THERMODYNAMICS

BASIC DEFINITIONS

System

A specified space on which study or analysis is to be carried out is called as system.

Surroundings

The mass or region outside the system is called the surroundings.

Boundary

The real or imaginary surface that separated the system from its surroundings is called boundary. The Boundary of the system can be fixed or movable. Boundary may be real or imaginary.
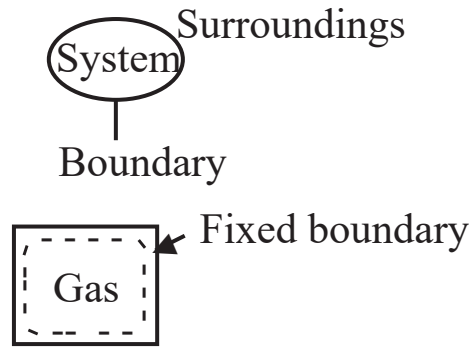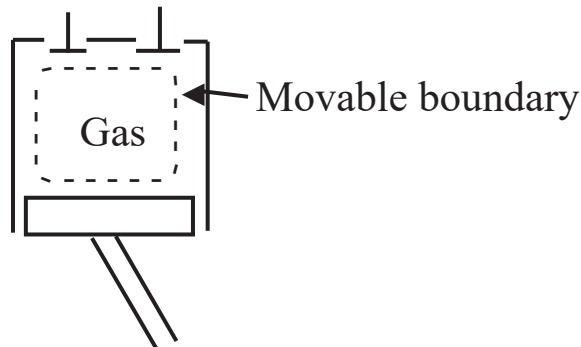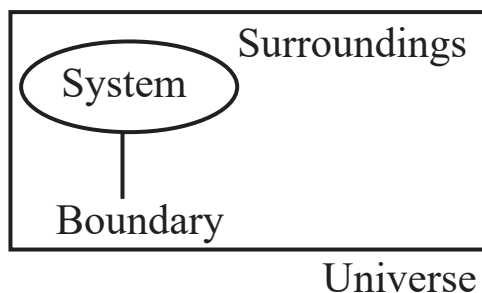

Figure 1 : Closed container

Figure 2 : Piston and Cylinder arrangement

Universe

The system and surroundings together called as universe

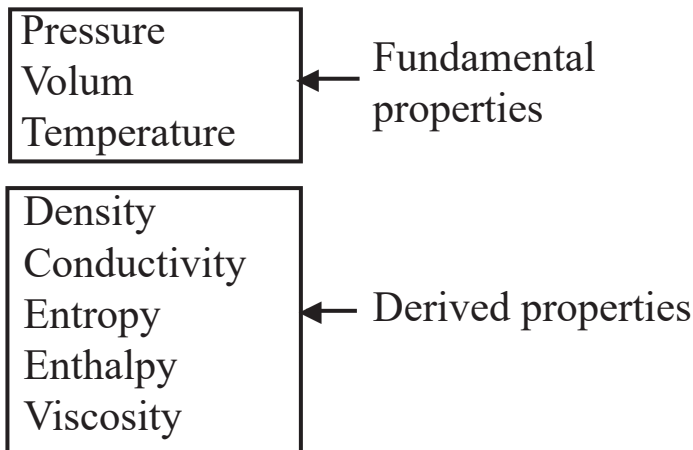## Classifications of the System

System is classified as :

1. Control mass system : Mass is fixed
   (i) Closed system
   (ii) Isolated system
2. Control volume system : Volume is fixed
   (i) Open system

Properties of a System

Any measurable characteristics od a system is called property.

Example : Pressure, temperature, volume, mass, viscosity, density, modulus of elasticity, thermal conductivity etc.

NOTE :

| Pressure
Volum
Temperature | ← Fundamental properties |
| Density
Conductivity
Entropy
Enthalpy
Viscosity | ← Derived properties |

Properties are classified into two types :

1. Intensive properties and
2. Extensive properties

Intensive Properties

Intensive properties are those that are independent of mass of a system.

Example : temperature, pressure, density, specific volume, specific mass.

Extensive Properties

Extensive properties are those that are dependent of mass of a system.

Example : Volume, momentum etc.

Consider a quantity of matter and divide into two equal parts as shown in figure.

Path Functions

The entities which cannot be represented by point, can be represented by area on co-ordinate system.
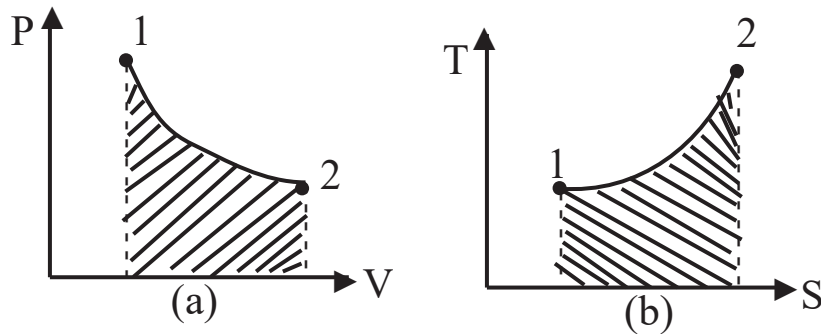
Example : Heat and work

Figure : (a) Area under P-V diagram = work transfer
(b) Area under T-S diagram = heat transfer

Continuum

Matter is made up of atoms that are widely spaced in the gas phase. It is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is a continuum. The continuum idealization allows us to treat properties as point function and to assume the properties vary continually in the space with no jump discontinuities.

Phase

If a quantity of matter is homogeneous or uniform throughout in physical structure and chemical composition is termed as phase.

Mechanical Equilibrium

It is related to pressure. A system will be in mechanical equillibrium is there is no change in pressure at any point of the system with time.
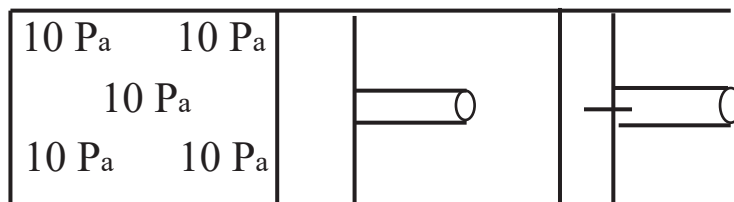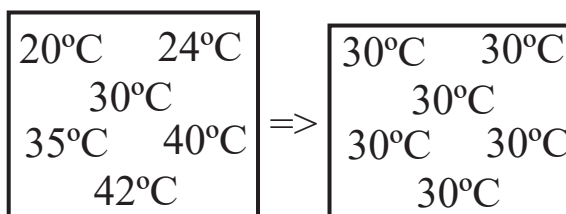
Example :

Figure : Slow compression, in mechanical equillibrium

Thermal Equilibrium

A system will be in thermal equillibrium if the temperature is the same througout the entire system.
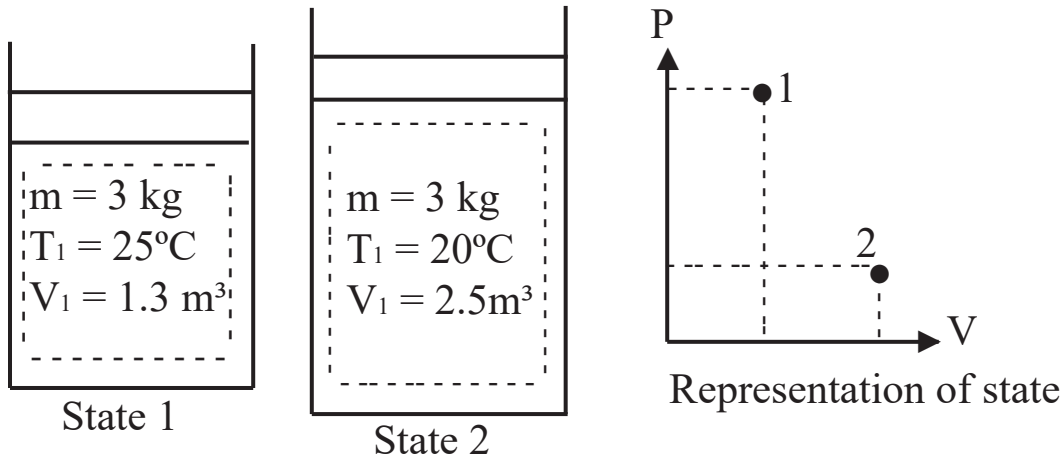
**Example :**

Chemical Equillibrium

A system is in chemical equilibrium if its chemical composition does not change with time i.e., no chemical reaction occurs. A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

State

Each and unique condition of the system is called stste. let a system shown in figure exist at different states.

State 1
$m = 3$ kg
$T_1 = 25°C$
$V_1 = 1.3$ m³

State 2
$m = 3$ kg
$T_1 = 20°C$
$V_1 = 2.5$m³

P

•1

2

V

Representation of state

When a body A is in thermal equilibrium with body B and body B is in thermal equilibrium with body C separately, then A and C are in thermal equilibrium.

A

C

B

$A \xrightarrow{TE} B$

$B \xrightarrow{TE} C$

$A \xrightarrow{TE} C$
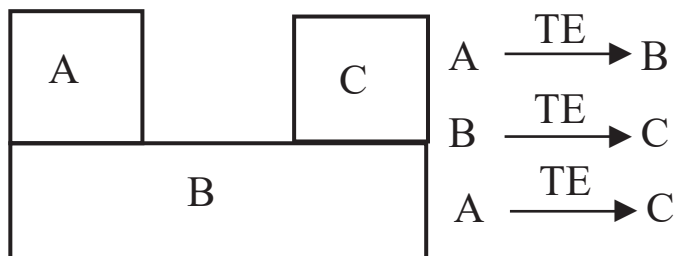
It serves the basic law of temperature measurement.

Temperature Scale

• A temperature scale is established by assigning numbrical values to certain reproducible ststes. It is customary to use the two fixed points - ice point and steam point.
• Ice point is the equilibrium temperature of ice with air saturated water at a pressure of 101.325 kPa which is assigned a value of 0°C.
• Steam point is the point where a mixture of liquid water and water vapour (with no air) is in equilibrium.

