Department of Mechanical Engineering
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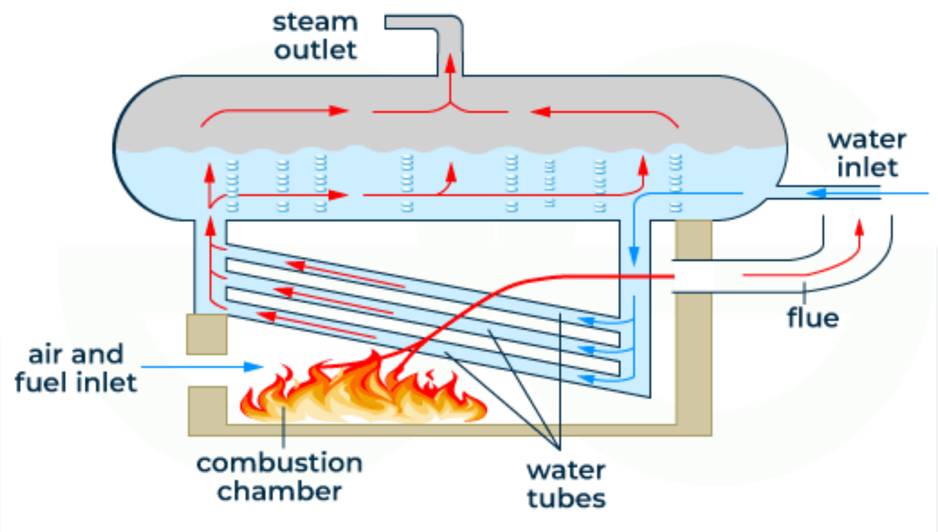
ELEMENTS OF MECHANICAL ENGINEERING-(2025 scheme)

UNIT-III
Steam and its Properties
Steam and Hydraulic Turbines
Refrigeration

Steam and its Properties

Introduction to Steam

- When water is heated in a boiler or steam generator at constant pressure, its heat content called enthalpy increases and its physical state changes.
- With the addition of heat, the temperature of water rises and vapourization takes place.
- The vapour so formed is called steam.
- Steam does not obey laws of perfect gases.
- In a highly superheated state, its behaviour approaches that of a perfect gas.



Water Tube Boiler

Basic Definitions

- **Evaporation:** It is the process of the conversion of water to water vapour.
- **Condensation:** It is the process where vapour turns into water.
- **Sensible heat:** The sensible heat of water is the heat added to or removed from water that causes a change in its temperature, but not its physical state (phase).
- **Specific heat:** It is the quantity of heat required to raise the temperature of one kilogram of water by one degree

  Specific heat of ice = 2.09 kJ/kg-K.

  Specific heat of water = 4.1868 kJ/kg-K.

  Specific heat of superheated steam = 2.1 kJ/kg-K

Basic Definitions

- **Latent heat of Vapourisation:** It is the energy that is absorbed by the water during the phase transition from liquid water to the vapour at the saturation temperature.

  Latent heat of vaporization of water = 2256.9 kJ/kg at 1 bar.

- **Latent Heat of Fusion:** It is the energy that is absorbed by the ice during the phase transition from ice to the water at the saturation temperature.

  Latent heat of fusion of ice = 335.7 kJ/kg at 1 bar.

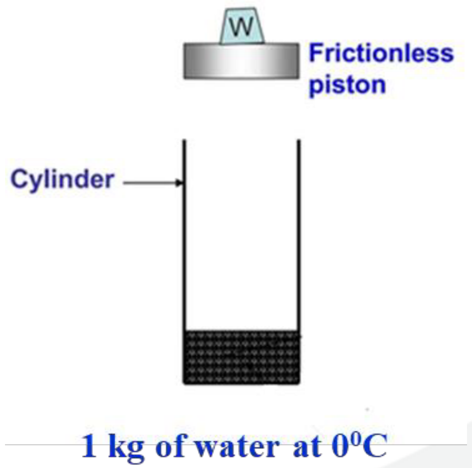
- **Boiling point:** It is the temperature at which water converts into a vapour.
- **Freezing point:** It is the temperature at which water converts to ice.

