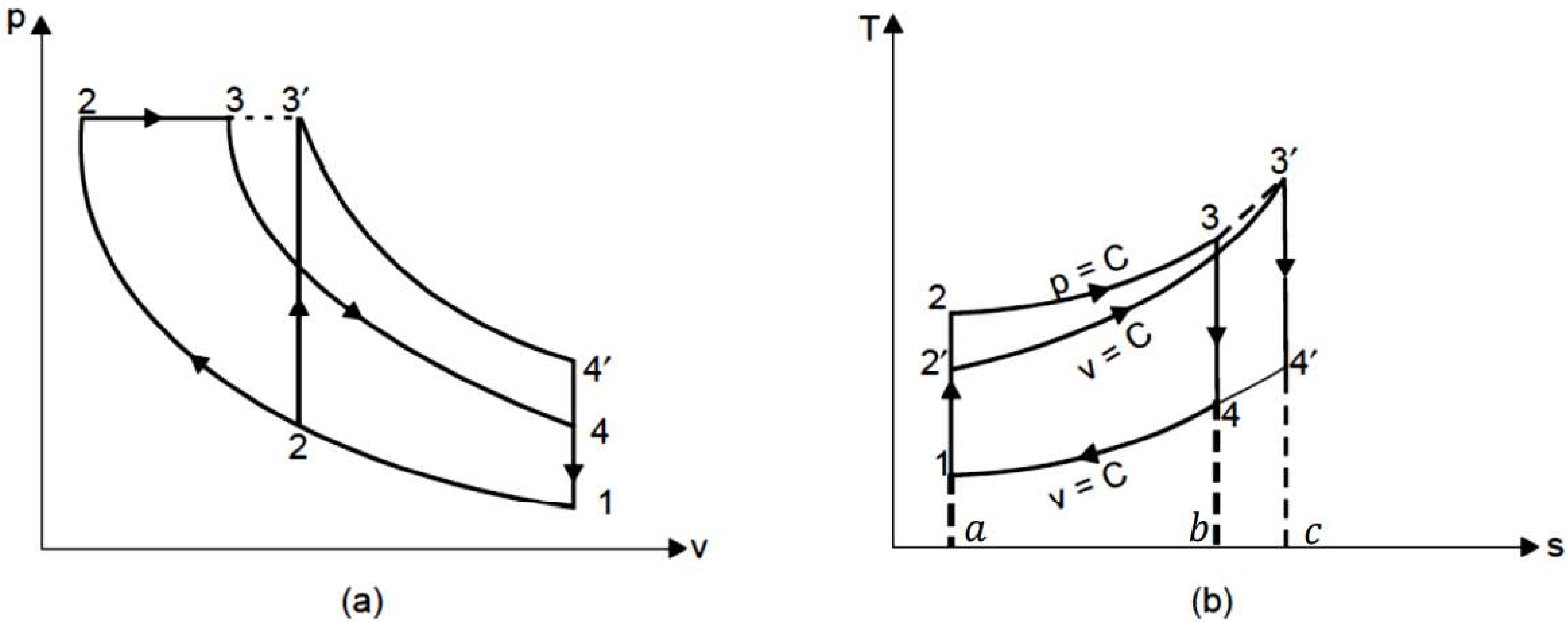
$$\eta = 1 - \frac{Heat\ Rejected}{Heat\ Supplied} = 1 - \frac{q_2}{q_1} - - - - - - - - - -(7.39)$$

- From Fig. 7.9,

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

C. For Constant Maximum Pressure and Heat Input

- Fig. shows the Otto and Diesel cycles on P-V and T-S diagrams for constant maximum pressure and heat input respectively.



