Lecture Note on
Subject: THERMAL ENGINEERING-I
Code TH – 4

Branch: Mechanical Engineering

Name of Faculty: - Er Litu Behera

Syllabus

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1.2 Thermodynamic properties of a system (pressure, volume, temperature, entropy, enthalpy, Internal energy and units of measurement).

1.3 Intensive and extensive properties

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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.

1.10Work transfer, Displacement work

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2.2 State & explain First law of thermodynamics.

2.3 Limitations of First law of thermodynamics

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Thermodynamic concept & Terminology

Definition of thermodynamics

Thermodynamics may be defined as follows:

Thermodynamics is an axiomatic science which deals with the relations among heat, work and properties of system which are in equilibrium. It describes state and changes in state of physical systems.

Or

Thermodynamics is the science of the regularities governing processes of energy conversion.

Or

Thermodynamics is the science that deals with the interaction between energy and material systems.

Thermodynamic Systems

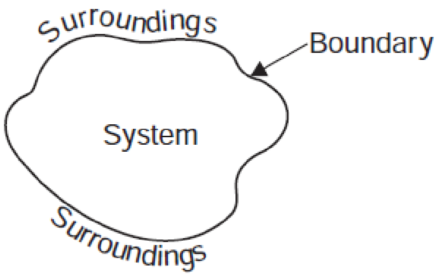
System, Boundary and Surroundings

System

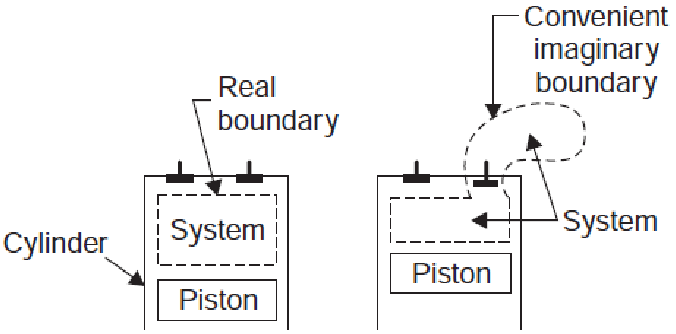
A system is a finite quantity of matter or a prescribed region of space.

Boundary

The actual or hypothetical envelope enclosing the system is the boundary of the system. The boundary may be fixed or it may move, as and when a system containing a gas is compressed or expanded. The boundary may be real or imaginary. It is not difficult to envisage a real boundary but an example of imaginary boundary would be one drawn around a system consisting of the fresh mixture about to enter the cylinder of an I.C. engine together with the remanants of the last cylinder charge after the exhaust process.



The system.



The real and imaginary boundaries.

Closed System

If the boundary of the system is impervious to the flow of matter, it is called a closed system. An example of this system is mass of gas or vapour contained in an engine cylinder, the boundary of which is drawn by the cylinder walls, the cylinder head and piston crown. Here the boundary is continuous and no matter may enter or leave.

Open System

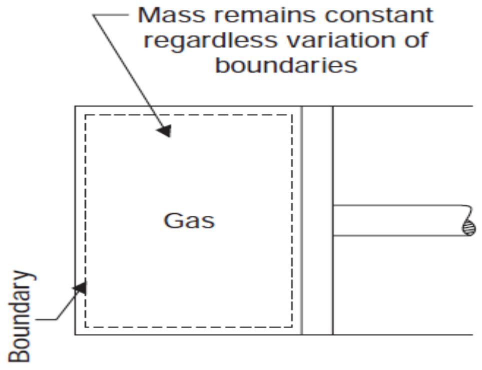
An open system is one in which matter flows into or out of the system. Most of the engineering systems are open.

Isolated System

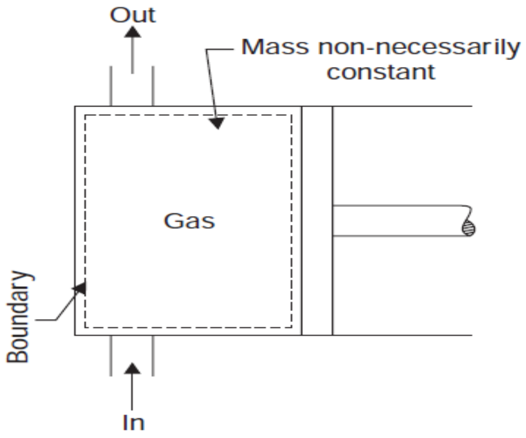
An isolated system is that system which exchanges neither energy nor matter with any other system or with environment.

Adiabatic System

An adiabatic system is one which is thermally insulated from its surroundings. It can, however, exchange work with its surroundings. If it does not, it becomes an isolated system.



Closed system.



Open system.

Thermodynamic properties of a system

Pressure

Pressure is defined as a force per unit area. Pressures are exerted by gases, vapours and liquids. The instruments that we generally use, however, record pressure as the difference between two pressures. Thus, it is the difference between the pressure exerted by a fluid of interest and the ambient atmospheric pressure. Such devices indicate the pressure either above or below that of the atmosphere. When it is above the atmospheric pressure, it is termed gauge pressure and is positive. When it is below atmospheric, it is negative and is known as vacuum. Vacuum readings are given in millimetres of mercury or millimetres of water below the atmosphere. It is necessary to establish an absolute pressure scale which is independent of the changes in atmospheric pressure. A pressure of absolute zero can exist only in complete vacuum. Any pressure measured above the absolute zero of pressure is termed an 'absolute pressure'.

A schematic diagram showing the gauge pressure, vacuum pressure and the absolute pressure is given in Fig. 2.14.

Mathematically :

(i) Absolute pressure = Atmospheric pressure + Gauge pressure

Pabs = Patm + Pgauge

(ii) Vacuum pressure = Atmospheric pressure – Absolute pressure.

Vacuum is defined as the absence of pressure. A perfect vacuum is obtained when absolute pressure is zero, at this instant molecular momentum is zero.

Unit for Pressure

The fundamental SI unit of pressure is N/m2 (sometimes called pascal, Pa) or bar.

1 bar = 105 N/m2 = 105 Pa.

Standard atmospheric pressure = 1.01325 bar = 0.76 m (or 760 mm) Hg.

Low pressures are often expressed in terms of mm of water or mm of mercury. This is an abbreviated way of saying that the pressure is such that which will support a liquid column of stated height.

Example. Convert the following readings of pressure to kPa assuming that barometer reads 760 mm of Hg.
(i) 80 cm of Hg (ii) 30 cm Hg vacuum
(iii) 1.35 m H_2O gauge (iv) 4.2 bar.
Solution
Assuming density of Hg, $\rho_{Hg} = 13.596 \times 1000$ kg/m3
Pressure of 760 mm of Hg will be
$= \rho \times g \times h = 13.596 \times 1000 \times 9.806 \times (760/1000)$
= 101325 Pa = 101.325 kPa.
(i) Pressure of 80 cm of Hg
= (800/760) × 101.325 = 106.65 kPa. (Ans.)
(ii) 30 cm Hg vacuum
= 76 – 30 = 46 cm of Hg absolute.
Pressure due to 46 cm of Hg
= (460/760) × 101.325 = 61.328 kPa. (Ans.)
(iii) Pressure due to 1.35 m H_2O gauge
= 1000 × 9.806 × 1.35 = 13238 Pa = 13.238 kPa. (Ans.)
(iv) 4.2 bar
= 4.2 × 102 kPa = 420 kPa. (Ans.)
Note. Pressure of 1 atmosphere
= 760 mm of Hg
or = 101325 N/m2.
The above values are standard. To get this value we have to use ρ_{Hg} = 13596 kg/m3 and g = 9.806 m/s2. When we use ρ_{Hg} = 13600 kg/m3 and g = 9.81 m/s2, we get patm. = 101396 N/m2 which is slightly different from 101325 N/m2. It is recommended that for pressure of 1 atm. the value 101325 N/m2 should be used.
Example- 2 A vacuum recorded in the condenser of a steam power plant is 740 mm of Hg. Find the absolute pressure in the condenser in Pa. The barometric reading is 760 mm of Hg.
Solution
Vacuum recorded in the condenser = 740 mm of Hg
Barometric reading = 760 mm of Hg
We know that,
Absolute pressure in the condenser
= Barometric reading – vacuum in the condenser
= 760 – 740 = 20 mm of Hg
= 20 × 133.4 N/m2 (1mm of Hg 133.4 N / m2)
= 2668 N/m2 = 2668 Pa. (Ans.)

Temperature

The temperature is a thermal state of a body which distinguishes a hot body from a cold body. The temperature of a body is proportional to the stored molecular energy
i.e., the average molecular kinetic energy of the molecules in a system. (A particular molecule does not hhave a temperature, it has energy. The gas as a system has temperature).
Instruments for measuring ordinary temperatures are known as thermometers and those for measuring high temperatures are known as pyrometers.

It has been found that a gas will not occupy any volume at a certain temperature. This temperature is known as absolute zero temperature. The temperatures measured with absolute zero as basis are called absolute temperatures. Absolute temperature is stated in degrees centigrade. The point of absolute temperature is found to occur at 273.15°C below the freezing point of water.

Then: Absolute temperature = Thermometer reading in °C + 273.15.

Absolute temperature is degree centigrade is known as degrees kelvin, denoted by K (SI unit).

The relation between a particular value C on celsius scale and F on Fahrenheit scale is found to be as mentioned below:

Volume

The specific volume of a system is the volume occupied by the unit mass of the system. The symbol used is v and units are; for example, m3/kg. The symbol V will be used for volume. (Note that specific volume is reciprocal of density).

Internal Energy

It is the heat energy stored in a gas. If a certain amount of heat is supplied to a gas the result is that temperature of gas may increase or volume of gas may increase thereby doing some external work or both temperature and volume may increase ; but it will be decided by the conditions under which the gas is supplied heat. If during heating of the gas the temperature increases its internal energy will also increase.

Enthalpy

One of the fundamental quantities which occur invariably in thermodynamics is the sum of internal energy (u) and pressure volume product (pv). This sum is called enthalpy (h).

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 small when heat is added at a high temperature and is greater when heat addition is made at a lower temperature. Thus for maximum entropy, there is minimum availability for conversion into work and for minimum entropy there is maximum availability for conversion into work.

Intensive and extensive properties

A property of a system is a characteristic of the system which depends upon its state, but not upon how the state is reached. There are two sorts of property:

1. Intensive properties. These properties do not depend on the mass of the system.

Examples: Temperature and pressure.

2. Extensive properties. These properties depend on the mass of the system.

Example: Volume. Extensive properties are often divided by mass associated with them to obtain the intensive properties. For example, if the volume of a system of mass m is V, then the specific volume of matter within the system is V/m = v which is an intensive property.

Define thermodynamic processes

A process occurs when the system undergoes a change in a state or an energy transfer at a steady state. A process may be *non-flow* in which a fixed mass within the defined boundary is undergoing a change of state.

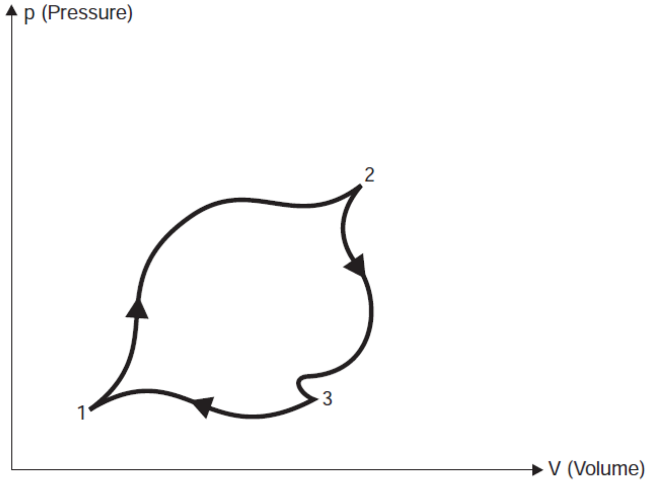
Example: A substance which is being heated in a closed cylinder undergoes a *non-flow process Closed systems undergo non-flow processes*. A process may be a *flow process in which mass is entering and leaving through the boundary of an open system*. In a steady flow process (Fig. 2.5) mass is crossing the boundary from surroundings at entry, and an equal mass is crossing the boundary at the exit so that the total mass of the system remains constant. In an open system it is necessary to take account of the work delivered from the surroundings to the system at entry to cause the mass to enter, and also of the work delivered from the system at surroundings to cause the mass to leave, as well as any heat or work crossing the boundary of the system.

Define path

When a thermodynamic system passes through a change in state, succession of states passed will be termed as path of the system or path of change of state. If path of change of state is completely specified, path of change of state will be termed as thermodynamic process.

Define cycle

Any process or series of processes whose end states are identical is termed a cycle. The processes through which the system has passed can be shown on a state diagram, but a complete section of the path requires in addition a statement of the heat and work crossing the boundary of the system. Fig. 2.6 shows such a cycle in which a system commencing at condition '1' changes in pressure and volume through a path 123 and returns to its initial condition '1'.



Define state

State is the condition of the system at an instant of time as described or measured by its properties. Or each unique condition of a system is called a state.

It follows from the definition of state that each property has a single value at each state. Stated differently, all properties are *state* or *point functions*. Therefore, all properties are identical for identical states. On the basis of the above discussion, we can determine if a given variable is *property* or not by applying the following *tests:*

A variable is a property, if and only if, it has a single value at each equilibrium state.

A variable is a property, if and only if, the change in its value between any two prescribed equilibrium states is single-valued. Therefore, *any variable whose change is fixed by the end states is a property*.

Define path function

There are certain quantities which cannot be located on a graph by a *point* but are given by the *area* or so, on that graph. In that case, the area on the graph, pertaining to the particular process, *is a function of the path of the process.* Such quantities are called path functions.

Examples: Heat, work etc.

Heat and work are *inexact differentials*. Their change cannot be written as difference between their end states.

Thus $\int_1^2 \delta Q \neq Q_2 - Q_1$ and is shown as ${}_1Q_2$ or Q_{1-2}

Similarly $\int_1^2 \delta W \neq W_2 - W_1$, and is shown as ${}_1W_2$ or W_{1-2}

Note. The operator δ is used to denote inexact differentials and operator *d* is used to denote exact differentials.

Define point function

When two properties locate a point on the graph (co-ordinate axes) then those properties are called as point function.

Examples: Pressure, temperature, volume etc.

$$\int_1^2 dV = V_2 - V_1 \text{ (an } \textit{exact differential}\text{).}$$

Thermodynamic Equilibrium

A system is in *thermodynamic equilibrium* if the temperature and pressure at all points are same ; there should be no velocity gradient ; the chemical equilibrium is also necessary. Systems under temperature and pressure equilibrium but not under chemical equilibrium are sometimes said to be in metastable equilibrium conditions. *It is only under thermodynamic equilibrium conditions that the properties of a system can be fixed*. Thus for attaining a state of *thermodynamic equilibrium* the following *three* types of equilibrium states must be achieved:

1. Thermal equilibrium. The temperature of the system does not change with time and has same value at all points of the system.
2. Mechanical equilibrium. There are no unbalanced forces within the system or between the surroundings. The pressure in the system is same at all points and does not change with respect to time.
3. Chemical equilibrium. No chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.

Quasi-static Process

Quasi means '*almost*'. A quasi-static process is also called a *reversible process. This process is a succession of equilibrium states and infinite slowness is its characteristic feature.*

Conceptual explanation of energy and its sources

Energy is a general term embracing *energy in transition* and *stored energy*. The stored energy of a substance may be in the forms of *mechanical energy* and *internal energy* (other forms of stored energy may be chemical energy and electrical energy). Part of the stored energy may take the form of either potential energy (which is the gravitational energy due to height above a chosen datum line) or kinetic energy due to velocity. The balance part of the energy is known as *internal energy*. In a *non-flow process usually there is no change of potential or kinetic energy and hence change of mechanical energy will not enter the calculations*. In a *flow process*, however, *there may be changes in both potential and kinetic energy and these must be taken into account while considering the changes of stored energy.*

Heat and work are *the forms of energy in transition*. These are the only forms in which energy can cross the boundaries of a system. *Neither heat nor work can exist as stored energy.*

Work

Work is said to be done when a *force moves through a distance*. If a part of the boundary of a system undergoes a displacement under the action of a pressure, the work done W is the product of the force (pressure × area), and the distance it moves in the direction of the force.

A force is exerted by the paddle as it changes the momentum of the fluid, and since this force moves during rotation of the paddle work is done. *Work is a transient quantity which only appears at the boundary while a change of state is taking place within a system. Work is 'something' which appears at the boundary when a system changes its state due to the movement of a part of the boundary under the action of a force*.

Sign convention :

If the work is done *by* the system *on* the surroundings, *e.g.*, when a fluid expands pushing a piston outwards, the work is said to be *positive*. *i.e., Work output of the system* = + W

If the work is done *on* the system *by* the surroundings, *e.g.*, when a force is applied to a rotating handle, or to a piston to compress a fluid, the work is said to be *negative*. *i.e., Work input to system* = – W

Heat

Heat (denoted by the symbol Q), may be, defined in an analogous way to work as follows : "*Heat is 'something' which appears at the boundary when a system changes its state due to a difference in temperature between the system and its surroundings*".

Heat, like work, is a transient quantity which only appears at the boundary while a change is taking place within the system.

It is apparent that neither δW or δQ are exact differentials and therefore any integration of the elemental quantities of work or heat which appear during a change from state 1 to state 2 must be written as

Sign convention :

If the heat flows *into* a system *from* the surroundings, the quantity is said to be *positive* and, conversely, if heat flows *from* the system to the surroundings it is said to be *negative*.

In other words :

Heat received by the system = + Q

Heat rejected or given up by the system = – Q.

Comparison between the work and heat

Similarities :

(*i*) Both are *path functions and inexact differentials*.

(*ii*) Both are boundary phenomenon *i.e.*, both are recognized at the boundaries of the system as they cross them.

(*iii*) Both are associated with a process, not a state. Unlike properties, work or heat has no meaning at a state.

(*iv*) Systems possess energy, but not work or heat.

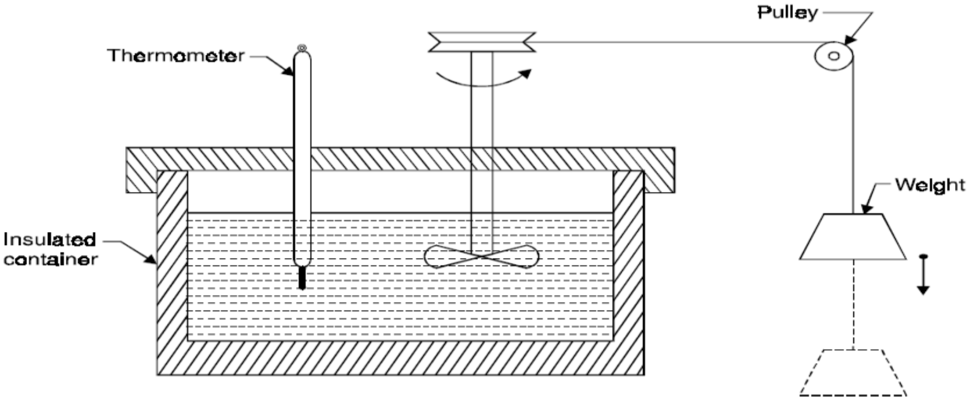
Dissimilarities :

(*i*) In heat transfer temperature difference is required.

(*ii*) In a stable system there cannot be work transfer, however, there is no restriction for the transfer of heat.

(*iii*) The sole effect external to the system could be reduced to rise of a weight but in the case of a heat transfer other effects are also observed.

Mechanical Equivalent of Heat



$$\oint dW = J \oint dQ$$

Where J is the proportionality constant and is known as *Mechanical Equivalent of heat*. In S.I. units its value is unity, *i.e.*, 1 Nm/J.

Work transfer, Displacement work

Let us consider an ideal frictionless fluid contained in a cylinder above a piston as shown in Fig. 2.32. *Assume that the pressure and temperature of the fluid are uniform and that there is no friction between the piston and the cylinder walls*.

Let A = Cross-sectional area of the piston,

p = Pressure of the fluid at any instant,

$(p - dp)\,A$ = Restraining *force exerted* by the surroundings on the piston, and

dl = The distance moved by the piston under the action of the *force exerted*.

Then work done by the fluid on the piston is given by force times the distance moved,
i.e., Work done by the fluid
$= (pA) \times dl = pdV$ (where dV = a small increase in volume)
Or considering unit mass
Work done = pdv (where v = specific volume)
This is only *true* when (*a*) the *process is frictionless and (b) the difference in pressure between the fluid and its surroundings during the process is infinitely small*. Hence when a reversible process takes place between state 1 and state 2, we have
Work done by the unit mass of fluid $=\int pdv$
When a fluid undergoes a reversible process a series of state points can be joined up to form a line on a diagram of properties. The work done by the fluid during any reversible process is therefore given by the area under the line of process plotted on a p-v diagram (Fig. 2.32).
i.e., Work done = Shaded area on Fig. 2.33
$= \int pdv$
When p can be expressed in terms of v then the integral, $\int pdv$ can be evaluated.
Example. *Gas from a cylinder of compressed helium is used to inflate an inelastic flexible balloon, originally folded completely flat, to a volume 0.6 m3. If the barometer reads 760 mm Hg, what is*

the amount of work done upon the atmosphere by the balloon? Sketch the system before and after the process.

