

# **THERMAL ENGINEERING**

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**CONTENTS**

<b>SL.NO</b>	<b>NAME OF TOPICS</b>	<b>PAGE NO.</b>
1	THERMODYNAMIC CONCEPT & LAWS OF THERMODYNAMICS	3-26
2	INTERNAL COMBUSTION ENGINE & ITS PERFORMANCE	27-34
3	STEAM GENERATOR & STEAM POWER CYCLE	35-68

## THERMODYNAMIC CONCEPT & LAWS OF THERMODYNAMICS

### **System:**

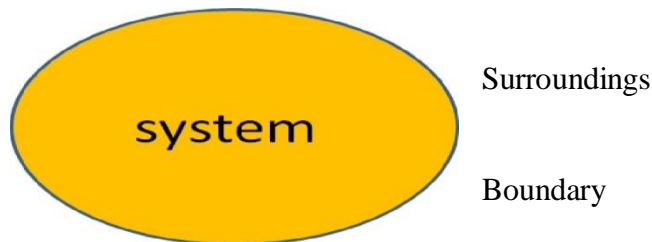
A thermodynamic system is defined as a quantity of matter or a region in space which is selected for the study.

### **Surrounding:**

The mass or region outside the system is called surroundings.

### **Boundary:**

The real or imaginary surfaces which separates the system and surroundings is called boundary. The real or imaginary surfaces which separates the system and surroundings is called boundary.



### Types of thermodynamic system

On the basis of mass and energy transfer the thermodynamic system is divided into three types .

1. Closed system
2. Open system
3. Isolated system

**Closed system:** A system in which the transfer of energy but not mass can take place across the boundary is called closed system. The mass inside the closed system remains constant.

For example: Boiling of water in a closed vessel. Since the water is boiled in a closed vessel so the mass of water cannot escape out of the boundary of the system but heat energy continuously enters and leaves the boundary of the vessel. It is an example of a closed system.

**Open system:** A system in which the transfer of both mass and energy takes place is called an open system. This system is also known as control volume.

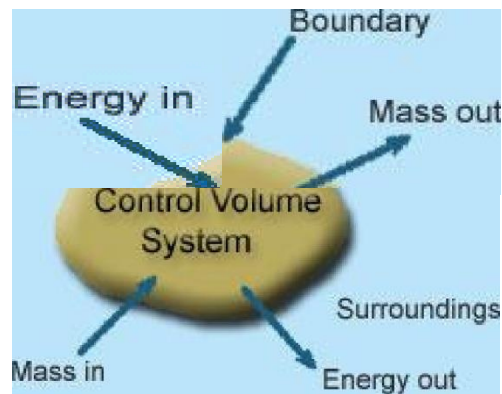
For example: Boiling of water in an open vessel is an example of open system because the water and heat energy both enters and leaves the boundary of the vessel.

**Isolated system:** A system in which the transfer of mass and energy cannot take place is called an isolated system.

For example: Tea present in a thermos flask. In this the heat and the mass of the tea cannot cross the boundary of the thermos flask. Hence the thermos flask is an isolated system.

Control Volume:

- ✓ Its a system of fixed volume.
- ✓ This type of system is usually referred to as "open system" or a "control volume" Mass transfer can take place across a control volume.
- ✓ Energy transfer may also occur into or out of the system.
- ✓ Control Surface- Its the boundary of a control volume across which the transfer of both mass and energy takes place.
- ✓ The mass of a control volume (open system) may or may not be fixed.
- ✓ When the net influx of mass across the control surface equals zero then the mass of the system is fixed and vice-versa.
- ✓ The identity of mass in a control volume always changes unlike the case for a control mass system (closed system).
- ✓ Most of the engineering devices, in general, represent an open system or control volume.



Example:

Heat exchanger - Fluid enters and leaves the system continuously with the transfer of heat across the system boundary.

Pump - A continuous flow of fluid takes place through the system with a transfer of mechanical energy from the surroundings to the system

### **THERMODYNAMIC EQUILIBRIUM:**

A thermodynamic system is said to exist in a state of thermodynamic equilibrium when no change in any macroscopic property is registered if the system is isolated from its surroundings.

An isolated system always reaches in the course of time a state of thermodynamic equilibrium and can never depart from it spontaneously.

Therefore, there can be no spontaneous change in any macroscopic property if the system exists in an equilibrium state. A thermodynamic system will be in a state of thermodynamic equilibrium if the system is the state of Mechanical equilibrium, Chemical equilibrium and Thermal equilibrium.

& Mechanical equilibrium: The criteria for Mechanical equilibrium are the equality of pressures.

& Chemical equilibrium: The criteria for Chemical equilibrium are the equality of chemical potentials.

& Thermal equilibrium: The criterion for Thermal equilibrium is the equality of temperatures.

### **STATE:**

The thermodynamic state of a system is defined by specifying values of a set of measurable properties sufficient to determine all other properties. For fluid systems, typical properties are pressure, volume and temperature. More complex systems may require the specification of more unusual properties. As an example, the state of an electric battery requires the specification of the amount of electric charge it contains.

### **PROPERTY:**

Properties may be extensive or intensive.

Intensive properties: The properties which are independent of the mass of the system. For example: Temperature, pressure and density are the intensive properties.

Extensive properties: The properties which depend on the size or extent of the system are called extensive properties.

For example: Total mass, total volume and total momentum.

### **Process:**

When the system undergoes change from one thermodynamic state to final state due change in properties like temperature, pressure, volume etc, the system is said to have undergone thermodynamic process.

Various types of thermodynamic processes are: isothermal process, adiabatic process, isochoric process, isobaric process and reversible process.

### **Cycle:**

Thermodynamic cycle refers to any closed system that undergoes various changes due to temperature, pressure, and volume, however, its final and initial state are equal. This cycle is important as it allows for the continuous process of a moving piston seen in heat engines and the expansion/compression of the working fluid in refrigerators, for example. Without the cyclical process, a car wouldn't be able to continuously move when fuel is added, or a refrigerator would not be able to stay cold.

Visually, any thermodynamic cycle will appear as a closed loop on a pressure volume diagram.

Examples: Otto cycle, Diesel Cycle, Brayton Cycle etc.

### **Reversibility:**

Reversibility, in thermodynamics, a characteristic of certain processes (changes of a system from an initial state to a final state spontaneously or as a result of interactions with other systems) that can be reversed, and the system restored to its initial state, without leaving net effects in any of the systems involved.

An example of a reversible process would be a single swing of a frictionless pendulum from one of its extreme positions to the other. The swing of a real pendulum is irreversible because a small amount of the mechanical energy of the pendulum would be expended in performing work against frictional forces, and restoration of the pendulum to its exact starting position would require the supply of an equivalent amount of energy from a second system, such as a compressed spring in which an irreversible change of state would occur.

### **QUASI STATIC PROCESS:**

When a process is processing in such a way that system will be remained infinitesimally close with equilibrium state at each time, such process will be termed as quasi static process or quasi equilibrium process.

In simple words, we can say that if system is going under a thermodynamic process through succession of thermodynamic states and each state is equilibrium state then the process will be termed as quasi static process.

We will see one example for understanding the quasi static process, but let us consider one simple example for better understanding of quasi static process. If a person is coming down from roof to ground floor with the help of ladder steps then it could be considered as quasi static process. But if he jumps from roof to ground floor then it will not be a quasi static process.

Weight placed over the piston is just balancing the force which is exerted in upward direction by gas. If we remove the weight from the piston, system will have unbalanced force and piston will move in upward direction due to force acting over the piston in upward direction by the gas.

### **Irreversible Process:**

The irreversible process is also called the natural process because all the processes occurring in nature are irreversible processes. The natural process occurs due to the finite gradient between the two states of the system. For instance, heat flow between two bodies occurs due to the temperature gradient between the two bodies; this is in fact the natural flow of heat. Similarly, water flows from high level to low level, current moves from high potential to low potential, etc.

& In the irreversible process the initial state of the system and surroundings cannot be restored from the final state.

- During the irreversible process the various states of the system on the path of change from initial state to final state are not in equilibrium with each other.
- During the irreversible process the entropy of the system increases decisively and it cannot be reduced back to its initial value.
- The phenomenon of a system undergoing irreversible process is called as irreversibility.

### **CAUSES OF IRREVERSIBILITY:**

**Friction:** Friction is invariably present in real systems. It causes irreversibility in the process as work done does not show an equivalent rise in the kinetic or potential energy of the system. The fraction of energy wasted due to frictional effects leads to deviation from reversible states.

**Free expansion:** Free expansion refers to the expansion of unresisted type such as expansion in a vacuum. During this unresisted expansion the work interaction is zero, and without the expense of any work, it is not possible to restore initial states. Thus, free expansion is irreversible.

Heat transfer through a finite temperature difference: Heat transfer occurs only when there exist temperature difference between bodies undergoing heat transfer. During heat transfer, if heat addition is carried out in a finite number of steps then after every step the new state shall be a non-equilibrium state.

Non-equilibrium during the process: Irreversibility's are introduced due to lack of thermodynamic equilibrium during the process. Non-equilibrium may be due to mechanical in equilibrium, chemical in equilibrium, thermal in equilibrium, electrical in equilibrium, etc. and irreversibility is called mechanical irreversibility, chemical irreversibility, thermal irreversibility, electrical irreversibility respectively. Factors discussed above are also causing non-equilibrium during the process and therefore make process irreversible.

### **Heat:**

It is the energy in transition between the system and the surroundings by virtue of the difference in temperature Heat is energy transferred from one system to another solely by reason of a temperature difference between the systems. Heat exists only as it crosses the boundary of a system and the direction of heat transfer is from higher temperature to lower temperature. For thermodynamics sign convention, heat transferred to a system is positive; Heat transferred from a system is negative.

### **Work:**

Thermodynamic definition of work: Positive work is done by a system when the sole effect external to the system could be reduced to the rise of a weight.

Work done BY the system is positive and work done ON the system is negative.

### **Types of work interaction:**

- & Expansion and compression work (displacement work) & Work of a reversible chemical cell
- & Work in stretching of a liquid surface & Work done on elastic solids
- & Work of polarization and magnetization

### **Point and Path functions:**

- & Point function does not depend on the history (or path) of the system. It only depends on the state of the system.
- & Examples of point functions are: temperature, pressure, density, mass, volume, enthalpy, entropy, internal energy etc.
  
- & Path function depends on history of the system (or path by which system arrived at a given state).
- & Examples for path functions are work and heat.
- & Path functions are not properties of the system, while point functions are properties of the system.
- & Change in point function can be obtained by from the initial and final values of the function, whereas path has to defined in order to evaluate path functions.

**ENERGY:-** Energy is the capacity for doing work. It may exist in potential, kinetic, thermal, chemical, nuclear, or other forms.

Energy are of two types

1. stored energy

- a) Potential energy ( $Mgh$ )
- b) Kinetic energy ( $\frac{1}{2}Mv^2$ )

- c) Internal energy (U)
- 2. Transitional energy

**DIFFERENCE BETWEEN WORK AND HEAT**

<b>Work</b>	<b>Heat</b>
Positive work defined in terms of the lifting of a weight being the sole effect during the interaction.	Defined as the interaction which occurs as a result of a temperature difference between two systems in thermal communication.
Can cause a temperature rise in an adiabatic system.	Being zero for an adiabatic system, cannot affect its temperature.
In almost universally employed sign convention, work done by system or transferred from a system, is considered to be positive.	In this sign convention, heat transferred to a system is considered to be positive.
There are as many types of work interactions as there are generalised forces, causing generalised displacements.	Three modes of heat transfer are recognised.
(Will be shown later that) complete conversion to other forms of work, or to heat, is possible.	Complete conversion to work (in a cyclic process) is prohibited by the second law.

**DISPLACEMENT WORK**

Consider a piston cylinder arrangement as given in the Figure 2.4. If the pressure of the fluid is greater than that of the surroundings, there will be an unbalanced force on the face of the piston. Hence, the piston will move towards right.

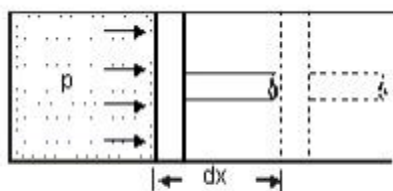


Figure 2.4 Displacement work

Work done = Force X distance

$$W = Pa \times dx$$

$$W = PdV$$

Where,

dV - change in volume.

This work is known as displacement work or pdV work corresponding to the elemental displacement dx. To obtain the total work done in a process, this elemental work must be added from the initial state to the final state.

**The displacement work for different processes:**

(a) Isochoric Process :



The process for which the volume remains constant is Isochoric Process.

Volume = constant

(b) Isobaric process: The process in which the pressure remains constant is called isobaric process.

$P = \text{constant}$

$W = P(V_2 - V_1)$

(c) Isothermal process:

The process in which the temperature remains constant is called isothermal process.

$T = \text{Constant}$

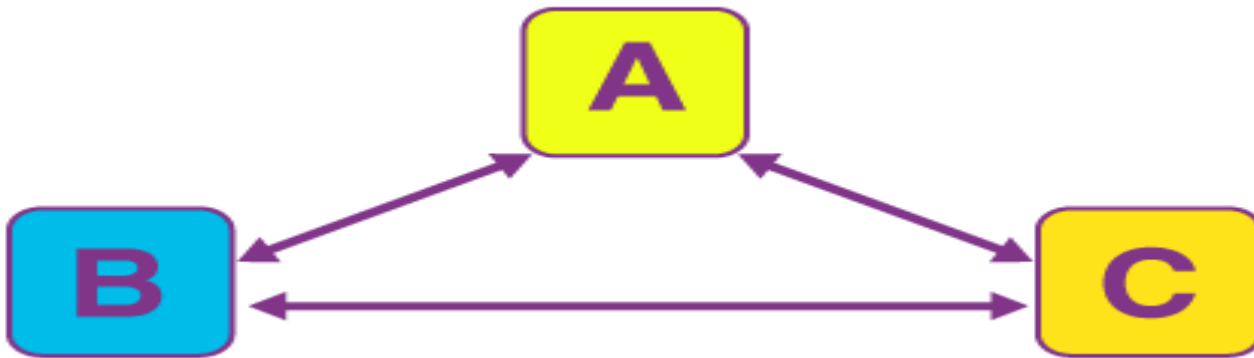
We know that

$PV = mRT$

$PV = C$

### LAWS OF THERMODYNAMICS

ZEROTH LAW OF THERMODYNAMICS: - The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.

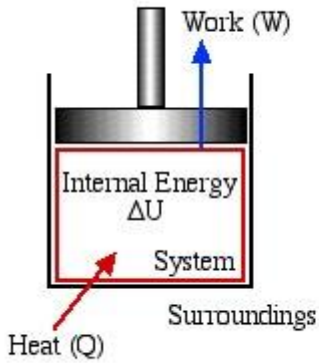


According to this law, if systems B and C separately are in thermal equilibrium with another system A, then systems B and C will also be in thermal equilibrium with each other. This is also the principle by which thermometers are used.

FIRST LAW OF THERMODYNAMIC: - The first law of thermodynamics is a version of the law of conservation of energy, adapted for thermodynamic processes, distinguishing three kinds of transfer of energy, as heat, as thermodynamic work, and as energy associated with matter transfer, and relating them to a function of a body's state, called internal energy.