(a) P-V diagram and (b) T-S diagram

- For the constant maximum pressure, points 3 and 3' must lie on the constant pressure line.
- Also for the same heat input the areas $a-2-3-b$ and $a-2'-3'-c$ on the T-S plot must be equal.
- Now,

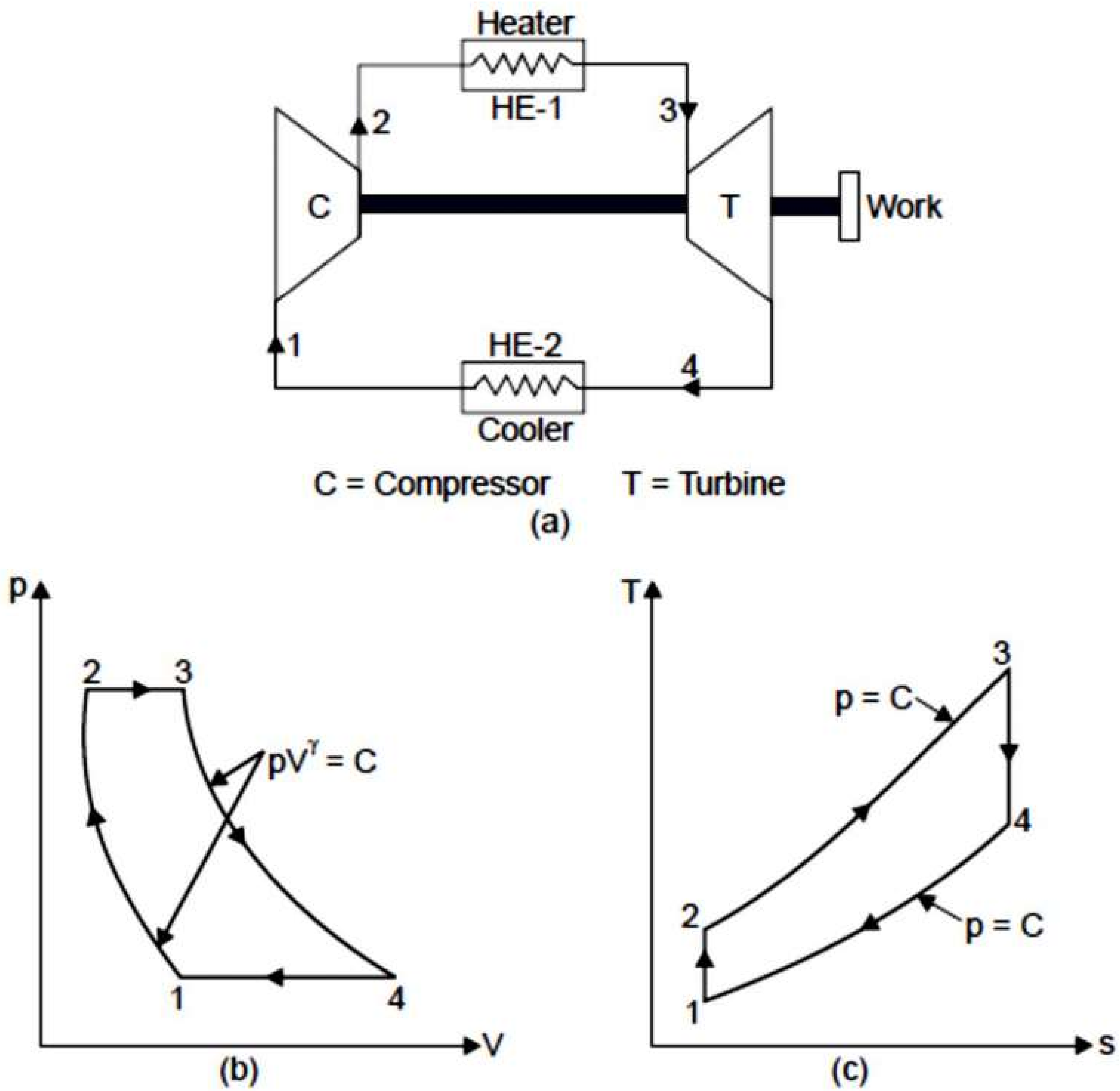
$$\eta = 1 - \frac{Heat\ Rejected}{Heat\ Supplied} = 1 - \frac{q_2}{q_1}$$

- Hence for the same amount of heat supplied the cycle with less heat rejected has a higher value of thermal efficiency.
- From Fig.

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

The Brayton Cycle OR The Joule Cycle

- The Brayton cycle is a constant pressure cycle for a perfect gas. It is also called Joule cycle.
- It is a theoretical cycle on which constant pressure gas turbine works
- The closed Brayton cycle is shown in the Fig. (a) and it is represented on p-v and T-s diagrams as shown in Figs. (b) and (c) respectively.