Solution.

Refer Fig. 2.34. The firm line *B*1 shows the boundary of the system before the process, and dotted line *B*2 shows the boundary after the process.

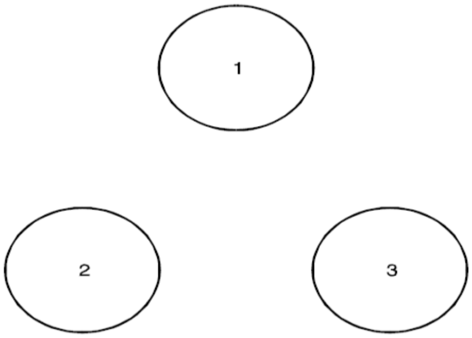
The displacement work, $W_d = (\int pdV)_{cylinder} + (\int pdV)_{balloon} = 0 + (\int pdV)_{balloon}$

$= 101.325 \times 0.6$ [$dV = 0.6$ m3]

$= 60.795$ kJ. (Ans.)

State & explain Zeroth law of thermodynamics

Zeroth law of thermodynamics' *states that if two systems are each equal in temperature to a third, they are equal in temperature to each other*.



Zeroth law of thermodynamics.

System '1' may consist of a mass of gas enclosed in a rigid vessel fitted with a pressure gauge. If there is no change of pressure when this system is brought into contact with system '2' a block of iron, then the two systems are equal in temperature (assuming that the systems 1 and 2 do not react each other chemically or electrically). Experiment reveals that if system '1' is brought into contact with a third system '3' again with no change of properties then systems '2' and '3' will show no change in their properties when brought into contact provided they do not react with each other chemically or electrically. Therefore, '2' and '3' must be in equilibrium.

This law was enunciated by R.H. Fowler in the year 1931. However, since the first and second laws already existed at that time, it was designated as ***zeroth law*** so that it *precedes* the first and second laws *to form a logical sequence*.

Law of conservation of energy

In the early part of nineteenth century the scientists developed the concept of energy and hypothesis that it can be neither created nor destroyed ; this came to be known as the *law of the conservation of energy*. The first law of thermodynamics is merely one statement of this general law/principle with particular reference to heat energy and mechanical energy *i.e.,* work.

State & explain First law of thermodynamics.

It is observed that when a system is made to undergo a complete cycle then net work is done *on* or *by* the system. Consider a cycle in which net work is done by the system. Since energy cannot be created, this mechanical energy must have been supplied from some source of energy. Now the system has been returned to its initial state. Therefore, its *intrinsic* energy is unchanged, and hence the mechanical energy has not been provided by the system itself. The only other energy involved in the cycle is the heat which was supplied and rejected in various processes. Hence, by the law of conservation of energy, the net work done by the system is equal to the net heat supplied to the system.

The First Law of Thermodynamics can, therefore, be stated as follows:

"When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings.

or
$$\oint dQ = \oint dW$$

where $\oint$ represents the sum for a complete cycle.

The first law of Thermodynamics *cannot be proved analytically, but experimental evidence has repeatedly confirmed its validity*, and since no phenomenon has been shown to contradict it, the first law is accepted as a *law of nature.* It may be remarked that no restriction was imposed which limited the application of first law to reversible energy transformation. Hence the first law applies to reversible as well as irreversible transformations: For non-cyclic process, a more general formulation of first law of thermodynamics is required. A new concept which involves a term called *internal energy* fulfills this need.

The First Law of Thermodynamics may also be stated as follows:

"Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant".

Limitations of First law of thermodynamics

It has been observed that *energy can flow* from a system in the form of *heat* or *work*. The first law of thermodynamics sets no limit to the amount of the total energy of a system which can be caused to flow out as work. A limit is imposed, however, as a result of the principle enunciated in the second law of thermodynamics which states that heat will flow naturally from one energy reservoir to another at a lower temperature, but not in opposite direction without assistance. This is very important because a heat engine operates between two energy reservoirs at different temperatures. Further the first law of thermodynamics *establishes equivalence between the quantity of heat used and the 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*. This gap has been *bridged* by the second law of thermodynamics.

Application of First law of Thermodynamics

Steady Flow Energy Equation (S.F.E.E.)

In many practical problems, the rate at which the fluid flows through a machine or piece of apparatus is constant. This type of flow is called *steady flow.*

Assumptions :

The following *assumptions* are made in the system analysis :

(*i*) The mass flow through the system remains constant.

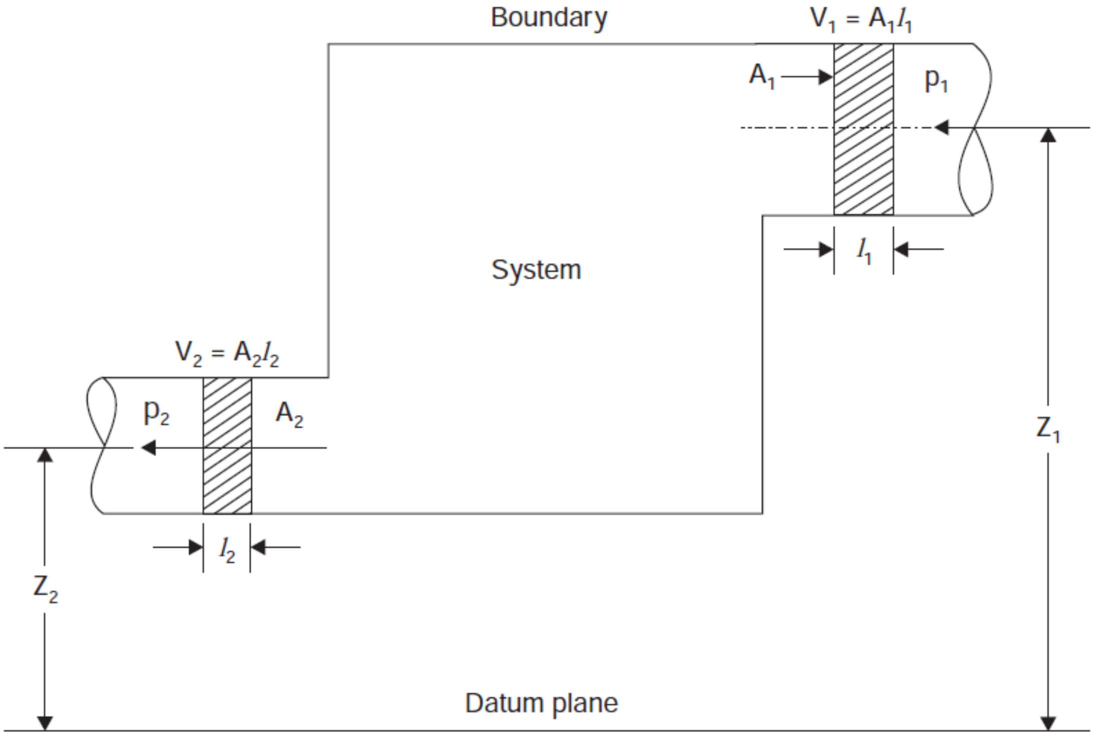
(*ii*) Fluid is uniform in composition.

(*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 flow energies are considered.

shows a schematic flow process for an open system. An open system is one in which both mass and energy may cross the boundaries. A wide interchange of energy may take place within an open system. Let the system be an automatic engine with the inlet manifold at the first state point and exhaust pipe as the second point. There would be an interchange of chemical energy in the fuel, kinetic energy of moving particles, internal energy of gas and heat transferred and shaft work within the system. From Fig. 4.30 it is obvious that if there is no variation of flow of mass or energy with time across the boundaries of the system the steady flow will prevail. The conditions may pass through the cyclic or non-cyclic changes within the system. As a result the mass entering the system equals the mass leaving, also energy entering the system equals energy leaving.



The steady flow equation can be expressed as follows :

$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W$$

$$(u_1 + p_1 v_1) + \frac{C_1^2}{2} + Z_1 g + Q = (u_2 + p_2 v_2) + \frac{C_2^2}{2} + Z_2 g + W$$

$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W$$

If Z_1 and Z_2 are neglected, we get

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W$$

where, Q = Heat supplied (or entering the boundary) per kg of fluid,

W = Work done by (or work coming out of the boundary) 1 kg of fluid,

C = Velocity of fluid ,

Z = Height above datum,

p = Pressure of the fluid,

u = Internal energy per kg of fluid, and

pv = Energy required for 1 kg of fluid.

This equation is applicable to any medium in any steady flow. It is applicable not only to rotary machines such as centrifugal fans, pumps and compressors but also to reciprocating machines such as steam engines.

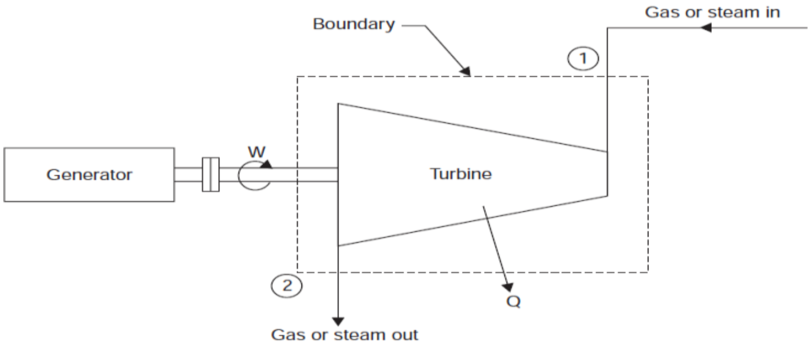
In a steady flow the rate of mass flow of fluid at any section is the same as at any other section. Consider any section of cross-sectional area *A*, where the fluid velocity is *C*, the rate of volume flow past the section is *CA*.

Continuity of mass equation

$$\dot{m} = \frac{C_1A_1}{v_1} = \frac{C_2A_2}{v_2}$$

Steady flow energy equation and its application to turbine
Steam or Gas Turbine

In a steam or gas turbine steam or gas is passed through the turbine and part of its energy is converted into work in the turbine. This output of the turbine runs a generator to produce electricity. The steam or gas leaves the turbine at lower pressure or temperature.



Applying energy equation to the system. Here, $Z1 = Z2$ (*i.e.*, $\Delta Z = 0$)

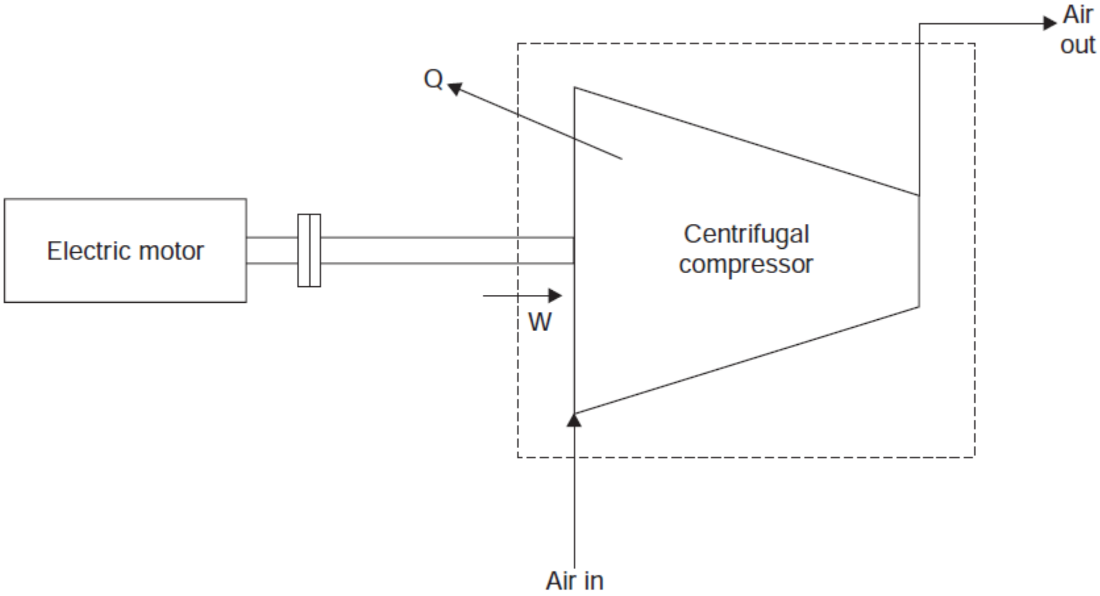
$$h_1 + \frac{C_1^{\ 2}}{2} - Q = h_2 + \frac{C_2^{\ 2}}{2} + W$$

The sign of *Q* is *negative* because heat is *rejected* (or comes out of the boundary). The sign of *W* is *positive* because work is done by the system (or work comes out of the boundary).

Steady flow energy equation and its application to compressor

Centrifugal Compressor

A centrifugal compressor compresses air and supplies the same at moderate pressure and in large quantity.



Applying energy equation to the system
ΔZ = 0 (generally taken)

$$\left(h_1 + \frac{C_1{}^2}{2}\right) - Q = \left(h_2 + \frac{C_1{}^2}{2}\right) - W$$

The Q is taken as *negative* as heat is *lost* from the system and W is taken as *negative* as work is *supplied* to the system.

Example. *In a gas turbine unit, the gases flow through the turbine is 15 kg/s and the power developed by the turbine is 12000 kW. The enthalpies of gases at the inlet and outlet are 1260 kJ/kg and 400 kJ/kg respectively, and the velocity of gases at the inlet and outlet are 50 m/s and 110 m/s respectively. Calculate:*

(*i*) *The rate at which heat is rejected to the turbine, and*

(*ii*) *The area of the inlet pipe given that the specific volume of the gases at the inlet is 0.45 m3/kg.*

Solution. Rate of flow of gases, $\dot{m} = 15$ kg/s

Volume of gases at the inlet, $v = 0.45$ m^3/kg

Power developed by the turbine, $P = 12000$ kW

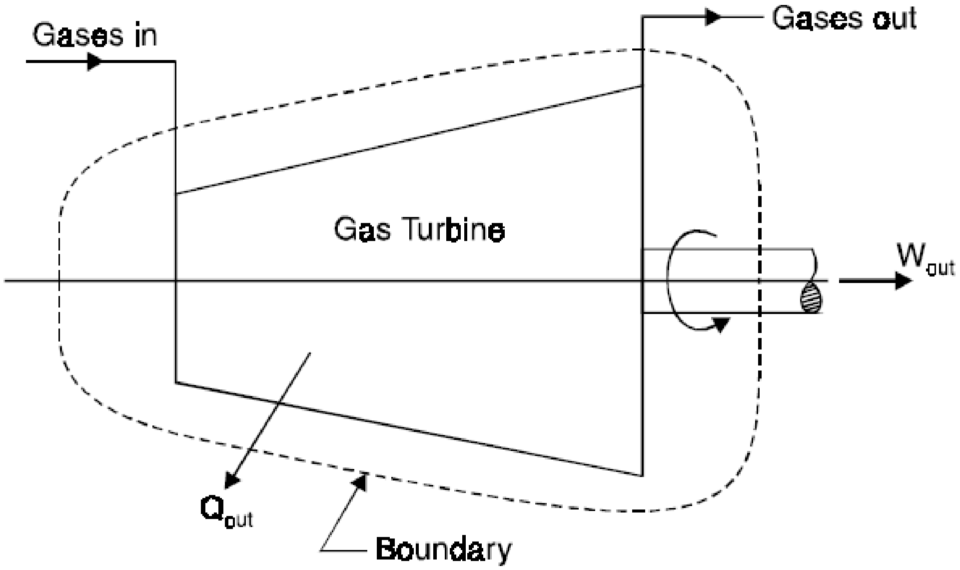
$\therefore$ Work done, $W = \dfrac{12000}{15} = 800$ kJ/kg

Enthalpy of gases at the inlet, $h_1 = 1260$ kJ/kg

Enthalpy of gases at the oulet, $h_2 = 400$ kJ/kg

Velocity of gases at the inlet, $C_1 = 50$ m/s

Velocity of gases at the outlet, $C_2 = 110$ m/s.



(*i*) **Heat rejected, Q :**

Using the flow equation,

$$h_1 + \frac{C_1^{\ 2}}{2} + Q = h_2 + \frac{C_2^{\ 2}}{2} + W \qquad \ldots(i) \ [\because \quad Z_1 = Z_2]$$

$$\text{Kinetic energy at inlet} = \frac{C_1^{\ 2}}{2} = \frac{50^2}{2} \ \text{m}^2/\text{s}^2 = \frac{50^2 \ \text{kg m}^3}{2 \ \text{s}^2\text{kg}} = 1250 \ \text{Nm/kg} = 1.25 \ \text{kJ/kg}$$

$$\text{Kinetic energy at outlet} = \frac{C_1^{\ 2}}{2} = \frac{110^2}{2 \times 1000} = 6.05 \ \text{kJ/kg}$$

Substituting these values in eqn. (*i*), we get

$$1260 + 1.25 + Q = 400 + 6.05 + 800$$

$$\therefore \qquad Q = -\ 55.2 \ \text{kJ/kg}$$

i.e., **Heat rejected** $= +\ 55.2$ kJ/kg $= 55.2 \times 15$ kJ/s = **828 kW. (Ans.)**

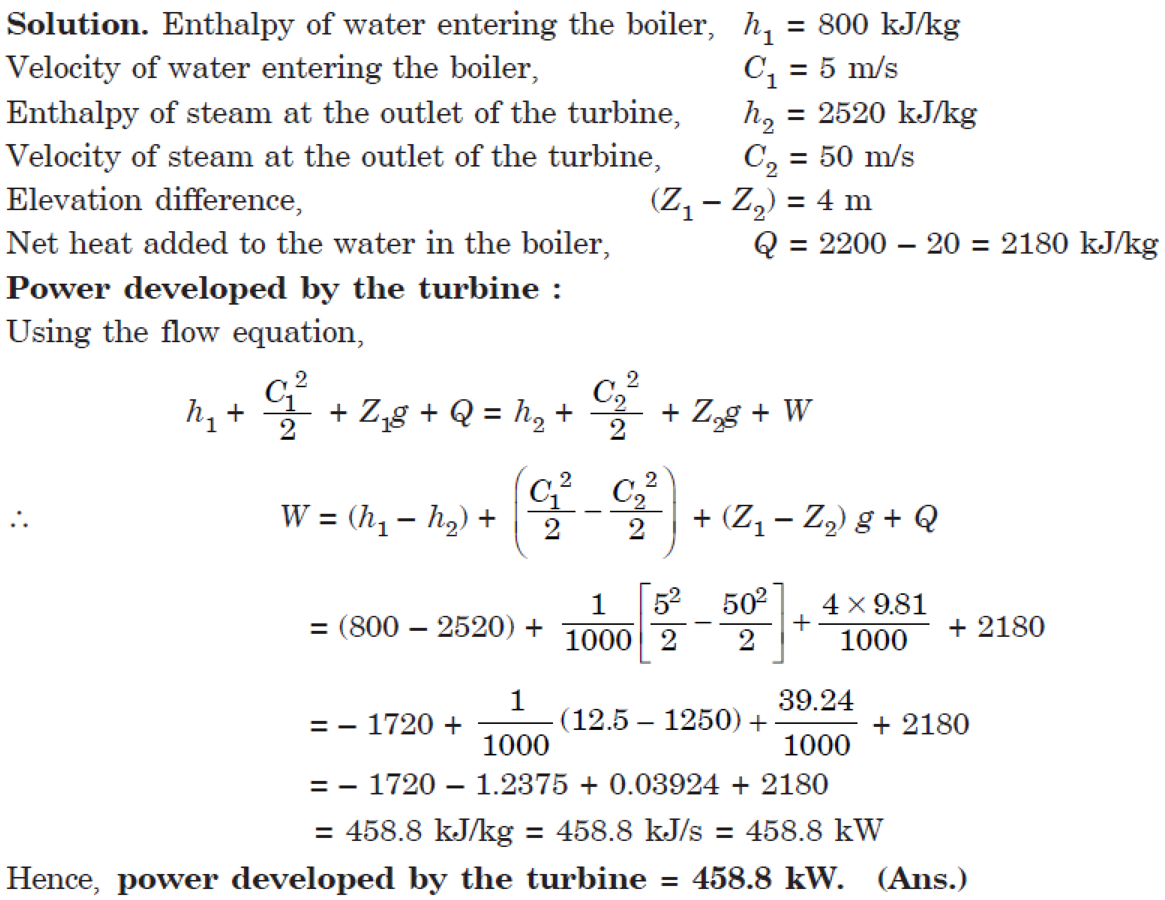
(*ii*) **Inlet area, A :**

Using the relation,

$$\dot{m} = \frac{CA}{v}$$

$$\therefore \qquad A = \frac{v\dot{m}}{C} = \frac{0.45 \times 15}{50} = \mathbf{0.135 \ m^2}. \quad \textbf{(Ans.)}$$

Example. *In a steam plant, 1 kg of water per second is supplied to the boiler. The enthalpy and velocity of water entering the boiler are 800 kJ/kg and 5 m/s. The water receives 2200 kJ/kg of heat in the boiler at constant pressure. The steam after passing through the turbine comes out with a velocity of 50 m/s, and its enthalpy is 2520 kJ/kg. The inlet is 4 m above the turbine exit. Assuming the heat losses from the boiler and the turbine to the surroundings are 20 kJ/s, calculate the power developed by the turbine. Consider the boiler and turbine as single system.*



Solution. Enthalpy of water entering the boiler, $h_1 = 800$ kJ/kg

Velocity of water entering the boiler, $C_1 = 5$ m/s

Enthalpy of steam at the outlet of the turbine, $h_2 = 2520$ kJ/kg

Velocity of steam at the outlet of the turbine, $C_2 = 50$ m/s

Elevation difference, $(Z_1 - Z_2) = 4$ m

Net heat added to the water in the boiler, $Q = 2200 - 20 = 2180$ kJ/kg

Power developed by the turbine :

Using the flow equation,

$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W$$

$$\therefore \quad W = (h_1 - h_2) + \left(\frac{C_1^2}{2} - \frac{C_2^2}{2}\right) + (Z_1 - Z_2)\, g + Q$$

$$= (800 - 2520) + \frac{1}{1000}\left[\frac{5^2}{2} - \frac{50^2}{2}\right] + \frac{4 \times 9.81}{1000} + 2180$$

$$= -1720 + \frac{1}{1000}(12.5 - 1250) + \frac{39.24}{1000} + 2180$$

$$= -1720 - 1.2375 + 0.03924 + 2180$$

$$= 458.8 \text{ kJ/kg} = 458.8 \text{ kJ/s} = 458.8 \text{ kW}$$

Hence, **power developed by the turbine = 458.8 kW. (Ans.)**

Second law of thermodynamics

The second law of thermodynamics has been enunciated meticulously by Clausius, Kelvin and Planck in slightly different words although both statements are basically identical. Each statement is based on an *irreversible process*. The *first considers transformation of heat between two thermal reservoirs* while the *second considers the transformation of heat into work*.