Formation of Steam at Constant Pressure

- Consider 1 kg of water at 0^0C in a cylinder fitted with a freely moving frictionless piston of negligible weight.
- The weight W is present on the piston. The pressure applied on the water due to weight W is

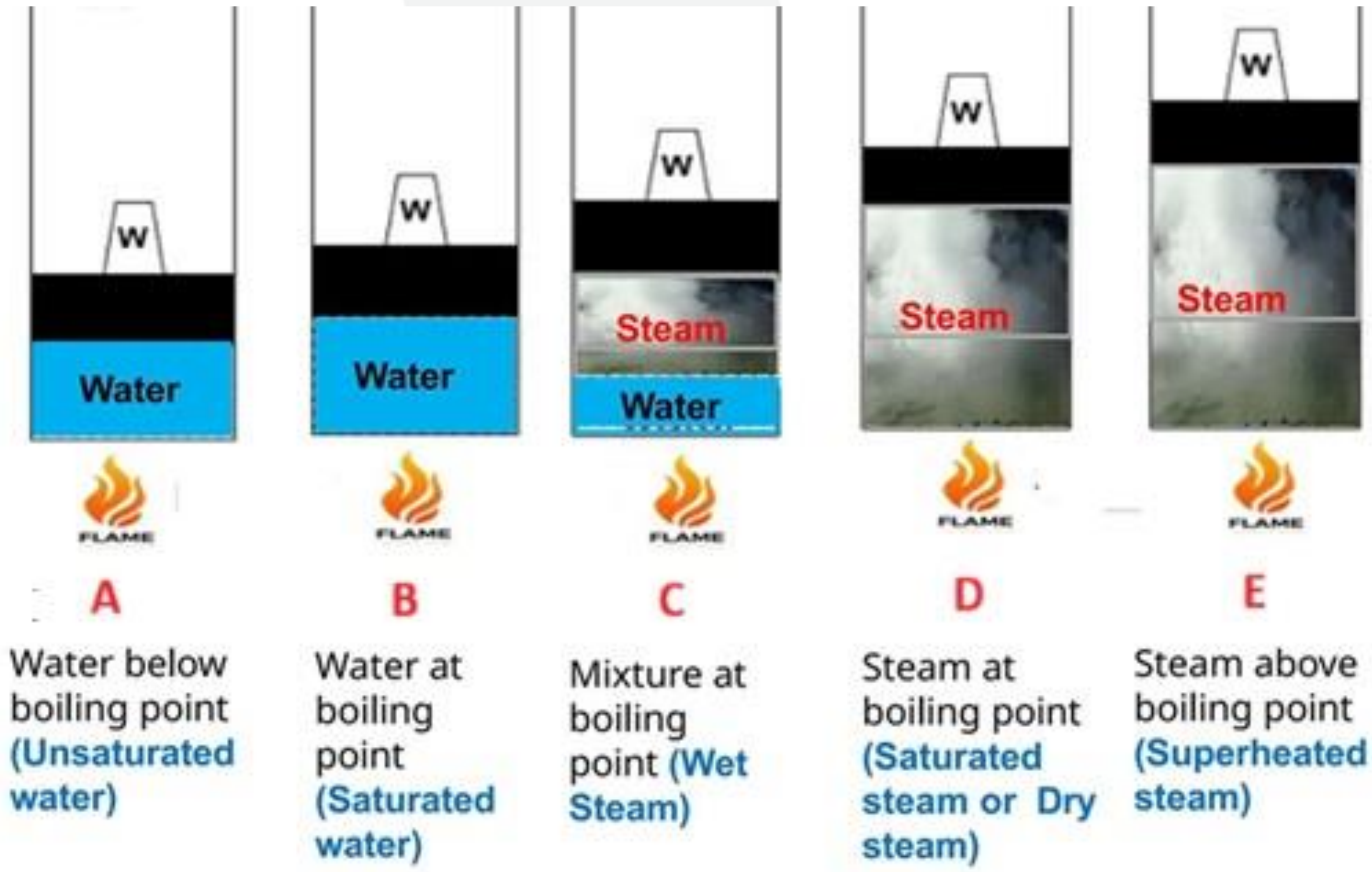
$$Pressure\ ,\ P = \frac{Weight\ applied\ on\ Piston}{Cross\ sectional\ area\ of\ piston},\ P = W/A$$

- Water at 0^0C will be heated till it converts to superheated steam using a source of heat in the above mentioned arrangement as shown in next slide