The law of conservation of energy states that the total energy of any isolated system (for which energy and matter transfer through the system boundary are not possible) is constant; energy can be transformed from one form to another, but can be neither created nor destroyed.

We consider the First Law of Thermodynamics applied to stationary closed systems as a conservation of energy principle. Thus energy is transferred between the system and the surroundings in the form of heat and work, resulting in a change of internal energy of the system. Internal energy change can be considered as a measure of molecular activity associated with change of phase or temperature of the system and the energy equation is represented as follows:



Energy Equation for Stationary Closed Systems:

$$Q - W = \Delta U \quad [\text{kJ}]$$

where:  $Q$  is the Heat Transferred to the System

$W$  is the Work Done by the System

$\Delta U$  is the Change of Internal Energy

Dividing each term by the system mass  $m$  [kg] we obtain the specific form of the Energy Equation:

$$q - w = \Delta u \quad \left[ \frac{\text{kJ}}{\text{kg}} \right]$$

Energy Equation for Stationary Closed Systems

### LIMITATIONS OF THE FIRST LAW:

- The first law of thermodynamics merely indicates that in any process there is a transformation between the various forms of energy involved in the process but provides no information regarding the feasibility of such transformation.
- First law does not provide any information regarding the direction processes will take whether it is a spontaneous or a non spontaneous process.

### APPLICATION OF FIRST LAW OF THERMODYNAMICS:-

**FLOW PROCESS:-** An open system which permits the transfer of mass from the system is called flow process.

There are two types of flow process

- Steady flow process
- Unsteady flow process

**CONDITION FOR A STEADY FLOW PROCESS:-** When a flow process is satisfying the following conditions, it is known as a steady flow process.

1. The mass and energy content of the control volume remains constant with time.
2. The state and energy of the fluid at inlet, at the exit and at every point within the control volume are time independent.
3. The rate of energy transfer in the form of work and heat across the control surface is constant with time.

Therefore for a steady flow process

$$M_{IN} = M_{OUT}$$

**STEADY FLOW ENERGY EQUATION:-** Since the steady flow process is that in which the condition of fluid flow within a control volume do not vary with time, i.e. the mass flow rate, pressure, volume, work and rate of heat transfer are not the function of time.

i.e., for steady flow  
entrance = exit

i.e,  $dm/dt = \text{constant}$

**ASSUMPTIONS:-**

The following conditions must hold good in a steady flow process.

- (a) The mass flow rate through the system remains constant.
- (b) The rate of heat transfer is constant.
- (c) The rate of work transfer is constant.
- (d) The state of working substance at any point within the system is same at all times.
- (e) There is no change in the chemical composition of the system. If any one condition is not satisfied, the process is called unsteady process.

Let;  $A_1, A_2 =$  Cross sectional Area at inlet and outlet

$\rho_1, \rho_2 =$  Density of fluid at inlet and outlet

$m_1, m_2 =$  Mass flow rate at inlet and outlet

$u_1, u_2 =$  I.E. of fluid at inlet and outlet

$P_1, P_2 =$  Pressure of mass at inlet and outlet

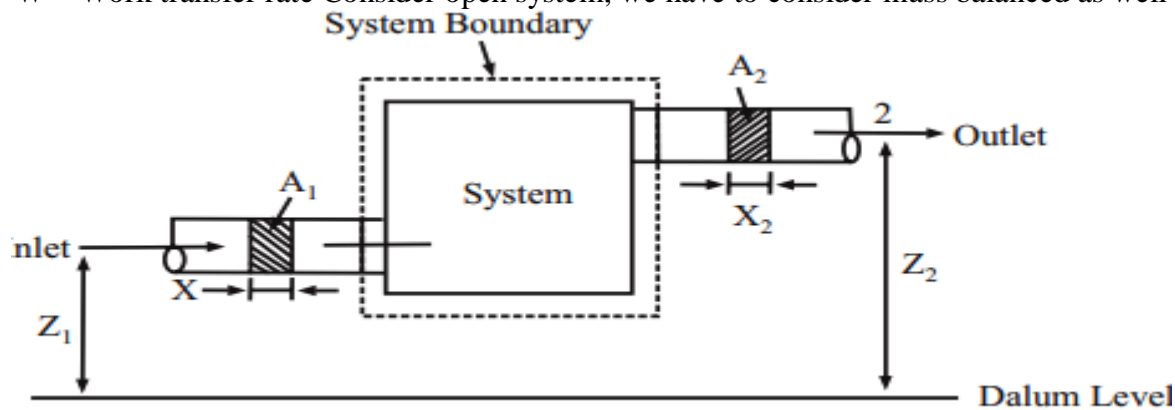
$v_1, v_2 =$  Specific volume of fluid at inlet and outlet

$V_1, V_2 =$  Velocity of fluid at inlet and outlet

$Z_1, Z_2 =$  Height at which the mass enter and leave

$Q =$  Heat transfer rate

$W =$  Work transfer rate Consider open system; we have to consider mass balanced as well as energy balance.



**Fig 2.3**

In the absence of any mass getting stored the system we can write;

Mass flow rate at inlet = Mass flow rate at outlet i.e.,  $m_1 = m_2$

since  $m_f = \text{density} \times \text{volume flow rate} = \text{density} \times \text{Area} \times \text{velocity}$

$$= \rho \cdot A \cdot V \quad \rho_1 \cdot A_1 \cdot V_1 = \rho_2 \cdot A_2 \cdot V_2$$

$$\text{or, } A_1 \cdot V_1 / v_1 = A_2 \cdot V_2 / v_2; \quad v_1, v_2$$

= specific volume Now total energy of a flow system consist of P.E, K.E., I.E., and flow work

Hence,  $E = PE + KE + IE + FW = h + V^2/2 + gz$  Now;

Total Energy rate cross boundary as heat and work

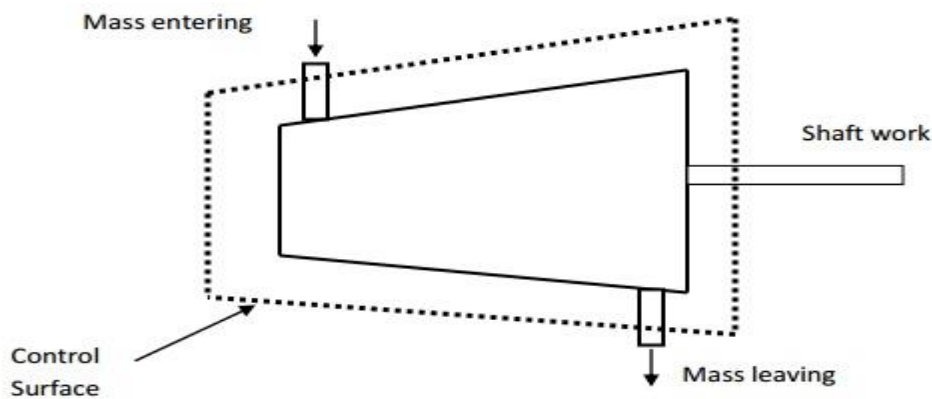
= Total energy rate leaving at (2) - Total energy rate leaving at (1)

### **APPLICATION OF SFEE**

SFEE governs the working of a large number of components used in many engineering practices. In this section a brief analysis of such components working under steady flow conditions are given and the respective governing equations are obtained.

### **TURBINES:**

Turbines are devices used in hydraulic, steam and gas turbine power plants. As the fluid passes through the turbine, work is done on the blades of the turbine which are attached to a shaft. Due to the work given to the blades, the turbine shaft rotates producing work.



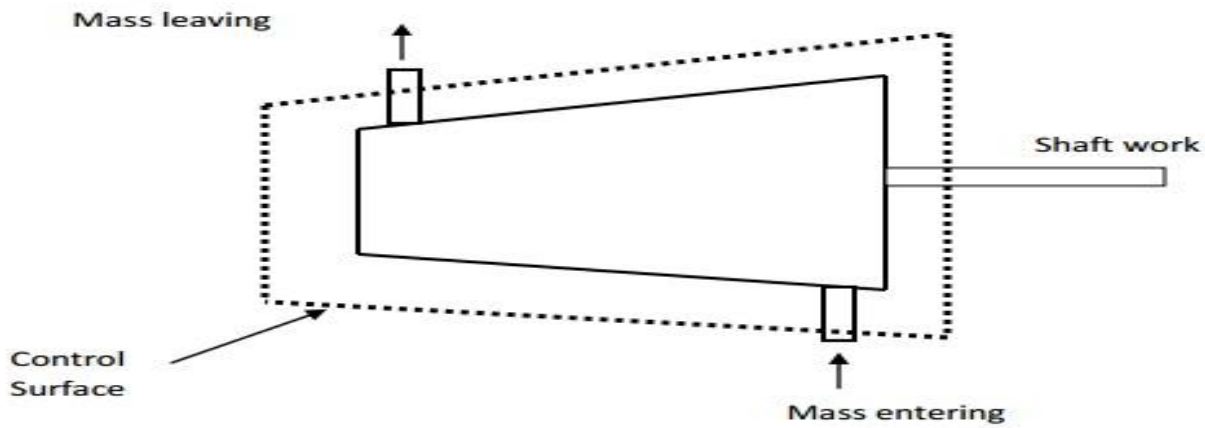
**Figure 3.4 Schematic Representation of a Turbine**

### **General Assumptions**

1. Changes in kinetic energy of the fluid are negligible
2. Changes in potential energy of the fluid are negligible.

### **COMPRESSORS:**

Compressors (fans and blowers) are work consuming devices, where a low-pressure fluid is compressed by utilizing mechanical work. Blades attached to the shaft of the turbine impart kinetic energy to the fluid which is later converted into pressure energy.



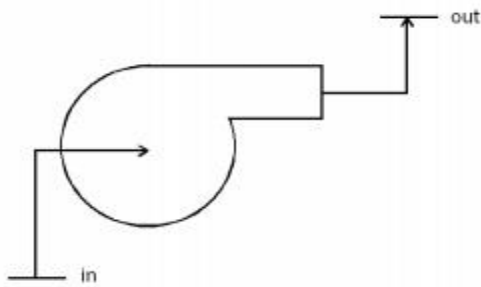
**Figure 3.5 Schematic Representation of a Compressor**

### General Assumptions

1. Changes in the kinetic energy of the fluid are negligible
2. Changes in the potential energy of the fluid are negligible

### PUMPS

Similar to compressors pumps are also work consuming devices. But pumps handle incompressible fluids, whereas compressors deal with compressible fluids.



**Figure 3.6 Schematic diagram of a pump**

### General Assumptions

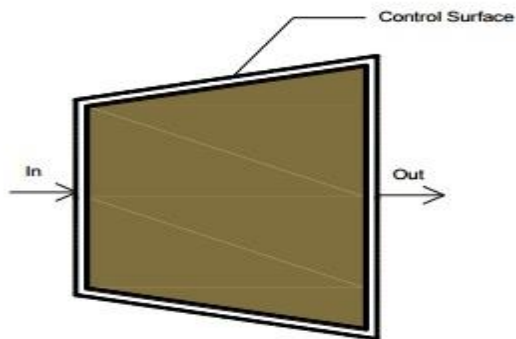
1. No heat energy is gained or lost by the fluids;
2. Changes in kinetic energy of the fluid are negligible.

## NOZZLES:

Nozzles are devices which increase the velocity of a fluid at the expense of pressure. A typical nozzle used for fluid flow at subsonic\* speeds is shown in Figure 3.7.

### General Assumptions

1. In nozzles fluids flow at a speed which is high enough to neglect heat lost or gained as it crosses the entire length of the nozzle. Therefore, flow through nozzles can be regarded as adiabatic. That is  $\dot{Q}=0$ . Changes in the potential energy of the fluid are negligible.



### Governing Equation:

$$C_2 = \sqrt{2(H_1 - H_2)}$$

## NUMERICALS:

**Q1) The head of water at the inlet of a pipe 2000m long and 500mm diameter is 60m. A nozzle of diameter 100mm at its outlet is fitted to the pipe. Find the velocity of water at the outlet of the nozzle if  $f=0.01$  for the pipe.**

**Solution:** Given:-

Head of water at inlet of pipe,  $H=60\text{m}$

Length of pipe,  $L=2000\text{m}$

Diameter of pipe,  $D=500\text{m}=0.50\text{m}$

Diameter of nozzle at outlet,  $d=100\text{mm}=0.1\text{m}$

Coefficient of friction,  $f=0.01$

Therefore to find the velocity,

$$\frac{v^2}{2gH} = \left[ \frac{1}{1 + \frac{4fL}{D} \times \frac{a^2}{A^2}} \right]$$

$$v^2 = \left[ \frac{2gH}{1 + \frac{4fL}{D} \times \frac{a^2}{A^2}} \right]$$

$$v^2 = \left[ \frac{2 \times 9.81 \times 60}{1 + \frac{4 \times 0.01 \times 2000}{0.5} \times \left( \frac{\frac{\pi}{4} d^2}{\frac{\pi}{4} D^2} \right)^2} \right]$$

$$v = \sqrt{\frac{2 \times 9.81 \times 60}{1 + \frac{4 \times 0.01 \times 2000}{0.5} \times \left( \frac{0.1^2}{0.5^2} \right)^2}}$$

$$v=30.61\text{m/s}$$

1. A convergent divergent adiabatic steam nozzle is supplied with steam at 10 bar and 250°C. The discharge pressure is 1.2 bar. Assuming that the nozzle efficiency is 100% and initial velocity of steam is 50 m/s. Find the discharge velocity.

**Given Data:-**

Initial pressure( $p_1$ )=10bar Initial

Temperature( $T_1$ )=250°C

Exit pressure( $p_2$ )=1.2 bar

Nozzle efficiency =100%

Initial velocity of steam ( $v_1$ )=50m/s

**To Find:-**

Discharge velocity ( $v_2$ )

**Solution:-**

From steam table, For 10 bar,  $250^\circ\text{C}$ ,  $h_1=2943 \text{ KJ/kg}$   $s_1=6.926 \text{ KJ/kgK}$

From steam table, For 1.2 bar,

$h_{f2} = 439.3 \text{ KJ/kg}$  ;  $h_{fg2} = 2244.1 \text{ KJ/kg}$ ;

$s_{f2} = 1.361 \text{ KJ/kg K}$  ;  $s_{fg2} = 5.937 \text{ KJ/kgK}$ .

Since  $s_1 = s_2$ ,

$$s_1 = s_{f2} + x_2 s_{fg2}$$

$$6.926 = 1.361 + x_2(5.937)$$

$$x_2 = 0.9373$$

We know that,

$$h_2 = h_{f2} + x_2 h_{fg2}$$

$$= 439.3 + (0.9373)2244.1$$

$$h_2 = 2542 \text{ KJ/Kg}$$

$$\text{Exit velocity } (V_2) = \sqrt{2000(h_1 - h_2) + 502}$$

$$= 896.91 \text{ m/s.}$$

2. Dry saturated steam at 6.5 bar with negligible velocity expands isentropically in a convergent divergent nozzle to 1.4 bar and dryness fraction 0.956. Determine the final velocity of steam from the nozzle if 13% heat is lost in friction. Find the % reduction in the final velocity.