Clausius Statement

"*It is impossible for a self acting machine working in a cyclic process unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature*". In other words, heat of, itself, cannot flow from a colder to a hotter body.

Kelvin-Planck Statement

"*It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work*". Although the Clausius and Kelvin-Planck statements appear to be different, they are really equivalent in the sense that a *violation of either statement implies violation of other*.

Application of second law in heat engine, heat pump, refrigerator & determination of efficiencies & C.O.P

A *heat engine* is used to produce the maximum work transfer from a given positive heat transfer. The measure of success is called the *thermal efficiency* of the engine,

$$\text{Thermal efficiency, } \eta_{th} = \frac{W}{Q_1}$$

$$\eta_{rev.} = \eta_{max} = 1 - \left(\frac{Q_2}{Q_1}\right)_{rev.} = 1 - \frac{T_2}{T_1}$$

$$\eta_{rev.} = \frac{T_1 - T_2}{T_1}$$

where, *W* = Net work transfer from the engine, and *Q*1 = Heat transfer to engine.
For a *reversed heat engine* acting as a *refrigerator* when the purpose is to achieve the maximum heat transfer from the cold reservoir, the measure of success is called the *co-efficient of performance* (C.O.P.). It is defined by the ratio:

$$\text{Co-efficient of performance, } (\text{C.O.P.})_{ref.} = \frac{Q_2}{W}$$

$$[(\text{C.O.P.})_{ref.}]_{rev.} = \frac{T_2}{T_1 - T_2}$$

where, *Q*2 = Heat transfer *from cold reservoir*, and *W* = The net work transfer to the refrigerator.

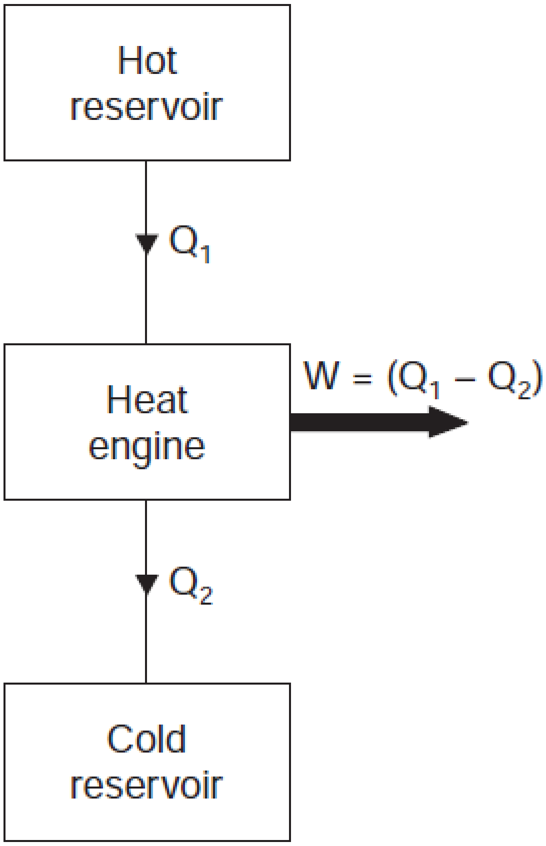
For a **reversed heat engine** acting as a *heat pump*, the measure of success is again called the *co-efficient of performance*. It is defined by the ratio:

$$\text{Co-efficient of performance, } (\text{C.O.P.})_{heat\ pump} = \frac{Q_1}{W}$$

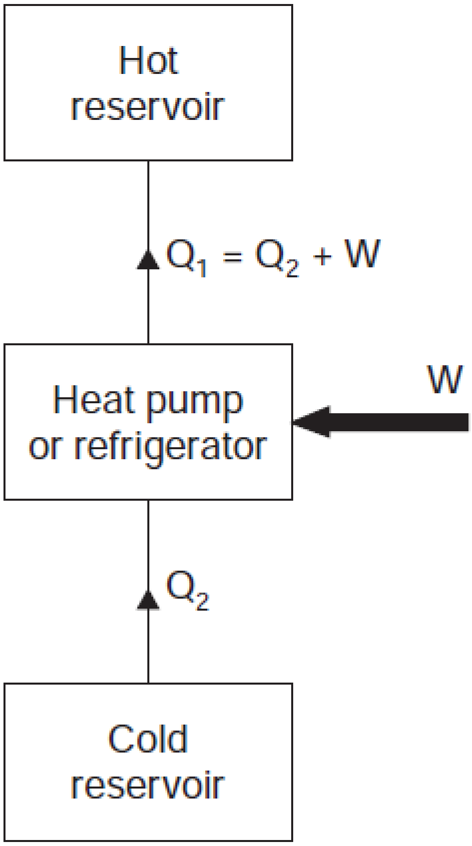
$$[(\text{C.O.P.})_{heat\ pump}]_{rev.} = \frac{T_1}{T_1 - T_2}$$

where, *Q*1 = Heat transfer *to hot reservoir*, and

W = Net work transfer to the heat pump. source at temperature *T*1 and the given sink at temperature *T*2.



(a)
Heat engine



(b)
Heat pump or refrigerator

In all the above three cases application of the first law gives the relation $Q1 - Q2 = W$, and this can be used to rewrite the expressions for thermal efficiency and co-efficient of performance solely in terms of the heat transfers.

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1}$$

$$(C.O.P.)_{ref} = \frac{Q_2}{Q_1 - Q_2}$$

$$(C.O.P.)_{heat\ pump} = \frac{Q_1}{Q_1 - Q_2}$$

It may be seen that efficiency is *always less than unity* and (*C.O.P.*) *heat pump* is *always greater than unity*.

Example. *A heat engine receives heat at the rate of 1500 kJ/min and gives an output of 8.2 kW. Determine :* (*i*) *The thermal efficiency ; (ii*) *The rate of heat rejection.*

Solution. Heat received by the heat engine,

$$Q_1 = 1500 \text{ kJ/min}$$

$$= \frac{1500}{60} = 25 \text{ kJ/s}$$

Work output, $W = 8.2 \text{ kW} = 8.2 \text{ kJ/s}$.

(*i*) Thermal efficiency, $\eta_{th} = \frac{W}{Q_1}$

$$= \frac{8.2}{25} = 0.328 = 32.8\%$$

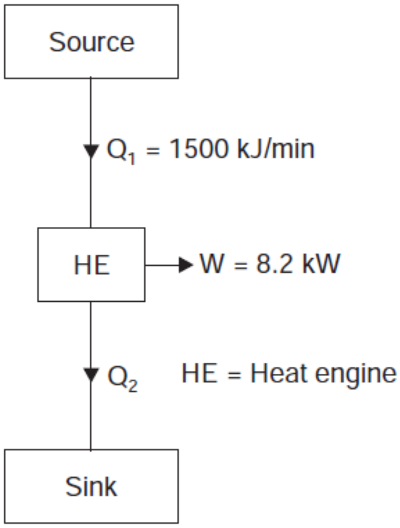
Hence, **thermal efficiency = 32.8%. (Ans.)**

(*ii*) Rate of heat rejection,

$$Q_2 = Q_1 - W = 25 - 8.2$$

$$= 16.8 \text{ kJ/s}$$

Hence, **the rate of heat rejection = 16.8 kJ/s.**



Example. *Find the co-efficient of performance and heat transfer rate in the condenser of a refrigerator in kJ/h which has a refrigeration capacity of 12000 kJ/h when power input is 0.75 kW.*

Solution. Refer Fig. 5.11.

Refrigeration capacity, $Q_2 = 12000 \text{ kJ/h}$

Power input, $W = 0.75 \text{ kW} (= 0.75 \times 60 \times 60 \text{ kJ/h})$

Co-efficient of performance, C.O.P. :

Heat transfer rate :

$$(\text{C.O.P.})_{refrigerator} = \frac{\text{Heat absorbed at lower temperature}}{\text{Work input}}$$

$$\therefore \qquad \text{C.O.P.} = \frac{Q_2}{W} = \frac{12000}{0.75 \times 60 \times 60} = 4.44$$

Hence **C.O.P. = 4.44. (Ans.)**

Hence transfer rate in condenser = Q_1

According to the first law

$$Q_1 = Q_2 + W = 12000 + 0.75 \times 60 \times 60 = 14700 \text{ kJ/h}$$

Hence, **heat transfer rate = 14700 kJ/h. (Ans.)**

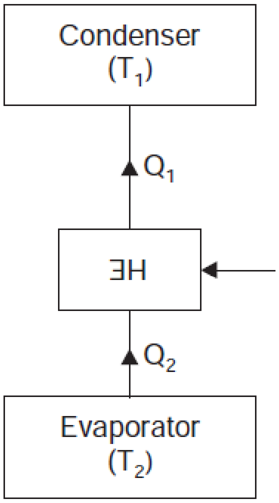


Fig. 5.11

Properties Processes of perfect gas

Laws of perfect gas:

Boyle's law.

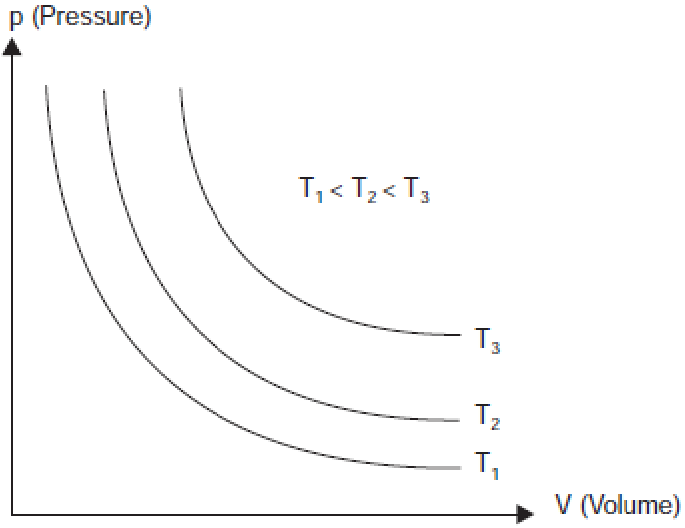
It states that *volume of a given mass of a perfect gas varies inversely as the absolute pressure when temperature is constant*.

If *p* is the absolute pressure of the gas and *V* is the volume occupied by the gas, then

$$V \propto \frac{1}{p}$$

pV = Constant, so long as the temperature is constant the graphical representation of Boyle's law. The curves are rectangular hyperbolas asymptotic to the *p*-*v* axis. Each curve corresponds to a different temperature. For any two points on the curve,

$$\frac{p_1}{p_2} = \frac{V_2}{V_1}$$



Charle's law.

It states that *if any gas is heated at constant pressure, its volume changes directly as its absolute temperature*.

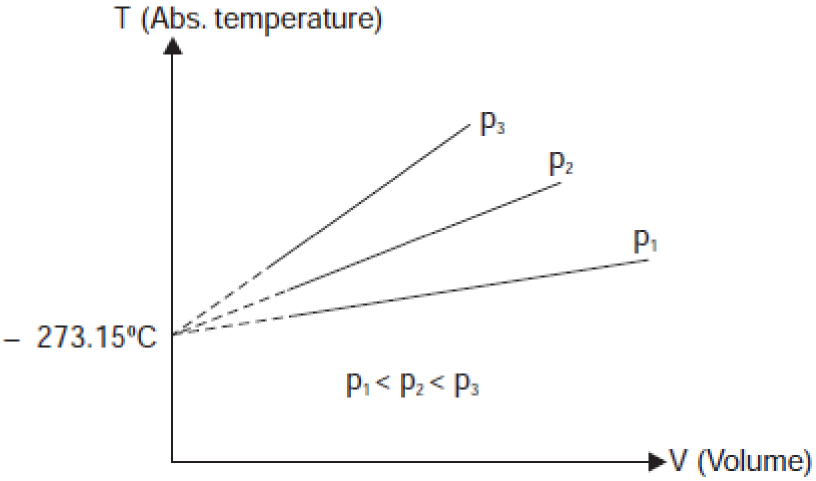
In other words,

$$V \propto T$$

$$\frac{V}{T} = \text{Constant, so long as pressure is constant}$$

If a gas changes its volume from *V*1 to *V*2 and absolute temperature from *T*1 to *T*2 without any change of pressure, then

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



Dalton's law

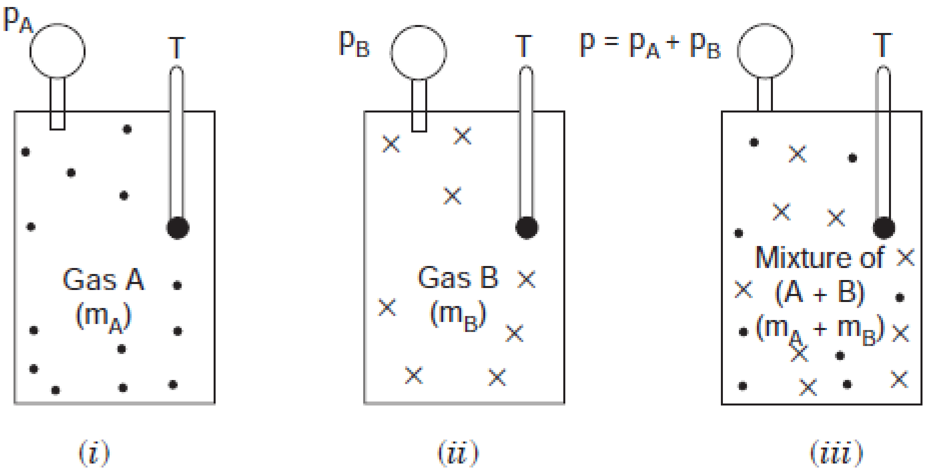
Let us consider a closed vessel of volume *V* at temperature *T*, which contains a mixture of perfect gases at a known pressure. If some of the mixture were removed, then the pressure would be *less* than the initial value. If the gas removed were the full amount of one of the constituents then the reduction in pressure would be equal to the contribution of that constituent to the initial total pressure. Each constituent contributes to the total pressure by an amount which is known as the *partial pressure* of the constituent.

The *relationship between the partial pressures of the constituents* is expressed by Dalton's law, as follows :

The pressure of a mixture of gases is equal to the sum of the partial pressures of the constituents.

The partial pressure of each constituent is that pressure which the gas would exert if it occupied alone that volume occupied by the mixtures at the same temperature.

This is expressed diagrammatically in Fig. 9.1. The gases *A* and *B*, originally occupying volume *V* at temperature *T* are mixed in the third vessel which is of the *same volume* and is *at the same Temperature*



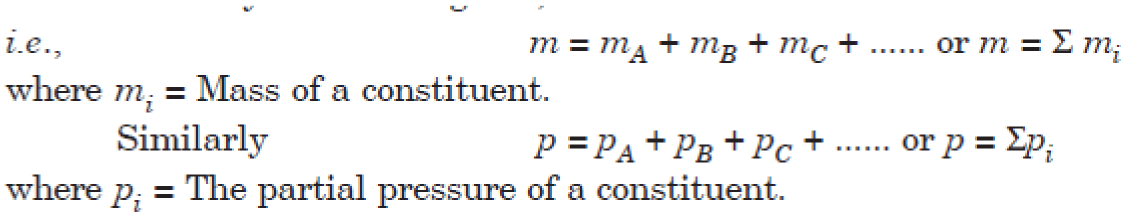
By the *consideration of mass, m = mA + mB*

By *Dalton's law, p = pA + pB*

Dalton's law is based on experiment and is found to be obeyed more accurately by gas mixtures at low pressures. As shown in Fig. 9.1 each occupant occupies the whole vessel. The example given in Fig. and relationship in eqns. refer to a mixture of two gases, but the law can be extended to any number of gases,

i.e., $m = mA + mB + mC + ...$ or $m = mi$ where mi = Mass of a constituent.

Similarly $p = pA + pB + pC + ...$ or $p = pi$ where pi = The partial pressure of a constituent.



i.e., $m = m_A + m_B + m_C + ...$ or $m = \Sigma m_i$

where m_i = Mass of a constituent.

Similarly $p = p_A + p_B + p_C + ...$ or $p = \Sigma p_i$

where p_i = The partial pressure of a constituent.

Avogadro's law, the *number of moles of any gas is proportional to the volume of the gas at a given pressure and temperature.* Referring to Fig. 9.2 (*a*), the volume V contains n moles of the mixture at p and T. In Fig. 9.2 (*b*), the gas A occupies a volume VA at p and T, and this volume contains nA moles. Similarly there are nB moles of gas B in volume VB and nC moles of gas C in volume VC. From eqn. (9.9), $\Sigma Vi = V$ or $VA + VB + VC = V$
The *total number of moles in the vessel must equal the sum of the moles of the individual constituents*,

$n = nA + nB + nC = \Sigma$□$ni$

Gay-Lussac's Law states that the pressure of a given mass of gas varies directly with the absolute temperature of the gas, when the volume is kept constant.

$$\frac{P}{T} = C \quad OR \quad \frac{P1}{T1} = \frac{P2}{T2}$$

The Characteristic Equation of State

At temperatures that are considerably in excess of critical temperature of a fluid, and also at very low pressure, the vapour of fluid tends to obey the equation $pv\, T$ = constant = R

In practice, no gas obeys this law rigidly, but many gases tend towards it.

An imaginary ideal gas which obeys this law is called a *perfect gas*, and the equation $pvT = R$, is called the *characteristic equation of a state of a perfect gas.* The constant R is called the *gas constant*. Each perfect gas has a different gas constant.

Units of R are Nm/kg K or kJ/kg K.

Usually, the characteristic equation is written as $pv = RT$ or for m kg, occupying V m3 $pV = mRT$

The characteristic equation in *another form*, can be derived by using kilogram-mole as a unit.

The *kilogram-mole* is defined as a quantity of a gas equivalent to M kg of the gas, where M is the molecular weight of the gas (*e.g.*, since the molecular weight of oxygen is 32, then 1 kg mole of oxygen is equivalent to 32 kg of oxygen).

As per definition of the kilogram-mole, for m kg of a gas, we have $m = nM$ where n = number of moles. Substituting for m $pV = nMRT$

universal gas constant is given the symbol, $R0$.

$MR = R0$, It has been found experimentally that the volume of 1 mole of any perfect gas at 1 bar is approximately 22.71 m3.

$$R_0 = \frac{pV}{nT} = \frac{1 \times 10^5 \times 22.71}{1 \times 273.15}$$
$$= 8314.3 \text{ Nm/mole K}$$

Specific Heats

The **specific heat** of a solid or liquid is usually defined as the *heat required to raise unit mass through one degree temperature rise.* For small quantities,

we have $dQ = mcdT$

where m = mass,

c = specific heat, and

dT = temperature rise.

For a gas there are an infinite number of ways in which heat may be added between any two temperatures, and hence a *gas could have an infinite number of specific heats*. However, only two specific heats for gases are defined.

Specific heat at constant volume, cv and, *Specific heat at constant pressure, cp*.

We have

$dQ = m\ cp\ dT$ For a reversible non-flow process at *constant pressure* and, $dQ = m\ cv\ dT$ For a reversible non-flow process at *constant volume*

Flow of heat in a reversible constant pressure process= $mcp\ (T2 - T1)$

Flow of heat in a reversible constant volume process= $mcv\ (T2 - T1)$

Relationship Between Two Specific Heats

Consider a perfect gas being heated at constant pressure from $T1$ to $T2$.