A kg of water in piston cylinder arrangement

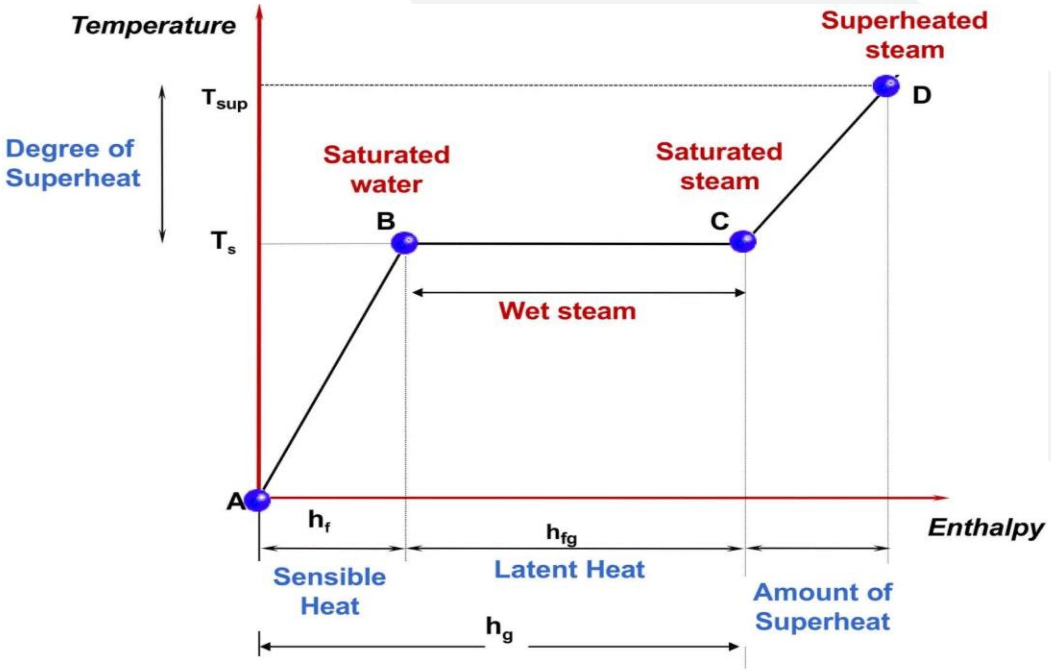
Formation of Steam at Constant Pressure



Formation of Steam at constant pressure

Temperature- enthalphy plot

- Steam to water conversion as depicted in the previous slide is represented using temperature enthalpy (T-h) plot here.
- Enthalpy is a measure of total heat energy in the water/steam.
- The total heat or enthalpy of steam is the sum of sensible heat, internal latent heat and the external work of evaporation



Definitions of terms present on T-h plot

- **Sensible Heat (h_f in J/kg):** Amount of heat required to raise the temperature of 1 kg of water from 0^0C to saturation temperature $T_{sat}{}^0$C at a given constant pressure.
- Line AB on T-h plot represents sensible heating. Also called *enthalpy of saturated water.*
- **Latent Heat (h_{fg} in J/kg):** Amount of heat required to convert 1 kg of saturated water to 1 kg of saturated steam at a saturation temperature $T_{sat}{}^0$C for the given constant pressure.
- Line BC on the T-h plot represents latent heating. Also called *enthalpy of evaporation or vapourisation.*
- **Amount of Superheat (J/kg) :** It is the amount of heat required to raise the temperature of 1 kg of dry steam at saturation temperature to the desired higher temperature at a given constant pressure.
- Line CD on the T-h plot represents superheating.

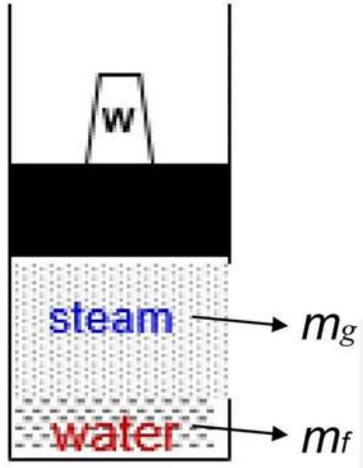
Definitions of terms present on T-h plot

- **Degree of Superheat:** The difference between the super-heated temperature and the saturation temperature (T_{sup} - T_s).
- **Wet Steam:** It is a two-phase mixture of water and vapour in thermal equilibrium at the saturation temperature corresponding to the given stated pressure.
- **Dry Steam:** When all the water present in wet steam converts to vapour at the saturation temperature, it is called dry steam. It is a single-phase vapour.
- **Superheated Steam:** When the dry steam at saturation temp is further heated, its temperature increases and the steam is called super-heated steam.
- Superheated steam comes with the advantage of higher energy content and lesser changes of corroding the turbine or engine parts