**Given data:**

Exit pressure ( $P_2$ ) = 1.4 bar

Dryness fraction ( $x_2$ ) = 0.956

Heat loss = 13%



**To Find:**

The percent reduction in final velocity

**Solution:**

From steam table for initial pressure  $P_1 = 6.5\text{bar}$ , take values  $h_1 =$

$$h_1 = 2758.8\text{KJ/Kg}$$

Similarly, at 1.4 bar,

$$h_{fg2} = 2231.9\text{ KJ/Kg}$$

$$h_{f2} = 458.4\text{KJ/Kg}$$

$$h_2 = h_{f2} + X_2 h_{fg2}$$

$$= 458.4 + (0.956) 2231.6$$

$$h_2 = 2592.1\text{ KJ/Kg}$$

Final velocity ( $V_2$ ) =  $\sqrt{2000(h_1 - h_2)}$

$$V_2 = 577.39\text{ m/s}$$

Heat drop is 13% = 0.13

$$\text{Nozzle efficiency } (\eta) = 1 - 0.13 = 0.87$$

Velocity of steam by considering the nozzle efficiency,

$$V_2 = \sqrt{2000(h_1 - h_2)} \times \eta$$

$$V_2 = 538.55\text{ m/s}$$

$$\% \text{ reduction in final velocity} = 6.72\%$$

3. A convergent divergent nozzle receives steam at 7bar and 200°C and it expands isentropically into a space of 3bar neglecting the inlet velocity calculate the exit area required for a mass flow of 0.1Kg/sec . when the flow is in equilibrium through all and super saturated with  $P_{V1.3=C}$ .

**Given Data:**

$$\text{Initial pressure } (P_1) = 7\text{bar} = 7 \times 10^5\text{N/m}^2$$

Initial temperature ( $T_1$ ) = 200°C

Pressure ( $P_2$ ) = 3 bar =  $3 \times 10^5 \text{ N/m}^2$

Mass flow rate ( $\dot{m}$ ) = 0.1 kg/sec

$PV^{1.3} = C$

**To Find:**

Exit area

**Solution:**

From steam table for  $P_1 = 7 \text{ bar}$  and  $T_1 = 200^\circ\text{C}$   $v_1 = 0.2999$

$h_1 = 2844.2$

$S_1 = 6.886$

Similarly for  $P_2 = 3 \text{ bar}$

$v_{f2} = 0.001074$   $v_{g2} = 0.60553$   $h_{f2} =$

$561.5$   $h_{fg2} = 2163.2$

$S_{f2} = 1.672$   $S_{fg2} = 5.319$

We know that,  $S_1 = S_2 = S_t$

$S_1 = S_{f2} + X_2 S_{fg2}$

$6.886 = 1.672 + X_2 (5.319)$   $X_2 = 0.98$

Similarly,

$h_2 = h_{f2} + X_2 h_{fg2}$

$h_2 = 561.5 + 0.98 (2163.2)$

(i) Flow is in equilibrium through all:

$V_2 = 569.56$

$v_2 = X_2 \times v_{g2}$

$= 0.98 \times 0.60553 = 0.5934$

$$v_2 = \sqrt{2000 (h_1 - h_2)}$$

$$v_2 = \sqrt{2000 (2844.2 - 2681.99)} \quad v_2 =$$

569.56

$$v_2 = X_2 \times v_{g2}$$

$$= 0.98 \times 0.60553 = 0.5934$$

$$m = \frac{[(A]_2 \times V_2)}{v_2}$$

$$A_2 = \frac{[m \times V_2]}{v_2} = \frac{0.5934 \times 0.1}{569.56}$$

$$A_2 = 1.041 \times 10^{-4} \text{ m}^2$$

(ii) For saturated flow:

$$v_2 = \sqrt{\frac{2n}{n-1} (P_1 v_1) \left(1 - \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right)}$$

$$v_2 = \sqrt{\frac{2(1.3)}{1.3-1} (7 \times 10^5 \times 0.2999) \left(1 - \frac{3 \times 10^5}{7 \times 10^5}\right)^{\frac{1.3-1}{1.3}}}$$

$$v_2 = 568.69 \text{ m/s}$$

specific volume of steam at exit. For super saturated flow,  $P_1 v_1^n = P_2$

$$\left(\frac{v_2}{v_1}\right)^n = \frac{P_1}{P_2}$$

$$\left(\frac{v_2}{v_1}\right)^n = \frac{P_1}{P_2}$$

$$v_2 = \left(\frac{7}{3}\right)^{\frac{1}{1.3}} \times 0.2999$$

$$v_2 = 0.5754$$

$$A_2 = \frac{[m \times V_2]}{v_2}$$

$$= \frac{0.1 \times 0.5754}{568.69}$$

$$A_2 = 1.011 \times 10^{-4} \text{ m}^2$$

## **SECOND LAW OF THERMODYNAMICS:**

The second law of thermodynamics establishes the concept of entropy as a physical property of a thermodynamic system.

### **CLAUSIUS STATEMENT:-**

The statement by Clausius uses the concept of 'passage of heat'. As is usual in thermodynamic discussions, this means 'net transfer of energy as heat', and does not refer to contributory transfers one way and the other.

Heat cannot spontaneously flow from cold regions to hot regions without external work being performed on the system, which is evident from ordinary experience of refrigeration, for example. In a refrigerator, heat flows from cold to hot, but only when forced by an external agent, the refrigeration system.

### **KELVIN STATEMENTS:-**

Lord Kelvin expressed the second law in several wordings.

- It is impossible for a self-acting machine, unaided by any external agency, to convey heat from one body to another at a higher temperature.
- It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects.
- 

### **PERPETUAL MOTION OF THE SECOND KIND**

Before the establishment of the second law, many people who were interested in inventing a perpetual motion machine had tried to circumvent the restrictions of first law of thermodynamics by extracting the massive internal energy of the environment as the power of the machine. Such a machine is called a "perpetual motion machine of the second kind". The second law declared the impossibility of such machines.

## CLAUSIUS INEQUALITY

The Clausius theorem (1854) states that in a cyclic process

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

The equality holds in the reversible case and the strict inequality holds in the irreversible case, with  $T$  as the temperature of the heat bath (surroundings) here. The reversible case is used to introduce the state function entropy. This is because in cyclic processes the variation of a state function is zero from state functionality.

### REFRIGERATOR:

A refrigerator, colloquially fridge, is a commercial and home appliance consisting of a thermally insulated compartment and a heat pump (mechanical, electronic or chemical) that transfers heat from its inside to its external environment so that its inside is cooled to a temperature below the room temperature.

$$T_1 > T_2$$

$$W + Q_2 = Q_1$$

$$W = Q_1 - Q_2$$

$$(\text{COP})_{\text{Ref}} = T_2 / (T_1 - T_2)$$

### HEAT PUMP:

A heat pump is a device that uses work to transfer heat from a cool space to a warm space by transferring thermal energy using a refrigeration cycle, cooling the cool space and warming the warm space.

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

## 3<sup>RD</sup> LAW OF THERMODYNAMICS:-

It states that “the entropy of a system becomes zero at absolute zero temperature”.

## PROPERTIES PROCESS OF PERFECT GAS

A perfect gas (or an ideal gas) may be defined as a state of a substance, whose evaporation from its liquid state is complete. It may be noted that if its evaporation is partial, the substance is called vapor. A vapor contains some particles of liquid in suspension. The behavior of super-heated vapors is similar to that of a perfect gas.

The physical properties of a gas are controlled by the following three variables :

1. Pressure exerted by the gas,
2. Volume occupied by the gas, and
3. Temperature of the gas.

The behavior of a perfect gas, undergoing any change in these three variables, is governed by the following laws:

## **1. BOYLES LAW**

This law was formulated by Robert Boyle in 1662. It states, "The absolute pressure of a given mass of a perfect gas varies inversely as its volume, when the temperature remains constant." Mathematically,

$$PV = \text{Constant}$$

The more useful form of the above equation is :

$$p_1 v_1 = p_2 v_2 = p_3 v_3 = \dots\dots\dots = \text{Constant}$$

where suffixes 1, 2 and 3 refer to different sets of conditions.

## **2. CHARLES' LAW**

This law was formulated by a Frenchman Jacques A.C. Charles in about 1787. It may be stated in two different forms :

(i) "The volume of a given mass of a perfect gas varies directly as its absolute temperature, when the absolute pressure remains constant." Mathematically,

$$V/T = V_1/T_1 = V_2/T_2 = \text{Constant}$$

where suffixes 1, 2 and 3 refer to different sets of conditions.

(ii) "All perfect gases change in volume by  $1/273$  th of its original volume at  $0^\circ\text{C}$  for every  $1^\circ\text{C}$  change in temperature, when the pressure remains constant."

Let

$V_0$  = Volume of a given mass of gas at  $0^\circ\text{C}$ , and

$V_t$  = Volume of the same mass of gas at  $t^\circ\text{C}$ .

Then, according to the above statement,

where

$T$  = Absolute temperature corresponding to  $t^\circ\text{C}$ .

$T_0$  = Absolute temperature corresponding to  $0^\circ\text{C}$ .

A little consideration will show that the volume of a gas goes on decreasing by  $1/273$ th of its original volume for every  $1^\circ\text{C}$  decrease in temperature. It is thus obvious, that at a temperature of  $-273^\circ\text{C}$ , the volume of the gas would become zero. The temperature at which the volume of a gas becomes zero is called absolute zero temperature.

## **3. GAY LUSSAC LAW**

This law states, "The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, when the volume remains constant." Mathematically

$P/T = \text{Constant}$

where suffixes 1, 2 and 3.... refer to different sets of conditions.

#### 4. AVOGADRO'S LAW:

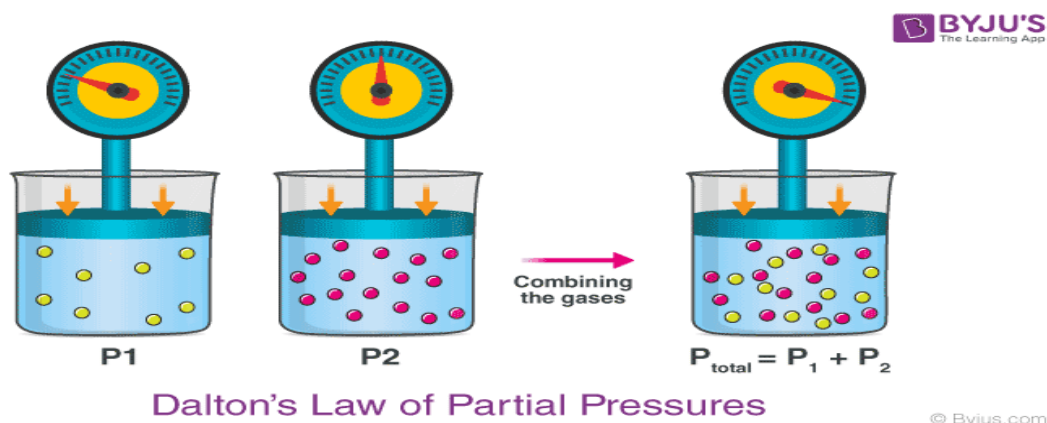
A statement that under the same conditions of temperature and pressure, equal volumes of different gases contain an equal number of molecules. This empirical relation can be derived from the kinetic theory of gases under the assumption of a perfect (ideal) gas. The law is approximately valid for real gases at sufficiently low pressures and high temperatures.

The specific number of molecules in one gram-mole of a substance, defined as the molecular weight in grams, is  $6.02214076 \times 10^{23}$ , a quantity called Avogadro's number, or the Avogadro constant. For example, the molecular weight of oxygen is 32.00, so that one gram-mole of oxygen has a mass of 32.00 grams and contains  $6.02214076 \times 10^{23}$  molecules.

The volume occupied by one gram-mole of gas is about 22.4 litres (0.791 cubic foot) at standard temperature and pressure (0 °C, 1 atmosphere) and is the same for all gases, according to Avogadro's law.

#### 5. DALTON'S LAW OF PARTIAL PRESSURE

Dalton's law of partial pressures is a gas law which states that the total pressure exerted by a mixture of gases is equal to the sum of the partial pressures exerted by each individual gas in the mixture. For example, the total pressure exerted by a mixture of two gases A and B is equal to the sum of the individual partial pressures exerted by gas A and gas B (as illustrated below).



#### Dalton's Law Formula

Dalton's law of partial pressures can be mathematically expressed as follows:

$$P_{total} = \sum_{i=1}^n p_i \quad \text{(or)} \quad P_{total} = P_1 + P_2 + P_3 + \dots + P_n$$

Where,

- $P_{total}$  is the total pressure exerted by the mixture of gases
- $P_1, P_2, \dots, P_n$  are the partial pressures of the gases 1, 2, ..., 'n' in the mixture of 'n' gases

## CHARACTERISTICS GAS EQUATION

The Ideal gas law is the equation of state of a hypothetical ideal gas. It is a good approximation to the behaviour of many gases under many conditions, although it has several limitations. The ideal gas equation can be written as

$$PV = nRT$$

Where,

- P is the pressure of the ideal gas.
- V is the volume of the ideal gas.
- n is the amount of ideal gas measured in terms of moles.
- R is the **universal gas constant**.
- T is the temperature.

According to the Ideal Gas equation-

The product of Pressure & Volume of a gas bears a constant relation with the product of Universal gas constant and the temperature.

i.e.  $pV=nRT$

## UNIVERSAL GAS CONSTANT

Let us consider the pressure exerted by the gas to be '**p**,'

The volume of the gas be – '**v**'

Temperature be – **T**

**n** – be the number of moles of gas

Universal gas constant – **R**

According to **Boyle's Law**,

At constant **n** & **T**, the volume bears an inverse relation with the pressure exerted by a gas.

i.e.  $v \propto 1/p$  .....(i)

According to Charles' Law,

When **p** & **n** are constant, the volume of a gas bears a direct relation with the Temperature.

i.e.  $v \propto T$  .....(ii)

According to Avogadro's Law,

When **p** & **T** are constant, then the volume of a gas bears a direct relation with the number of moles of gas.

i.e.  $v \propto n$  .....(iii)

Combining all the three equations, we have-

$$v \propto nT/p$$

$$\text{or } pv = nRT$$

$$pv = nRT$$

where **R** is the **Universal gas constant**, which has a value of 8.314 J/mol-K



## MAYER'S FORMULA: (Relation between $C_p$ , $C_v$ and $R$ )

Consider one mole of an ideal gas. Let  $dQ$  be the amount of heat is given to the system to raise the temperature by  $dT$ , and change in internal energy be  $dU$ .

Then, from first law of Thermodynamics,

$$dQ = dU + PdV \dots$$

(1) If heat is supplied to one mole at constant volume, i.e.,  $V = \text{constant}$ , then,  $dV = 0$  From equation

(2),  $dQ = dU \dots$

(3) Molar specific heat ( $C_V$ ) at constant volume,

$$C_V = \left( \frac{dQ}{dT} \right)_V$$

From equation (4),

$$dQ = dU = C_V dT \dots(5)$$

If one mole of gas is supplied heat at constant pressure, i.e., from equation (3) of molar specific heat  $C_p$  at constant pressure

$$C_P = \left( \frac{dQ}{dT} \right)_P$$

or,  $dQ = C_P dT$

From equation

$$dQ = C_P dT = dU + PdV$$

Again, from equation (2) substituting

$$dU = C_V dT$$

$$C_P dT = C_V dT + PdV \dots(4)$$

For one mole of gas ( $\mu = 1$ ), from ideal gas equation,

$$PV = RT$$

$$P dV = R dT$$

From equations

$$(C_P - C_V) dT = R dT$$

or  $C_P - C_V = R$

The above expression is called Mayer's relation where  $R = 8.31 \text{ J.mol}^{-1} \text{ K}^{-1}$ . This relation is for one mole of gas.