According to non-flow equation,

$Q = (U2 - U1) + W$

Also for a perfect gas,

$U2 - U1 = mcv\ (T2 - T1)$

$Q = mcv\ (T2 - T1) + W$

In a constant pressure process, the work done by the fluid, $W = p(V2 - V1) = mR(T2 - T1)$

On substituting

$$Q = mc_v\,(T_2 - T_1) + mR\,(T_2 - T_1) = m(c_v + R)\,(T_2 - T_1)$$

But for a constant pressure process,

$$Q = mc_p\,(T_2 - T_1)$$

By equating the two expressions, we have

$$m(c_v + R)(T_2 - T_1) = mc_p(T_2 - T_1)$$

$$\therefore \quad c_v + R = c_p$$

or

$$c_p - c_v = R$$

Dividing both sides by c_v, we get

$$\frac{c_p}{c_v} - 1 = \frac{R}{c_v}$$

$$\therefore \quad c_v = \frac{R}{\gamma - 1} \quad \ldots$$

(where $\gamma = c_p/c_v$)

Similarly, dividing both sides by c_p, we get

$$c_p = \frac{\gamma R}{\gamma - 1} \quad \ldots$$

Enthalpy of gas

One of the fundamental quantities which occur invariably in thermodynamics is the sum of internal energy (u) and pressure volume product (pv). This sum is called **Enthalpy** (h).

i.e., $h = u + pv$

The enthalpy of a fluid is the property of the fluid, since it consists of the sum of a property and the product of the two properties. Since enthalpy is a property like internal energy, pressure, specific volume and temperature, it can be introduced into any problem whether the process is a flow or a non-flow process.

The total enthalpy of mass, m, of a fluid can be

$H = U + pV$, where $H = mh$.

For a **perfect gas,**

Referring equation

$h = u + pv = cvT + RT = (cv + R)T = cpT$

i.e., $h = cpT$ and $H = mcpT$.

Work done during a non- flow process

Assume that the pressure and temperature of the fluid are uniform and that there is no friction between the piston and the cylinder walls.

Let A = Cross-sectional area of the piston,

p = Pressure of the fluid at any instant,

$(p - dp)\, A$ = Restraining *force exerted* by the surroundings on the piston, and

dl = The distance moved by the piston under the action of the *force exerted*.

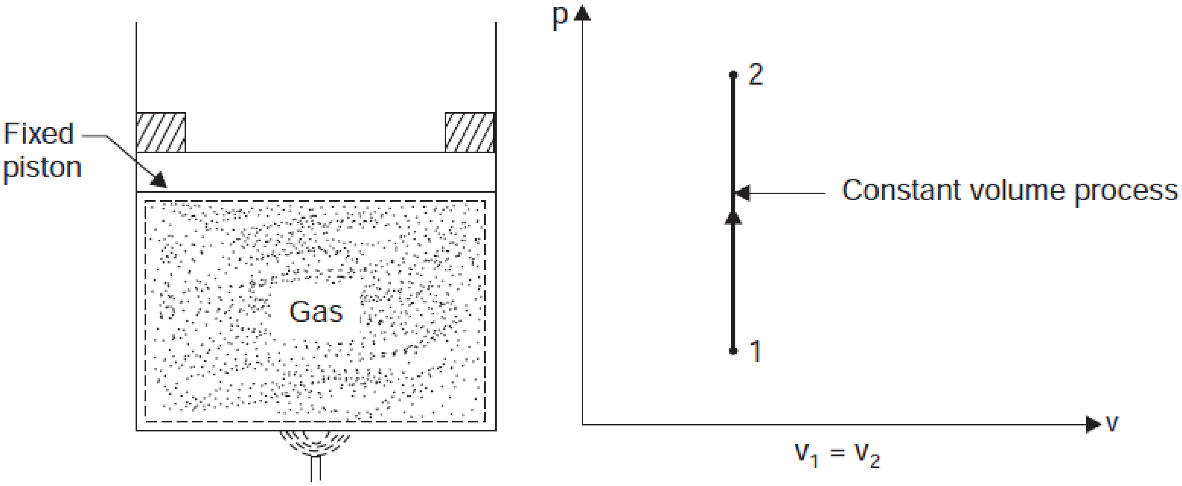
Then work done by the fluid on the piston is given by force times the distance moved,
i.e., Work done by the fluid
$= (pA) \times dl = pdV$ (where dV = a small increase in volume)
Or considering unit mass
Work done = pdv (where v = specific volume)
This is only *true* when (*a*) the *process is frictionless and (b) the difference in pressure between the fluid and its surroundings during the process is infinitely small*. Hence when a reversible process takes place between state 1 and state 2, we have
Work done by the unit mass of fluid $= \int pdv$
When a fluid undergoes a reversible process a series of state points can be joined up to form a line on a diagram of properties. The work done by the fluid during any reversible process is therefore given by the area under the line of process plotted on a p-v diagram (Fig. 2.32).
i.e., Work done = Shaded area on Fig. 2.33

$$= \int pdv$$

When p can be expressed in terms of v then the integral, $\int pdv$ can be evaluated.

Application of first law of thermodynamics to various non flow process

Reversible Constant Volume (or Isochoric) Process (v = constant):
In a constant volume process the working substance is contained in a rigid vessel, hence the boundaries of the system are immovable and no work can be done on or by the system, other than paddle-wheel work input. It will be assumed that '*constant volume*' implies zero work unless stated otherwise.



(a) (b)

Considering mass of the working substance *unity* and applying first law of thermodynamics to the process

$$Q = (u_2 - u_1) + W$$

The work done $W = \int_1^2 p\,dv = 0$ as $dv = 0$.

$$\therefore \quad Q = (u_2 - u_1) = c_v(T_2 - T_1)$$

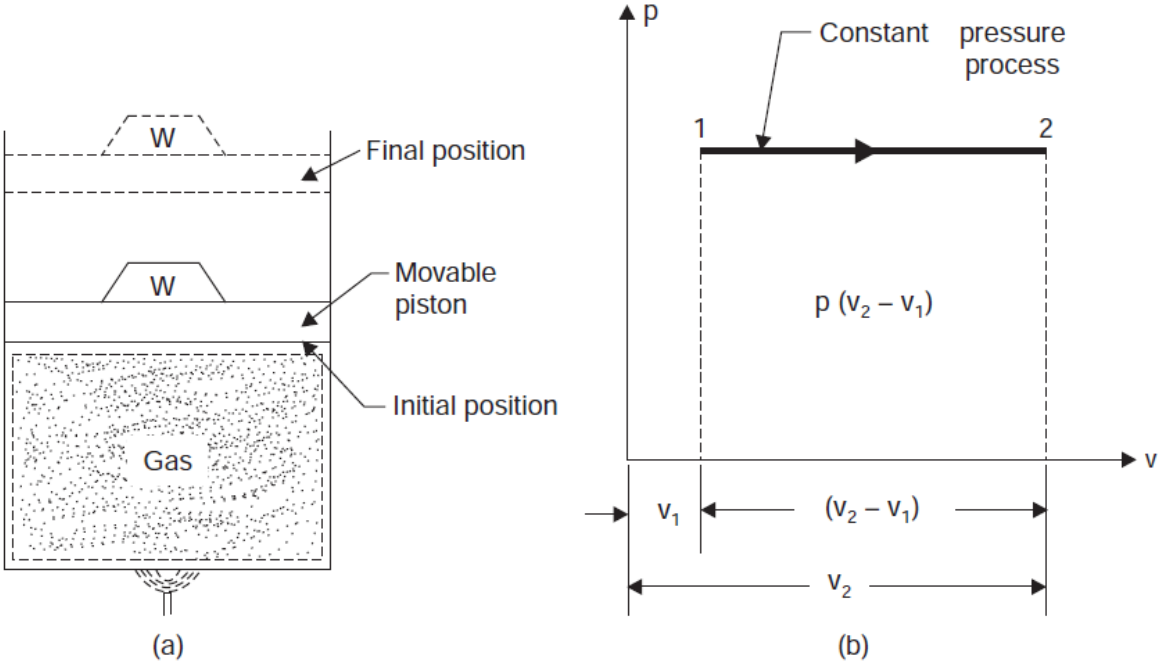
where c_v = Specific heat at constant volume.

For mass, m, of working substance

$$Q = U_2 - U_1 = mc_v(T_2 - T_1)$$

Reversible Constant Pressure (or Isobaric) Process (*p* = constant).

It can be seen from Fig. 4.5 (*b*) that when the boundary of the system is *inflexible* as in a constant volume process, then the pressure rises when heat is supplied. Hence for a constant pressure process, the boundary must move against an external resistance as heat is supplied; for instance a gas in a cylinder behind a piston can be made to undergo a constant pressure process. Since the *piston is pushed through a certain distance* by the force exerted by the gas, then the work is done by the gas on its surroundings.



Considering unit mass of working substance and applying first law of thermodynamics to the process

$$Q = (u_2 - u_1) + W$$

The work done, $W = \int_1^2 p\,dv = p(v_2 - v_1)$

$\therefore$ $$Q = (u_2 - u_1) + p(v_2 - v_1) = u_2 - u_1 + pv_2 - pv_1$$

$$= (u_2 + pv_2) - (u_1 + pv_1) = h_2 - h_1$$

or $$Q = h_2 - h_1 = c_p\,(T_2 - T_1)$$

where h = Enthalpy (specific), and

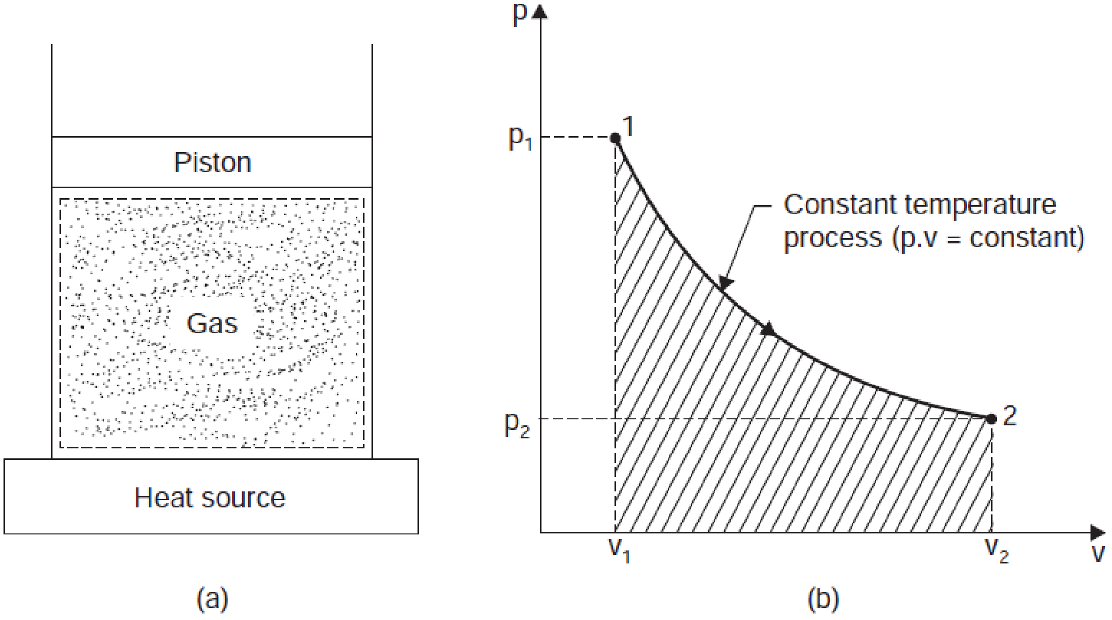
c_p = Specific heat at constant pressure.

For mass, m, of working substance

$$Q = H_2 - H_1 = mc_p\,(T_2 - T_1)$$

Reversible Temperature (or Isothermal) Process (pv = constant, T = constant) :

A *process at a constant temperature is called an isothermal process.* When a working substance in a cylinder behind a piston expands from a high pressure to a low pressure there is a tendency for the temperature to fall. In an isothermal expansion heat must be added continuously in order to keep the temperature at the initial value. Similarly in an isothermal compression heat must be removed from the working substance continuously during the process.



(a) (b)

Considering unit mass of working substance and applying first law to the process

$$\begin{aligned} Q &= (u_2 - u_1) + W \\ &= c_v\,(T_2 - T_1) + W \\ &= 0 + W \qquad\qquad [\because \quad T_2 = T_1] \end{aligned}$$

The work done, $W = \int_1^2 p\,dv$

In this case pv = constant or $p = \dfrac{C}{v}$ (where C = constant)

$$\therefore \qquad W = \int_{v_1}^{v_2} C\,\frac{dv}{v} = C\big[\log_e v\big]_{v_1}^{v_2} = C\,\log_e \frac{v_2}{v_1}$$

The constant C can either be written as p_1v_1 or as p_2v_2, since

$$p_1v_1 = p_2v_2 = \text{constant, } C$$

i.e., $W = p_1v_1 \log_e \dfrac{v_2}{v_1}$ per unit mass of working substance

or $W = p_2v_2 \log_e \dfrac{v_2}{v_1}$ per unit mass of working substance

$$\therefore \qquad Q = W = p_1v_1 \log_e \frac{v_2}{v_1}$$

For mass, m, of the working substance

$$Q = p_1V_1 \log_e \frac{V_2}{V_1}$$

or $Q = p_1V_1 \log_e \dfrac{p_1}{p_2} \qquad \left[\because \dfrac{V_2}{V_1} = \dfrac{p_1}{p_2}\right]$

Reversible Adiabatic Process

An **adiabatic process** *is one in which no heat is transferred to or from the fluid during the process.* Such a process can be reversible or irreversible. The reversible adiabatic non-flow process will be considered in this section.

Considering unit mass of working substance and applying first law to the process

$Q = (u2 - u1) + W$

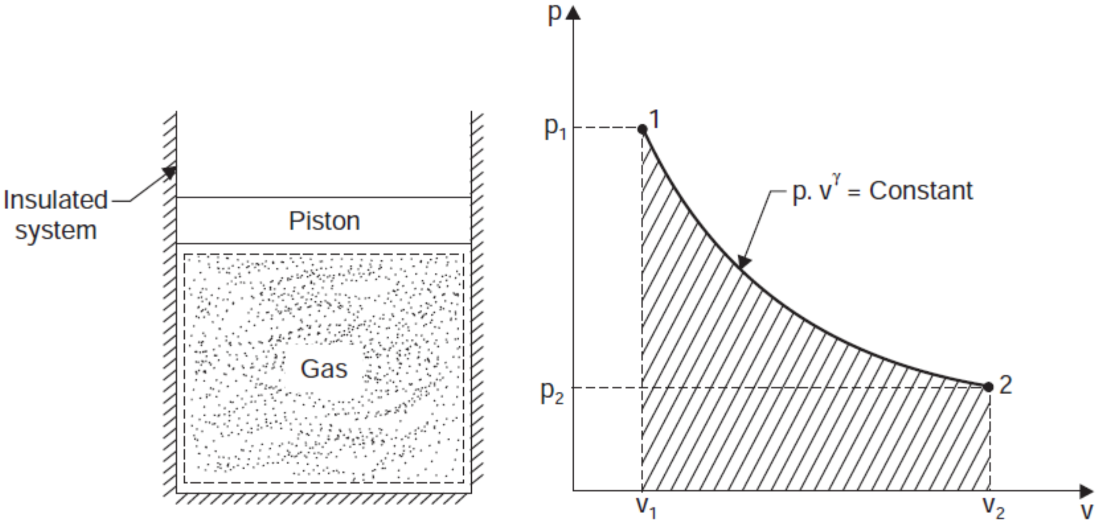
$O = (u2 - u1) + W$ or $W = (u1 - u2)$ for any adiabatic process

Equation is true for an adiabatic process whether the process is reversible or not. In an adiabatic expansion, the work done W by the fluid is at the expense of a reduction in the internal energy of the fluid. Similarly in an adiabatic compression process all the work done on the fluid goes to increase the internal energy of the fluid.

For an adiabatic process to take place, perfect thermal insulation for the system must be available.

Expression for work W:

A reversible adiabatic process for a perfect gas is shown on a *p-v* diagram



(a) (b)

The work done is given by the shaded area, and this area can be evaluated by integration.

i.e.,
$$W = \int_{v_1}^{v_2} p\,dv$$

Therefore, since pv^γ = constant, C, then

$$W = \int_{v_1}^{v_2} C\,\frac{dv}{v^\gamma} \qquad \left[\because\ p = \frac{C}{v^\gamma}\right]$$

i.e.,
$$W = C\int_{v_1}^{v_2} \frac{dv}{v^\gamma} = C\left|\frac{v^{-\gamma+1}}{-\gamma+1}\right|_{v_1}^{v_2}$$

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

The constant in this equation can be written as $p_1 v_1^\gamma$ or as $p_2 v_2^\gamma$. Hence,

$$W = \frac{p_1\,v_1^\gamma v_1^{-\gamma+1} - p_2\,v_2^\gamma v_2^{-\gamma+1}}{\gamma-1} = \frac{p_1 v_1 - p_2 v_2}{\gamma-1}$$

i.e.,
$$W = \frac{p_1 v_1 - p_2 v_2}{\gamma-1}$$

or
$$W = \frac{R(T_1 - T_2)}{\gamma-1}$$

Relationship between T and v, and T and p :

By using equation $pv = RT$, the relationship between T and v, and T and p, may by derived as follows:

i.e.,
$$pv = RT$$

$$\therefore \quad p = \frac{RT}{v}$$

Putting this value in the equation pv^{γ} = constant

$$\frac{RT}{v} \cdot v^{\gamma} = \text{constant}$$

i.e.,
$$Tv^{\gamma-1} = \text{constant}$$

Also $v = \frac{RT}{p}$; hence substituting in equation pv^{γ} = constant

$$p\left(\frac{RT}{p}\right)^{\gamma} = \text{constant}$$

$$\therefore \quad \frac{T^{\gamma}}{p^{\gamma-1}} = \text{constant}$$

or
$$\frac{T}{(p)^{\frac{\gamma-1}{\gamma}}} = \text{constant}$$

Therefore, for a reversible adiabatic process for a perfect gas between states 1 and 2, we can write:

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{\gamma}$$

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

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Polytropic Reversible Process:

It is found that many processes in practice approximate to a reversible law of form *pvn* = constant, where *n* is a constant. Both vapours and perfect gases obey this type of law closely in many non-flow processes. Such processes are *internally reversible*.

We know that for any reversible process,

$$\text{Work done,}\quad W = \frac{p_1v_1 - p_2v_2}{n-1}$$

$$W = \frac{R(T_1 - T_2)}{n-1}$$

Heat transfer during polytropic process (for perfect gas pv = RT) :

Using non-flow energy equation, the heat flow/transfer during the process can be found,

i.e.,
$$Q = (u_2 - u_1) + W$$
$$= c_v(T_2 - T_1) + \frac{R(T_1 - T_2)}{n-1}$$

i.e.,
$$Q = \frac{R(T_1 - T_2)}{n-1} - c_v\,(T_1 - T_2)$$

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

On substituting,

$$Q = \frac{R}{n-1}(T_1 - T_2) - \frac{R}{(\gamma-1)}\,(T_1 - T_2)$$

i.e.,
$$Q = R(T_1 - T_2)\left(\frac{1}{n-1} - \frac{1}{\gamma-1}\right)$$
$$= \frac{R\,(T_1 - T_2)(\gamma - 1 - n + 1)}{(\gamma-1)(n-1)} = \frac{R(T_1 - T_2)(\gamma - n)}{(\gamma-1)(n-1)}$$

$\therefore$
$$Q = \frac{(\gamma - n)}{(\gamma - 1)}\,\frac{R(T_1 - T_2)}{(n-1)}$$

or
$$Q = \left(\frac{\gamma - n}{\gamma - 1}\right)W \qquad \left[\because\ W = \frac{R(T_1 - T_2)}{(n-1)}\right]$$

Free Expansion

Consider two vessels 1 and 2 interconnected by a short pipe with a valve *A*, and perfectly thermally insulated. Initially let the vessel 1 be filled with a fluid at a certain pressure, and let 2 be completely evacuated. When the valve *A* is opened the fluid in 1 will expand rapidly to fill both vessels 1 and 2. The pressure finally will be lower than the initial pressure in vessel 1.