Gauge Pressure (P_{gauge})

Pressure measured with respect to atmospheric pressure is called gauge

pressure.

• Gauge pressure may be positive or negative.
• If the pressure lies above atmospheric pressure (i.e. at point A shown in figure) is called gauge pressure which is positive.
• If the pressure lies below atmospheric pressure (i.e. at point A' as shown in figure) is called vacuum pressure which is negative.

Absolute Pressure (P_{abs})
The pressure measure with respect to absolute zero pressure is called absolute pressure.

$$P_{abs} = P_{atm} + P_{gauge}$$

Energy Transfer
A closed system and its surroundings can interact in two ways.
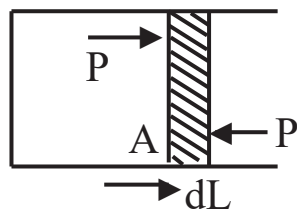1. By work transfer and
2. By heat transfer
   These are called as energy interactions and these bring about changes in the properties of the system.

Work Transfer
• In mechanics, work is defined as the product of force (F) and the distance (dL) moved in the direction of force.

$$dW = F \cdot dL$$

• Consider a piston-cylinder mechanism which is shown above. A pressure 'P' of the gas inside the cylinder is acting on a cross-sectional area 'A'. Then the force acting on the piston is PA. This force is balanced by an external opposing force. If the piston is allowed to move a distance 'dL' under these conditions such that opposing force is balanced by the gas pressure, then infinitesimal work done is given by

$$dW = FdL$$
$$= PA\ dL$$
$$= pdV$$

If there are two states 1 and 2, then the total work done is given by

$$W = \int_1^2 PdV$$ for non flow process

Heat Transfer

The energy transfer across the boundary by virtue of a temperature difference is called heat transfer.

• Heat is not an exact differential it is not a property of the system. It is a path function.

• Heat is a boundary phenomenon.

• Consider a geyser which is used to heat water.

• If we take water alone as a system, the interaction is heat interaction as the temperature of the water rises. If we take geyser and water as a system, there is only work interaction because geyser receives electrical energy from outside. And heat interaction is not there as the temperature difference occurs only inside the system.

• If heat is added into the system, it is taken as positive heat transfer and if heat is removed from the system, it is taken as neagtive heat transfer.
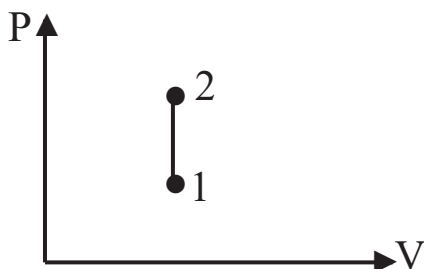
BASIC PROCESS
Non-Flow Process
Constant Volume Process (Isochoric Process)

$$V = C \text{ (Constant)}$$
$$dV = 0$$

Work done, $W = \int PdV = 0$

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

Constant Pressure Process (Isobaric Process)

$$P = C \text{ (Constant)}$$
$$dP = 0$$

Work done $W_{1\text{-}2} = P(V_2 - V_1)$

Constant Temperature Process (Isothermal Process)

$$T = C \text{ (Constant)}$$

$dT = 0$

$P_1V_1 = P_2V_2$

i.e., $PV = C$ => $P = \dfrac{C}{V}$

$W_{1\text{-}2} = \int_1^2 PdV = \int_1^2 \dfrac{C}{V}\, dV$

$\overset{2}{W}_{1\text{-}2} = C \ln \dfrac{V_2}{V_1}$

$$W_{1\text{-}2} = P_1V_1 \ln \dfrac{V_2}{V_1} = P_1V_1 \ln \dfrac{P_1}{P_2}$$

$$= P_2V_2 \ln \dfrac{V_2}{V_1} = P_2V_2 \ln \dfrac{P_1}{P_2}$$

$$= mRT_1 \ln \dfrac{V_2}{V_1}$$

$$= mRT_2 \ln \dfrac{V_2}{V_1}$$

Adiabatic Process

Adiabatic process is a process where heat transfer is zero. i.e. $Q = 0$. Also, any process which is very fast is called adiabatic process.

$PV^r = C$
$TV^{r-1} = C$ for an adiabatic process
$TP^{\frac{1-r}{r}} = C$ where $r = \dfrac{C_P}{C_v}$

$PV^r = C$ => $P = \dfrac{C}{V^r}$

$c\int_1^2 PdV = \int_1^2 \dfrac{C}{V^r}\, dV$

Polytropic Process

For a polytropic process,

$PV^n = C$
$TV^{n-1} = C$
$TP^{\frac{1-n}{n}} = C$ where $n = \dfrac{C_P}{C_v}$

Work done $W_{1\text{-}2} = \dfrac{P_1V_1 - P_2V_2}{n - 1}$

First Law of Thermodynamics

The first law of thermodynamics is also known as the 'Conservation of energy principle'. It states that 'energy can neither be created nor be destroyed during a process.' It can only change forms. Therefore every bit of energy should be accounted for during a process.

Example : A rock or stone at some elevation possesses some potential energy and part of this potential energy is converted to kinetic energy as the rock falls i.e., the decrease in potential energy ($mg\Delta z$) exactly equals the increase in kinetic energy.

First Law for a Closed System Undergoing a Cycle

Let a cycle completed by a system with two energy interactions. i.e., adiabatic work transfer W_{1-2} followed by heat transfer Q_{2-1}
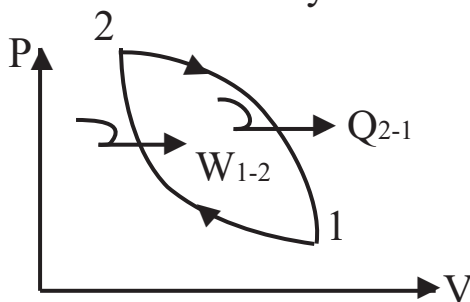
- W_{1-2} is always proportional to heat Q_{2-1}.
- The constant of proportionality is called Joule's equivalent or mechanical equivalent of heat.

$$\therefore (\Sigma W)_{cycle} = J(PQ)_{cycle}$$

Where J = Joule's equivalent

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

In S.I units J = 1 Nm

Mathematically first law of thermodynamics can be stated as $\boxed{\oint \partial Q = \oint \partial W}$ i.e. in a cyclic process the sum of heat interactions is equal to the sum of work interactionsin a cyclic process.
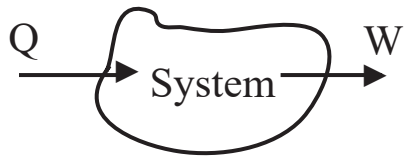
$$\therefore \oint \partial Q - \oint \partial W = 0$$

i.e. Q - W = a constant

Q - W = internal energy + kinetic energy + potential energy

First Law for a Closed System Undergoing a Change of State

If a system undergoes a change of state during which both heat transfer and work are involved, the net energy transfer will be stored within the system. This stored energy is called internal energy of the system.

$$Q - W = \Delta E$$
$$Q = \Delta E + W$$

But $\Delta E = \Delta PE + \Delta KE + \Delta U$

Where

ΔPE = change in potential energy

ΔKE = change in Kinetic energy

ΔU = change in Internal energy

In the absence of ΔKE and ΔPE

$$\Delta E = \Delta U$$
$$Q = \Delta E + W$$
$$Q = \Delta U + W$$
$$\delta Q = dU + \delta W$$

Enthalpy

$$H = U + PV$$

- $H \rightarrow$ Extensive property

- $h = \dfrac{H}{m}$, specific enthalpy is an intensive property

- $h = u + pv$

- **Joule's law :** Internal energy of an ideal gas is purely a function of temperature.

$$U = f(T)$$
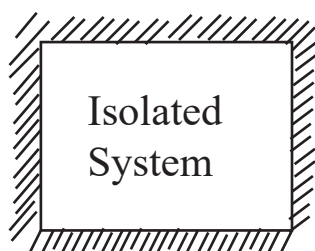$$H = U + PV$$

For an ideal gas $PV = RT$

$$H = U + RT$$
$$H = f(T) + RT$$
$$H = f(T)$$

The enthalpy of an ideal gas also depends on the temperature.

Energy of an Isolated System

$\delta Q = 0$

$\delta W = 0$

According to first law

$$\delta Q = dE + \delta W$$
$$dE = 0$$

E = constant

i.e., the energy of an isolated system is always constant.

Heat Transfer in Various Non-Flow Process Constant Volume Process

$$\delta Q = dU + \delta dW$$
$$\delta Q = dU + PdV$$
$$dV = 0 \ (\because V_1 = V_2)$$
$$\delta Q = dU$$
$$= mc_v \, dT \text{ for an ideal gas}$$

Constant Pressure Process

$$\delta Q = dU + PdV$$
$$P = constant$$
$$\delta Q = d(U + PV)$$
$$\delta Q = dH$$
$$= mc_p \, dT \text{ for an ideal gas}$$

Isothermal Process

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

For an ideal gas U = f(T)

$$\because \ T_1 = T_2 \, , \, dT = 0 \rightarrow du = 0$$
$$\delta Q = \delta W$$

Adiabatic Process

The amount of heat transfer in adiabatic process is zero.

Polytropic Process

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

Second law of Thermodynamics

Second law of thermodynamics follows two statements.

Kelvin-Plank Statement

'It is impossible to develop a device operating on a cycle and which produce work by exchanging heat with single reservoir.'

Such a device is known as perpetual motion machine of second kind.