### FREE EXPANSION:-

The **Joule expansion** (also called **free expansion**) is an irreversible process in thermodynamics in which a volume of gas is kept in one side of a thermally isolated container (via a small partition), with the other side of the container being evacuated. The partition between the two parts of the container is then opened, and the gas fills the whole container.

### Ideal gases

If the gas is ideal, both the initial ( $T_i, P_i, V_i$ ) and final ( $T_f, P_f, V_f$ ) conditions follow the Ideal Gas Law, so that initially

$$P_i V_i = nRT_i$$

and then, after the tap is opened,

$$P_f V_f = nRT_f$$

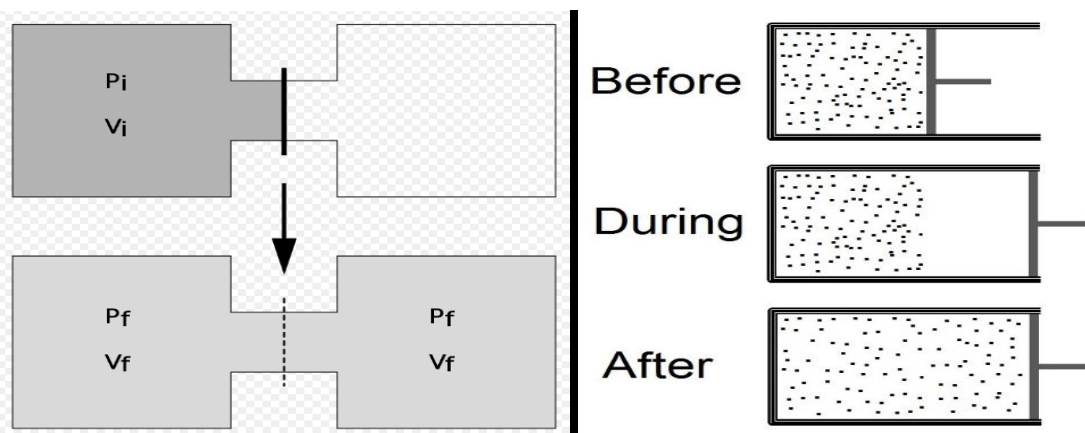
Here  $n$  is the number of moles of gas and  $R$  is the molar ideal gas constant. Because the internal energy does not

change and the internal energy of an ideal gas is solely a function of temperature, the temperature of the gas does not change; therefore  $T_i = T_f$ . This implies that

$$P_i V_i = P_f V_f = nRT_i$$

Therefore if the volume doubles, the pressure halves.

The fact that the temperature does not change makes it easy to compute the change in entropy of the universe for this process.



### **THROTTLING PROCESS:**

This is an expansion process at constant enthalpy.

That it exists in refrigeration and air-conditioning. The LIQUID throttles in the expansion valve.

Liquefaction of gases uses this process.

Throttling is an irreversible process.

No work is obtainable with decrease of pressure. Thus, it is an useless process. It is a compulsion in refrigeration and in the liquefaction of gases. A turbine is not usable for this expansion because of phase change in throttling. The amount of work obtained will also be extremely small.

## INTERNAL COMBUSTION ENGINE & ITS PERFORMANCE

### HEAT ENGINE:

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

(a) External combustion engine (b) Internal combustion engine

#### **External combustion engine:**

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

Examples:

\*In the steam engine or a steam turbine plant, the heat of combustion is employed to generate steam which is used in a piston engine (reciprocating type engine) or a turbine (rotary type engine) for useful work.

\*In a closed cycle gas turbine, the heat of combustion in an external furnace is transferred to gas, usually air which the working fluid of the cycle.

#### **Internal combustion engine:**

In this engine, the combustion of air and fuels take place inside the cylinder and are used as the direct motive force. It can be classified into the following types:

1. According to the basic engine design- (a) Reciprocating engine (Use of cylinder piston arrangement), (b) Rotary engine (Use of turbine)
2. According to the type of fuel used- (a) Petrol engine, (b) diesel engine, (c) gas engine (CNG, LPG), (d) Alcohol engine (ethanol, methanol etc)
3. According to the number of strokes per cycle- (a) Four stroke and (b) Two stroke engine
4. According to the method of igniting the fuel- (a) Spark ignition engine, (b) compression ignition engine and (c) hot spot ignition engine
5. According to the working cycle- (a) Otto cycle (constant volume cycle) engine, (b) diesel cycle (constant pressure cycle) engine, (c) dual combustion cycle (semi diesel cycle) engine.
6. According to the fuel supply and mixture preparation-  
(a) Carburetted type (fuel supplied through the carburetor),  
(b) Injection type (fuel injected into inlet ports or inlet manifold, fuel injected into the cylinder just before ignition).
7. According to the number of cylinder-  
(a) Single cylinder and  
(b) multi-cylinder engine
8. Method of cooling- water cooled or air cooled
9. Speed of the engine- Slow speed, medium speed and high speed engine
10. Cylinder arrangement-Vertical, horizontal, inline, V-type, radial, opposed cylinder or piston engines.
11. Valve or port design and location- Overhead (I head), side valve (L head); in two stroke engines: cross

scavenging, loop scavenging, uniflow scavenging.

## 12. Method governing- Hit and miss governed engines, quantitatively governed engines and qualitatively governed engine

Application- Automotive engines for land transport, marine engines for propulsion of ships, aircraft engines for aircraft propulsion, industrial engines, prime movers for electrical generators.

### **Main components of reciprocating IC engines:**

**Cylinder:** It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above 2000 °C. The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.

**Cylinder head:** The top end of the cylinder is covered by cylinder head over which inlet and exhaust valve, spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

**Piston:** Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at higher temperature.

**Piston rings:** These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature. 2 types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

**Connecting rod:** It converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin and bigger end of the connecting rod is connected with the crank

with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

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

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

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

### **TERMINOLOGY USED IN IC ENGINE:**

**1. Cylinder bore (D):** The nominal inner diameter of the working cylinder.

**2. Piston area (A):** The area of circle of diameter equal to the cylinder bore.

**3. Stroke (L):** The nominal distance through which a working piston moves between two successive reversals of its direction of motion.

**4. Dead centre:** The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).

(a) Bottom dead centre (BDC): Dead centre when the piston is nearest to the crankshaft.

(b) Top dead centre (TDC): Dead centre when the position is farthest from the crankshaft.

**5. Displacement volume or swept volume (Vs):** The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as,

$$V_s = A \times L$$

**6. Clearance volume (Vc):** the nominal volume of the space on the combustion side of the piston at the top dead

centre.

**7. Cylinder volume (V):** Total volume of the cylinder.

$$V = V_s + V_c$$

**8. Compression ratio (r):**

**FOUR STROKE ENGINE:**

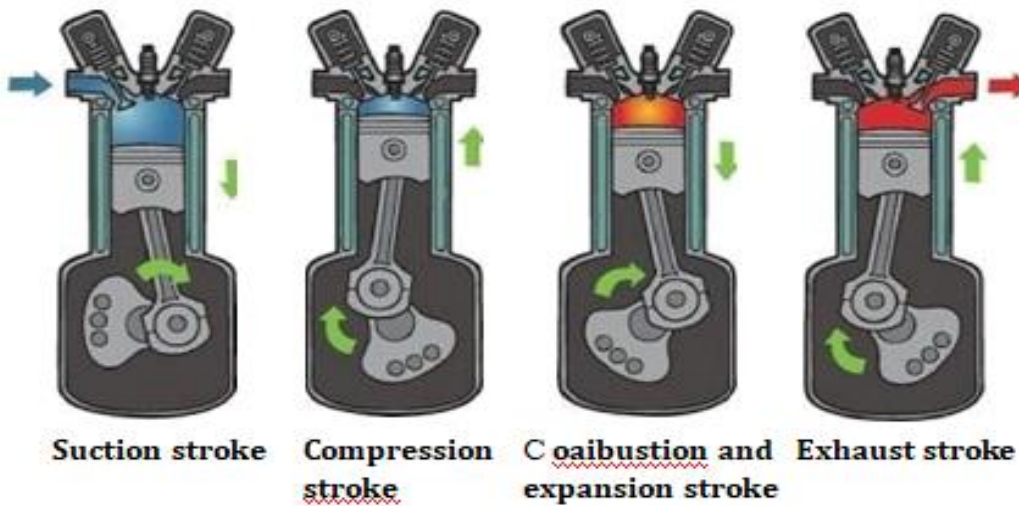
- Cycle of operation completed in four strokes of the piston or two revolution of the piston.

(i) Suction stroke (suction valve open, exhaust valve closed)-charge consisting of fresh air mixed with the fuel is drawn into the cylinder due to the vacuum pressure created by the movement of the piston from TDC to BDC.

(ii) Compression stroke (both valves closed)-fresh charge is compressed into clearance volume by the return stroke of the piston and ignited by the spark for combustion. Hence pressure and temperature is increased due to the combustion of fuel

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

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



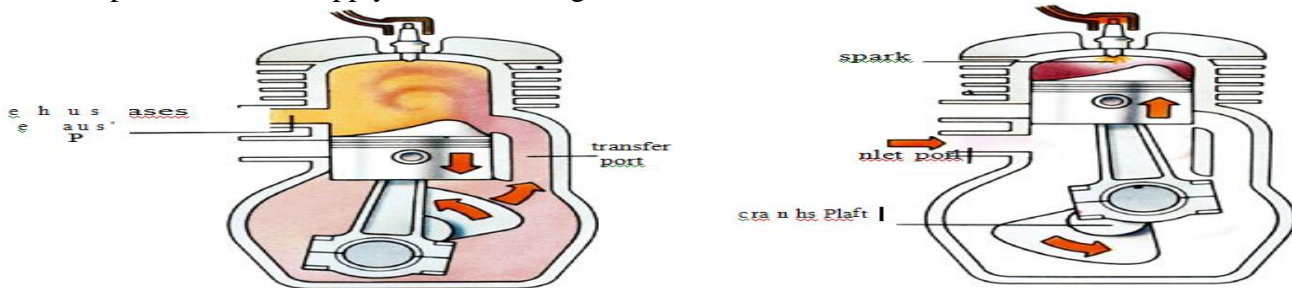
**TWO STROKE ENGINE:**

-No piston stroke for suction and exhaust operations

-Suction is accomplished by air compressed in crankcase or by a blower

-Induction of compressed air removes the products of combustion through exhaust ports

-Transfer port is there to supply the fresh charge into combustion chamber



### **Comparison of Four-stroke and two-stroke engine:**

Four-stroke engine Two-stroke engine

1. Four stroke of the piston and two revolution of crankshaft Two stroke of the piston and one revolution of crankshaft
2. One power stroke in every two revolution of crankshaft One power stroke in each revolution of crankshaft
3. Heavier flywheel due to non-uniform turning movement Lighter flywheel due to more uniform turning movement
4. Power produce is less Theoretically power produce is twice than the four stroke engine for same size
5. Heavy and bulky Light and compact
6. Lesser cooling and lubrication requirements Greater cooling and lubrication requirements
7. Lesser rate of wear and tear Higher rate of wear and tear
8. Contains valve and valve mechanism Contains ports arrangement
9. Higher initial cost Cheaper initial cost
10. Volumetric efficiency is more due to greater time of induction Volumetric efficiency less due to lesser time of induction
11. Thermal efficiency is high and also part load efficiency better Thermal efficiency is low, part load efficiency lesser
12. It is used where efficiency is important.

Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation etc.

It is used where low cost, compactness and light weight are important. Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.

### **Comparison of SI and CI engine:**

SI engine CI engine Working cycle is Otto cycle. Working cycle is diesel cycle. Petrol or gasoline or high octane fuel is used. Diesel or high cetane fuel is used. High self-ignition temperature. Low self-ignition temperature. Fuel and air introduced as a gaseous mixture in the suction stroke. Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke. Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced. Injector and high pressure pump used to supply of fuel. Quantity of fuel regulated in pump. Use of spark plug for ignition system Self-ignition by the compression of air which increased the temperature required for combustion Compression ratio is 6 to 10.5 Compression ratio is 14 to 22 Higher maximum RPM due to lower weight Lower maximum RPM Maximum efficiency lower due to lower compression ratio Higher maximum efficiency due to higher compression ratio Lighter Heavier due to higher pressures

### **Performance of I.C engine**

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

It is classified into two types- (a) External combustion engine

(b) Internal combustion engine

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7. **Cylinder volume (V):** Total volume of the cylinder.  $V = V_s + V_c$

8. **Compression ratio (r):**  $(V_s + V_c) / V_c$

**Power and Mechanical efficiency:**

**BREAK POWER:-**

Power developed at the output shaft is known as brake power (b.p.),

$$b.p. = 2\pi NT$$

where, T is Torque in Nm

N is rotational speed in revolutions per second  $T=WR$

$W=9.81 \times \text{net mass (in kg) applied}$   $R=\text{radius in m}$

### **INDICATED POWER:-**

The actual power generated in an engine cylinder is known as indicated power (i.p.).

It forms the basis for evaluation of combustion efficiency or heat release in the cylinder.

### **FRICTION POWER:-**

power utilised in overcoming friction is known as friction power (f.p.). **f.p.=i.p.- b.p.**

**Mechanical Efficiency=  $b.p./i.p.=b.p./(b.p.+f.p.)$**

#### **Mean effective pressure and Torque:**

Hypothetical pressure acted upon the piston throughout the power stroke.

$P_m = \text{net area of indicator diagram length of indicator diagram} \times \text{spring constant}$

Indicated power per cylinder,

**$i.p.= (P_m A L N / 60) \text{ KW}$**

n= number of revolution required to complete one engine cycle (n=1 for two stroke engine, 2 for four stroke engine)

For hit and miss governing,  $i.p./\text{cylinder} = P_m A L \times \text{number of working strokes per second}$   
Brake power per cylinder

**$b.p.= 2\pi NT / 60$**

Then,  $T = P_m A L n \times 1 / 2\pi$

For same mep, larger engine produces more torque Higher mep, higher will be the power developed by the engine for a given displacement. Mep is basis of comparison of relative performance of different engines, horsepower of an engine is dependent on its size and speed

**Specific output:** It describes the efficiency of an engine in terms of the brake horsepower.

**Specific output=  $b.p./AL = \text{constant} \times b_{mep} \times \text{rpm}$**

For same piston displacement and  $b_{mep}$  an engine running at higher speed will give more output. Increasing speed increase mechanical stresses  $\square$  Increasing  $b_{mep}$  requires better heat release and



more load on engine cylinder

### **VOLUMETRIC EFFICIENCY: $\eta_v$**

*Mass of charge actually inducted* *Mass of charge inducted in swept volume at NTP*  
Power output is proportional to the amount of air inducted  $\eta_v$  of supercharged engine has more than unity due to forced induction.  $\eta_v$  can be improved by compressing the induction charge (forced induction) or by aggressive cam phasing in naturally aspirated engines. In the case of forced induction volumetric efficiency can exceed 100%. Modern technique for four-stroke engines, variable valve timing, attempts to changes in volumetric efficiency with changes in speed of the engine: at higher speeds the engine needs the valves open for a greater percentage of the cycle time to move the charge in and out of the engine.