This is known as *free or unresisted expansion*. The process is *highly irreversible* ; since the fluid is eddying continuously during the process. Now applying first law of thermodynamics (or non-flow energy equation) between the initial and final states,

$Q = (u2 - u1) + W$

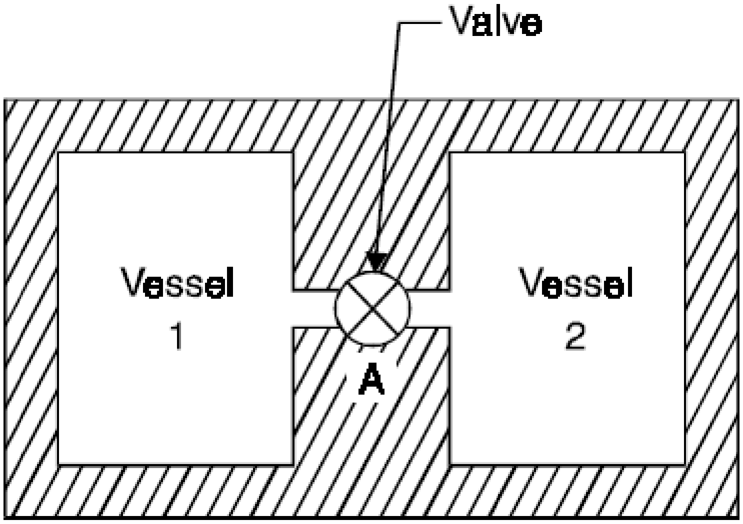
In this process, no work is done on or by the fluid, since the boundary of the system does not move. No heat flows to or from the fluid since the system is well lagged. The process is therefore, *adiabatic but irreversible*.

i.e., $u2 - u1 = 0$ or $u2 = u1$

In a free expansion, therefore, the internal energy initially equals the initial energy finally.

For a perfect gas,

$u = cvT$

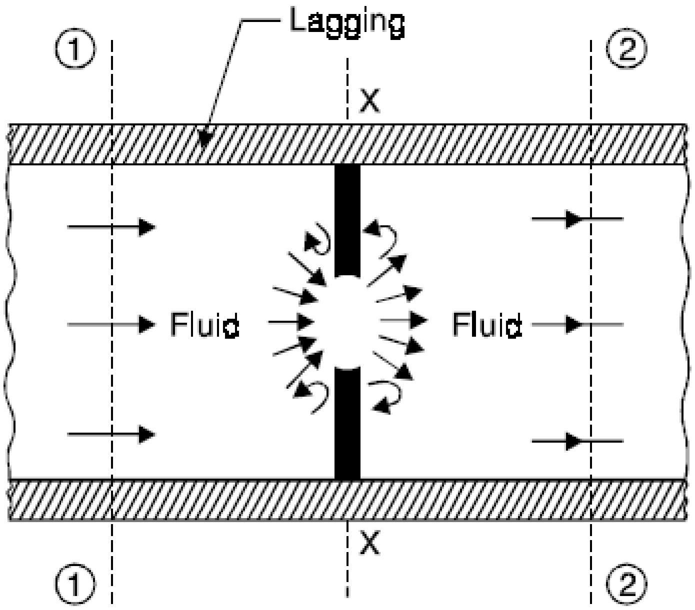


For a free expansion of a perfect gas, $cvT1 = cvT2$ *i.e.*, $T1 = T2$

That is, for a perfect gas undergoing a free expansion, the initial temperature is equal to the final temperature.

Throttling. A flow of fluid is said to be throttled when there is some *restriction to the flow*, when the velocities before and after the restriction are either equal or negligibly small, and when there is a *negligible heat loss to the surroundings.*
The restriction to the flow can be :
(*i*) partly open valve
(*ii*) an orifice or
(*iii*) any other sudden reduction in the crosssection of the flow.
An example of throttling is shown in Fig. 4.72. It is represented on *T-s* and *h-s* diagrams as shown in Figs. 4.73 and 4.74 respectively. The fluid (say steam) flowing steadily along a well-lagged pipe, passes through an orifice at section *X*. Since the pipe is well-lagged it can be assumed that no heat flows to or from the fluid.
Applying flow equation between any two sections of the flow, we have

$$h_1 + \frac{C_1^{\,2}}{2} + Q = h_2 + \frac{C_2^{\,2}}{2} + W$$



Now since $Q = 0$, and $W = 0$, then

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

When the velocities $C1$ and $C2$ are small, or when $C1$ is very nearly equal to $C2$, then the K.E. terms may be neglected.

Then $h1 = h2$ ...(4.81)

i.e., For a throttling process : *Initial enthalpy = Final enthalpy*.

Example. *In an internal combustion engine, during the compression stroke the heat rejected to the cooling water is 50 kJ/kg and the work input is 100 kJ/kg.*

Calculate the change in internal energy of the working fluid stating whether it is a gain or loss.

Solution. Heat rejected to the cooling water, $Q = -50$ kJ/kg

(–ve sign since heat is rejected)

Work input, $W = -100$ kJ/kg

(–ve sign since work is supplied to the system)

Using the relation, $Q = (u_2 - u_1) + W$

$$-50 = (u_2 - u_1) - 100$$

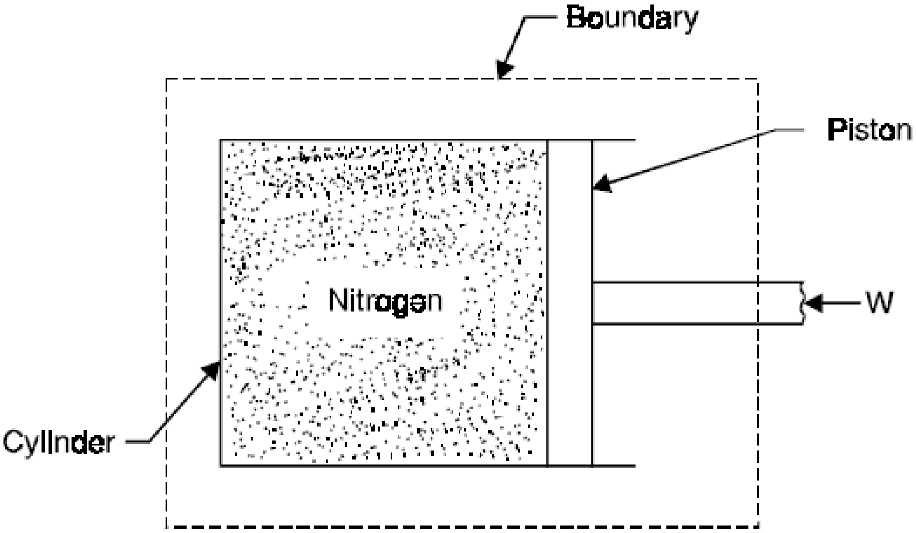
$$u_2 - u_1 = -50 + 100 = 50 \text{ kJ/kg}$$

Hence, **gain in internal energy = 50 kJ/kg. (Ans.)**

Example 2. *0.3 kg of nitrogen gas at 100 kPa and 40°C is contained in a cylinder. The piston is moved compressing nitrogen until the pressure becomes 1 MPa and temperature becomes 160°C.*

The work done during the process is 30 kJ. Calculate the heat transferred from the nitrogen to the surroundings. cv for nitrogen = 0.75 kJ/kg K.

Solution. Mass of nitrogen, $m = 0.3$ kg



Temperature before compression = 40°C or 313 K

Temperature after compression = 160°C or 433 K

The work done during the compression process, $W = -30$ kJ

According to first law of thermodynamics,

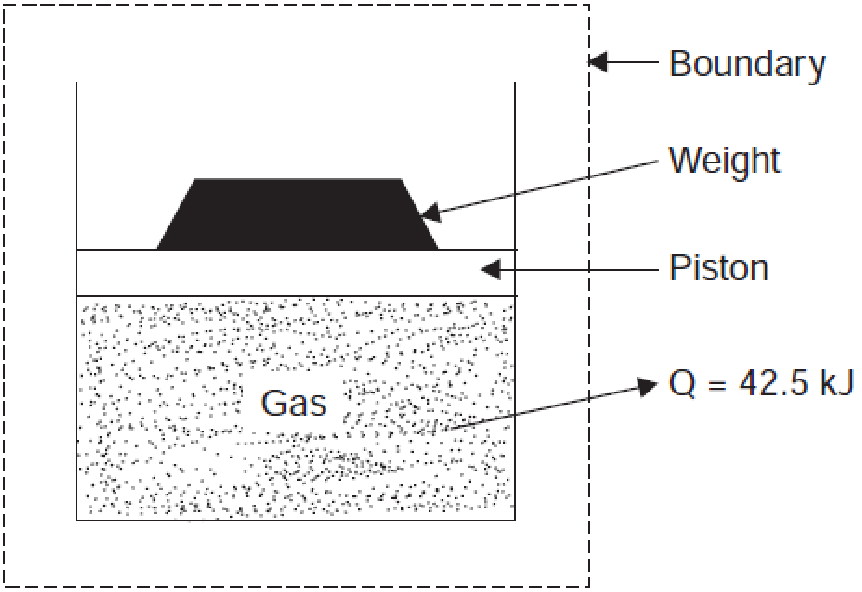
$$Q = \Delta U + W = (U_2 - U_1) + W$$
$$= mc_v\,(T_2 - T_1) + W$$
$$= 0.3 \times 0.75(433 - 313) - 30 = -3 \text{ kJ}$$

Hence, **heat 'rejected' during the process = 3 kJ. (Ans.)**

Note. Work, W has been taken –ve because it has been supplied from outside.

Example 3. *When a stationary mass of gas was compressed without friction at constant pressure its initial state of 0.4 m3 and 0.105 MPa was found to change to final state of 0.20 m3 and 0.105 MPa. There was a transfer of 42.5 kJ of heat from the gas during the process. How much did the internal energy of the gas change ?*

Solution.



Initial state

Pressure of gas, $p_1 = 0.105$ MPa

Volume of gas, $V_1 = 0.4\ \text{m}^3$

Final state

Pressure of gas, $p_2 = 0.105$ MPa

Volume of gas, $V_2 = 0.20\ \text{m}^3$

Process used : *Constant pressure*

Heat transferred, $Q = -\ 42.5$ kJ

(–ve sign indicates that heat is rejected)

Change in internal energy, $\Delta U = U_2 - U_1$:

First law for a stationary system in a process gives

$$Q = \Delta U + W$$

or
$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

Here
$$W_{1-2} = \int_{V_1}^{V_2} p dV = p(V_2 - V_1)$$

$$= 0.105(0.20 - 0.40)\ \text{MJ} = -21\ \text{kJ} \qquad [\because\ 1\ \text{MJ} = 10^3\ \text{kJ}]$$

Substituting this value of W_{1-2} in equation (i), we get

$$-42.5 = (U_2 - U_1) - 21$$

$$\therefore \qquad U_2 - U_1 = -42.5 + 21 = -21.5\ \text{kJ}$$

Hence **'decrease' in internal energy = 21.5 kJ. (Ans.)**

Internal combustion engine

Explain & classify I.C engine

According to type of ignition (according to method of ignition)

A)SI engine :- A spark-ignition engine (SI engine) is an internal combustion engine, usually a petrol engine, where the combustion cycle of an air-fuel mixture is ignited by a spark plug.

B)CI engine :- A CI engine is type of an internal combustion engine in which the fuel charge is ignited by the heat of compression.

Classification of IC Engine (Internal combustion engine) based on Types of fuel used

A)petrol engine;-The petrol engine (British English) or the gasoline engine (American English) is a spark-ignition internal combustion engine designed to run on petrol (gasoline) and similar volatile fuels.

B)Diesel engine:-The diesel engine (also known as the compression-ignition or CI engine), named after Rudolf Diesel, is an internal combustion engine in which the ignition of the fuel is caused by the high temperature of the air in the cylinder due to mechanical compression (adiabatic compression)
C)Gas engine:-The gas engine is an internal combustion engine operating on gaseous fuel, such as coal gas, producer gas, biogas, landfill gas or natural gas.
D)Dual fuel engine :- Dual-fuel engine is a diesel engine designed to operate on both gaseous and liquid fuels.

Classification of ic engine based on number of strokes per cycle (according to cycle of operation)A)2 stroke engine :- A two-stroke (or two-cycle) engine is a type of internal combustion engine that completes a two-stroke (up and down) power cycle of the piston during a single rotation of the crankshaft.

B)4 stroke engine :- The four-stroke (also four-cycle) engine is an internal combustion (IC) engine in which the piston completes four separate strokes while rotating the crankshaft.

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

Bore is the inner diameter of the cylinder. The volume at bottom dead centre (VBDC) is defined as the volume occupied between the cylinder head and the piston face when the piston is farthest from the cylinder head.

In a reciprocating engine, the dead centre is the position of a piston in which it is either farthest from, or nearest to, the crankshaft. The former is known as Top Dead Centre (TDC) while the latter is known as Bottom Dead Centre (BDC).

Swept volume can be defined as the volume swept by the engine piston during one stroke. Swept volume is also the product of piston area and stroke. Clearance volume can be defined as the volume that remains in the cylinder when the engine piston is in the top centre position.

Piston speed, also known as the mean or average piston speed, is the average speed that a piston moves from the Top Dead Center (TDC) and Bottom Dead Center (BDC) and back again, completing a full cycle. It can be displayed in different units, with feet per minute or meters per second being the most common ones.

Piston speed = 2 * Stroke * RPM

Piston speed - Mean or average piston speed that a piston completes a full cycle within the cylinder;

Stroke - Full distance that the piston travels in one cycle within the cylinder; and

RPM - Stands for revolution per minute which is the number of revolutions, or full cycles, that a piston can perform in 1 minute.

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

WORKING PRINCIPLE OF I.C. ENGINE/ FOUR STROKE CYCLE ENGINE / TWO STROKE CYCLE ENGINE

A mixture of fuel with correct amount of air is exploded in an engine cylinder which is closed at one end. As a result of this explosion, heat is released and this heat causes the pressure of the burning gases to increase. This pressure forces a close fitting piston to move down the cylinder. The movement of piston is transmitted to a crankshaft by a connecting rod so that the crankshaft rotates and turns a flywheel connected to it. Power is taken from the rotating crank shaft to do mechanical work. To obtain continuous rotation of the crankshaft the explosion has to be repeated continuously. Before the explosion to take place, the used gases are expelled from the cylinder, fresh charge of fuel and air are admitted in to the cylinder and the piston moved back to its starting position. The sequences of events taking place in an engine is called the working cycle of the engine. The sequence of events taking place inside the engine are as follows

1. Admission of air or air-fuel mixture inside the engine cylinder (suction)

2. Compression of the air or air fuel mixture inside the engine (compression)

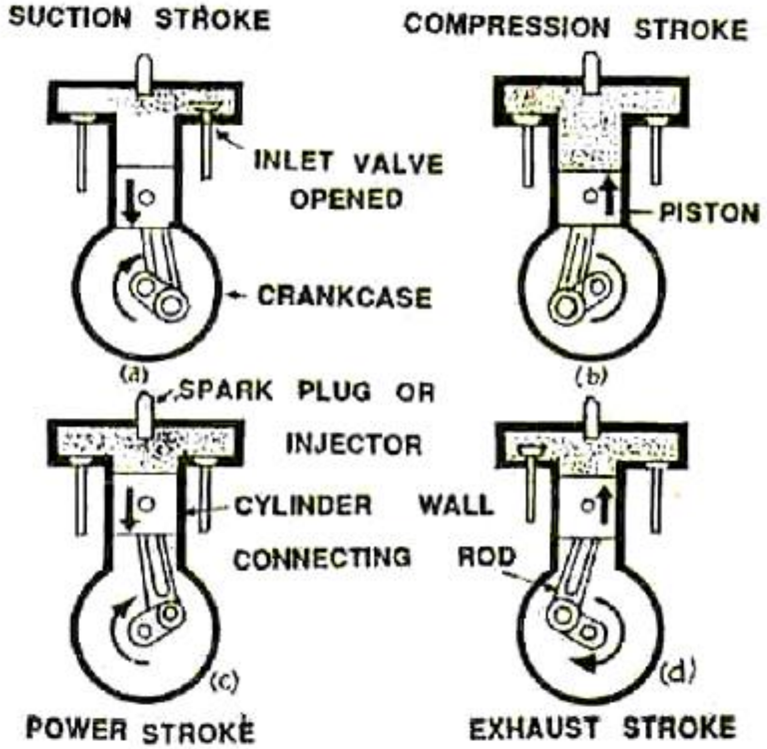
3. Injection of fuel in compressed air for ignition of the fuel or ignition of air-fuel mixture by an electric spark using a spark plug to produce thermal power inside the cylinder (power)

4. Removal of all the burnt gases from the cylinder to receive fresh charge (exhaust)

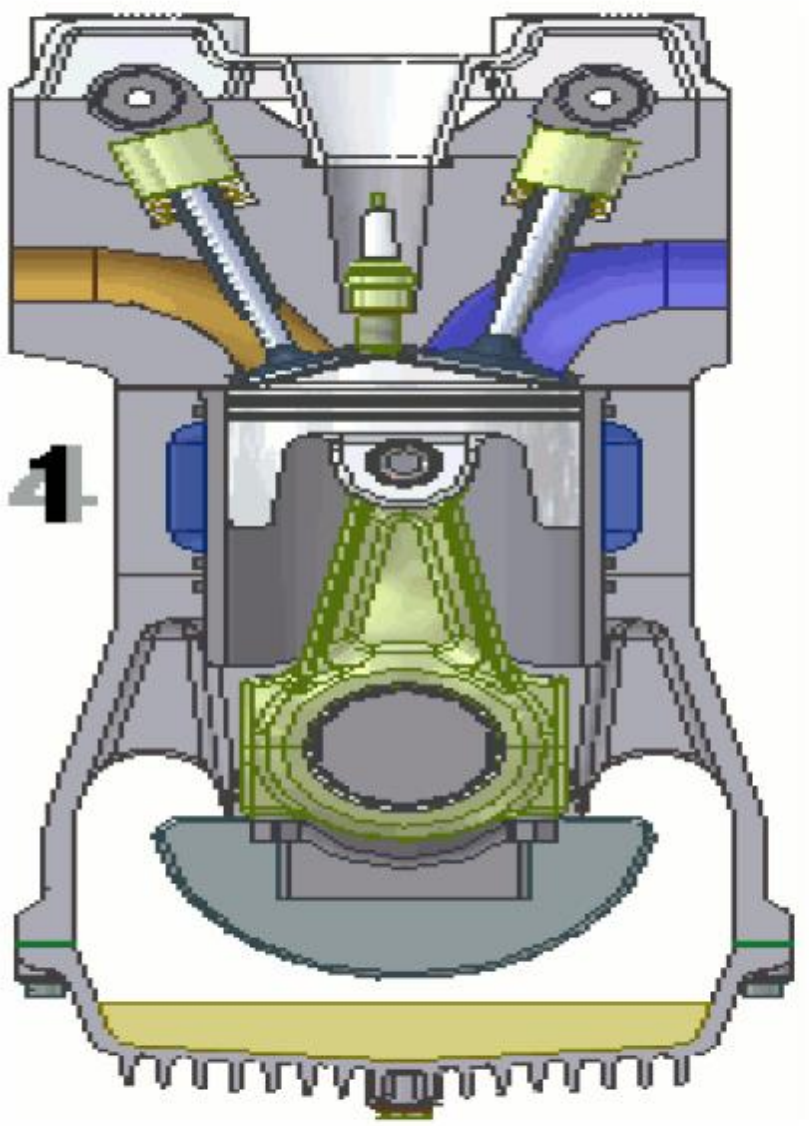
Note: Charge means admitting fresh air in to the cylinder in the case of compression ignition engines (diesel engines) or admitting a mixture of air and fuel in to the cylinder in the case of spark ignition engines.

FOUR STROKE CYCLE ENGINE (DIESEL/ PETROL ENGINE)

In four stroke cycle engines the four events namely suction, compression, power and exhaust take place inside the engine cylinder. The four events are completed in four strokes of the piston (two revolutions of the crank shaft). This engine has got valves for controlling the inlet of charge and outlet of exhaust gases. The opening and closing of the valve is controlled by cams, fitted on camshaft. The camshaft is driven by crankshaft with the help of suitable gears or chains. The camshaft runs at half the speed of the crankshaft. The events taking place in I.C. engine are as follows: 1. Suction stroke 2. Compression stroke 3. Power stroke 4. Exhaust stroke



Four stroke cycle engine



Four stroke cycle engine

Suction stroke
During suction stroke inlet valve opens and the piston moves downward. Only air or a mixture of air and fuel are drawn inside the cylinder. The exhaust valve remains in closed position during this stroke. The pressure in the engine cylinder is less than

atmospheric pressure during this stroke (Fig. 1a)

Compression stroke
During this stroke the piston moves upward. Both valves are in closed position. The charge taken in the cylinder is compressed by the upward movement of piston. If only air is compressed, as in case of diesel engine, diesel is injected at the end of the compression stroke and ignition of fuel takes place due to high pressure and

temperature of the compressed air. If a mixture of air and fuel is compressed in the cylinder, as in case of petrol engine, the mixture is ignited by a spark plug.

Power stroke

After ignition of fuel, tremendous amount of heat is generated, causing very high pressure in the cylinder which pushes the piston downward (Fig.1b). The downward movement of the piston at this instant is called power stroke. The connecting rod transmits the power from piston to the crank shaft and crank shaft rotates. Mechanical work can be taped at the rotating crank shaft. Both valves remain closed during power stroke.