Perpetual Motion Machine of Second Kind

It is a machine which interacts with single thermal reservoir and produce work.
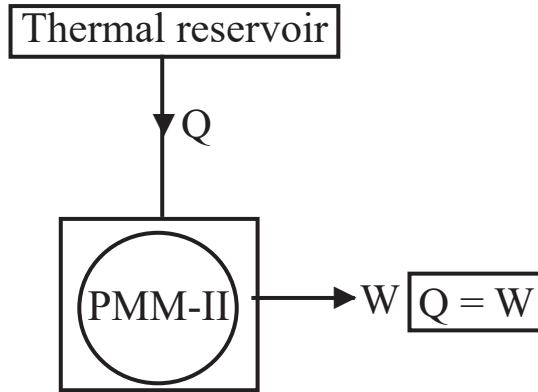
Efficiency of PMM-II $= \dfrac{\text{output}}{\text{input}} = \dfrac{W}{Q}$

$$= 100\% \ (\because W = Q)$$

$$\therefore \quad \eta_{\text{PMM-II}} = 100\%$$

Achieving 100% efficiency is impossible and hence PMM-II is impossible.

Heat Engine

Heat engine is a device which interacts with two Thermal reservoirs, converts part of heat into work and rejects remaining to sink or surrounding.
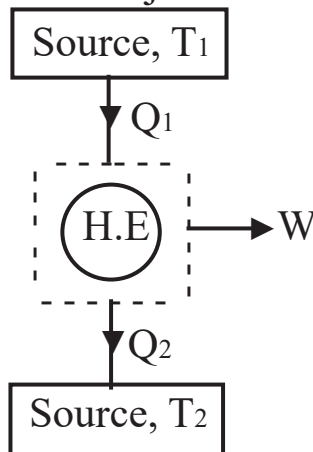

Figure : Heat engine operates on a cycle

Efficiency $= \dfrac{\text{Output}}{\text{Input}} = \dfrac{W}{Q_1}$

But $\quad Q_1 = W + Q_2$

$\qquad W = Q_1 - Q_2$

$\eta_{\text{H.E}} = \dfrac{Q_1 - Q_2}{Q_1}$

$\eta_{\text{H.E}} = 1 - \dfrac{Q_2}{Q_1}$

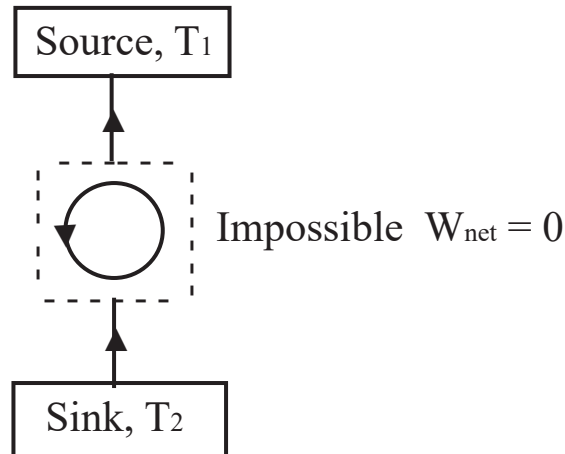Where

Q_1 = heat supplied (Q_S)

Q_2 = heat rejected (Q_R)

$$\eta_{H.E} = 1 - \frac{Q_R}{Q_S}$$

This equation is valid for any process (i.e. rev/irreversible process)
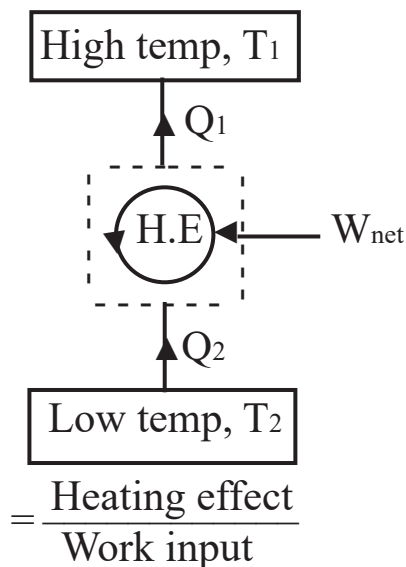
Clausius Statement

It is impossible to construct a device which transfers heat from low temperature reservoir to high temperature reservoir without any external input.

Source, T_1

Impossible $W_{net} = 0$

Sink, T_2

Heat Pump

It is a device which maintains higher temperature compared to surroundings.

$$\text{Co-efficient of performance (COP)} = \frac{\text{Desired effect}}{\text{Work input}}$$

High temp, T_1

Q_1

H.E $\longleftarrow W_{net}$

Q_2

Low temp, T_2

$$= \frac{\text{Heating effect}}{\text{Work input}}$$

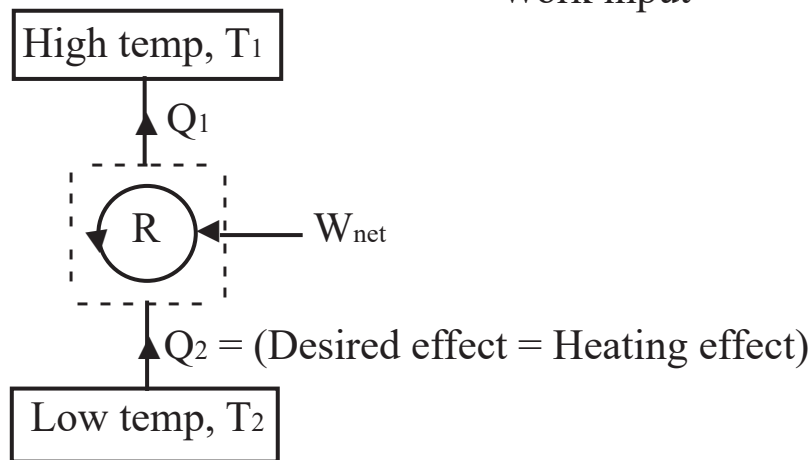$$(COP)_{H.P} = \frac{Q_1}{W_{net}} = \frac{Q_1}{Q_1 - Q_2}$$

Valid for any cycle (i.e. rev/irrev)

Refrigerator

Refrigerator is a device which maintains lower temperature compared to surrounding.

Co-efficient of performance (COP) $= \dfrac{\text{Desired effect}}{\text{Work input}}$

$\qquad\qquad\qquad\qquad\qquad = \dfrac{\text{Cooling effect}}{\text{Work input}}$

High temp, T_1

$\uparrow Q_1$

R $\leftarrow$ W_{net}

$\uparrow Q_2 = $ (Desired effect = Heating effect)

Low temp, T_2

$(COP)_R = \dfrac{Q_2}{W_{net}} = \dfrac{Q_2}{Q_1 - Q_2}$

Valid for any cycle (i.e. rev/irrev)

Carnot Cycle

• It is reversible cycle and ideal cycle.
• A cycle is said to be reversible cycle only when each process in a cycle is a reversible process.
• Carnot cycle is not a practical cycle but this cycle is used for comparing other cycles.
• Carnot cycle consists of two Isothermal process and two adiabatic processes.
• Isothermal process is a slow process and adiabatic process is a fast process and hence these two combinations in a single stroke is not possible.
• Kelvin-plank and Clausius statements can be defined on the basis of the Carnot cycle.

Refrigerator

Refrigerator is a device which maintains the temperature lower than the atmosphere temperature, continuously removing heat from it and doing work.

T_1

$\uparrow Q_1 = Q_2 + W$

$W = Q_1 - Q_2 \rightarrow$ R

$\uparrow Q_2$

T_2
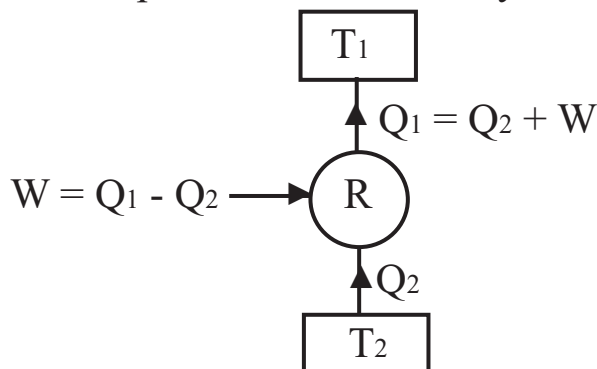
The efficiency of a refrigerator is expressed in terms of the coefficient of performance [COP].

Clausius Inequality

'When a system undergoes a complete cyclic process, the integral of $\frac{\delta Q}{T}$ around the cycle is less than zero or equal to zero.'

This is known as Clausius inequality.

$$\therefore \oint \frac{\delta Q}{T} \leq 0$$

$$\oint \frac{\delta Q}{T} = 0 \quad \text{For reversible cycle}$$

$$\oint \frac{\delta Q}{T} < 0 \quad \text{For irreversible cycle}$$

Entropy

Entropy is the measure of molecular disorderness. More the disorderness is, more the probability of not predicting the position of the molecules and less the efficiency will be.

Entropy Changes of a Closed System

1. The entropy will decrease when heat is removed from the system, all processes being reversible ones.
2. The entropy will remain constant when reversible adiabatic processes occur within a system.
3. The entropy will increase when heat is added to the system, reversibly or irreversibly.
4. The entropy of an isolated system will increase when irreversible processes occur within it.

Third Law of Thermodynamics

Definition : It is impossible by any procedure, no matter how idealized, to reduce any system to the absolute zero of temperature in a finite number of operation.

The 'entropy of a pure crystalline substance at absolute zero temperature is zero' since there is no uncertainty about the state of the molecules at that instant. This statement is known as the third law of thermodynamics.
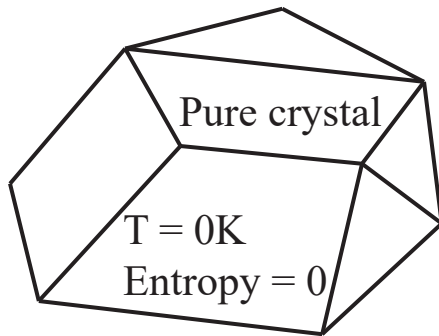
Figure : A pure substance at absolute zero temperature is in perfect order and its entropy is zero.

Notes :
1. The third law of thermodynamics provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is called absolute entropy.
2. There is no entropy transfer associated with energy transfer as work.