**Fuel-air ratio (F/A):** Ratio of mass of fuel to mass of air in mixture affects the combustion phenomenon, determines the flame propagation velocity, the heat release, maximum temperature and completeness of combustion, unwanted pollutants formation produced in the reaction. stoichiometric mixture- Enough air is provided to completely burn all of the fuel Rich mixtures: lower than stoichiometric; little air present to burn the given quantity of fuel; are less efficient, but may produce more power and burn cooler Lean mixtures: higher than stoichiometric; more air than required to burn fuel; are more efficient but may cause higher temperatures, which can lead to the formation of nitrogen oxides. Some engines are designed with features to allow lean-burn. AFR (air-fuel ratio) = 1/FAR. Relative fuel-air ratio = actual fuel-air ratio / stoichiometric fuel-air ratio Air-fuel equivalence ratio ( $\lambda$ ): ratio of actual AFR to stoichiometry for a given mixture.  $\lambda = 1.0$  is at stoichiometry, rich mixtures  $\lambda < 1.0$ , and lean mixtures  $\lambda > 1.0$  For pure octane or gasoline fuel the stoichiometric mixture is approximately 15:1, or  $\lambda$  of 1.00 exactly.

**Specific Fuel Consumption (sfc):** Specific fuel consumption is the indication of efficiency with which the engine develops power from fuel. *sfc = fuel consumed horse power developed* Unit: g/kW.h Basis of comparison of different sizes of engine as per efficient utilization of fuel.

The engine which consumes least amount of fuel can produce high power. For IC engines, it is of two types:

**Indicated Specific Fuel Consumption (ISFC)** ISFC = Fuel consumption per unit time / Indicated horse power  
**Brake Specific Fuel Consumption (BSFC)** BSFC = Fuel consumption per unit time / Brake Horse Power: measure of the efficiency of any prime mover that burns fuel and produces rotational, or shaft power.

**Thermal Efficiency ( $\eta_{th}$ ) and Heat Balance:** Ratio of engine power output to input power i.e. chemical energy in the form of fuel supply.

Based on power output, it may be divided into

**brake thermal efficiency ( $\eta_{bth}$ ) indicated thermal efficiency ( $\eta_{ith}$ ).**

**Brake thermal efficiency =  $\frac{b. p.}{mf \times C. V.}$  Indicated thermal efficiency =**

**$\frac{i. p.}{mf \times C. V.}$**

**Heat balance:** In IC engine, total input energy is not fully converted to useful work, energy goes out in various ways.

The heat balance gives the detail of amount of energy wasted in percentage from various parts.

The components of heat balance are brake output, coolant losses, heat going to exhaust, radiation and other losses. 8. Exhaust smoke and other emissions:

**Specific weight:** Exhaust emissions such as smoke, oxides of nitrogen, unburned hydrocarbons, carbon monoxides etc. are necessary to consider as performance parameters and components of air pollution.

It gives the engine bulkiness i.e. weight of the engine in kg for each brake power developed. In aircraft engines, specific weight plays an important role

**calorific value of fuel:-** The calorific value of a fuel is the quantity of heat produced by its combustion – at constant pressure and under “normal” (standard) conditions (i.e. to 0°C and under a pressure of 1,013 mbar)

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

## **STEAM GENERATOR & STEAM POWER CYCLE**

### **Difference between Vapor and Gas**

Usually, a vapour phase consists of a phase with two different substances at room temperature, whereas a gas phase consists of a single substance at a defined thermodynamic range, at room temperature. Thus, this is defined as the key differences between Vapor and Gas. You can find the major differences in the table below.

<b>Difference between Vapor and Gas</b>	
Vapour	Gas
Vapour is a mixture of two or more different phases at room temperature, these phases are liquid and gaseous phase.	Gas usually contains a single thermodynamic state at room temperature.
Vapour has a collection of particles without any definite shape when observed under a microscope.	Gas does not a definite shape when it is observed under a microscope.
Vapour consists of random molecules and atoms moving randomly about.	Gas also consists of random molecules and atoms moving about randomly.
Vapour is not a state of matter, unlike gases.	Gases are a state of matter.
Vapours of water are around us all the time at temperatures below the boiling point of water.	Gases are usually formed above its critical temperature, but below critical pressure.

### **FORMATION OF STEAM AND ITS PROPERTIES:-**

#### **Introduction:-**

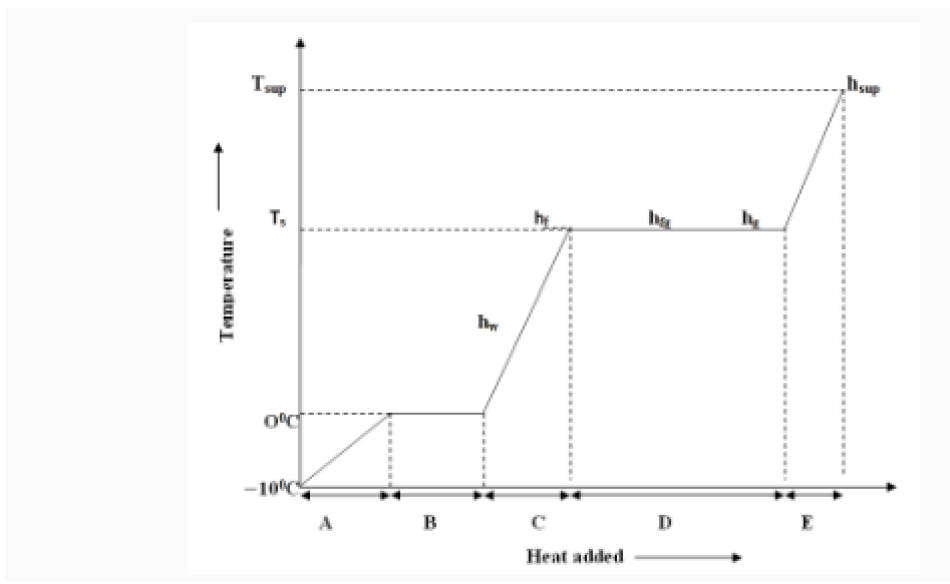
Steam, which is gaseous form of pure water, is an excellent working medium in various thermodynamic systems because of its following properties:

- 1) It can carry large quantities of heat
- 2) It is produced from water which is cheap and readily available

- 3) It can be used for heating purposes after its duty as working agent is completed.
- 4) It can be used purely as a heating medium in food processing Industries because of a fast, easily controllable and hygienic method of heating.

**Formation of Steam:-**

In general, steam can be formed by boiling water in a vessel. But to use it effectively as a working or heating medium, it has to produce in a closed vessel under pressure. Steam formed at a higher pressure has higher temperature and can be made to flow easily through insulated pipes from steam generator to point of use. A simple arrangement of formation of steam at constant pressure



**A = Sensible Heat taken by Ice**  
**B= Latent Heat of Fusion**

**C = Sensible Heat taken by Water**  
**D = Latent Heat of evaporation**

**E = Sensible Heat taken by Steam**  
**hw = Specific enthalpy of water**

**hf = Specific enthalpy of saturated water**  
**hfg = Latent heat of evaporation**

**$h_g$  = Specific enthalpy of dry saturated steam  $h_{sup}$  = Specific enthalpy of super heated steam**

### **Temperature enthalpy curve of formation of steam at constant pressure**

Consider 1 kg of ice at temperature  $-10^{\circ}\text{C}$  which is below the freezing point. Let it be heated at constant pressure  $P$ . The temperature of ice starts increasing until it reaches the melting temperature of ice i.e.,  $0^{\circ}\text{C}$  and during this course ice absorbs its sensible heat. On further addition of heat, ice starts melting, its temperature remains constant at  $0^{\circ}\text{C}$  and it absorbs latent heat of fusion and converts completely into water at  $0^{\circ}\text{C}$ .

On further addition of heat, the temperature of water starts rising until it reaches the boiling temperature or saturation temperature corresponding to pressure  $P$ . This heat absorbed by water is sensible heat.

Note: Saturation temperature or boiling temperature increases with increase in pressure

After the boiling temperature is reached, it remains constant with further addition of heat and vaporization takes place. The water absorbs its latent heat and converts into dry saturated steam remaining at same saturation temperature. The intermediate stage of water and dry saturated steam is wet steam, which is actually a mixture of steam and water.

If further the heat is added, the temperature of this dry saturated steam starts rising from saturation temperature and it converts into superheated steam. This heat absorbed is again the sensible heat. The total rise in temperature of superheated steam above the saturation temperature is called degree of superheat. We must know here that the saturation temperature, latent heat and other properties of steam remain same at constant pressure but varies with the variation of pressure.

### **Advantages of superheated steam**

- 1) The superheated steam can be considerably cooled during expansion in an engine cylinder, before its temperature falls so low as to cause condensation on cylinder walls which is a direct heat loss.
- 2) The temperature of superheated steam being higher, it gives a high thermal efficiency in heat engine.
- 3) It has high heat content and so high capacity of doing work. Thus it results in an economy in steam consumption.

### **Enthalpy of Steam:-**

To find out the total heat content or enthalpy of any state of water/ steam we have to add all types of heat added i.e., sensible and latent to convert the water to that state starting from some initial state or datum which is assumed as a zero enthalpy point or where the heat content is taken as zero. Generally in engineering calculations the datum is water at 0°C where it is considered as having zero heat content or zero enthalpy. Enthalpy of one kg of water or steam is called as specific enthalpy.

### **Specific enthalpy of un-saturated water (h<sub>w</sub>)**

It is simply the amount of heat required to raise the temperature of one kg of water from 0 °C to its actual temperature which is below its saturation temperature. It can be calculated by multiplying actual temperature of unsaturated water with its specific heat which is considered equal to 4.187 kJ/ kg/ K. It is denoted as h<sub>w</sub>.

$$h_w = C_w \cdot t$$

### **Specific enthalpy of saturated water (h<sub>f</sub>):-**

It is the quantity of heat required to raise the temperature of one kg of water at 0°C to its boiling point or saturation temperature corresponding to the pressure applied. It is denoted as h<sub>f</sub>. It can be calculated by multiplying the specific heat of water to the total rise in temperature. The specific heat C<sub>pw</sub> of water may be approximately taken as constant i.e., 4.187 kJ/kg K, but in actual it slightly increases with increase in saturation temperature or pressure.

### **Latent heat of steam (h<sub>fg</sub>):-**

Latent heat of steam at a particular pressure may be defined as the quantity of heat in kJ required to convert one kg of water at its boiling point (saturated water) into dry saturated steam at the same pressure. It is usually denoted by L or h<sub>fg</sub>. It decreases with increase in pressure or saturation temperature.

### **Wet and dry steam:-**

Wet steam is that steam in which the whole of water has not vaporized but the un-vaporized water is present in the form of mist/fog suspended in completely vaporized water or steam. Due to this mist the wet steam is visible. However the dry steam i.e., in which the vaporization is complete is invisible or colorless. Any steam which is completely dry and present at saturation temperature is called dry

saturated steam

### **Dryness fraction:-**

This term refers to quality of wet steam. It is defined as the ratio of the weight of dry steam actually present to the weight of total wet steam which contains it. It is denoted by  $x$

$$x = \frac{W_d}{W_d + W}$$

$W_d$  = Weight of dry steam in 1 kg of wet steam,

$W$  = Weight of water in suspension in 1 kg of wet steam

Dryness fraction is zero for saturated water and one for dry saturated steam.

### **Wetness fraction:-**

It is the ratio of the weight of water/ moisture in suspension in a wet steam sample to the total weight of wet steam. It is calculated by subtracting  $x$  from 1

$$\text{wetness fraction, } (1 - x) = \frac{W}{W_d + W}$$

### **Specific enthalpy of wet steam ( $h_{ws}$ ):-**

It may be defined as the quantity of heat required to convert 1 kg of water at  $0^\circ\text{C}$  into wet steam of a given quality and at constant pressure. It may be denoted by  $h_{ws}$ . It is equal to the sum of specific enthalpy of saturated water and latent heat of dry fraction of steam. So

$$h_{ws} = h_f + x h_{fg}$$

### **Specific enthalpy of dry saturated steam ( $h_g$ ):-**

It may be defined as the quantity of heat required to convert 1 kg of water at  $0^\circ\text{C}$  into dry saturated steam at given constant pressure. It may be denoted by  $h_g$ . It is equal to the sum of specific enthalpy of saturated water and latent heat corresponding to given saturation pressure and temperature. Thus

$$h_g = h_f + h_{fg}$$

### **Specific enthalpy of superheated steam ( $h_{sup}$ ):-**

It is defined as the quantity of heat required to convert 1kg of water at 0°C into the superheated steam at given temperature and pressure. It may be denoted as  $h_{sup}$  and is equal to the sum of specific enthalpy of dry saturated steam and product of specific heat of superheated steam ( $C_s$ ) to degree of superheat.

$$h_{sup} = h_g + C_s(t_{sup} - t_s)$$

Where,  $h_g$  and  $t_s$  are the specific enthalpy of dry steam and saturation temperature at corresponding pressure and  $C_s$  &  $t_{sup}$  are specific heat of superheated steam and temperature of superheated steam at the same pressure.

$$C_s = \frac{h_{sup} - h_g}{t_s - t}$$

The superheated steam behave like the perfect gas and law of expansion has been found to be  $pv^{1.3} = \text{constant}$ .

### **Specific Volume of Water/Steam:-**

The volume of a unit mass of water/steam is known as its specific volume

### **Specific volume of saturated water (vf):-**

It is defined as volume of 1kg of water at saturation temperature corresponding to the given pressure. It is denoted by  $v_f$ . It can be calculated experimentally. It slightly increases with increase in saturation temperature and hence the pressure. The reciprocal of sp-volume is equal to density.

### **Specific volume of dry saturated steam (vg):-**

It is defined as volume of 1kg of dry saturated steam corresponding to the given pressure. It is denoted by  $v_g$  and can be calculated experimentally. As dry saturated steam is a gas, its specific volume decreases with increase in pressure or the saturation temperature.

### **Specific volume of wet steam of quantity x:-**

It is the volume of 1kg of wet steam and is denoted as

$$v_{ws} = x.v_g + (1-x) v_f$$

At low pressure the value of  $v_f$  is very small as compared to  $v_g$ ; so the term  $(1-x) v_f$  may be neglected. Then volume of 1kg of wet steam =  $x.v_g$



### **Specific volume of Superheated Steam ( $v_{sup}$ ):-**

It is the volume of 1kg of superheated steam and can be determined by assuming that the steam behaves as a perfect gas i.e., obeys the gas laws. It is denoted by  $v_{sup}$

Let  $P$  = pressure under which steam is superheated.