Definitions of terms present on T-h plot

- **Dryness Fraction:** The wet steam is a mixture of dry steam and saturated water. The vapour fraction in the wet steam is called dryness fraction (X)

$$X = \frac{mass\ of\ dry\ steam\ in\ the\ mixture}{total\ mass\ of\ wet\ steam} = \frac{m_g}{m_f + m_g}$$



- *For dry steam, X = 1*
- *For Saturated water, X = 0*
- *For Wet Steam, 0 < X < 1*

Enthalpy Equations

- **Enthalpy of unsaturated water (h_w):**

$$h_w = C_P(T_w - 0) \ kJ/kg$$

- **Enthalpy of saturated water(h_f):**

$$h_f = C_P(T_s - 0) \ kJ/kg$$

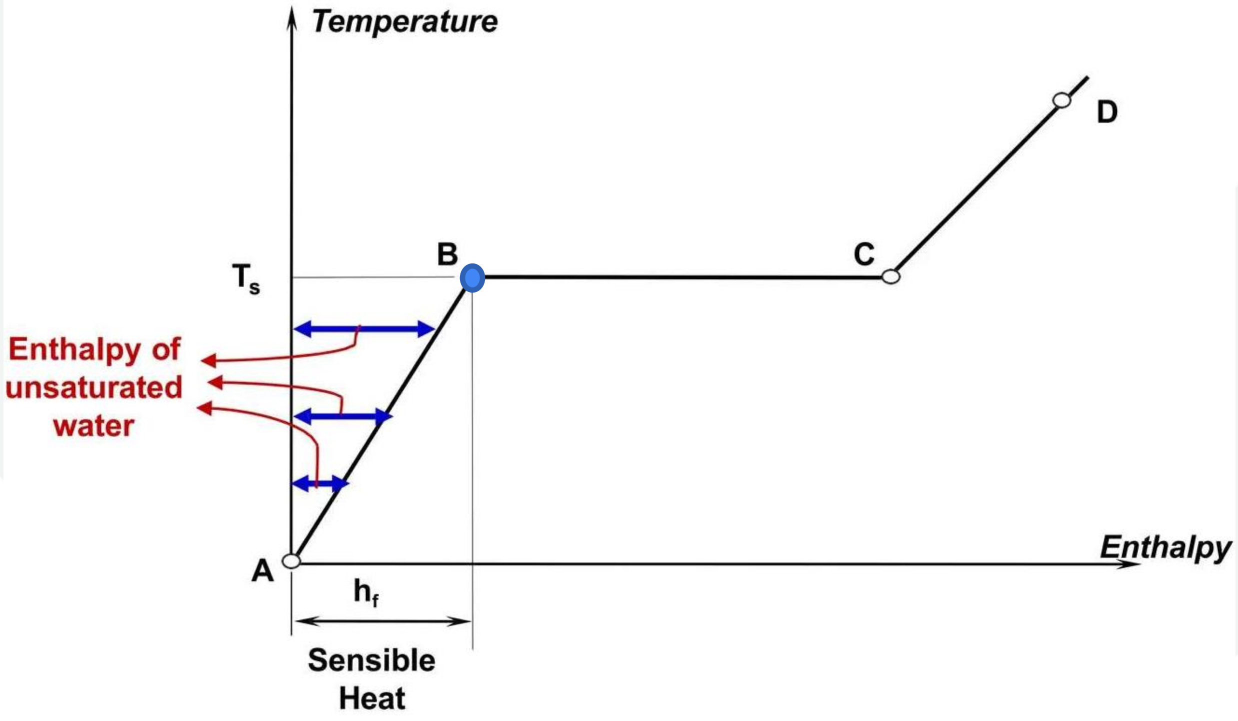
Where,

C_P = *Specific heat in kJ/kgK,*

T_w = *Temperature of water in* ^0C

T_s = *Temperature of water in* ^0C ($T_w < T_s$)