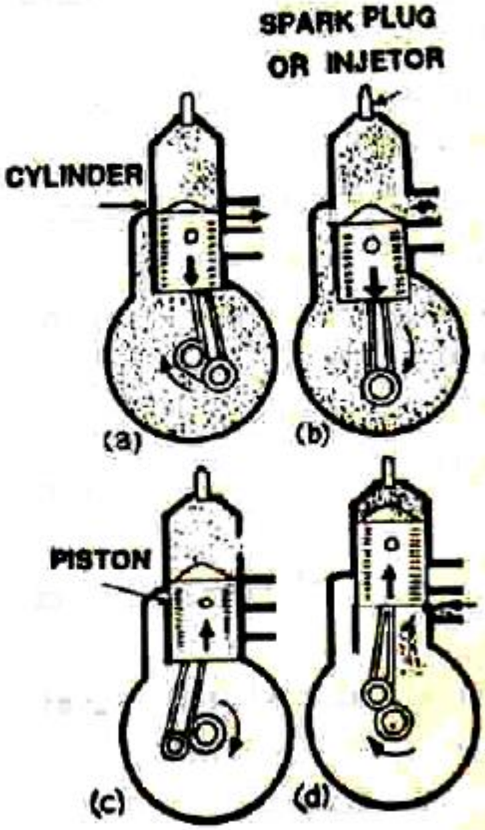
Exhaust stroke

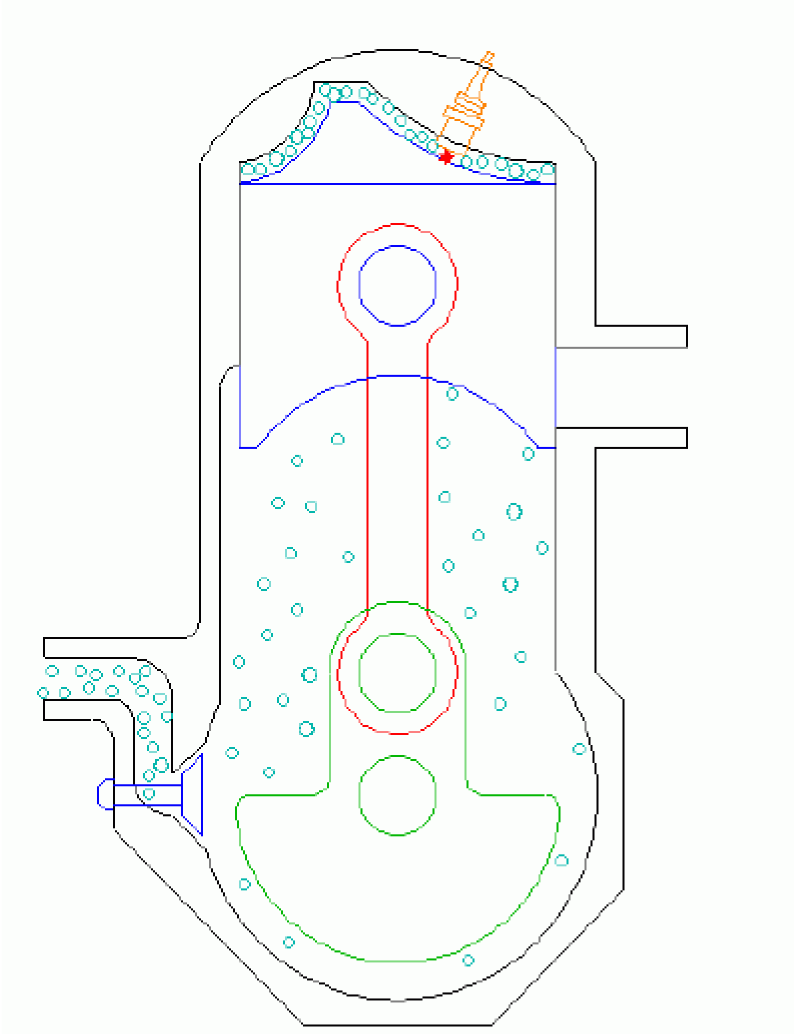
During this stroke piston moves upward. Exhaust valve opens and exhaust gases go out through exhaust valves opening. All the burnt gases go out of the engine and the cylinder becomes ready to receive the fresh charge. During this stroke inlet valve remains closed (Fig.1d).

Thus it is found that out of four strokes, there is only one power stroke and three idle strokes in four stroke cycle engine. The power stroke supplies necessary momentum for useful work.

TWO STROKE CYCLE ENGINE (PETROL ENGINE)

In two stroke cycle engines, the whole sequence of events i.e., suction, compression, power and exhaust are completed in two strokes of the piston i.e. one revolution of the crankshaft. There is no valve in this type of engine. Gas movement takes place through holes called ports in the cylinder. The crankcase of the engine is air tight in which the crankshaft rotates.


SPARK PLUG
OR INJETOR
CYLINDER
(a)
(b)
PISTON
(c)
(d)



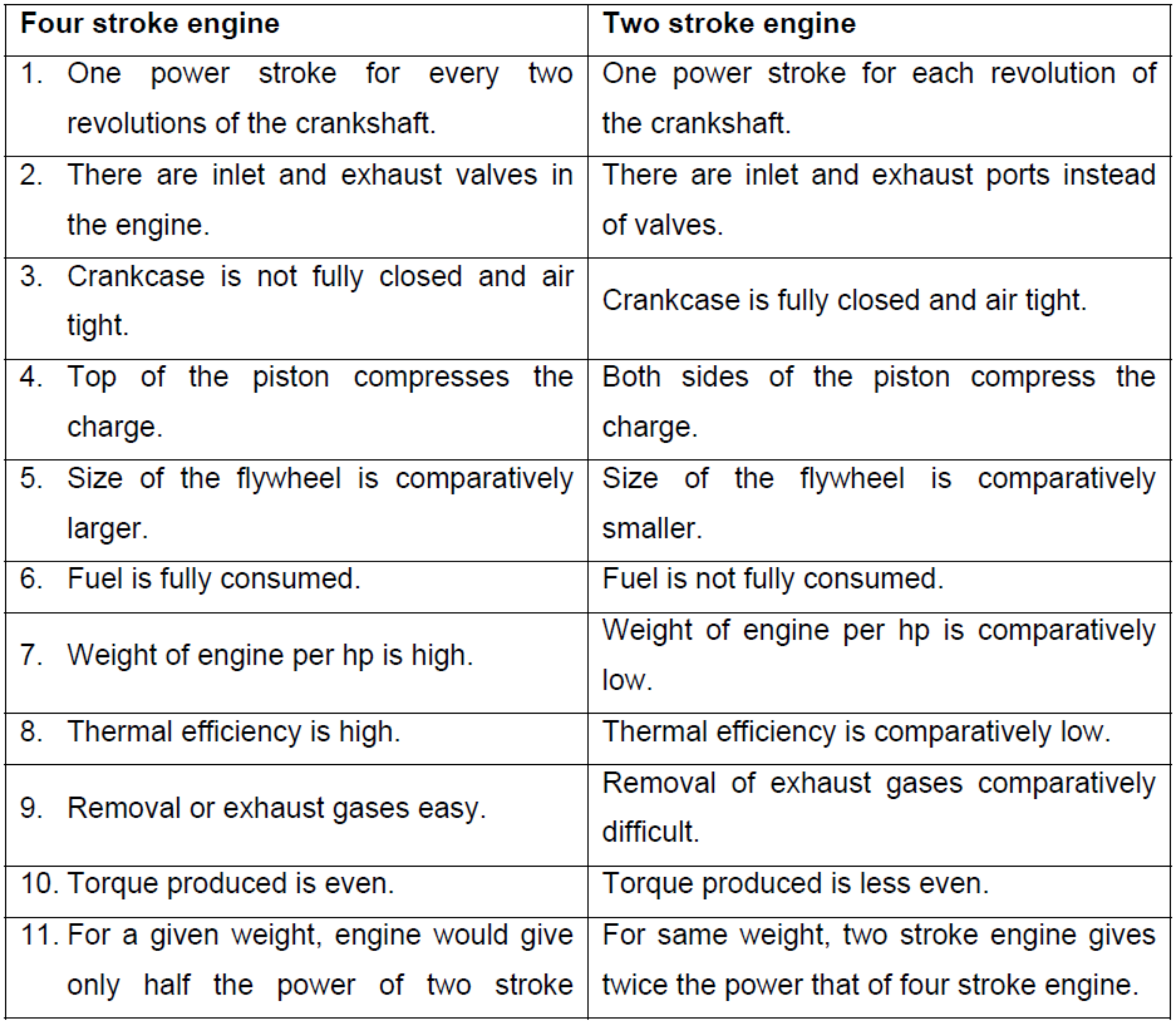
Two stroke cycle

Upward stroke of the piston (Suction + Compression)
When the piston moves upward it covers two of the ports, the exhaust port and transfer port, which are normally almost opposite to each other. This traps the charge of air- fuel mixture drawn already in to the cylinder. Further upward movement of the piston compresses the charge and also uncovers the suction port. Now fresh mixture is drawn through this port into the crankcase. Just before the end of this stroke, the mixture in the cylinder is ignited by a spark plug (Fig 2 c &d). Thus, during this stroke both suction and compression events are completed.

Downward stroke (Power + Exhaust)
Burning of the fuel rises the temperature and pressure of the gases which forces the piston to move down the cylinder. When the piston moves down, it closes the suction port, trapping the fresh charge drawn into the crankcase during the previous upward stroke. Further downward movement of the piston uncovers first the exhaust port and then the transfer port. Now fresh charge in the crankcase moves in to the cylinder through the transfer port driving out the burnt gases through the exhaust port. Special shaped piston crown deflect the incoming mixture up around the cylinder so that it can

help in driving out the exhaust gases . During the downward stroke of the piston power and exhaust events are completed.

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



Four stroke engine	Two stroke engine
1. One power stroke for every two revolutions of the crankshaft.	One power stroke for each revolution of the crankshaft.
2. There are inlet and exhaust valves in the engine.	There are inlet and exhaust ports instead of valves.
3. Crankcase is not fully closed and air tight.	Crankcase is fully closed and air tight.
4. Top of the piston compresses the charge.	Both sides of the piston compress the charge.
5. Size of the flywheel is comparatively larger.	Size of the flywheel is comparatively smaller.
6. Fuel is fully consumed.	Fuel is not fully consumed.
7. Weight of engine per hp is high.	Weight of engine per hp is comparatively low.
8. Thermal efficiency is high.	Thermal efficiency is comparatively low.
9. Removal or exhaust gases easy.	Removal of exhaust gases comparatively difficult.
10. Torque produced is even.	Torque produced is less even.
11. For a given weight, engine would give only half the power of two stroke	For same weight, two stroke engine gives twice the power that of four stroke engine.

Gas Power Cycle

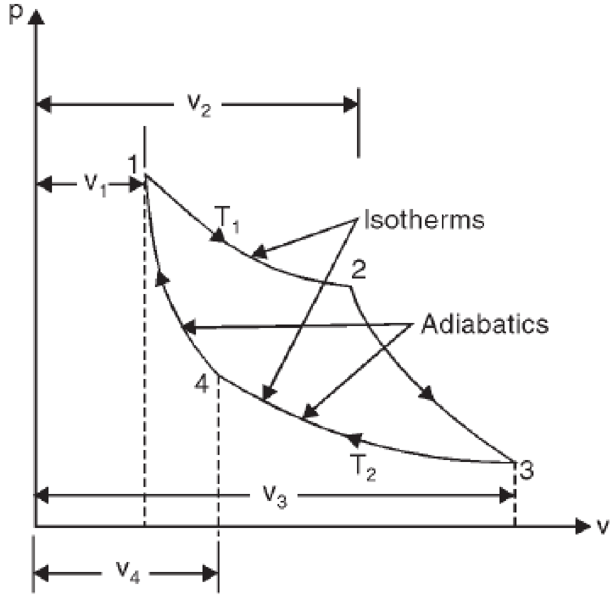
Carnot cycle

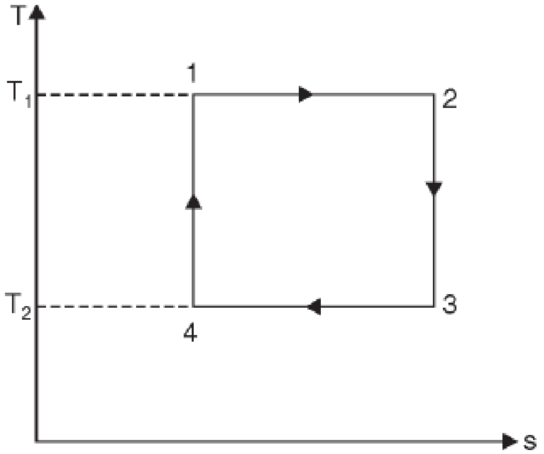
This cycle has the *highest possible efficiency* and consists of four simple operations namely,

(*a*) Isothermal expansion
(*b*) Adiabatic expansion
(*c*) Isothermal compression
(*d*) Adiabatic compression.

The condition of the Carnot cycle may be imagined to occur in the following way: One kg of a air is enclosed in the cylinder which (except at the end) is made of perfect non-conducting material. A source of heat '*H*' is supposed to provide unlimited quantity of heat, non-conducting cover '*C*' and a sump '*S*' which is of infinite capacity so that its temperature remains unchanged irrespective of the fact how much heat is supplied to it. The temperature of source *H* is *T*1 and the same is of

the working substance. The working substance while rejecting heat to sump '*S*' has the temperature. *T*2 *i.e.*, the same as that of sump *S*.
Following are the *four stages* of the Carnot cycle. Refer Fig





Stage (1). Line 1-2 [Fig. 13.1 (*a*)] represents the isothermal expansion which takes place at temperature *T*1 when source of heat *H* is applied to the end of cylinder. Heat supplied in this case is given by *RT*1 log*e* *r* and where *r* is the ratio of expansion.
Stage (2). Line 2-3 represents the application of non-conducting cover to the end of the cylinder. This is followed by the adiabatic expansion and the temperature falls from *T*1 to *T*2.
Stage (3). Line 3-4 represents the isothermal compression which takes place when sump '*S*' is applied to the end of cylinder. Heat is rejected during this operation whose value is given by *RT*2 log*e* *r* where *r* is the ratio of compression.
Stage (4). Line 4-1 represents repeated application of non-conducting cover and adiabatic compression due to which temperature increases from *T*2 to *T*1. It may be noted that ratio of expansion during isotherm 1-2 and ratio of compression during isotherm 3-4 must be equal to get a closed cycle.
Fig. represents the Carnot cycle on *T-s* coordinates.
Now according to law of conservation of energy,
Heat supplied = Work done + Heat rejected
Work done = Heat supplied – Heat rejected= *RT*1log*e* *r* – *RT*2 log*e* *r*

$$\text{Efficiency of cycle} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{R \log_e r\,(T_1 - T_2)}{RT_1 \,.\, \log_e r}$$

$$= \frac{T_1 - T_2}{T_1}$$

From this equation, it is quite obvious that if temperature *T*2 decreases efficiency increases and it becomes 100% if *T*2 becomes absolute zero which, of course is impossible to attain. Further more *it is not possible to produce an engine that should work on Carnot's cycle as it would necessitate* *the piston to travel very slowly during first portion of the forward stroke (isothermal expansion) and to travel more quickly during the remainder of the stroke (adiabatic expansion) which however is not practicable.*

Example 13.1. *A Carnot engine working between 400°C and 40°C produces 130 kJ of work. Determine :*

(*i*) *The engine thermal efficiency.*

(*ii*) *The heat added.*

(*iii*) *The entropy changes during heat rejection process.*

Solution. Temperature, $T1 = T2 = 400 + 273 = 673$ K

Temperature, $T3 = T4 = 40 + 273 = 313$ K

Work produced, $W = 130$ kJ.

(*i*) **Engine thermal efficiency, ηth :**

$$\eta_{th.} = \frac{673 - 313}{673} = \mathbf{0.535 \text{ or } 53.5\%.}$$

(*ii*) **Heat added :**

$$\eta_{th.} = \frac{\text{Work done}}{\text{Heat added}}$$

i.e.,
$$0.535 = \frac{130}{\text{Heat added}}$$

$$\therefore \quad \text{Heat added} = \frac{130}{0.535} = \mathbf{243 \text{ kJ.}}$$

Otto cycle

This cycle is so named as it was conceived by ‘Otto’. On this cycle, petrol, gas and many types of oil engines work. It is the standard of comparison for internal combustion engines. Figs. 13.5 (*a*) and (*b*) shows the theoretical *p-V* diagram and *T-s* diagrams of this cycle respectively.

The point 1 represents that cylinder is full of air with volume $V1$, pressure $p1$ and absolute temperature $T1$.

Line 1-2 represents the *adiabatic compression* of air due to which $p1$, $V1$ and $T1$ change to $p2$, $V2$ and $T2$, respectively.

Line 2-3 shows the *supply of heat* to the air *at constant volume* so that $p2$ and $T2$ change to $p3$ and $T3$ ($V3$ being the same as $V2$).

Line 3-4 represents the *adiabatic expansion* of the air. During expansion $p3$, $V3$ and $T3$ change to a final value of $p4$, $V4$ or $V1$ and $T4$, respectively.

Line 4-1 shows the *rejection of heat* by air at *constant volume* till original state (point 1) reaches.

Consider **1 kg of air** (working substance) :

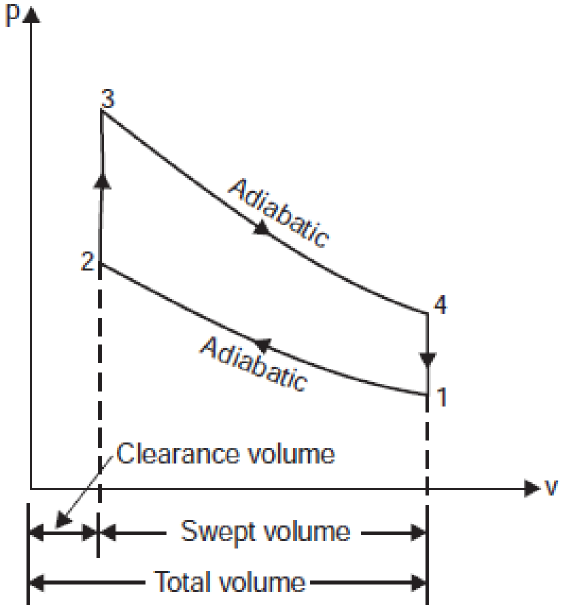
Heat supplied at constant volume = $cv(T3 – T2)$.

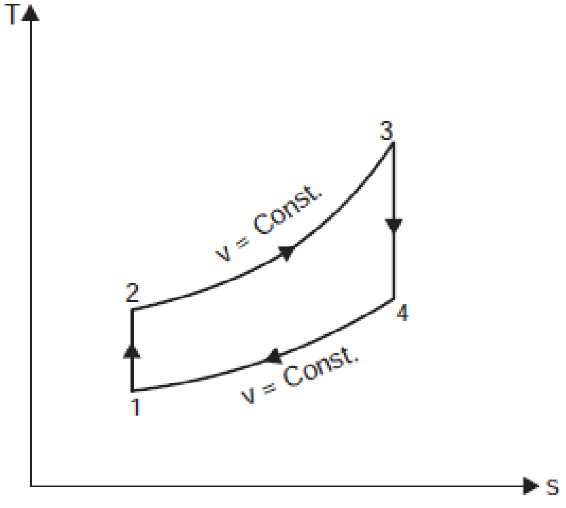
Heat rejected at constant volume = $cv\,(T4 – T1)$.

But, work done = Heat supplied – Heat rejected= $cv\,(T3 – T2) – cv\,(T4 – T1)$

$$\text{Efficiency} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{c_v\,(T_3 - T_2) - c_v\,(T_4 - T_1)}{c_v\,(T_3 - T_2)}$$

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





Let compression ratio, $r_c\ (= r) = \dfrac{v_1}{v_2}$

and expansion ratio, $r_e\ (= r) = \dfrac{v_4}{v_3}$

(These *two ratios are same* in this cycle)

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

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

Similarly, $\dfrac{T_3}{T_4} = \left(\dfrac{v_4}{v_3}\right)^{\gamma - 1}$

or $T_3 = T_4\,.\,(r)^{\gamma - 1}$

Inserting the values of T_2 and T_3 in equation (*i*), we get

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

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

Example 13.7. *The efficiency of an Otto cycle is 60% and © = 1.5. What is the compression ratio ?*

Solution. Efficiency of Otto cycle, | = 60%

Ratio of specific heats, © = 1.5

Compression ratio, *r* = ?

Efficiency of Otto cycle is given by,

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

$$0.6 = 1 - \frac{1}{(r)^{1.5 - 1}}$$

$$\frac{1}{(r)^{0.5}} = 0.4 \quad \text{or} \quad (r)^{0.5} = \frac{1}{0.4} = 2.5 \quad \text{or} \quad r = 6.25$$

Hence, *compression ratio* **= 6.25. (Ans.)**

Example 13.8. *An engine of 250 mm bore and 375 mm stroke works on Otto cycle. The clearance volume is 0.00263 m*$_3$*. The initial pressure and temperature are 1 bar and 50°C. If the maximum pressure is limited to 25 bar, find the following :*

(*i*) *The air standard efficiency of the cycle.*

(*ii*) *The mean effective pressure for the cycle.*

Assume the ideal conditions.