$t_{sup}$  = temperature of superheated steam

$v_g$  = Specific volume of dry saturated steam  $t_s$

= saturation temperature at pressure  $P$ . Since,

$P$  = constant

### **Entropy of Steam**

#### **Specific entropy of saturated water ( $s_f$ ):-**

The specific entropy of saturated water at a particular pressure  $P$  and saturation temperature  $T_s$  is given as the change in entropy during conversion of one kg of water at  $0^\circ\text{C}$  into saturated water at that pressure. The water at freezing point  $0^\circ\text{C}$  or  $273\text{ K}$  is considered as datum where, absolute entropy is taken as zero. If  $C_W$  is specific heat of water then the change in entropy of 1kg water during temperature change from  $273\text{ K}$  to  $T\text{ K}$  is given as

$$s_w = C_W \log_e \frac{T}{273}$$

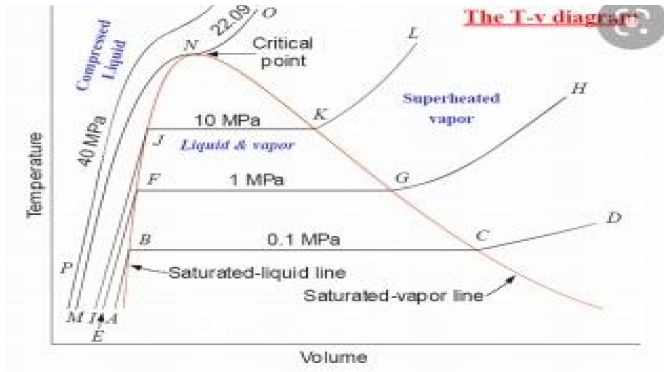
As the Initial entropy at  $273\text{ K}$  is zero, so this change in entropy above  $273\text{ K}$  is taken as entropy of water at temperature  $T$ . In case of Saturated Water,  $T = T_s$ .

#### **Change in specific entropy during evaporation, ( $s_{fg}$ ):-**

During evaporation heat added =  $h_{fg}$  = Latent heat of water

Temperature remains constant during evaporation and is equal to saturation Temperature  $T_s$ .

**Specific entropy of dry saturated steam (sg):-**



It is the entropy of one kg of dry saturated steam and is given as the sum of entropy of 1kg of saturated water and entropy change during evaporation. It is denoted by  $s_g$ .

Thus  $s_g = s_f + s_{fg}$

**Specific entropy of wet steam:-**

It is the sum of specific entropy of dry saturated steam and entropy change during superheating from saturation temp  $T_s$  to superheated temp  $T_{sup}$ .

Change in entropy during superheating

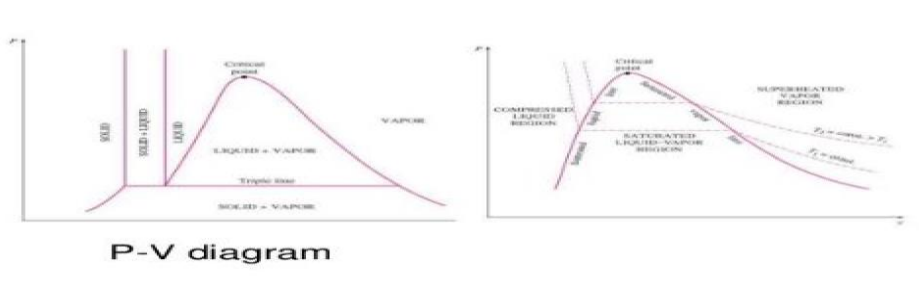
$$= C_{sup} \log_e \frac{T_{sup}}{T_s} \text{ where, } C_{sup} = \text{Sp. heat of super heated steam}$$

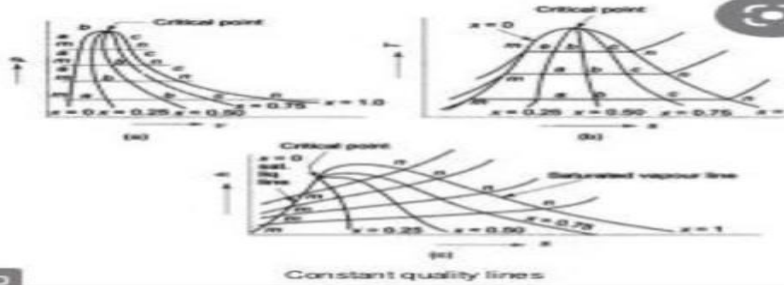
Total specific entropy of superheated steam

$$s_{sup} = s_g + C_{sup} \log_e \frac{T_{sup}}{T_s}$$

$$= s_f + \frac{h_{fg}}{T_s} + C_{sup} \log_e \frac{T_{sup}}{T_s}$$

**Representation on P-V, T-S, H-S, & T-H diagram.**





320 = 240

## **STEAM GENERATOR**

### **Steam Generator:-**

A boiler is a closed vessel in which fluid (generally water) is heated. The fluid does not necessarily boil. The heated or vaporized fluid exits the boiler for use in various processes or heating applications, including water heating, central heating, boiler-based power generation, cooking, and sanitation

The equipment used for producing steam is called **Boiler** or Steam Generator. Or it is also defined as “A closed vessel in which steam is produced from water by the combustion of fuel.”

The steam generated is used for:

- Power generation
- Heating
- Utilization in industries like chemical industries, sugar mills, etc.

### **Classification & types of Boiler:-**

**The boilers may be classified as follows:**

1. Horizontal, Vertical and Inclined Boilers
2. Externally Fired and Internally Fired
3. Fire-tube boiler and Water-tube boiler.
4. Natural circulation and Forced Circulation
5. High Pressure and Low-Pressure boilers
6. Stationary and Portable boilers
7. Single tube and Multitube boilers.

The explanation of the above types of boilers is as follows.

#### **1. Horizontal, Vertical, and Inclined Boilers:**

- If the axis of the boiler is horizontal, then the boiler is of *horizontal type*.
- If the axis of the boiler is vertical, then it is called a *vertical boiler*.
- If the axis of the boiler is inclined, then it is called an *inclined boiler*.

The parts of a horizontal boiler can be inspected and repaired easily. But, it occupies more space and the vertical boiler occupies less floor area.

## **2. Externally Fired and Internally Fired Boilers**

- The boiler is known as **externally fired boiler** if the fire is outside the shell.

**For example,** Babcock and Wilcox Boiler.

- In the case of internally fired boilers, the furnace is located inside the boiler shell.

**For example,** Cochran, Lancashire boiler, etc.

## **3. Fire-tube boiler and Water-tube boiler:**

- In the fire tube boilers, the hot gases are inside the tubes and the water surrounds the tubes.

**For Example,** Cochran, Lancashire boiler, etc.

- In the water tube boilers, the water is inside the tubes and hot gases around them

**For example,** Babcock and Wilcox Boiler.

## **4. Natural circulation and Forced Circulation:**

- In forced Circulation type of boilers, the circulation of water is done by a forced pump.

**For example,** Lamont Boiler, Benson Boiler, etc.

- In the natural circulation type of boilers, the circulation of water in the boiler takes place due to the natural convection currents produced by the application of heat.

**Ex:** Lancashire, Babcock and Wilcox boiler.

## **5. High Pressure and Low-Pressure boilers:**

**High-Pressure Boilers:**

The boilers which produce steam at pressures of 80 bar and above are called high-pressure boilers.

**For example,** Babcock and Wilcox, Lamont, Benson boilers.

### **Low-Pressure Boilers:**

The boilers which produce steam at a pressure below 80 bar are called low-pressure boilers.

**For example,** Cochran, Lancashire, and locomotive boiler.

## **6. Stationary and Portable Boilers:**

- Primarily, the boilers are classified as either stationary or mobile (marine and Locomotives)

Stationary boilers are used for power plant steam for Central station utility power plants.

### **Portable Boilers:**

Portable or mobile boilers include the locomotive type and other small units for temporary usage at sites (Just as in small coal-field pits).

## **7. Single tube and Multi-tube Boilers:**

- If a fire tube is just one, then it is called a Single tube boiler.

**For example,** Cornish, Simple Vertical Boiler.

- If fire tubes are more than one, they are called as Multi-tub

### **Important terms of Boiler**

#### **Shell :-**

The shell of a boiler consists of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell ends are closed with the end plates.

#### **Setting:-**

The primary function of setting is to confine heat to the boiler and form a passage for gases. It is made of brickwork and may form the wall of the furnace and the combustion chamber. It also provides support in some types of boilers (e.g., Lancashire boilers).

#### **Grate:-**

It is the platform in the furnace upon which fuel is burnt and it is made of cast iron bars. The

bars are so arranged that air may pass on to the fuel for combustion. The area of the grate on which the fire rests in a coal or wood fired boiler is called grate surface.

### **Furnace:-**

It is a chamber formed by the space above the grate and below the boiler shell, in which combustion takes place. It is also called a fire box.

### **Water space and steam space :-**

The volume of the shell that is occupied by the water is termed water space while the entire shell volume less the water and tubes (if any) space is called steam space.

### **Mountings:-**

The items such as stop valve, safety valves, water level gauges, fusible plug, blow-off cock, pressure gauges, water level indicator etc. are termed as mountings and a boiler cannot work safely without them.

### **Accessories:-**

The items such as superheaters, economisers, feed pumps etc. are termed as accessories and they form integral part of the boiler. They increase the efficiency of the boiler.

### **Water level :-**

The level at which water stands in the boiler is called water level. The space above the water level is called steam space.

### **Foaming :-**

Formation of steam bubbles on the surface of boiler water due to high surface tension of the water.

### **Scale :-**

A deposit of medium to extreme hardness occurring on water heating surfaces of a boiler because of an undesirable condition in the boiler water.

### **Blowing off :-**

The removal of the mud and other impurities of water from the lowest part of the boiler (where they usually settle) is termed as 'blowing off'. This is accomplished with the help of a blow off cock or valve.

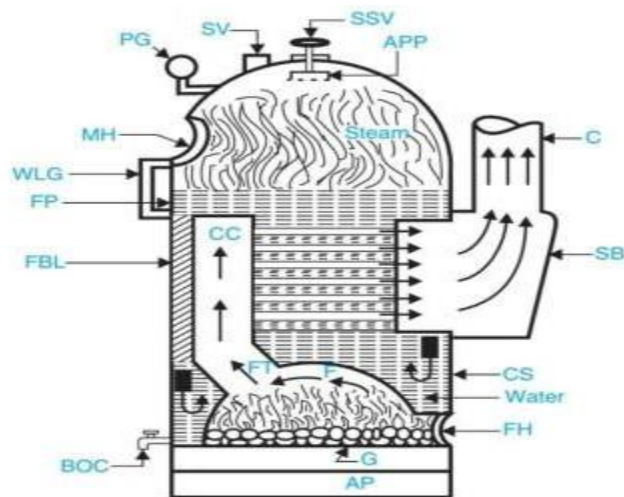
### Lagging:-

Blocks of asbestos or magnesia insulation wrapped on the outside of a boiler shell or steam piping.

**Refractory:-** A heat insulation material, such as fire brick or plastic fire clay, used for such purposes as lining combustion chambers.

## Description & Working of Common boilers (Cochran ,Lancashire ,Babcock & Wilcox Boiler )

### Cochran Boiler :-



CS = Cylindrical shell	FT = Flue tube
CC = Combustion chamber	SB = Smoke box
FBL = Fir brick lining	C = Chimney
F = Furnace (dome shaped)	FH = Fire hole
G = Grate	BOC = Blow-off cock
AP = Ash pit	SSV = Steam stop valve
SV = Safety valve	APP = Antipriming pipe
MH = Man hole	PG = Pressure gauge
WL = Water level gauge	

### Cochran Boiler

- It is one of the best types of vertical multi-tubular boiler, and has a number of horizontal fire tubes.
- Cochran boiler consists of a cylindrical shell with a dome shaped top where the space is provided for steam.
- The furnace is one piece construction and is seamless.
- Its crown has a hemispherical shape and thus provides maximum volume of space. The fuel is burnt on the grate and ash is collected and disposed of from ash pit.
- The gases of combustion produced by burning of fuel enter the combustion chamber through the



flue tube and strike against fire brick lining which directs them to pass through number of horizontal tubes, being surrounded by water.

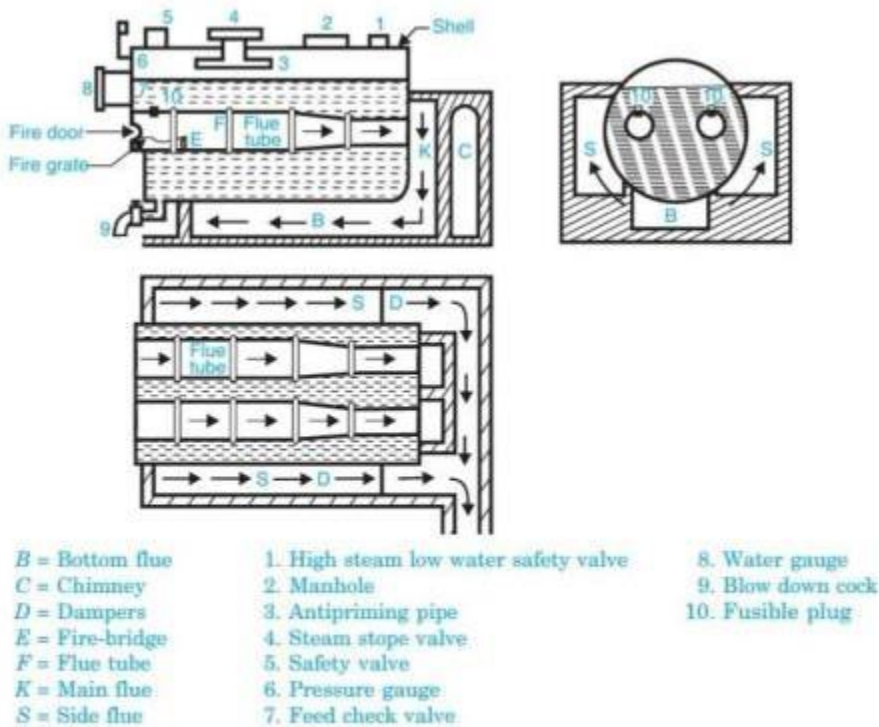
- After which the gases escape to the atmosphere through smoke box and chimney.
- A number of hand-holes are provided around the outer shell for cleaning purposes.

The various boiler mountings shown in Fig. above are :

- Water level gauge
- Safety valve,
- Steam stop valve
- Blow off cock
- Manhole
- Pressure gauge.

### **Lancashire boiler:-**

- This boiler is reliable, has simplicity of design, ease of operation and less operating and maintenance costs.
- It is commonly used in sugar-mills and textile industries where alongwith the power steam and steam for the process work is also needed.
- In addition this boiler is used where larger reserve of water and steam are needed
- The Lancashire boiler consists of a cylindrical shell inside which two large tubes are placed.
- The shell is constructed with several rings of cylindrical form and it is placed horizontally over a brick work which forms several channels for the flow of hot gases.

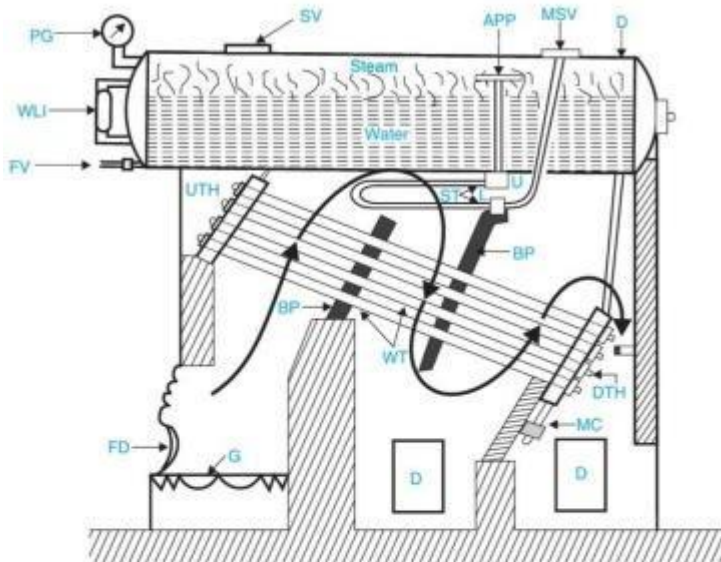


## Lancashire boiler

- These two tubes are also constructed with several rings of cylindrical form.
- They pass from one end of the shell to the other and are covered with water.
- The furnace is placed at the front end of each tube and they are known as furnace tubes.
- The coal is introduced through the fire hole into the grate.
- There is low brickwork fire bridge at the back of the gate to prevent the entry of the burning coal and ashes into the interior of the furnace tubes.
- The combustion products from the grate pass up to the back end of the furnace tubes and then in downward direction. Thereafter they move through the bottom channel or bottom flue up to the front end of the boiler where they are divided and pass up to the side flues.
- Now they move along the two side flues and come to the chimney flue from where they lead to the chimney.
- To control the flow of hot gases to the chimney, dampers (in the form of sliding doors) are provided.
- As a result the flow of air to the grate can be controlled.