- h_f is also known as **sensible heat**



Enthalpy Equations

- **Enthalpy of dry saturated steam(h_g):**

$$h_g = h_f + h_{fg} \ kJ/kg$$

- **Enthalpy of wet steam(h):**

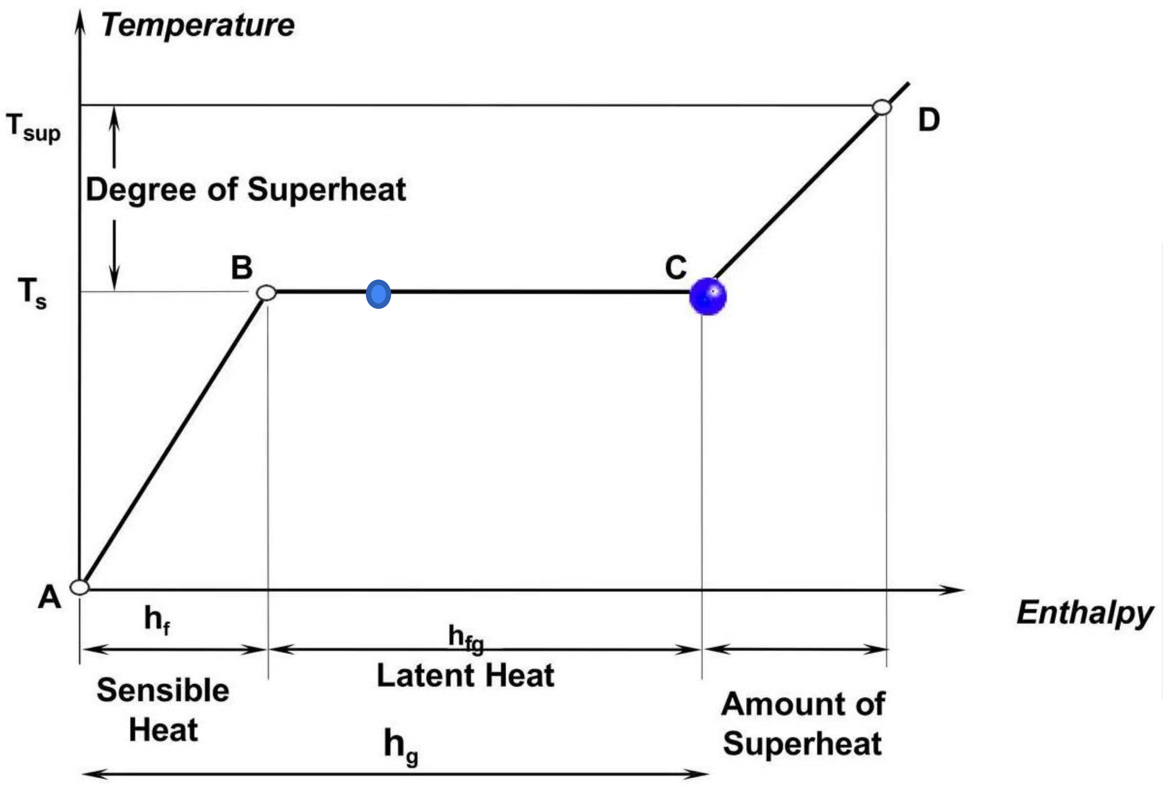
$$h = h_f + x h_{fg} \ kJ/kg$$

Where,

h_f = *sensible heat in kJ/kgK,*

h_{fg} = *latent heat in kJ/kgK*

x = *dryness fraction*



Enthalpy Equations

- **Enthalpy of superheated steam(h_{sup}):**

$$h_{sup} = h_f + h_{fg} + C_{sup}(T_{sup} - T_s) \ kJ/kg$$

- **Amount or Enthalpy of Super-heat:**

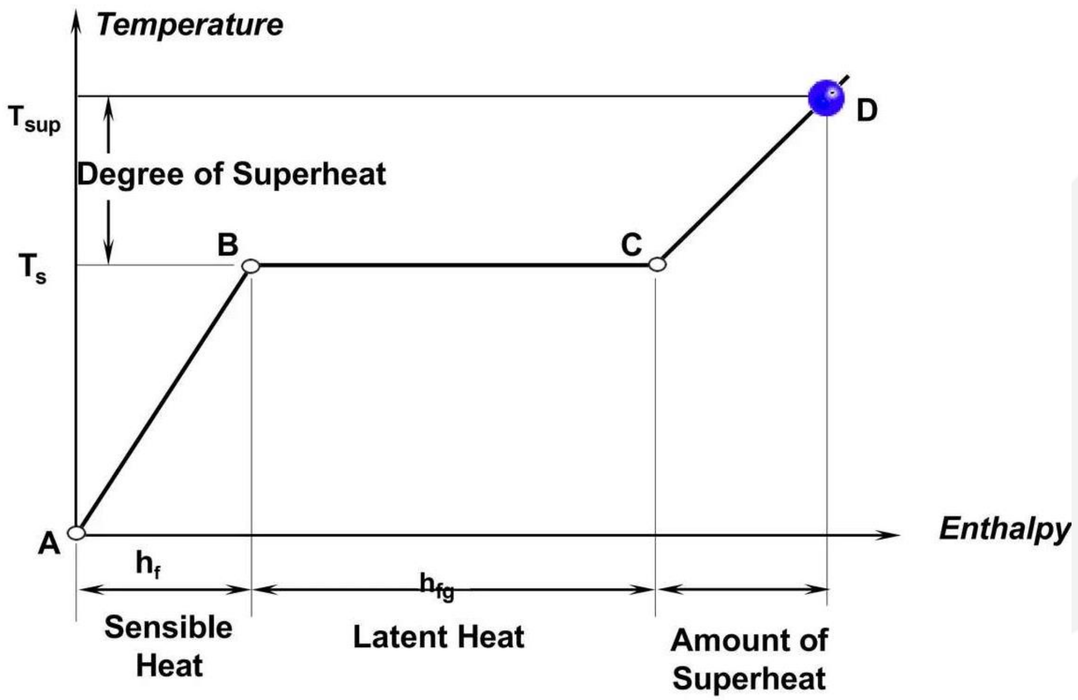
$$AOS = C_{sup}(T_{sup} - T_s) \ kJ/kg$$

Where,

C_{sup} = *Specific heat of super heated steam in kJ/kg K,*

T_{sup} = *Superheated Temperature in* ^0C

T_s = *Saturation Temperature in* ^0C



Steam Table

- The working fluid in any system has six basic thermodynamic properties which are needed to define the state of the working medium completely.
- These properties may not be independent and may be specific at specific conditions and are tabulated in the steam table at different pressure and saturation temperature conditions.
- These properties are *pressure (P), temperature (T), volume (v), internal energy (u), enthalpy (h) and entropy (s).*
- *Sample steam table is presented below*

Absolute pressure (P bar)	*Saturation temperature* (t°C)	*Specific enthalpy* (kJ/kg)			*Specific entropy*			*Specific volume* (m^3/kg)	
		h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_g
1.0	99.7	417.51	2257.9	2675.4	1.3027	6.050	7.359	0.001043	1.725
5.0	151.1	640.12	210.7	274.7	1.86	4.588	6.819	0.001092	0.382
20.0	211.4	908.99	1888.6	2797.2	2.4469	3.779	6.3567	0.001175	0.1015

Property values from Steam Table