Availability and Irreversibility

1. Useful work
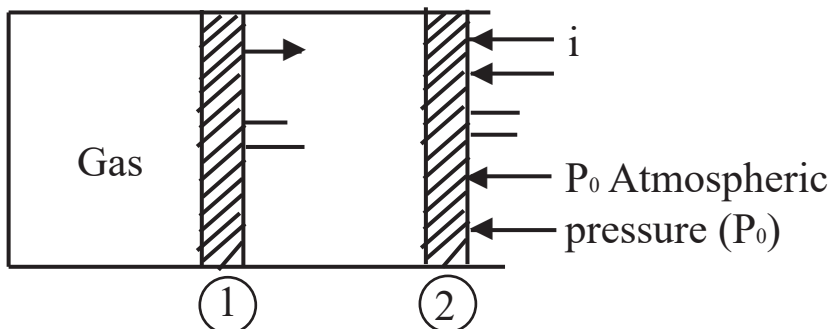
When the piston moves from initial position (1) to final position (2) i.e., the gas is expanding, work has been doneby the system, but some workis used to push the piston from (1) to (2) against atmospheric pressure and this work is not useful or not utilized for any useful purpose. This work is termed as surrounding work and is given by

$$W = P_0 (V_2 - V_1)$$

That is, $W_{surs} = P_0 (V_2 - V_1)$

The difference between the actual work 'W' and the surrounding work W_{surs} is called the useful work 'W_u'

$$W_u = W - W_{surs} = W - P_0 (V_2 - V_1)$$

Thermodynamics Relations

Theorem 1

$$dz = Mdx + Ndy$$

Is an exact differential equation when

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

Theorem 2

$$f = \phi(x, y, z)$$

$$\left(\frac{\partial x}{\partial y}\right)_f \cdot \left(\frac{\partial y}{\partial z}\right)_f \cdot \left(\frac{\partial z}{\partial x}\right)_f = 1$$

Theorem 3

$$z = \phi(x, y)$$

$$\left(\frac{\partial x}{\partial y}\right)_z \cdot \left(\frac{\partial y}{\partial z}\right)_x \cdot \left(\frac{\partial z}{\partial x}\right)_y = -1$$

Maxwell's Equations

1. Tds = du + pdv

   du = Tds - pdv, but exact differential equations are of the form

   dx = Mdx + Ndy

   Where M = T, x = s, N = -P, dx = ds, dy = dv

   $$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

   $$\left(\frac{\partial T}{\partial v}\right)_S = \left(\frac{\partial P}{\partial S}\right)_V \qquad (1)$$

2. Tds = dh - Vdp

   dh = Tds + Vdp, But exact differential equations are of the form

   dz = Mdx + Ndy

   Z = h, M = T, x = S, N = V, dx = ds, dv = dv

   $$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P \qquad (2)$$

ENGINES

Applications

1. Road vehicles such as trucks, tractors, etc.
2. Rail, aviation and marine.
3. Lawn mowers, motorboats, concrete mixing equipment etc.

Difference Between Steam Engine and I.C Engine

Steam Engine	IC Engine
1. Combustion takes place outside the engine i.e., steam is generated outside the plant.	(a) Combustion takes place inside the engine
2. Operates at less temperature, 600ºC	(b) Operates at temperature about 2300ºC
3. Does not require cooling system	(c) Requires cooling system
4. Exhaust of steam is used as feedwater by feeding into the	(d) Exhaust gases are simple fed into the atmosphere
5. Efficiency is very low - 15 to 20% condenser.	(e) Efficiency is high - 30 to 35%

Classification of I.C. Engines

I.C. Engines are classified based on following parameters :

Number of Strokes Per Cycle

1. 4-Stroke-Cycle is completed in four strokes and two revolutions of the crankshaft.
2. 2-Stroke engine-Cycle is completed in two strokes and one revolution of the crankshaft.

Nature of Thermodynamic Cycle

1. Constant volume combustion (Otto cycle)
2. Constant pressure combustion (diesel cycle)
3. Partly constant volume and pressure combustion (dual or mixed cycle)

Ignition System

1. Spark Ignition (S.I) engine : Spark plug is used for combustion (petrol engine).
2. Compression ignition (C.I engine) : Combustion starts automatically due to compression (diesel engine)

Fuel Used

1. Gas engine : Uses gaseous fuels such as methane, etc.
2. Petrol engine : Uses highly volatile liquid level such as petrol.
3. Oil engine : Uses less volatile liquid fuel such as diesel oil, kerosene, heavier residual fuels.
4. Bi-fuel engine : Gas is used as basic fuel. Liquid fuel is used for starting purpose.

Terminology Used in I.C. Engine
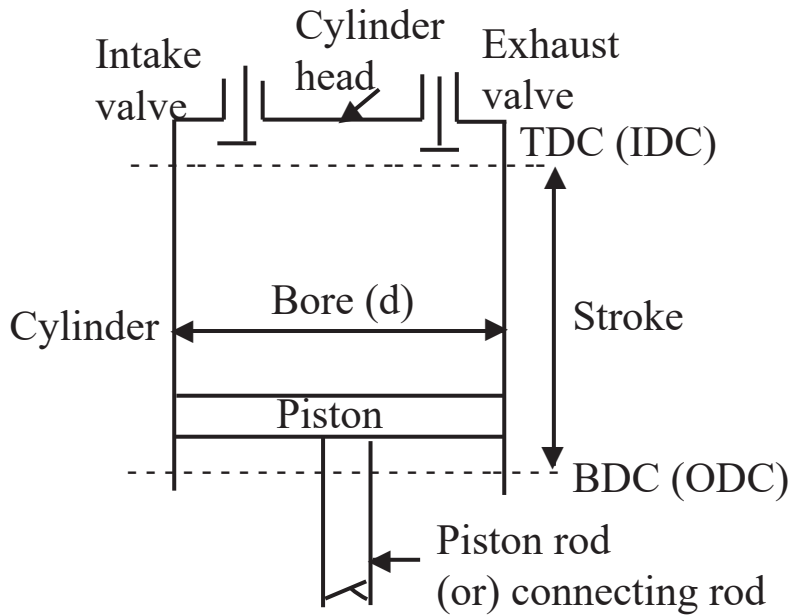
Bore The diameter of the piston is called bore (d).

Stoke The maximum distance travelled by the piston in the cylinder in one direction is known as stroke.
1 stroke = 2 × radius of crank

Top dead centre (TDC) or (IDC) The extreme position piston at the top of the cylinder is called TDC or IDC in case of horizontal engine.

Bottom dead centre (BDC) or ODC The extreme position of piston at the bottom of the cylinder is called BDC or ODC in case of horizontal engine.

Stroke length The distance between extreme positions is called stroke length.

Clearance volume (Vc) The volume contained in the cylinder above the top of the piston when the piston is at TDC.

Swept volume (or) piston displacement Volume swept by the piston in moving between TDC and BDC is called swept volume.

NOTES

1. Displacement volume (or) swept volume
   (V_S) = piston area × stroke
   $$V_S = \frac{\pi}{4} d^2 \times L$$
2. Total volume = $V_S + V_C$

Compression ratio (r)

$$\frac{\text{maximum volume formed in the cylinder}}{\text{minimum volume}}$$

$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}} = \frac{V_C + V_S}{V_C}$$

$$r = 1 + \frac{V_S}{V_C}$$

> **NOTES**
> 1. Petrol engine : $r \rightarrow 5 : 1$ to $7 : 1$
> 2. Diesel engine : $r \rightarrow 14 : 1$ to $22 : 1$
> 3. Compression ratio is only volume ratio not related to pressure ratio.

Clearance ratio (C)

$$\frac{\text{clearance volume}}{\text{stroke volume}} = \frac{V_C}{V_S}$$

Relationship between C and r

$$\therefore r = 1 + \frac{V_S}{V_C} = 1 + \frac{1}{C}$$

$$r = 1 + \frac{1}{C}$$

Combustion in S.I Engine

Homogeneous mixture In S.I engine mixture of air and fuel is formed in the carburetor, outside the engine cylinder.

Combustion is initiated inside the cylinder at the end of compression stroke.

Normal flame velocity $\rightarrow$ velocity of flame i.e., 40 cm/s

$$\text{Equivalence ratio } (\phi) = \frac{\text{actual fuelair ratio}}{\text{stoichio metric fuel}} = 1.0$$

In S.I engine maximum flame speed at ϕ - 1.1 to 1.2. That is, when φ is out of the above range, flame speed drops rapidly to a low valve.

Heterogeneous mixture Combustion can take place in an overall lean mixture.

Combustion in C.I Engines

In C.I engine the air-fuel mixture is not homogeneous and AFR in the various parts of the combustion chamber is different.

Fuel is injected all at once but continuous over a number of degree of crank angles/up to about 35º.

In S.I engine too lean mixture cannot support the combustin, but in C.I engine burning can take place in a mixture which is infinitely lean.

(1) Start of ignition
(2) Start of combustion
(3) End of ignition
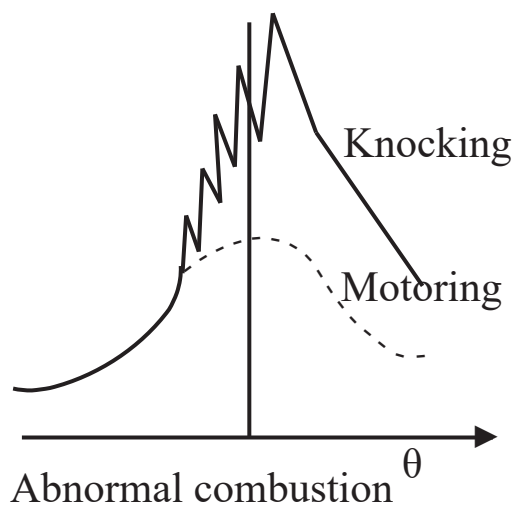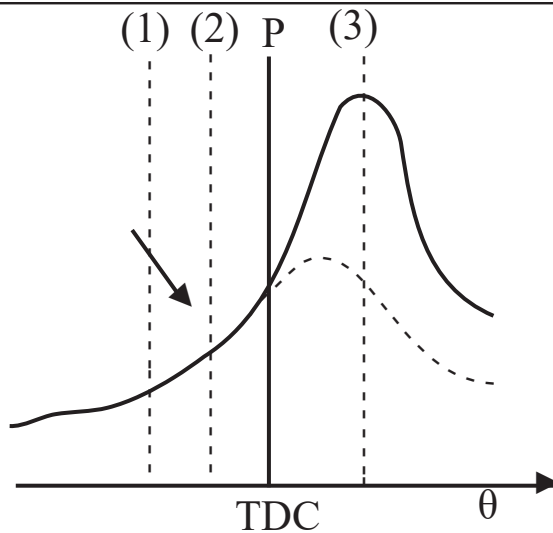
1. Start of ignition
2. Start of combustion
3. End of ignition

PERFORMANCE I.C. ENGINES
Engine Performance Parameters

Continuous power Power which the engine is capable of delivering continuously b/w the normal maintenance intervals.