**Babcock and wilcox water tube boiler :-**

- The water tube boilers are used exclusively, when pressure above 10 bar and capacity in excess of 7000 kg of steam per hour is required.
- Babcock and Wilcox water tube boiler is an example of horizontal straight tube boiler and may be designed for stationary or marine purposes.
- Fig. above shows a Babcock and Wilcox boiler with longitudinal drum.
- It consists of a drum connected to a series of front end and rear end headers by short riser tubes.
- To these headers are connected a series of inclined water tubes of solid drawn mild steel.
- The angle of inclination of the water tubes to the horizontal is about 15° or more.
- A hand hole is provided in the header in front of each tube for cleaning and inspection of tubes.



- |                             |                        |
|-----------------------------|------------------------|
| D = Drum                    | PG = Pressure gauge    |
| DTH = Down take header      | ST = Superheater tubes |
| WT = Water tubes            | SV = Safety valve      |
| BP = Baffle plates          | MSV = Main stop valve  |
| D = Doors                   | APP = Antipriming pipe |
| G = Grate                   | L = Lower junction box |
| FD = Fire door              | U = Upper junction box |
| MC = Mud collector          | FV = Feed valve.       |
| WLI = Water level indicator |                        |

**Babcock and wilcox water tube boiler**

- A feed valve is provided to fill the drum and inclined tubes with water the level of which is indicated by the water level indicator.

- Through the fire door the fuel is supplied to grate where it is burnt.
- The hot gases are forced to move upwards between the tubes by baffleplates provided.
- The water from the drum flows through the inclined tubes via down takeheader and goes back into the shell in the form of water and steam via uptake header.
- The steam gets collected in the steam space of the drum.
- The steam then enters through the anti priming pipe and flows in the superheater tubes where it is further heated and is finally taken out through the main stop valve and supplied to the engine when needed.
- At the lowest point of the boiler is provided a mud collector to remove the mud particles through a blow-down cock.
  - The entire boiler except the furnace are hung by means of metallic slings or straps or wrought iron girders supported on pillars.
  - This arrangement enables the drum and the tubes to expand or contract freely.
  - The brickwork around the boiler encloses the furnace and the hot gases.

### **Boiler Draught :-**

#### **Boiler Draught:-**

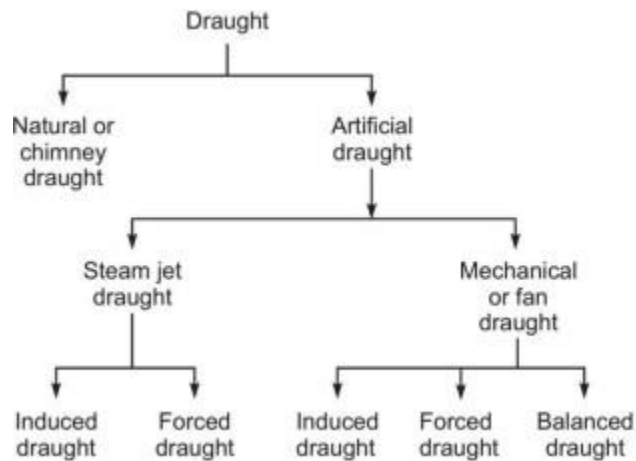
The boiler draught may be defined as the small pressure difference which causes the continuous flow of gases inside the boiler. In other words, the draught is a small pressure difference between the air outside the boiler and gases within the furnace or chimney.

### **Function of Draught :-**

It forces a sufficient quantity of air into the furnace for proper combustion of fuel.

It circulates the hot flue gases through the flue tubes, superheater, economiser, air preheater etc.

It discharges the hot flue gases to the atmosphere through the chimney



**Draught produced by a fan or blower may be of three types:**

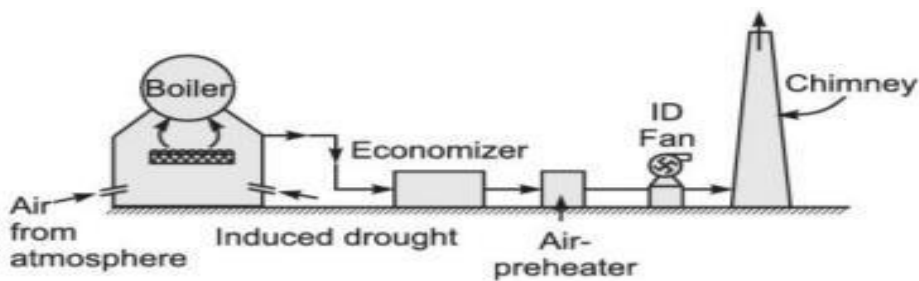
- (a) induced
- (b) forced
- (c) balanced draught.

**Induced draught :-**

The fan is placed near the base of the chimney as shown in Fig.

The fan draws the flue gases from the furnace. So the pressure above the fuel bed is reduced below the atmospheric pressure.

The fresh air rushes to the furnace and after combustion, the flue gases get discharged through the chimney in the atmosphere.

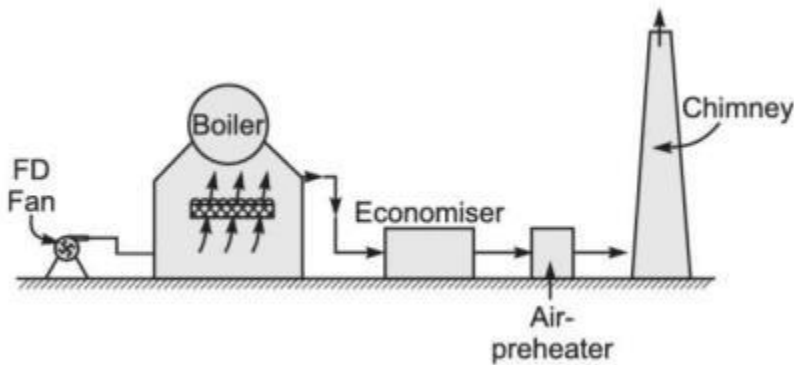


**Forced Draught :-**

The fan or blower is located near or at the base of the boiler grate to force atmospheric air on to the

furnace under pressure.

This pressure helps in circulation of flue gases through components of the boiler and then through chimney to atmosphere. It is shown in above Fig.

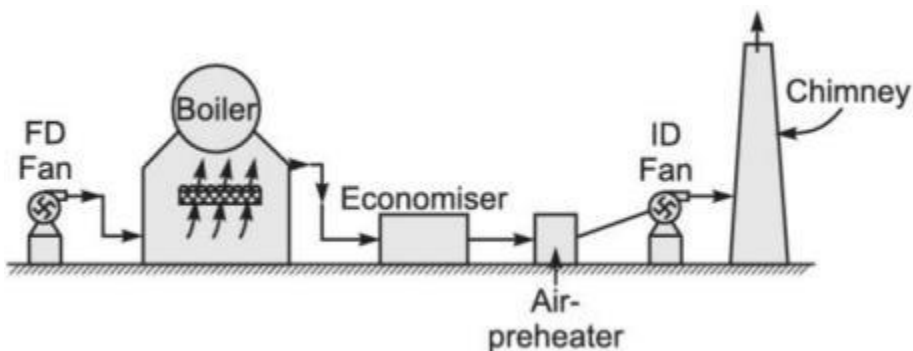


### **Balanced draught :-**

A combination of induced and forced draught in a boiler is known as abalanced draught.

A forced draught fan located near the grate supplies air under the pressure through the furnace and an induced draught fan located near the chimney base, draws in flue gases through the economiser, air preheater, etc., and discharges them into the atmosphere through a chimney.

Figure above illustrates the balanced draught system.



### **Boiler mounting & Accessories:-**

The boiler mountings are the different fittings and devices which are mounted on a boiler shell for proper functioning and safety. These form an integral part of the boiler.

(a) Mountings for Safety :-

1. Safety valve
2. Water-level indicator
3. Fusible plug

(b) Mountings for Control :-

4. Pressure gauge
5. Steam stop valve
6. Feed check valve
7. Blow off cock

**Safety valve :-**

Safety valves are located on the top of the boiler.

They guard the boiler against the excessive high pressure of steam inside the drum.

If the pressure of steam in the boiler drum exceeds the working

pressure then the safety valve allows to blow-off a certain quantity of steam to the atmosphere, and thus the pressure of steam falls in the drum

The escape of steam makes an audible noise as alarm to warn the boiler attendant. There are four types of safety valves.

1. Dead-weight safety valve
2. Spring-loaded safety valve
3. Level-loaded safety valve
4. High steam and low water safety valve

## STEAM POWER CYCLE

### Carnot cycle with vapour

When we think of a power cycle of maximum efficiency, the Carnot cycle immediately conjures up in our mind.

It is a cycle, which has maximum efficiency, operating between given temperature limits and its efficiency is independent of properties of working fluid.

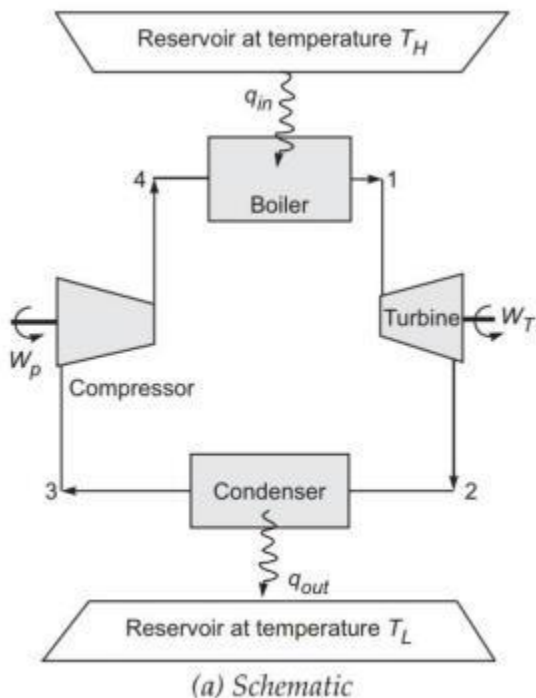
A Carnot vapour power cycle is executed within saturation dome of a pure substance. It uses a two phase fluid as the working medium.

Figure (a) gives the arrangement of components in the cycle,

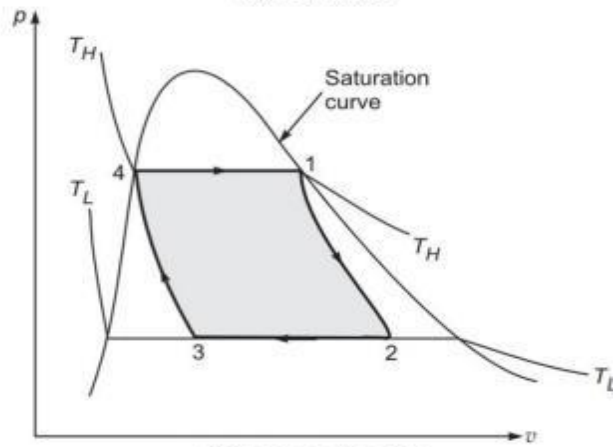
(b) shows Carnot vapour power cycle on  $p$ - $v$  coordinates,

(c) on  $T$ - $s$  coordinates, and

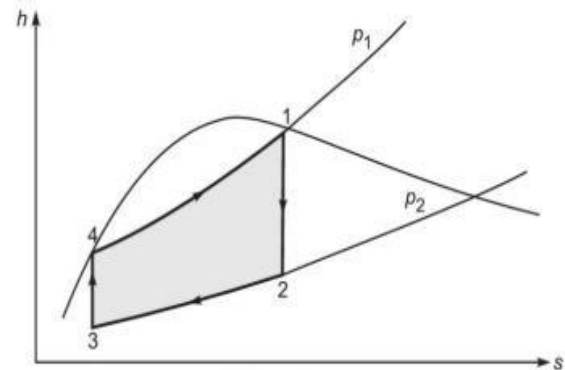
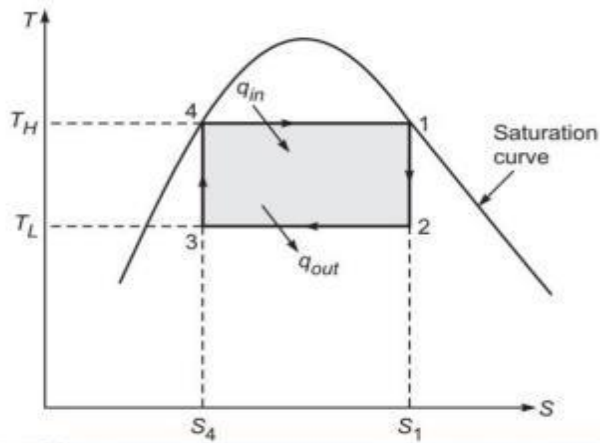
(d) on  $h$ - $s$  coordinates. The boundary of the region in which liquid and vapour are both present (the vapour dome) is also indicated







(b)  $p-v$  as diagram



(d)  $h-s$  diagram

Figure (a) gives the arrangement of components in the cycle , Figure (b) shows  
 Carnot vapour power cycle on  $p-v$  coordinates ,

Figure (c) on  $T-s$  coordinates . The four processes in the cycle are as follows :- 1. Reversible  
 Adiabatic Expansion 1-2

Saturated steam expands in the turbine .

The temperature lowers from  $T_H$  to  $T_L$  .The state 2 is reached in the wet region

## **2. Controlled Condensation 2-3**

During this process ,the condensation starts from state 2 and stops at state 3 and the heat  $q_L$  per unit mass is rejected in the condenser to the sink at  $T_L$ .

## **3. Reversible Adiabatic compression 3-4**

The mixture of liquid and vapour is compressed to the saturation liquid state 4 at boiler pressure .

## **4. Reversible Isothermal heat addition 4-1**

During this process , a quantity of heat  $q_H$  per unit mass is added in the boiler from heat source at the temperature  $T_H$  .