The P-v, T-s and Schematic diagram of Brayton cycle

- **Isentropic Compression (1 – 2):**

  The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2, the temperature rising from T_1 to T_2. No heat flow occurs.

- **Constant Pressure Heat Addition (2 – 3):**

  The compressed air is passed through a heat exchanger, where heat is externally supplied to it at constant pressure. Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2.

- **Isentropic Expansion (3 – 4):**

  Isentropic expansion of high pressure & high temperature air takes place in the turbine during which the work is done by the system. The air is expanded isentropically from p_2 to p_1, the temperature falling from T_3 to T_4. No heat flow occurs.

- **Constant Pressure Heat Rejection (4 – 1):**

  The air at state point 4 is passed through a heat exchanger and heat is rejected at constant pressure. The volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1.

Thermal Efficiency for Closed Brayton Cycle:

- For unit mass of air,
- **Heat supplied** during process 2 – 3,

$$q_1 = C_P(T_3 - T_2)$$

- **Heat rejected** during process 4 – 1,

$$q_2 = C_P(T_4 - T_1)$$

- **Work done,**

$$W = q_1 - q_2$$

$$\therefore W = C_P(T_3 - T_2) - C_P(T_4 - T_1)$$

- **Thermal efficiency,**

$$\eta = \frac{Work\ done}{Heat\ supplied}$$

$$\therefore \eta = \frac{C_P(T_3 - T_2) - C_P(T_4 - T_1)}{C_P(T_3 - T_2)}$$

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

- Take **pressure ratio**,

$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$

- For isentropic compression process (1 – 2),

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (r_p)^{\frac{\gamma-1}{\gamma}}$$ -

- For isentropic expansion process (3 – 4),

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

- Thus from equation

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

$$\therefore \frac{T_4}{T_1} = \frac{T_3}{T_2}.$$

- From equation

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

$$\therefore \eta = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)} = 1 - \frac{T_1\left(\frac{T_3}{T_2} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

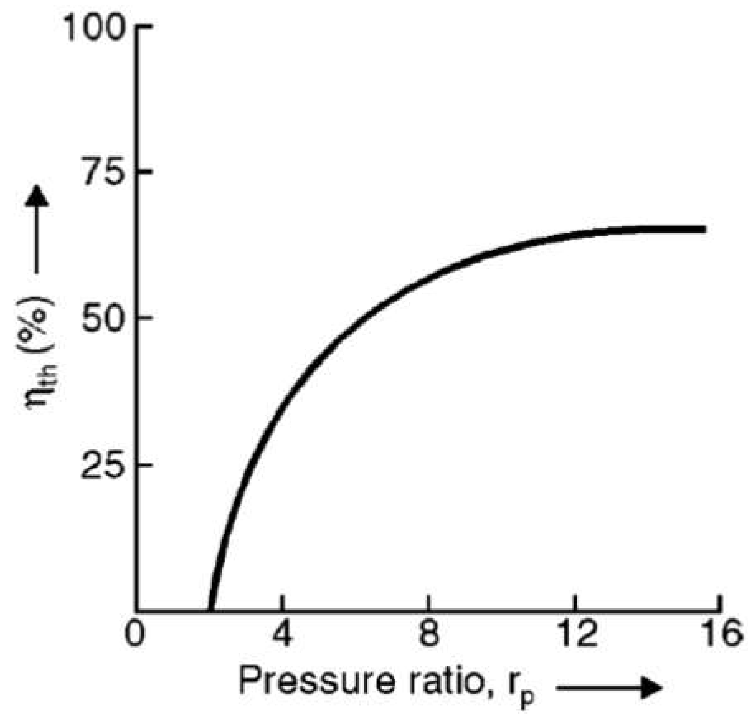
$$\therefore \eta = 1 - \frac{T_1}{T_2}$$

$$\therefore \eta = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \boldsymbol{\eta = 1 - \left(\frac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}}}$$

- Thermal efficiency of Brayton cycle is function of pressure ratio. Efficiency increases with pressure ratio as shown in Fig.

- The curve tends to become flat at higher pressure ratios, which implies that though the efficiency is increasing, the rate of increase starts diminishing at higher pressures.



THANK YOU