Indicated power (IP) Power developed in its cylinder measured by pressure indicator connected to cylinder head.

Work done per minute $= P_m \times A \times L \times n$ N - m

Power developed at the engine cylinder

$$IP = \frac{P_m\, ALn}{60}$$

$$IP = \frac{P_m\, ALnk}{60}\ W$$

$$IP = \frac{P_m\, ALnk}{60{,}000}\ kW$$

Where P_m = m.e.p. in N/m²

A = Area of c/s of piston in m²

L = Length of stroke in m

n = Number of working stroke per minute or number of explosions per minute.

Efficiencies

Indicated thermal efficiency

$$(\eta_{l\,th}) = \frac{IP}{\text{Energy supplied per second (kJ/S)}} = \frac{IP}{m_f \times c.v}$$

Where m_f = mass of fuel; CV = calorific value of fuel

The indicated thermal efficiency of modern engines is about 28%.

Brake thermal efficiency

$$\text{Brake thermal efficiency} = \frac{BP}{m_f \times C.V}$$

For S.I engine $\eta_b{}^{th}$ = 25% - 33%

For C.I engine $\eta_b{}^{th}$ = 30% - 45%

Mechanical Efficiency

$$\eta_m = \frac{BP}{IP}$$

Mechanical efficiency of engines varies from 65 to 85%.

Volumetric efficiency Important parameters, which decides the performance of 4-stroke engines.

Engine must be able to take in as much air as possible.

$$\eta_{vol} = \frac{\text{Volume flow rate of air in to the intake system}}{\text{Total volume displaced}}$$

It is the ratio of volume of air drawn in to the volume of air that can be drawn in at standard pressure temperature conditions

$$\eta_{vol} = \frac{m_a}{\rho_a\, V_{disp}} \left(\frac{N}{2}\right), \rho_a = \text{density of air}$$