### **Derive work & efficiency of the cycle**

Isothermal heat addition to a vapourising fluid in the boiler;  $Q_{in} = T_H (s_1$

$- s_4)$

Isothermal heat rejected by the working substance in the condenser;  $Q_{out} = T_L (s_1 -$

$s_4)$

The net work done of the cycle;  $W_{net} = q_{in} - q_{out}$

$$= T_H (s_1 - s_4) - T_L (s_1 - s_4)$$

$$= (T_H - T_L)(s_1 - s_4)$$

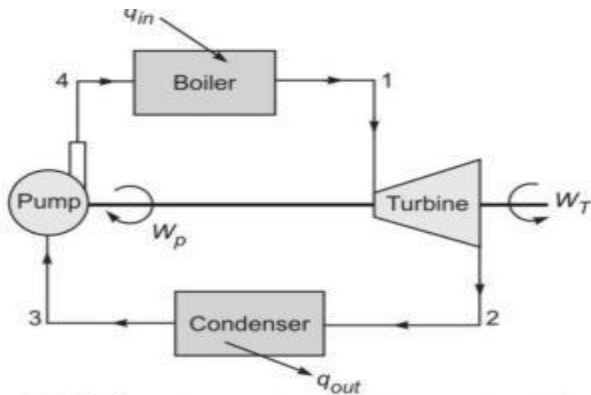
The thermal efficiency of the cycle;

$$\begin{aligned}\eta_{Carnot} &= \frac{w_{net}}{q_{in}} = \frac{(T_H - T_L)(s_1 - s_4)}{T_H(s_1 - s_4)} \\ &= 1 - \frac{T_L}{T_H}\end{aligned}$$

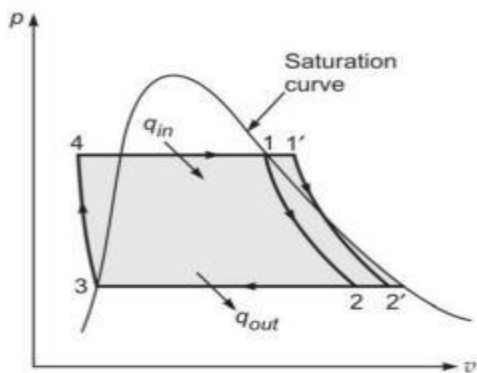
### **Rankine Cycle :-**

Many of the practical difficulties associated with the Carnot vapour power cycle are eliminated in Rankine cycle. The steam coming out of the boiler is usually in superheated state, and expands in the turbine. After expanding in the turbine, the steam is condensed completely in the condenser.

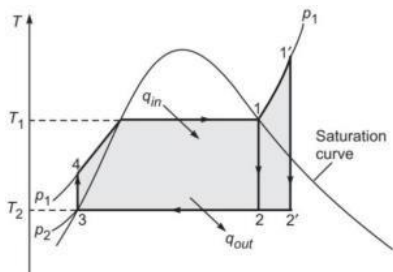
**Representation in P-V, T-S, & h-s diagram :-**



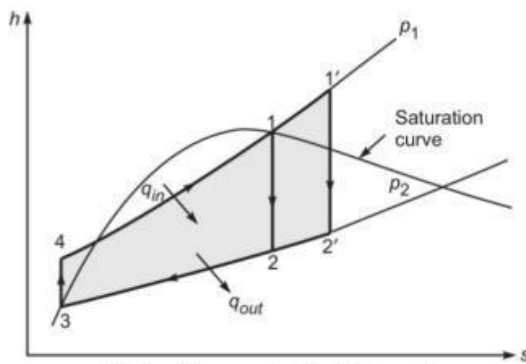
(a) Basic components of vapour power cycle



(b)  $p-v$  diagram for Rankine cycle



(c)  $T-s$  diagram for Rankine cycle



(d)  $h-s$  diagram for Rankine cycle

Process 1-2 :- Isentropic expansion of the working fluid in turbine from boiler pressure to condenser pressure . Process 2-3 :- Heat rejection from the working fluid at constant pressure in the condenser till the fluid reaches the saturated liquid state 3 .

Process 3-4 :- Isentropic compression of the working fluid in the pump to the boiler pressure at the state 4 in the compressed liquid region .

Process 4-1:- Heat addition to working fluid at constant pressure in the boiler from state 4 to 1.

### **Derive work & efficiency of the cycle**

We assume 1 kg of working substance in the cycle and applying steady flow energy equation to each component in the cycle. If changes of kinetic and potential energy are neglected then the steady-flow energy equation reduces to

$$q - w = \Delta h$$

For isentropic compression ( $q = 0$ ) in the pump (process 3-4);  $w_P = h_4 - h_3$  Taking

pump work negative;

then  $w_p = h_4 - h_3$  where  $h_3$  is hf enthalpy of liquid at condenser pressure  $p_2$ .

$h_4$  is the enthalpy of water at state 4, calculated as  $h_4 = h_3 + w_p$

Then the isentropic compression work  $w_p$  is obtained as

$$w_p = \int_{p_2}^{p_1} v dp = v(p_1 - p_2)$$

where  $v_f$  is the specific volume of liquid at condenser pressure  $p_2$  For constant-pressure

heat addition process in the boiler ( $w = 0$ ):  $q_{2-3} = q_{in} = h_1 - h_4$  For isentropic expansion

process 1-2 in the turbine ( $q = 0$ ):  $w_T = h_2 - h_1$  or  $w_T = h_1 - h_2$  For isentropic expansion

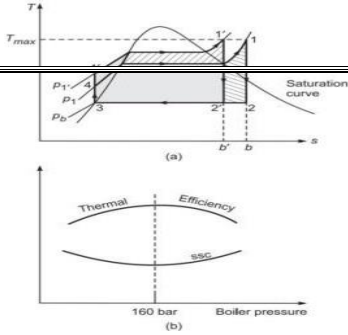
process 1-2 in the turbine ( $q = 0$ ):  $w_T = h_2 - h_1$

or  $w_T = h_1 - h_2$

For constant-pressure heat removal process 2-3 in the condenser ( $w = 0$ ):

$q_{2-3} = q_{out} = h_3 - h_2$  Taking negative sign for heat rejection, then  $q_{out} = h_2 - h_3$  .

The thermal efficiency of any power cycle is expressed as  $\eta = \text{Net work done in the cycle} / \text{Heat supplied in the cycle} = w_{net} / q_{in}$



For Rankine cycle,  $w_{net} = w_T - w_p$

$= (h_1 - h_2) - v_f (p_1 - p_2)$  For a thermodynamic cycle, the net work is also equal to net heat transfer;

$$\eta_{Rankine} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{h_2 - h_3}{h_1 - h_4}$$

$w_{net} = q_{in} - q_{out} = (h_1 - h_4) - (h_2 - h_3)$  Efficiency of Rankine cycle can be expressed as :

### **Effect of Various end conditions in Rankine Cycle :-**

#### **By Increase in Boiler pressure :-**

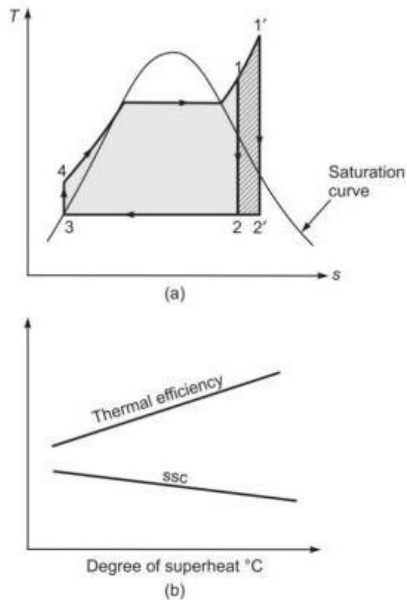
By increasing the boiler pressure, the mean temperature of heat addition increases, and thus raises the thermal efficiency of the cycle. Fig (a) illustrates the effect of boiler pressure on Rankine cycle efficiency.

#### **Effect due to Increase in Boiler pressure:-**

- 1) Turbine work (WT) increase
- 2) Pump work (WP) increase
- 3) Net Work = WT - WP increase
- 4) Efficiency increase
- 5) Heat rejection (QR) decrease
- 6) Heat addition (QS) cannot say

## Super heating :-

Superheating of steam increases the mean temperature of heat addition . The effect of superheated steam on performance of the Rankine cycle is shown in below fig.

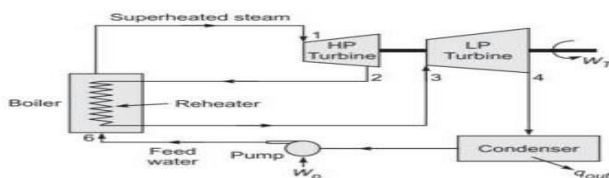


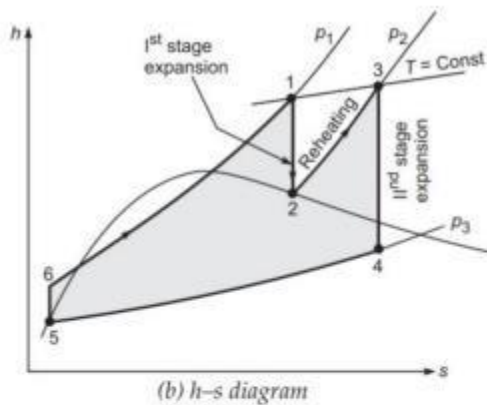
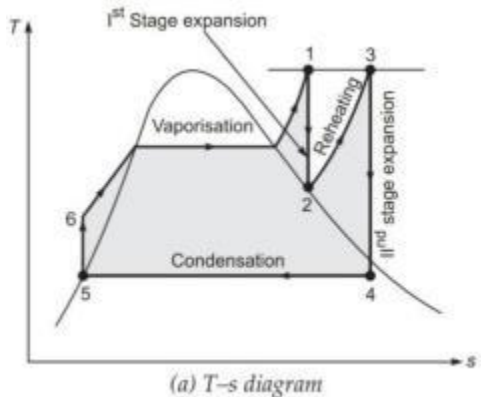
## Effect of superheating :-

- 1) Turbine work (WT) increase
- 2) Pump work (WP) remain constant
- 3) Net Work = WT - WP increase
- 4) Efficiency increase
- 5) Heat rejection (QR) increases
- 6) Heat addition (QS) increases

## Reheating of Cycle:-

In this process heat is added to the steam .The reheated steam then further expands in the next stage of the turbine .Due to reheating , the work output of the turbine increases ,thus improving the thermal efficiency.





### Effect of Reheating of steam :-

- 1) Turbine work ( $W_T$ ) =  $(h_1 - h_2) + (h_3 - h_4)$  increases
- 2) Pump work ( $W_P$ ) =  $h_6 - h_5$  increases
- 3) Net Work =  $W_T - W_P$  increases
- 4) Heat supplied =  $(h_1 - h_6) + (h_3 - h_2)$  increases Regenerative

### Cycle :-

In a simple Rankine cycle, a significant amount of heat is added for sensible heating of compressed liquid coming out the pump. The mean temperature at which sensible heat added is much lower than source temperature. Thus, the efficiency of the Rankine cycle is much lower than that of Carnot vapour power cycle. The efficiency of Rankine cycle can be improved by heating the feed water regeneratively.





### efficiency of the cycle ?

Given :- A steam power plant operating on Carnot cycle  $p_1 = 17.5 \text{ bar}$  ,  $p_2 = 0.075 \text{ bar}$   $S = 20 \text{ kg/min}$

To Find :- (i) Power developed, and (ii) Thermal efficiency of the cycle.

Analysis Properties of steam At boiler pressure from Table A-12  $P_1 = 17.5 \text{ bar} = 1750 \text{ kPa}$   $T_H = 205.76^\circ\text{C} = 478.77 \text{ K}$   $h_4 = h_f = 878.48 \text{ kJ/kg}$   $h_1 = h_g = 2796.43 \text{ kJ/kg}$

At condenser pressure from Table A-12,  $P_2 = 0.075 \text{ bar} = 7.5 \text{ kPa}$   $T_L = 40.29^\circ\text{C} = 313.3 \text{ K}$

The heat supplied in the cycle  $Q_{in} = h_1 - h_4 = 2796.43 - 878.48 = 1917.95 \text{ kJ/kg}$

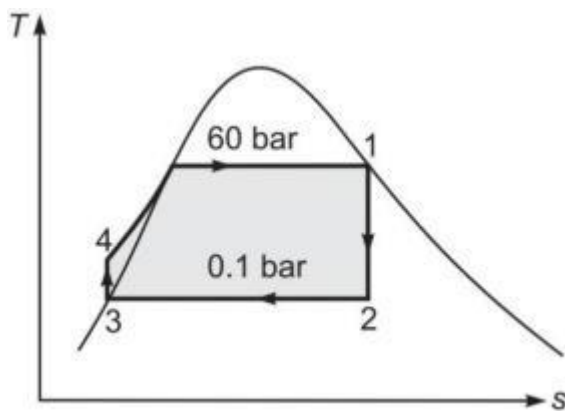
The Carnot efficiency is given as =

$$\eta_{Carnot} = \frac{w_{net}}{q_{in}} = \frac{(T_H - T_L)(s_1 - s_4)}{T_H(s_1 - s_4)}$$
$$= 1 - \frac{T_L}{T_H}$$

$$= 1 - (313.3/478.77)$$

$$= 0.3456 \text{ or } 34.56\%$$

**Q 2. A steam power plant has boiler and condenser pressures of 60 bar and 0.1 bar, respectively. Steam coming out of the boiler is dry and saturated. The plant operates on the Rankine cycle. Calculate thermal efficiency ?**



Given :- Rankine cycle with dry saturated steam  $P_1 = 60$

$\text{bar} = 6000 \text{ kPa}$ ,

$P_2 = 0.1 \text{ bar} = 10 \text{ kPa}$  To

find :-

Thermal efficiency of steam power plant.

Analysis Properties of steam at principal states State 1:

Dry saturated steam; from Table A-13 P1 =

6000 kPa,

$h_1 = 2785.10 \text{ kJ/kg}$  S1 =

5.8891 kJ/kg  $\diamond$  KState 2 :

Wet steam;

P2 = 10 kPa

$h_{f2} = 191.81 \text{ kJ/kg}$   $h_{fg2} =$

2392.82 kJ/kg  $S_{f2} = 0.6492$

kJ/kg  $\diamond$  K  $S_{fg2} = 7.5010$

kJ/kg  $\diamond$  KState 3:

Saturated liquid; P3 = 0.1 bar = 10 kPa

$h_3 = h_{f3} = 191.81 \text{ kJ/kg}$   $v_{f3} = 0.001010 \text{ m}^3/\text{kg}$  State 4:

Compressed liquid; p4 = 6000 kPa,

The state 2, after isentropic expansion can be defined by equating entropy at states 1 and 2;

$s_1 = s_2 = (s_f + x s_{fg}) @ 10 \text{ kPa } 5.8891$

$= 0.6492 + x (7.5010)$

or  $x = (5.8891 - 0.6492) / 7.5010$

$= 0.698$

Specific enthalpy at the state 2

$$h_2 = (hf_2 + x hfg_2) @ 10 \text{ kPa} = 191.81 + 0.698 \times 2392.82 = 1863.34 \text{ kJ/kg}$$

The pump work:-  $w_p = v_f (p_1 - p_2)$

$$= 0.001010 \times (6000 - 10) = 6.05 \text{ kJ/kg}$$

Enthalpy at the state 4;  $h_4 = h_3 + w_p$

$$= 191.81 + 6.05 = 197.86 \text{ kJ/kg.}$$

Rankine cycle efficiency =

$$\begin{aligned} \eta_{Rankine} &= \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \\ &= 1 - \frac{h_2 - h_3}{h_1 - h_4} \end{aligned}$$

$$= 1 - (1863.34 - 191.81) / (2785.10 - 197.86)$$

$$= 0.353 \text{ or } 35.35\%$$