Solution. Bore of the engine, $D = 250 \text{ mm} = 0.25 \text{ m}$

Stroke of the engine, $L = 375 \text{ mm} = 0.375 \text{ m}$

Clearance volume, $V_c = 0.00263 \text{ m}^3$

Initial pressure, $p_1 = 1 \text{ bar}$

Initial temperature, $T_1 = 50 + 273 = 323 \text{ K}$

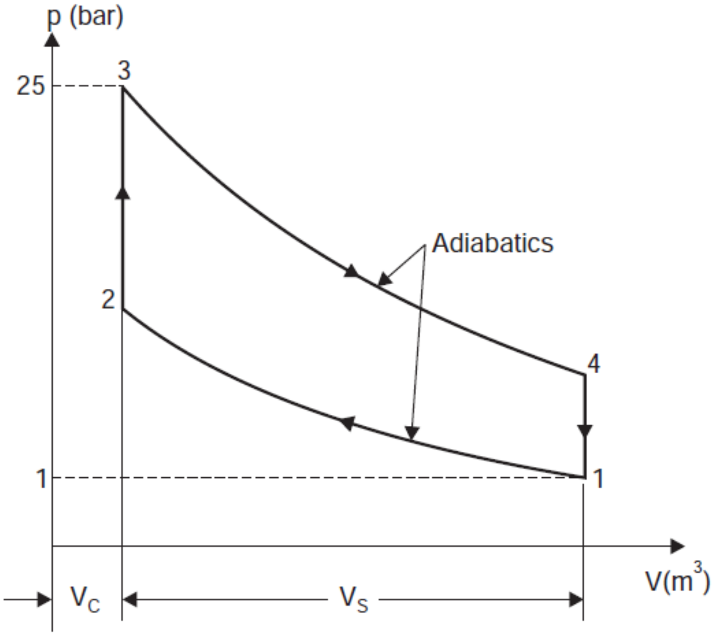


Fig. 13.6

Maximum pressure, $p_3 = 25 \text{ bar}$

Swept volume, $V_s = \pi/4\ D^2L = \pi/4 \times 0.25^2 \times 0.375 = 0.0184 \text{ m}^3$

Compression ratio, $$r = \frac{V_s + V_c}{V_c} = \frac{0.0184 + 0.00263}{0.00263} = 8.$$

(*i*) **Air standard efficiency :**

The air standard efficiency of Otto cycle is given by

$$\eta_{\text{Otto}} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(8)^{1.4-1}} = 1 - \frac{1}{(8)^{0.4}}$$

$$= 1 - 0.435 = \mathbf{0.565} \quad \textbf{or} \quad \mathbf{56.5\%.} \quad \textbf{(Ans.)}$$

(*ii*) **Mean effective pressure, p_m :**

For adiabatic (or isentropic) process 1-2

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}$$

$$p_2 = p_1 \left(\frac{V_1}{V_2}\right)^{\gamma} = 1 \times (r)^{1.4} = 1 \times (8)^{1.4} = 18.38 \text{ bar}$$

∴ Pressure ratio, $$r_p = \frac{p_3}{p_2} = \frac{25}{18.38} = 1.36$$

The mean effective pressure is given by

$$p_m = \frac{p_1 r[(r^{\gamma-1} - 1)(r_p - 1)]}{(\gamma - 1)(r - 1)} = \frac{1 \times 8\,[\{(8)^{1.4-1} - 1\}\,(1.36 - 1)]}{(1.4 - 1)\,(8 - 1)}$$

$$= \frac{8\,(2.297 - 1)(0.36)}{0.4 \times 7} = 1.334 \text{ bar}$$

Hence *mean effective pressure* = **1.334 bar. (Ans.)**

Diesel cycle

This cycle was introduced by Dr. R. Diesel in 1897. It differs from Otto cycle in that *heat is supplied at constant pressure instead of at constant volume*. Fig. 13.15 (*a* and *b*) shows the *p-v* and *T-s* diagrams of this cycle respectively.

This cycle comprises of the following ***operations*** :

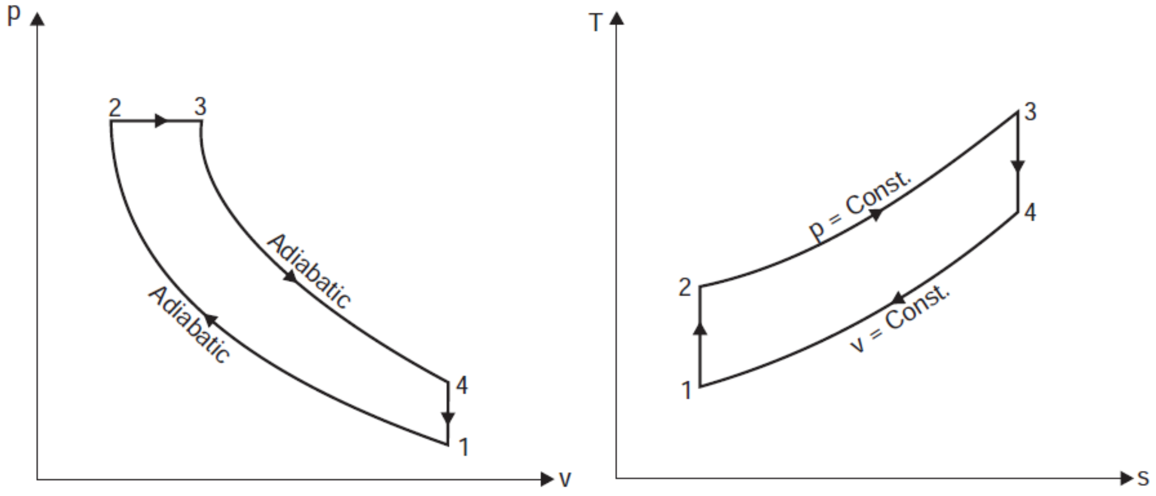
(*i*) 1-2......*Adiabatic compression*.

(*ii*) 2-3......*Addition of heat at constant pressure.*

(*iii*) 3-4......*Adiabatic expansion*.

(*iv*) 4-1......*Rejection of heat at constant volume.*

Point 1 represents that the cylinder is full of air. Let p_1, V_1 and T_1 be the corresponding pressure, volume and absolute temperature. The piston then compresses the air adiabatically (*i.e.,* pV© = constant) till the values become p_2, V_2 and T_2 respectively (at the end of the stroke) at point 2. Heat is then added from a hot body at a constant pressure. During this addition of heat let volume increases from V_2 to V_3 and temperature T_2 to T_3, corresponding to point 3. This point (3) is called the ***point of cut-off***. The air then expands adiabatically to the conditions p_4, V_4 and T_4 respectively corresponding to point 4. Finally, the air rejects the heat to the cold body at constant volume till the point 1 where it returns to its original state.



Consider 1 kg of air.

Heat supplied at constant pressure = $c_p(T_3 - T_2)$

Heat rejected at constant volume = $c_v(T_4 - T_1)$

Work done = Heat supplied – heat rejected

$= c_p(T_3 - T_2) - c_v(T_4 - T_1)$

$$\therefore \qquad \eta_{\text{diesel}} = \frac{\text{Work done}}{\text{Heat supplied}}$$

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

$$= 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} \qquad \ldots(i) \left[\because \frac{c_p}{c_v} = \gamma\right]$$

Let compression ratio, $r = \frac{v_1}{v_2}$, and cut-off ratio, $\rho = \frac{v_3}{v_2}$ *i.e.,* $\frac{\text{Volume at cut-off}}{\text{Clearance volume}}$

Now, during *adiabatic compression 1-2,*

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = (r)^{\gamma - 1} \quad \text{or} \quad T_2 = T_1 \, . \, (r)^{\gamma - 1}$$

During *constant pressure process 2-3,*

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = \rho \quad \text{or} \quad T_3 = \rho \, . \, T_2 = \rho \, . \, T_1 \, . \, (r)^{\gamma - 1}$$

During *adiabatic expansion 3-4*

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

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

$$\therefore \qquad T_4 = \frac{T_3}{\left(\frac{r}{\rho}\right)^{\gamma - 1}} = \frac{\rho \, . \, T_1 (r)^{\gamma - 1}}{\left(\frac{r}{\rho}\right)^{\gamma - 1}} = T_1 \, . \, \rho^{\gamma}$$

By inserting values of T_2, T_3 and T_4 in eqn. (*i*), we get

$$\eta_{\text{diesel}} = 1 - \frac{(T_1 \, . \, \rho^{\gamma} - T_1)}{\gamma\,(\rho \, . \, T_1 \, . \, (r)^{\gamma - 1} - T_1 \, . \, (r)^{\gamma - 1})}$$

$$\eta_{\text{diesel}} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1}\right]$$

It may be observed that eqn. (13.7) for efficiency of diesel cycle is different from that of the Otto cycle only in bracketed factor. This factor is always greater than unity, because 〉 > 1. Hence *for a given compression ratio, the Otto cycle is more efficient*.

The *net work* for diesel cycle can be expressed in terms of *pv* as follows :

$$W = p_2(v_3 - v_2) + \frac{p_3v_3 - p_4v_4}{\gamma - 1} - \frac{p_2v_2 - p_1v_1}{\gamma - 1}$$

$$= p_2\,(\rho v_2 - v_2) + \frac{p_3\rho v_2 - p_4rv_2}{\gamma - 1} - \frac{p_2v_2 - p_1rv_2}{\gamma - 1}$$

$$\left[\begin{array}{l} \because \dfrac{v_3}{v_2} = \rho \quad \therefore \; v_3 = \rho v_2 \;\text{ and } \dfrac{v_1}{v_2} = r \quad \therefore \; v_1 = rv_2 \\ \text{But } v_4 = v_1 \quad \therefore \quad v_4 = rv_2 \end{array}\right]$$

$$= p_2v_2\,(\rho - 1) + \frac{p_3\,\rho v_2 - p_4rv_2}{\gamma - 1} - \frac{p_2v_2 - p_1rv_2}{\gamma - 1}$$

$$= \frac{v_2\,[p_2\,(\rho - 1)(\gamma - 1) + p_3\rho - p_4r - (p_2 - p_1r)]}{\gamma - 1}$$

$$= \frac{p_1v_1r^{\gamma - 1}\,[\gamma(\rho - 1) - r^{1-\gamma}\,(\rho^{\gamma} - 1)]}{(\gamma - 1)}$$

Mean effective pressure p_m is given by :

$$p_m = \frac{p_1v_1r^{\gamma - 1}\,[\gamma(\rho - 1) - r^{1-\gamma}\,(\rho^{\gamma} - 1)]}{(\gamma - 1)v_1\left(\dfrac{r - 1}{r}\right)}$$

$$\mathbf{p_m} = \frac{p_1r^{\gamma}\,[\gamma(\rho - 1) - r^{1-\gamma}\,(\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)} \quad .$$

Example 13.17. *A diesel engine has a compression ratio of 15 and heat addition at constant pressure takes place at 6% of stroke. Find the air standard efficiency of the engine.*
Take © for air as 1.4.
Solution.

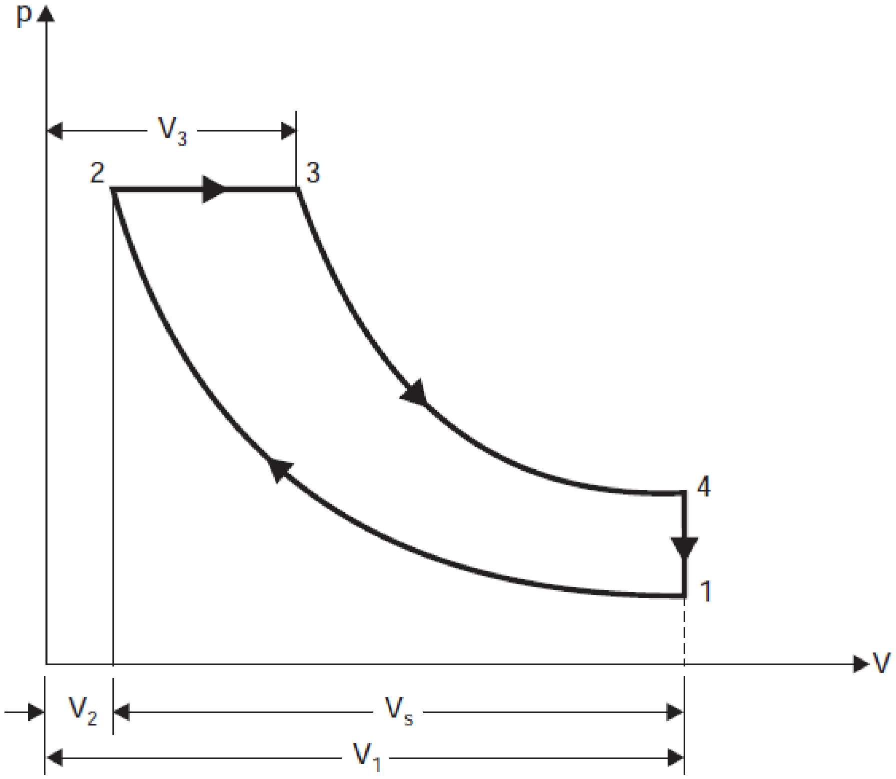


Fig. 13.16

Compression ratio, $r \left(= \frac{V_1}{V_2}\right) = 15$

γ for air = 1.4

Air standard efficiency of diesel cycle is given by

$$\eta_{\text{diesel}} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^{\gamma} - 1}{\rho - 1} \right]$$

where ρ = cut-off ratio = $\frac{V_3}{V_2}$

But $$V_3 - V_2 = \frac{6}{100} V_s \qquad (V_s = \text{stroke volume})$$

$$= 0.06\,(V_1 - V_2) = 0.06\,(15\,V_2 - V_2)$$

$$= 0.84\,V_2 \quad \text{or} \quad V_3 = 1.84\,V_2$$

$$\therefore \qquad \rho = \frac{V_3}{V_2} = \frac{1.84\,V_2}{V_2} = 1.84$$

Putting the value in eqn. (*i*), we get

$$\eta_{diesel} = 1 - \frac{1}{1.4\,(15)^{1.4-1}}\left[\frac{(1.84)^{1.4}-1}{1.84-1}\right]$$

$$= 1 - 0.2417 \times 1.605 = \mathbf{0.612 \text{ or } 61.2\%.} \quad \textbf{(Ans.)}$$

Example 13.18. *The stroke and cylinder diameter of a compression ignition engine are 250 mm and 150 mm respectively. If the clearance volume is 0.0004 m3 and fuel injection takes place at constant pressure for 5 per cent of the stroke determine the efficiency of the engine. Assume the engine working on the diesel cycle.*

Solution.

Length of stroke, $L = 250 \text{ mm} = 0.25 \text{ m}$

Diameter of cylinder, $D = 150 \text{ mm} = 0.15 \text{ m}$

Clearance volume, $V_2 = 0.0004 \text{ m}^3$

Swept volume, $V_s = \pi/4\, D^2 L = \pi/4 \times 0.15^2 \times 0.25 = 0.004418 \text{ m}^3$

Total cylinder volume = Swept volume + clearance volume

$= 0.004418 + 0.0004 = 0.004818 \text{ m}^3$

Volume at point of cut-off, $V_3 = V_2 + \frac{5}{100} V_s$

$$= 0.0004 + \frac{5}{100} \times 0.004418 = 0.000621 \text{ m}^3$$

$\therefore$ Cut-off ratio, $\rho = \frac{V_3}{V_2} = \frac{0.000621}{0.0004} = 1.55$

Compression ratio, $r = \frac{V_1}{V_2} = \frac{V_s + V_2}{V_2} = \frac{0.004418 + 0.0004}{0.0004} = 12.04$

Hence,

$$\eta_{diesel} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}}\left[\frac{\rho^{\gamma}-1}{\rho-1}\right] = 1 - \frac{1}{1.4 \times (12.04)^{1.4-1}}\left[\frac{(1.55)^{1.4}-1}{1.55-1}\right]$$

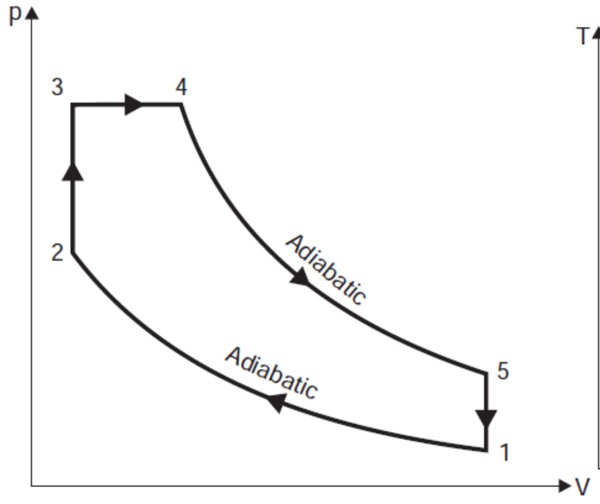
$$= 1 - 0.264 \times 1.54 = \mathbf{0.593 \text{ or } 59.3\%.} \quad \textbf{(Ans.)}$$

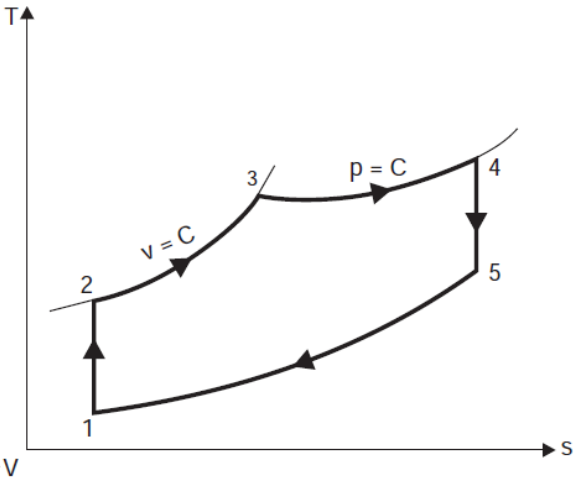
Dual cycle.

This cycle (also called the *limited pressure cycle or mixed cycle*) is a combination of Otto and Diesel cycles, in a way, that heat is added partly at constant volume and partly at constant pressure ; *the advantage of which is that more time is available to fuel (which is injected into the engine cylinder before the end of compression stroke) for combustion. Because of lagging characteristics of fuel this cycle is invariably used for diesel and hot spot ignition engines.*

The dual combustion cycle (Fig. 13.19) consists of the following **operations** :

(*i*) 1-2—*Adiabatic compression*
(*ii*) 2-3—*Addition of heat at constant volume*
(*iii*) 3-4—*Addition of heat at constant pressure*
(*iv*) 4-5—*Adiabatic expansion*
(*v*) 5-1—*Rejection of heat at constant volume.*





Consider 1 kg of air.