$$\eta_{vol} = \frac{m_a}{\rho_a\, V_d}$$

```
                    ┌─────────────────────┐
                    │ Thermodynamic cycles│
                    └─────────────────────┘
                               │
        ┌──────────────┐  Divided depending      ┌─────────────────────┐
        │ Power cycles │◄─ on phase of the       │ Refrigeration cycles│
        └──────────────┘  working fluid          └─────────────────────┘
            │
    ┌───────────┐        ┌──────────────┐
    │ Gas power │        │ Vapour power │
    │  cycles   │        │   cycles     │
    └───────────┘        └──────────────┘
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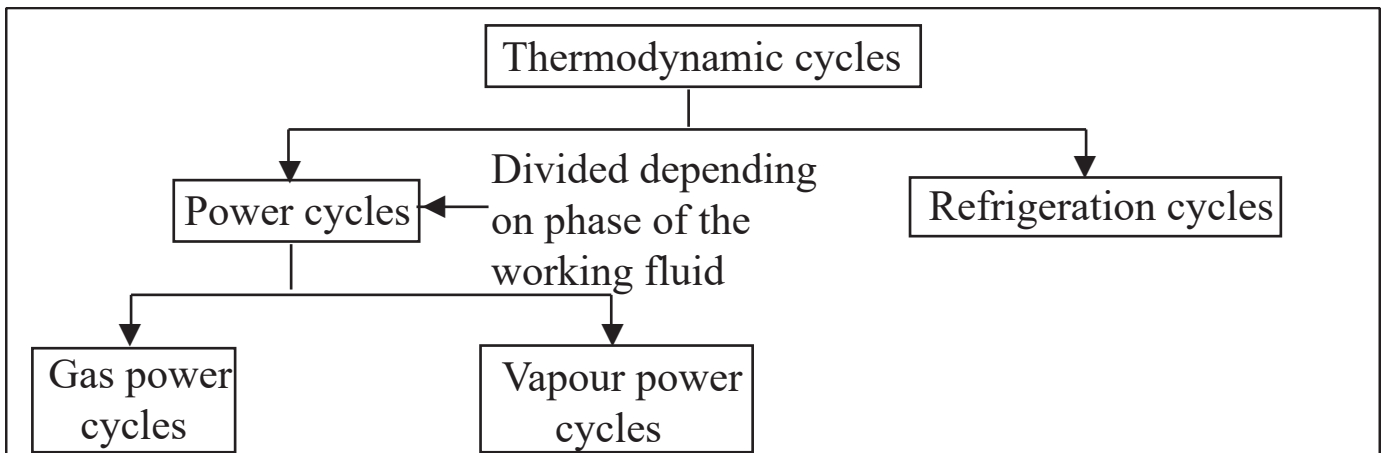
- The devices or systems used to produce a net power output are often called engines, and the thermodynamic cycles they operate on are called power cycles.
- The devices or systems used to produce a refrigeration effect are called refrigerators, cycles.

Gas Power Cycles

The working fluid remains in the gaseous phase throughout the entire cycle.

Vapour Power Cycles

Working fluids exists in the vapour phase during one part of the cycle and in the liquid phase during another part.

Power Cycles

Elements of thermodynamics power cycles :

1. Working fluid
2. Heat source and sink
3. Arrangement

Air Standard Cycles

- Working fluid is pure air.
- In gas power plants such as IC engines and gas turbines, the working fluid remains gas throughout the cycle.
- The plants take in either a mixture of air and fuel separately compresses it to a high pressure, and cause it to burn in a combustion chamber liberating heat energy.
- The product of combustion at high pressure, temperature expands and do work and the exhaust leaves the engine or turbine.
- In most of the gas power cycles, the working fluid consists mainly air.

ENTRI
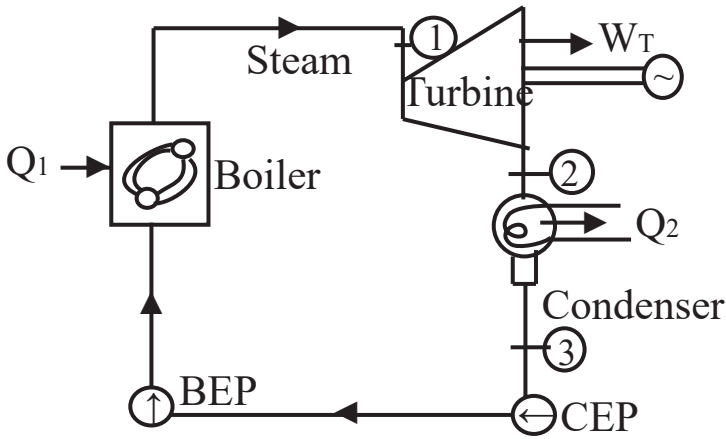
Rankine Cycle

BEP : Boiler feed pump
CEP : Condensate extraction pump
Basic elements of steam power plant :
(i) Boiler
(ii) Steam turbine
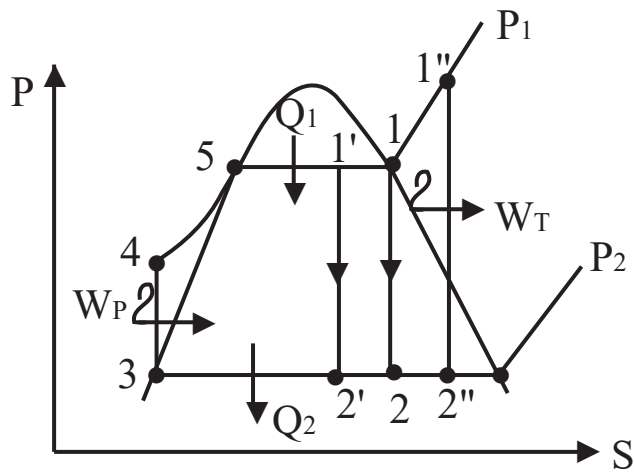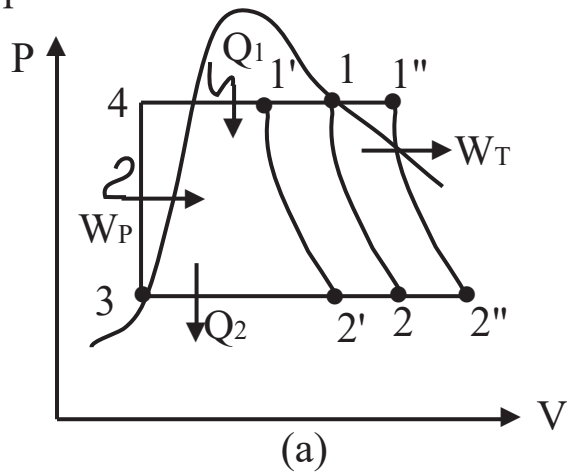(iii) Condenser
(iv) Feed pump

(a)

Figure : Rankine cycle (a) P-V diagram (b) T-S diagram

Processes :

1 - 2 :   Isentropic expansion (Turbine)
2 - 3 :   Constant pressure heat rejection (Condenser)
3 - 4 :   Pumping process
4 - 5 :   Sensible heating
5 - 1 :   Constant pressure heat addition (Latent heat of vaporization)

Gas Power Cycles
Carnot Cycle

It consists of the following reversible processes :

1 - 2 : Isothermal heat addition process
2 - 3 : Isentropic expansion
3 - 4 : Isothermal heat rejection process
4 - 1 : Isentropic compression
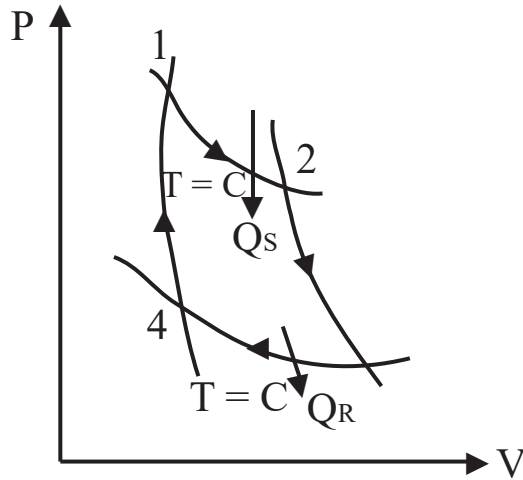
Figure : P-V diagram
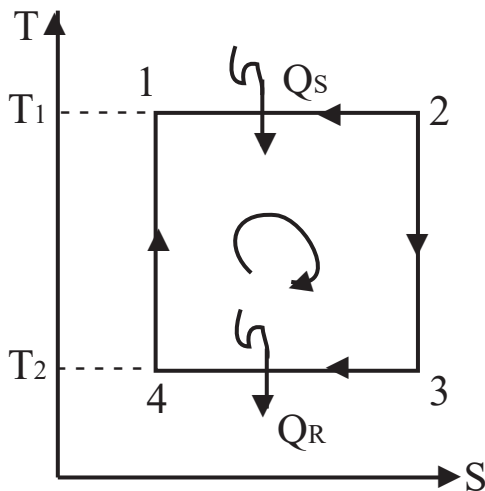
Figure : T-S diagram

- Thermal efficiency, $\eta_{carnot} = \dfrac{W_{net}}{Q_S} = \dfrac{Q_S - Q_R}{Q_S}$

$$= 1 - \dfrac{Q_R}{Q_S}$$

- $\eta_{carnot} = \dfrac{T_1 - T_2}{T_1} = 1 - \dfrac{T_2}{T_1}$

- Carnot cycle is ideal cycle used to compare the other thermodynamic cycles.
- Carnot cycle is not possible practically.

Otto Cycle (Constant Volume Cycle)

- Invented by Dr. A.N Otto (1876), a German scientist, for spark ignition IC engine.
- Heat addition takes place at constant volume hence it is named as constant volume cycle.

Cycle consists of the following reversible processes :

1 - 2 : Isentropic compression
2 - 3 : Constant volume heat addition
3 - 4 : Isentropic expansion
4 - 1 : Constant volume heat rejection
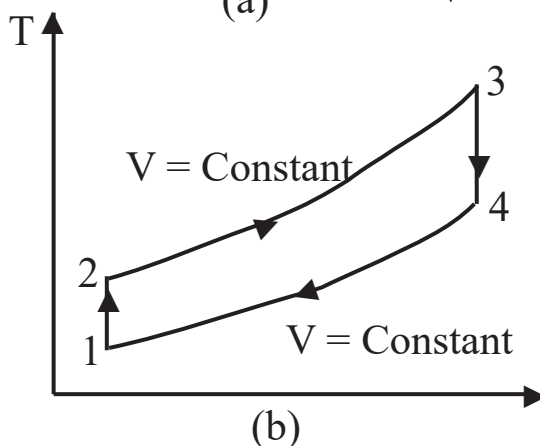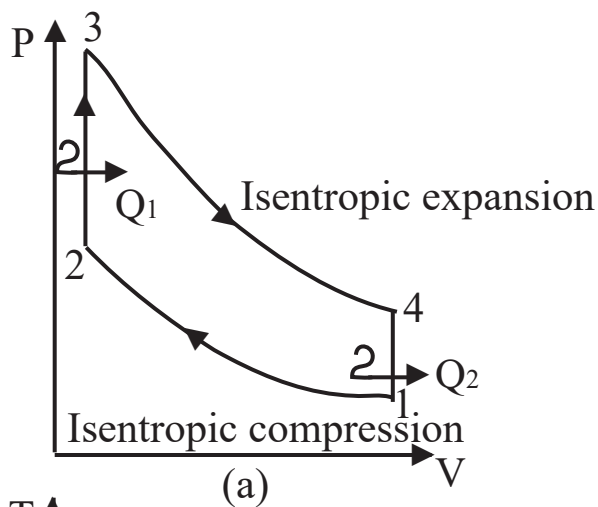
Figure : Ideal Otto cycle (a) P-V diagram ; (b) T-S diagram

Heat supplied $Q_1 = Q_{2-3} = mc_v(T_3 - T_2)$

Heat rejected $Q_2 = Q_{4-1} = mc_v(T_4 - T_1)$

Efficiency $\eta = 1 - \dfrac{Q_2}{Q_1} = 1 - \dfrac{(T_4 - T_1)}{(T_3 - T_2)}$

For process 1 - 2 ; $\dfrac{T_2}{T_1} = \left(\dfrac{V_1}{V_2}\right)^{\gamma-1}$

For process 3 - 4 ; $\dfrac{T_3}{T_4} = \left(\dfrac{V_4}{V_3}\right)^{\gamma-1} = \left(\dfrac{V_1}{V_2}\right)^{\gamma-1}$

$\therefore \dfrac{T_2}{T_1} = \dfrac{T_3}{T_4} = \dfrac{T_3}{T_2} = \dfrac{T_4}{T_1}$

$\therefore \eta_{otto} = 1 - \dfrac{T_2}{T_1}$

$\eta_{otto} = 1 - \dfrac{1}{(r)^{\gamma-1}}$

where r = compression ratio = $\dfrac{V_1}{V_2}$

γ = specific heat ratio = $\dfrac{C_P}{C_V}$

Compression ratio (r)

The thermal efficiency of the Otto cycle increases with the specific heat ratio (γ) of the working fluid.

Work Output

$W_{net} = \dfrac{P_1 V_1}{\gamma - 1}(\gamma_p - 1)(r^{\gamma-1} - 1)$

where $r_p = \dfrac{P_3}{P_2} = \dfrac{P_4}{P_1}$ pressure ratio

Mean Effective Pressure

$P_{mep} = \dfrac{\text{Net work output}}{\text{Swept volume}}$

$P_m = \dfrac{P_1 r(\gamma_p p - 1)(r^{\gamma-1} - 1)}{(\gamma - 1)(r - 1)}$

Diesel Cycle (Constant Pressure Cycles)

• It is proposed by Rudolph Diesel in the 1890s. In SI engines, a mixture of fuel and air is compressed during the compression stroke, and the compression ratios are limited by the onset of the auto-ignition or engine knock. In diesel engines, only air is compressed during the compression

stroke, eliminating the possibility of auto-ignition. Therefore, diesel engines are designed to operate at much higher compression ratios, typically between 12 and 24.

• Heat addition takes place at constant pressure hence it is named as constant pressure cycles.

Processes :

1 - 2 : Isentropic Compression

2 - 3 : Constant pressure heat addition

3 - 4 : Isentropic expansion
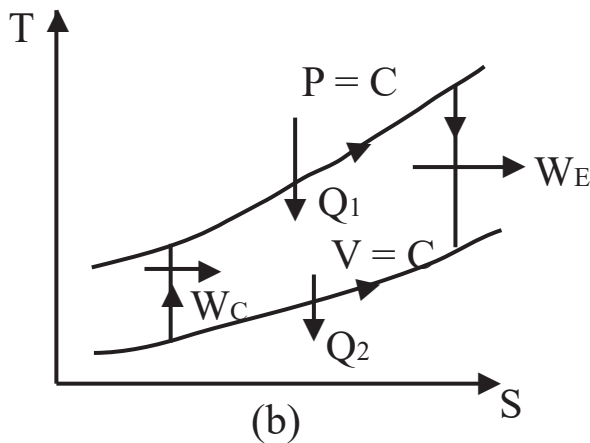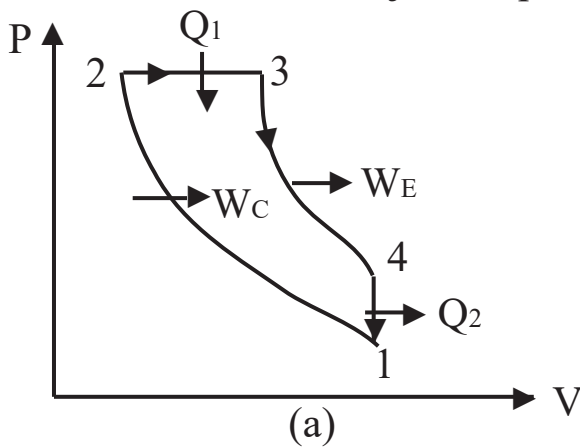
4 - 1 : Constant volume heat rejection process.

(a)

(b)

Figure : Diesel cycle (CI engines) (a) P-V diagram ; T-S diagram

Thermal Efficiency

$$\eta_{th} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{C_P (T_3 - T_2) - C_V (T_4 - T_1)}{C_P (T_3 - T_2)}$$

$$= 1 - \frac{1}{\gamma} \left[\frac{T_4 - T_1}{T_3 - T_2} \right]$$

Let cut-off ratio $(\alpha_C) = \dfrac{V_3}{V_2}$

$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}} \left[\frac{\alpha_C{}^\gamma - 1}{\gamma(\alpha_C - 1)} \right]$$

Dual Cycle (Limited Pressure Cycle)
• In dual cycle, part of heat addition takes place of constant volume and rest at constant pressure.
• The dual cycle is also called mixed or limited pressure cycle.

Processes :
1 - 2 : Reversible adiabatic compression
2 - 3 : Constant volume heat supply
3 - 4 : Constant pressure heat supply
4 - 5 : Reversible adiabatic expansion
5 - 1 : Constant volume heat rejection
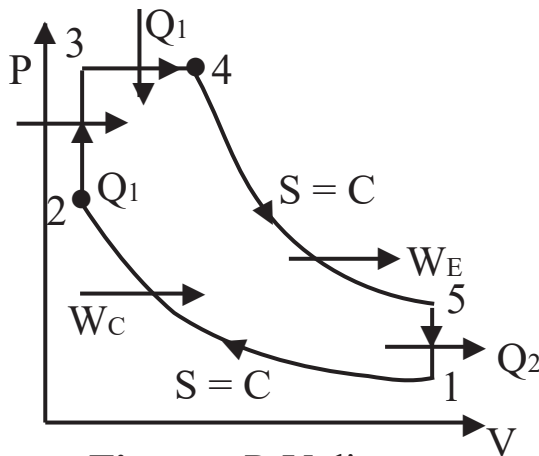
Figure : P-V diagram
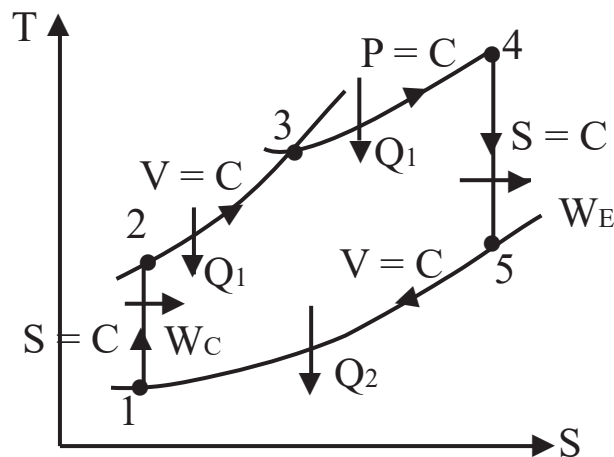
Figure : T-S diagram

Compression ratio $r = \dfrac{V_1}{V_2}$

Expansion ratio $r_e = \dfrac{V_5}{V_4}$

Cut-off ratio $\alpha_C = \dfrac{V_4}{V_3}$

Constant volume pressure ratio, $r_p = \dfrac{P_3}{P_2}$

Thermal Efficiency

$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}} \left[\frac{(\gamma_p \, \alpha_C{}^\gamma - 1)}{(\gamma_p - 1) + \gamma r_p \,(\alpha_C - 1)} \right]$$

Stirling Cycle (1827)

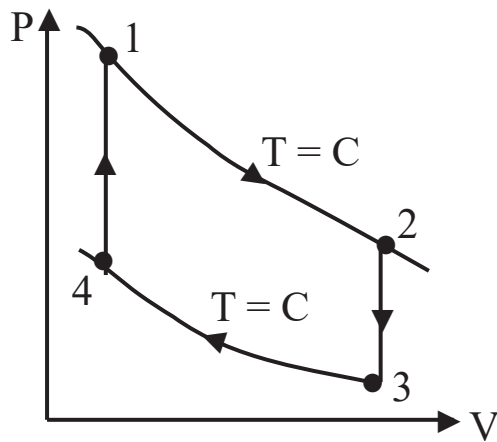It consists of two reversible Isothermal processes and two reversible constant volume processes.
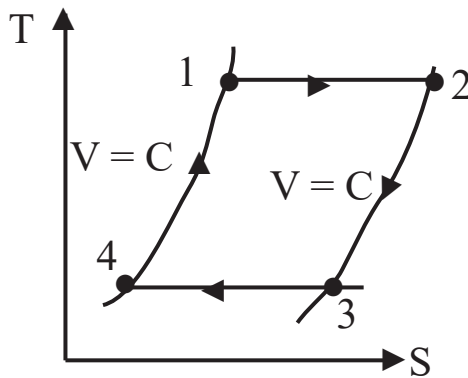

Figure : P-V diagram

Figure : T-S diagram

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

Ericsson Cycle (1850)

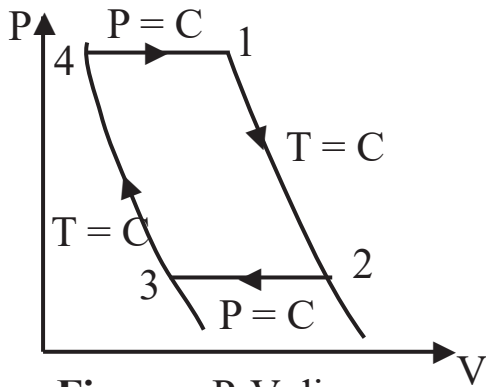It consists of two reversible Isothermal processes and two reversible constant pressure processes.
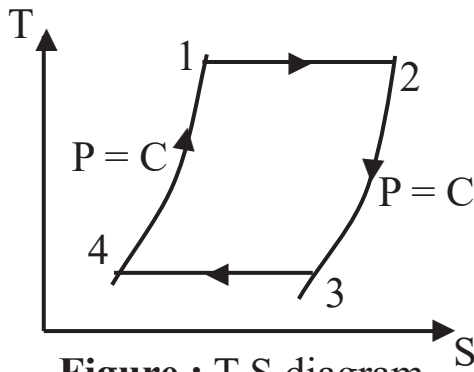
Figure : P-V diagram

Figure : T-S diagram

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

Air Conditioning Processes

The air conditioning processes include

(a) Simple heating (raising the temperature)

(b) Simple cooling (lowering temperature)

(c) Humidifying (adding moisture)

(d) Dehumidifying (removing moisture)

   Sometimes two or more of these processes are needed to bring the air to a desired temperature and humidity level.

   Air is commonly heated and humidified in winter and cooled and dehumidified in summer.

(a) Sensible heating and sensible cooling

Heating coil

Air

T_1, ω_1, Q_1

$T_2 - \omega_2, Q_2 < Q_1$
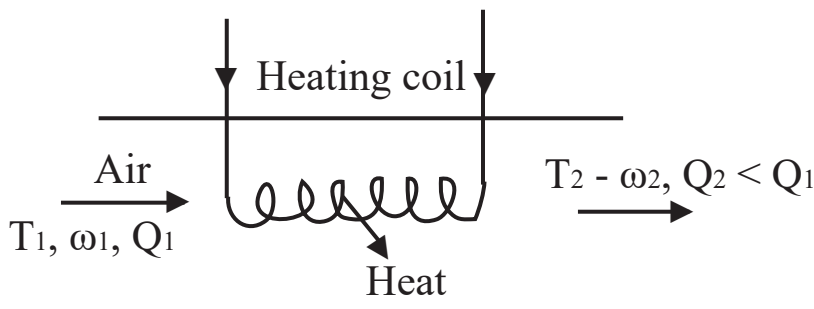
Heat

In simple heating the air is heated by circulating it through a duct that contains the tubing. For the hot gases or the electric resistance wires as shown above.

The amount of moisture in the air remains constant during this process since no moisture is added to or removed from the air. That is, the specific humidity of the air remains constant (ω = constant) during a heating or cooling process with no humidification or dehumidification process. Such a heating proceeds in the direction of increasing dry bulb temperature.

Useful tip The relative humidity of air decreases during a heating process even if the specific humidity ω remains constant. This is because the relative humidity is the ratio of the moisture content to the moisture capacity of the air at the same temperature and moisture capacity of air increases with increase in temperature.
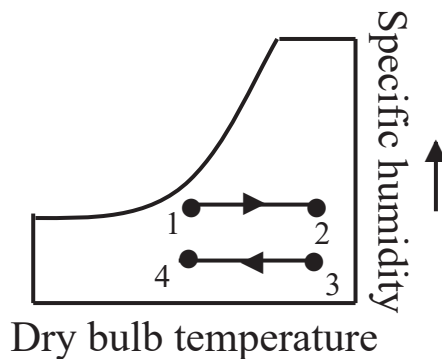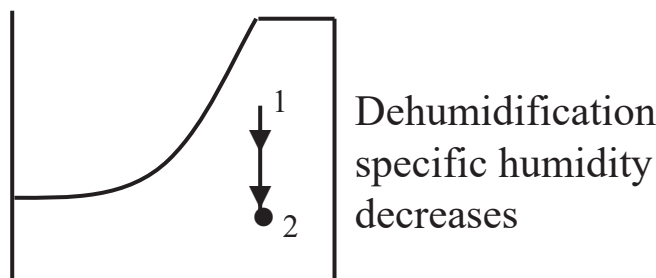

1 - 2 → Sensible heating
3 - 4 → Sensible cooling

(b) Humidification

Humidification is a process in which moisture is added at constant temperature.
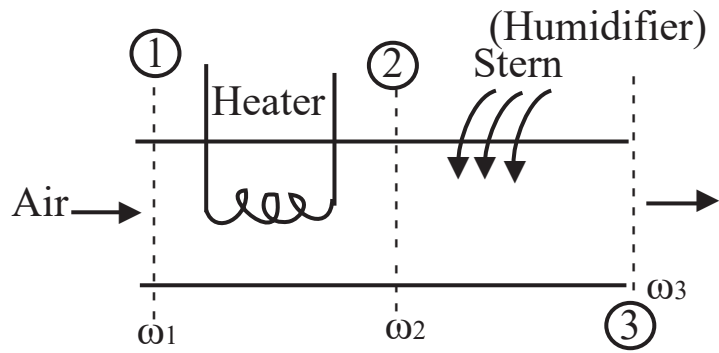

Humidification specific humidity increases
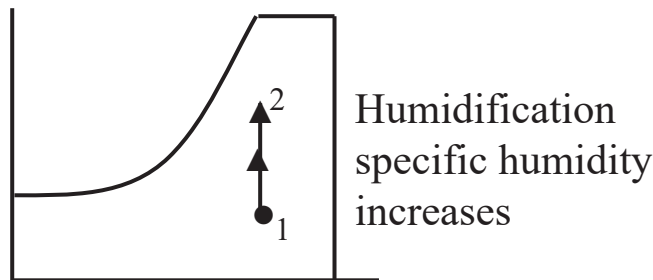
(c) Dehumidification

Dehumidification is a process in which moisture is removed at constant temperature.

Dehumidification specific humidity decreases

(d) Heating and Humidification

Problem associated with sensible heating is that it reduces the relative humidity and this can be eliminated by spraying steam in the heated air.

1 - 2 → Sensible heating

2 - 3 → Humidification

Specific humidity, $\omega_1 = \omega_2$ and $\omega_3 > \omega_2$

Useful tip If steam is introduced in the humidification section, this will result in humidification with additional heating ($T_3 > T_2$).