Total heat supplied = Heat supplied during the operation 2-3 + heat supplied during the operation 3-4

$$= c_v(T_3 - T_2) + c_p(T_4 - T_3)$$

Heat rejected during operation 5-1 $= c_v(T_5 - T_1)$

Work done = Heat supplied – heat rejected

$$= c_v(T_3 - T_2) + c_p(T_4 - T_3) - c_v(T_5 - T_1)$$

$$\eta_{\text{dual}} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{c_v(T_3 - T_2) + c_p(T_4 - T_3) - c_v(T_5 - T_1)}{c_v(T_3 - T_2) + c_p(T_4 - T_3)}$$

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

$$= 1 - \frac{c_v(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} \qquad \ldots(i) \qquad \left(\because \ \gamma = \frac{c_p}{c_v}\right)$$

Compression ratio, $r = \dfrac{v_1}{v_2}$

During *adiabatic compression process 1-2,*

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

During *constant volume heating process,*

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = \beta,$$ where β is known as **pressure or explosion ratio.**

$$T_2 = \frac{T_3}{\beta} \qquad ...(iii)$$

During *adiabatic expansion process,*

$$\frac{T_4}{T_5} = \left(\frac{v_5}{v_4}\right)^{\gamma - 1}$$

$$= \left(\frac{r}{\rho}\right)^{\gamma - 1} \qquad ...(iv)$$

$$\left(\because \ \frac{v_5}{v_4} = \frac{v_1}{v_4} = \frac{v_1}{v_2} \times \frac{v_2}{v_4} = \frac{v_1}{v_2} \times \frac{v_3}{v_4} = \frac{r}{\rho}, \rho \text{ being the cut-off ratio}\right)$$

During *constant pressure heating process,*

$$\frac{v_3}{T_3} = \frac{v_4}{T_4}$$

$$T_4 = T_3 \ \frac{v_4}{v_3} = \rho \ T_3 \qquad ...(v)$$

Putting the value of T_4 in the eqn. (*iv*), we get

$$\frac{\rho T_3}{T_5} = \left(\frac{r}{\rho}\right)^{\gamma - 1} \quad \text{or} \quad T_5 = \rho \ . \ T_3 \ . \left(\frac{\rho}{r}\right)^{\gamma - 1}$$

Putting the value of T_2 in eqn. (*ii*), we get

$$\frac{\dfrac{T_3}{\beta}}{T_1} = (r)^{\gamma - 1}$$

$$T_1 = \frac{T_3}{\beta} \cdot \frac{1}{(r)^{\gamma - 1}}$$

Now inserting the values of T_1, T_2, T_4 and T_5 in eqn. (*i*), we get

$$\eta_{\text{dual}} = 1 - \frac{\left[\rho \,.\, T_3\left(\dfrac{\rho}{r}\right)^{\gamma - 1} - \dfrac{T_3}{\beta} \cdot \dfrac{1}{(r)^{\gamma - 1}}\right]}{\left[\left(T_3 - \dfrac{T_3}{\beta}\right) + \gamma(\rho T_3 - T_3)\right]}$$

,

$$\eta_{\text{dual}} = 1 - \frac{1}{(r)^{\gamma - 1}} \cdot \frac{(\beta \,.\, \rho^{\gamma} - 1)}{[(\beta - 1) + \beta\gamma(\rho - 1)]}$$

Work done is given by,

$$W = \frac{v_3[p_3(\rho - 1)(\gamma - 1) + p_3(\rho - \rho^{\gamma} r^{1-\gamma}) - p_2(1 - r^{1-\gamma})]}{(\gamma - 1)}$$

$$= \frac{p_2 v_2[\beta(\rho - 1)(\gamma - 1) + \beta(\rho - \rho^{\gamma} r^{1-\gamma}) - (1 - r^{1-\gamma})]}{(\gamma - 1)}$$

$$= \frac{p_1 (r)^{\gamma} v_1/r[\beta\gamma(\rho - 1) + (\beta - 1) - r^{1-\gamma}(\beta\rho^{\gamma} - 1)]}{\gamma - 1}$$

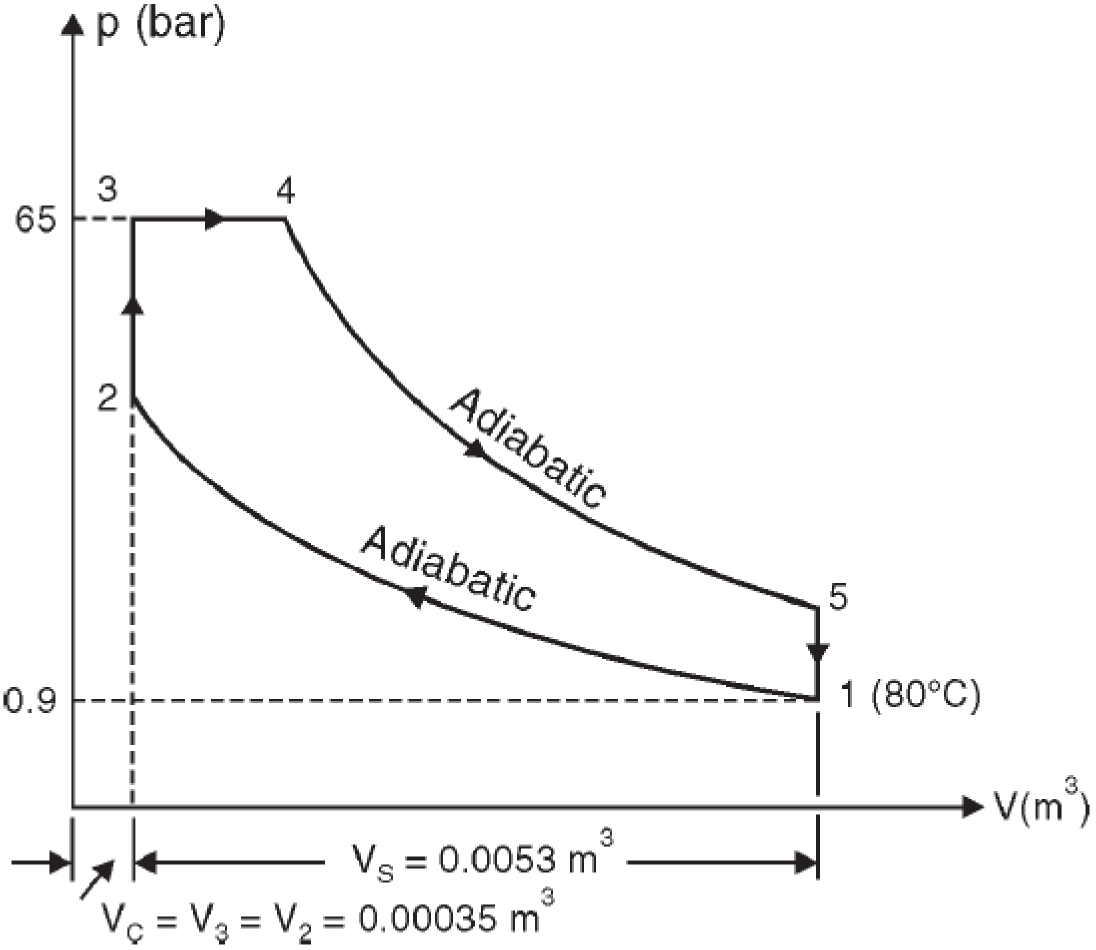
$$= \frac{p_1 v_1 r^{\gamma - 1}[\beta\gamma(\rho - 1) + (\beta - 1) - r^{\gamma - 1}(\beta\rho^{\gamma} - 1)]}{\gamma - 1} \qquad \ldots($$

Mean effective pressure (p_m) is given by,

$$\mathbf{p_m} = \frac{p_1(r)^{\gamma}[\beta(\rho - 1) + (\beta - 1) - r^{1-\gamma}(\beta\rho^{\gamma} - 1)]}{(\gamma - 1)(r - 1)}$$

Example 13.23. *The swept volume of a diesel engine working on dual cycle is 0.0053 m3 and clearance volume is 0.00035 m3. The maximum pressure is 65 bar. Fuel injection ends at 5 per cent of the stroke. The temperature and pressure at the start of the compression are 80°C and 0.9 bar. Determine the air standard efficiency of the cycle. Take © for air = 1.4.*

Solution.


p (bar)
65
0.9
3
4
2
5
1 (80°C)
Adiabatic
Adiabatic
V(m³)
V_S = 0.0053 m³
V_C = V_3 = V_2 = 0.00035 m³

Swept volume, $V_s = 0.0053 \text{ m}^3$
Clearance volume, $V_c = V_3 = V_2 = 0.00035 \text{ m}^3$
Maximum pressure, $p_3 = p_4 = 65$ bar
Initial temperature, $T_1 = 80 + 273 = 353$ K
Initial pressure, $p_1 = 0.9$ bar
$\eta_{\text{dual}} = ?$

The efficiency of a dual combustion cycle is given by

$$\eta_{\text{dual}} = 1 - \frac{1}{(r)^{\gamma-1}}\left[\frac{\beta \,.\, \rho^{\gamma} - 1}{(\beta - 1) + \beta\gamma(\rho - 1)}\right] \qquad \ldots(i)$$

Compression ratio, $$r = \frac{V_1}{V_2} = \frac{V_s + V_c}{V_c} = \frac{0.0053 + 0.00035}{0.00035} = 16.14$$

$[\because \; V_2 = V_c = \text{Clearance volume}]$

Cut-off ratio, $$\rho = \frac{V_4}{V_3} = \frac{\frac{5}{100}V_s + V_3}{V_3} = \frac{0.05V_s + V_c}{V_c} \qquad (\because \; V_2 = V_3 = V_c)$$

$$= \frac{0.05 \times 0.0053 + 0.00035}{0.00035} = 1.757 \text{ say } 1.76$$

Also during the *compression operation 1-2,*

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}$$

or $$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (16.14)^{1.4} = 49.14$$

or $$p_2 = p_1 \times 49.14 = 0.9 \times 49.14 = 44.22 \text{ bar}$$

Pressure or explosion ratio, $$\beta = \frac{p_3}{p_2} = \frac{65}{44.22} = 1.47$$

Putting the value of r, ρ and β in eqn. (i), we get

$$\eta_{\text{dual}} = 1 - \frac{1}{(16.14)^{1.4-1}}\left[\frac{1.47 \times (1.76)^{1.4} - 1}{(1.47 - 1) + 1.47 \times 1.4\,(1.76 - 1)}\right]$$

$$= 7 - 0.328\left[\frac{3.243 - 1}{0.47 + 1.564}\right] = \mathbf{0.6383 \text{ or } 63.83\%.} \quad \textbf{(Ans.)}$$

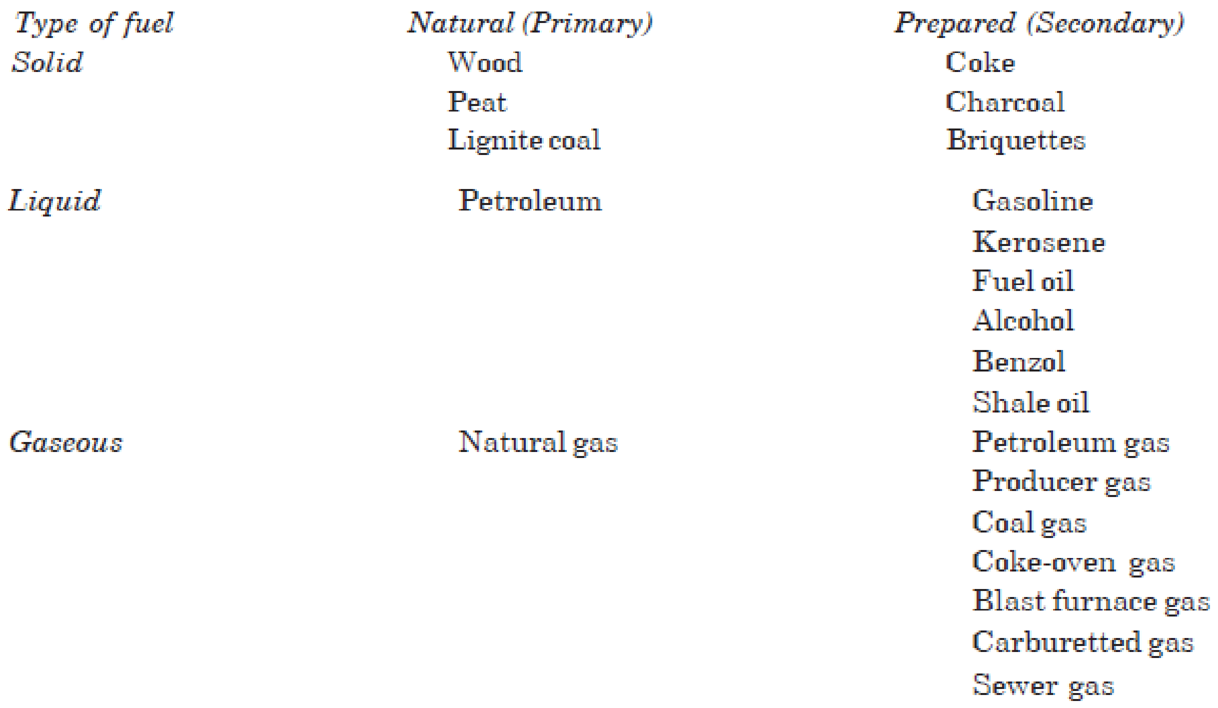
Fuels and Combustion

Fuel may be *chemical* or *nuclear*. Here we shall consider briefly *chemical fuels* only. *A chemical fuel is a substance which releases heat energy on combustion.* The principal combustible elements of each fuel are *carbon* and *hydrogen*. Though *sulphur* is a combustible element too but its presence in the fuel is considered to be *undesirable*.

CLASSIFICATION OF FUELS

Fuels can be classified according to whether :

1. They occur in nature called **primary fuels** or are prepared called **secondary fuels** ;
2. They are in solid, liquid or gaseous state. The detailed classification of fuels can be given in a summary form as follows :



Type of fuel	*Natural (Primary)*	*Prepared (Secondary)*
Solid	Wood	Coke
	Peat	Charcoal
	Lignite coal	Briquettes
Liquid	Petroleum	Gasoline
		Kerosene
		Fuel oil
		Alcohol
		Benzol
		Shale oil
Gaseous	Natural gas	Petroleum gas
		Producer gas
		Coal gas
		Coke-oven gas
		Blast furnace gas
		Carburetted gas
		Sewer gas

SOLID FUELS

Coal. Its main constituents are carbon, hydrogen, oxygen, nitrogen, sulphur, moisture and ash. Coal passes through different stages during its formation from vegetation. These stages are enumerated and discussed below : Plant debris—Peat—Lignite—Brown coal—sub-bituminous coal—Bituminous coal—Semibituminous coal—Semi-anthracite coal—Anthracite coal—Graphite.

Peat. It is the first stage in the formation of coal from wood. It contains huge amount of moisture and therefore it is dried for about 1 to 2 months before it is put to use. It is used as a domestic fuel in Europe and for power generation in Russia. In India it does not come in the categories of good fuels.

Lignites and brown coals. These are intermediate stages between peat and coal. They have a woody or often a clay like appearance associated with high moisture, high ash and low heat contents. Lignites are usually amorphous in character and impose transport difficulties as they break easily. They burn with a smoky flame. Some of this type are suitable for local use only.

Bituminous coal. It burns with long yellow and smoky flames and has high percentages of volatile matter. The average calorific value of bituminous coal is about 31350 kJ/kg. It may be of two types, namely *caking* or *noncaking.*

Semi-bituminous coal. It is softer than the anthracite. It burns with a very small amount of smoke. It contains 15 to 20 per cent volatile matter and has a tendency to break into small sizes during storage or transportation.

Semi-anthracite. It has less fixed carbon and less lustre as compared to true anthracite and gives out longer and more luminous flames when burnt.

Anthracite. It is very hard coal and has a shining black lustre. It ignites slowly unless the furnace temperature is high. It is non-caking and has high percentage of fixed carbon. It burns either with very short blue flames or without flames. The calorific value of this fuel is high to the tune of 35500 kJ/kg and as such is *very suitable for steam generation*.

Wood charcoal. It is obtained by destructive distillation of wood. During the process the volatile matter and water are expelled. The physical properties of the residue (charcoal), however depends upon the rate of heating and temperature.

Coke. It consists of carbon, mineral matter with about 2% sulphur and small quantities of hydrogen, nitrogen and phosphorus. It is solid residue left after the destructive distillation of certain kinds of coals. It is smokeless and clear fuel and can be produced by several processes. It is *mainly used in blast furnace* to produce heat and at the same time to reduce the iron ore.

Briquettes. These are prepared from fine coal or coke by compressing the material under high pressure.

LIQUID FUELS

The chief source of liquid fuels is *petroleum* which is obtained from wells under the earth's crust. These fuels have proved *more advantageous in comparison to sold fuels* in the following respects.

Advantages :

1. Require less space for storage.
2. Higher calorific value.
3. Easy control of consumption.
4. Staff economy.
5. Absence of danger from spontaneous combustion.
6. Easy handling and transportation.
7. Cleanliness.
8. No ash problem.
9. Non-deterioration of the oil in storage.

Petroleum. There are different opinions regarding the origin of petroleum. However, now it is accepted that petroleum has originated probably from organic matter like fish and plant life etc., by bacterial action or by their distillation under pressure and heat. It consists of a mixture of gases, liquids and solid hydrocarbons with small amounts of nitrogen and sulphur compounds. In India, the main sources of Petroleum are Assam and Gujarat. Heavy fuel oil or crude oil is imported and then refined at different refineries. The refining of crude oil supplies the most important product called *petrol*. Petrol can also be made by polymerization of refinery gases. Other liquid fuels are kerosene, fuels oils, colloidal fuels and alcohol.

GASEOUS FUELS

Natural gas. The main constituents of natural gas are *methane* (CH4) and *ethane* (C2H6).

It has calorific value nearly 21000 kJ/m3. Natural gas is used alternately or simultaneously with oil for internal combustion engines.

Coal gas. Mainly consists of *hydrogen, carbon monoxide* and *hydrocarbons*. It is prepared by carbonisation of coal. It finds its use in boilers and sometimes used for commercial purposes.

Coke-oven gas. It is obtained during the production of coke by heating the bituminous coal. The volatile content of coal is driven off by heating and major portion of this gas is utilised in heating the ovens. This gas *must be thoroughly filtered before using in gas engines.*

Blast furnance gas. It is obtained from smelting operation in which air is forced through layers of coke and iron ore, the example being that of pig iron manufacture where this gas is produced as by product and contains about 20% carbon monoxide (CO). After filtering it may be blended with richer gas or used in gas engines directly. The heating value of this gas is very low.

Producer gas. It results from the partial oxidation of coal, coke or peat when they are burnt with an insufficient quantity of air. It is produced in specially designed retorts. It has low heating value and in general is suitable for large installations. It is also used in steel industry for firing open hearth furnaces.

Water or illuminating gas. It is produced by blowing steam into white hot coke or coal. The decomposition of steam takes place liberating free hydrogen, and oxygen in the steam combines with carbon to form carbon monoxide according to the reaction : $C + H2O \rightarrow CO + H2$

The gas composition varies as the hydrogen content if the coal is used.

Sewer gas. It is obtained from sewage disposal vats in which fermentation and decay occur. It consists of mainly marsh gas (CH4) and is collected at large disposal plants. It works as a fuel for gas engines which in turn drive the plant pumps and agitators. Gaseous fuels are becoming popular because of following *advantages* they possess.

Advantages :

1. Better control of combustion.
2. Much less excess air is needed for complete combustion.
3. Economy in fuel and more efficiency of furnace operation.
4. Easy maintenance of oxidizing or reducing atmosphere.
5. Cleanliness.
6. No problem of storage if the supply is available from public supply line.
7. The distribution of gaseous fuels even over a wide area is easy through the pipe lines and as such handling of the fuel is altogether eliminated.
8. Gaseous fuels give economy of heat and produce higher temperatures (as they can be preheated in regenerative furnances and thus heat from hot flue gases can be recovered).

STOICHIOMETRIC AIR FUEL (A/F) RATIO

Stoichiometric (or chemically correct) *mixture* of air and fuel is one that contains *just sufficient oxygen for complete combustion of the fuel*.

A *weak mixture* is one which has an *excess of air*.

A *rich mixture* is one which has a *deficiency* of air.

The percentage of excess air is given as under :

$$\%\text{age excess air} = \frac{\text{Actural A/F ratio} - \text{Stoichiometric A/F ratio}}{\text{Stoichiometric A/F ratio}}$$

(where A and F denote *air* and *fuel* respectively)

The ratios are expressed as follows :

For *gaseous fuels By volume*

For solid and liquid fuels *By mass*

For *boiler* plant the mixture is usually greater than 20% weak ; for *gas turbines* it can be as much as 300% weak. *Petrol engines* have to meet various conditions of load and speed, and operate over a wide range of mixture strength. The following definition is used :

$$\text{Mixture strength} = \frac{\text{Stoichiometric A/F ratio}}{\text{Actual A/F ratio}}$$

The working value range between 80% (weak) and 120% (rich).

Note. The reciprocal of the air fuel ratio is called the *fuel-air (F/A) ratio*.

CALORIFIC OR HEATING VALUES OF FUELS

The "calorific value or heating value" of the fuel is defined as the energy liberated by the complete oxidation of a unit mass or volume of a fuel. It is expressed in kJ/kg for solid and liquid fuels and kJ/m3 for gases. If a fuel contains hydrogen water will be formed as one of the products of combustion. If this *water is condensed, a large amount of heat will be released* than if the water exists in the vapour phase. For this reason *two heating values* are defined ; the *higher or gross heating value* and the *lower* or *net heating value*. The *higher heating value*, HHV, is obtained when the *water formed by combustion is completely condensed*. The *lower heating value*, LHV, is obtained when the water formed by combustion exists *completely in the vapour phase*.

Thus :

$(HHV)p = (LHV)p + m\ hfg$

$(HHV)v = (LHV)v + m(ug - uf)$

where m = Mass of water formed by combustion,

hfg = Enthalpy of vaporisation of water, kJ/kg,

ug = Specific internal energy of vapour, kJ/kg, and

uf = Specific internal energy of liquid, kJ/kg.

In almost all practical cases, the water vapour in the products is vapour, the lower value is the one *which usually applies*.

Quality of I.C engine fuels Octane number, Cetane number

OCTANE Number • Knock quality is rated by comparing with Primary Reference Fuels (PRF) 1. Iso-octane, C_8H_{18} (2-2-4- trimethyl pentane) …….O.N. – 100 2. n-heptane, C_7H_{16} …….O.N. – 0 • The % by volume of Iso-octane in a mixture of isooctane and n- heptane which exactly matches the knocking intensity of the test fuel in a standard engine under a set of standard operating conditions is defined as the Octane Number. • Cooperative Fuel Research Engine (CFR); 900 rpm, 38 0C Intake T, Coolant temperature 100 0C, Ignition advance 13 BTDC

CETANE Number • Knock quality is rated by comparing with Primary Reference Fuels (PRF) • n-cetane, $C_{16}H_{34}$ …….C.N. – 100 • Alpha methyl naphthalene, $C_{11}H_{10}$ …….C.N. – 0 • The % by volume of n-cetane in a mixture of ncetane and Alpha methyl naphthalene which has the same ignition characteristics (ignition delay) as the test fuel in a standard engine under specified operating conditions is defined as Cetane Number. • Cooperative Fuel Research diesel Engine (CFR); 900 rpm, 65.5 0C Intake T, Coolant temperature 100 0C, injection advance 130 bTDC, ignition delay 130.