If humidification is accomplished by spraying water into the air atream, part of the latent heat of vapourization come from air, which results in the cooling of the heated air stream ($T_3 > T_2$). Air should be heated to a higher temperature in the heating section in this case to make up for the cooling effect during the humidification process.

This process can be shown in the psychrometric charts as :
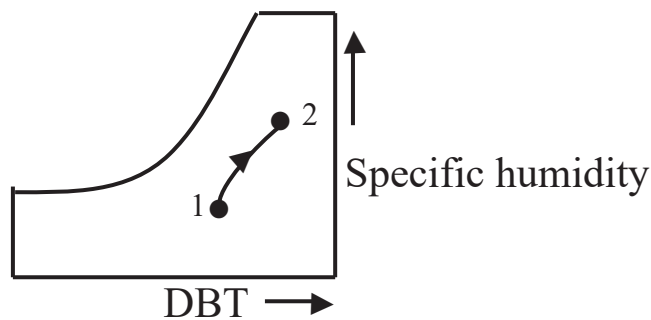
(e) Cooling with dehumidification

This process is generally followed in summer air conditioning. After sensible cooling the air, the relative humidity increases and to reduce the humidity or moisture content from the air, the air has to dehumidify. This needs cooling of air below the dew point temperature.

Refrigeration and Air Conditioning
Refrigeration
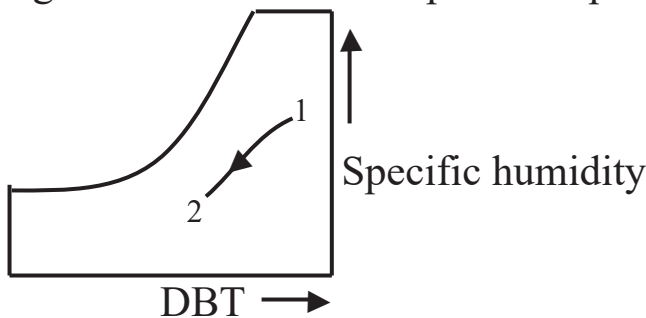
It is defined as the process by which the temperature of a given space or a substance is lowered below that of the atmosphere or surroundings.

- Production of low temperature is achieved by following processes :
  1. Throttling expansion of a liquid with flashing
  2. Reversible adiabatic expansion of a gas
  3. Irreversible adiabatic expansion of a real gas
  4. Thermoelectric cooling
  5. Adiabatic demagnetization

Air Conditioning

- Air conditioning is the process of altering the properties of air such as temperature, humidity, air movement and circulation to more favourable conditions.
- Air conditioning can refer to any form of technological cooling or heating that modifies the condition of air.
- Comfort conditions :

  Temperature   :   22.8ºC to 25ºC
  Humidity   :   35% to 60%
  Air circulation :   5 m/min to 8 m/min

Tonne of Refrigeration

It is defined as the amount of heat removed from 2000 pounds of water at 32ºF = to convert into ice at 32ºF in 24 hours.

$$OR$$

It is defined as the amount of heat removed from 1000 kg of water at 0ºC to convert into ice at 0ºC in 24 hours.

$$\therefore 1 \text{ tonne of regrigeration} = \frac{1000 \times 336}{24 \times 60}$$

$$= 233 \text{ kJ/min}$$
$$= 210 \text{ kJ/min}$$
$$= 3.52 \text{ kW}$$

- A machine which has the capacity of producing a cooling effect of 210 kJ/min is designed as 1 ton machine

Refrigerator

If the heat engine operates in reverse direction used for cooling purpose is called as refrigerator.
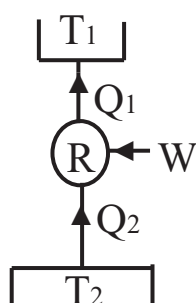
- $(COP)_R = \dfrac{\text{Desired effect}}{W}$

$$= \dfrac{Q_2}{W} = \dfrac{Q_2}{Q_1 - Q_2} = \dfrac{T_2}{T_1 - T_2}$$

- $(COP)_{HP} = 1 + (COP)_R$
- Energy performance ratio $(EPR) = 1 + (COP)_R$
- Heat rejection ratio $(HRR) = 1 + \dfrac{1}{(COP)_R}$
- Horse power per tonne of refrigeration $\left(\dfrac{HP}{TR}\right) = \dfrac{4.71}{(COP)_R}$

Types of Refrigeration Systems

(a) Dry ice refrigeration
- Solid CO_2 is called dry ice.
- Changes from solid state to vapour state without converting in to liquid state.
- Evaporation (OR) sublimation temperature of dry ice at atmospheric pressure is -78°C.
  Application :
  Dry ice is used to preserve food stuff during transportation.

(b) Evaporation refrigeration
- Evaporation cooling is adiabatic transfer of heat from air to water.
  Application :
  (i) Used in desert coolers or room coolers.
  (ii) Used in making artificial snow.
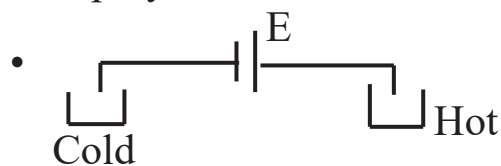
(c) Liquid gas refrigeration
- Refrigerants : Liquid nitrogen, liquid CO_2 .
- Refrigerants should be non toxic in nature.
  Application :
  Used for cooling the vehicles transporting food stuff.

(d) Thermoelectric refrigeration
- Employs Peltier effect.
-

Cold   Hot

- Antimony (Sb), Bismuth (Be) metals are commonly used.

(e) Steam jet refrigeration
  Principle : Boiling point of water can be reduced by reducing the pressure.

Classification of Refrigerants

Primary refrigerants : Take part directly in the refrigerating systems.
Secondary Refrigerants : Are first cooled by primary refrigerants and then used for cooling purpose.

Primary refrigerants	Secondary refrigerants
NH_3, CO_2, SO_2, methyl chlorides, methylene chloride, Freon group, ammonia	Air Water Brine (salt solution of water)

Refrigeration Cycles Vapour Compression Refrigeration Cycle

Components :
(1) Compressor
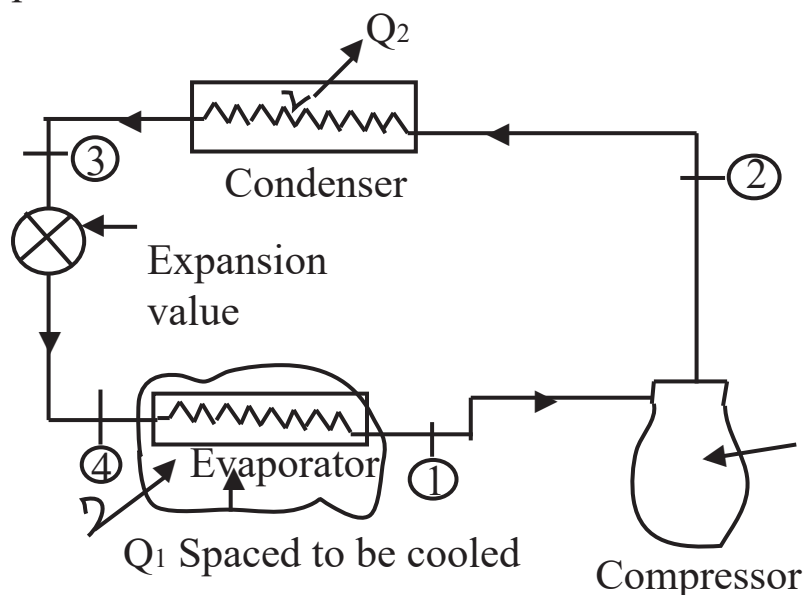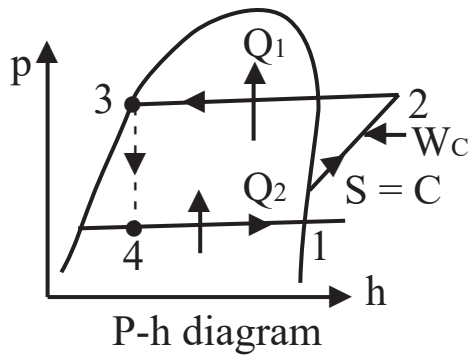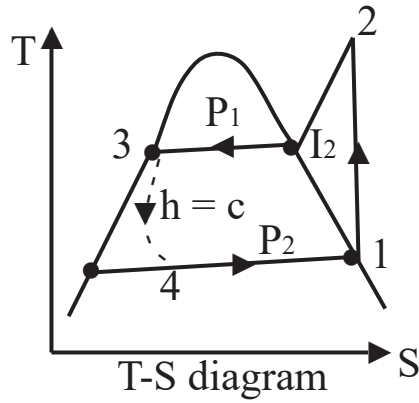(2) Condenser
(3) Expansion valve
(4) Evaporator

Figure : Simple vapour compression refrigeration plant

1 - 2 : Reversible adiabatic compression process
2 - 3 : Reversible constant pressure heat rejection process
3 - 4 : Adiabatic throttling process
4 - 1 : Reversible constant pressure heat absorption.

T-S diagram

P-h diagram

Compressor : $h_1 + W_C = h_2$; $W_C = (h_2 - h_1)$ kJ/kg

Condenser : $h_2 = Q_1 + h_3$; $Q_1 = (h_2 - h_3)$ kJ/kg

Expansion valve : $h_3 = h_4$

$$h_{f3} = h_{f4} + x_4 h_{fg4}$$

$$\Rightarrow x_4 = \frac{h_{f3} - h_{f4}}{h_{fg4}}$$

Evaporator : $h_4 + Q_2 = h_1$

$Q_2 = (h_1 - h_4)$ kJ/kg

'Q_2' is called refrigerating effect, i.e., the amount of heat removed from the surroundings per unit mass flow of refrigerant.

$$\therefore COP = \frac{\text{Refrigeration effect}}{\text{Compression work}} = \frac{Q_2}{W_C} = \frac{h_1 - h_4}{h_2 - h_1}$$