- **Specific volume (v):** *Specific volume of dry and saturated steam (v_g) and saturated water (v_f) is directly obtained from the steam table corresponding to that pressure or saturation temperature.*
- For wet steam, the dryness fraction 'x' has to be used to estimate the specific volume.

Volume of 1 kg of wet steam = Volume of dry steam + Volume of water

$$v = xv_g + (1-x)v_f$$

$$v = xv_g \qquad \text{(since } v_f << v_g\text{)}$$

- The specific volume of superheated steam can be estimated with the help of gas laws since steam at these temperatures behaves like an ideal gas.

$$\frac{Pv_{sup}}{T_{sup}} = \frac{Pv_g}{T_s} \implies v_{sup} = \frac{T_{sup}v_g}{T_s}$$

- If the specific volume of any steam is v, then its **density (ρ)** will be $1/v$

Property values from Steam Table

- **Entropy (s):** Entropy is a measure of randomness associated with the system and mathematically the change in entropy between initial and final state is defined as

$$s_2 - s_1 = \int_i^f \frac{dQ}{T}$$

where dQ is the heat transfer in kJ and T is the temperature in kelvin (K). The unit used to measure entropy is kJ/kg K.

- **Entropy of water:** Consider heating of unit mass of water from a temp. of T_1°C to T_2°C at constant pressure.

Amount of heat addition for infinitesimal process is given by

$$dQ = C_P dT$$

Then change in entropy for the process is defined as

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{dQ}{T} = \int_{T_1}^{T_2} \frac{C_P dT}{T} = C_P ln(\frac{T_2}{T_1})$$

Property values from Steam Table

- **Entropy of wet steam**

In case the steam remains wet during heat transfer of evaporating water and its dryness fraction is x, then

$$s = s_f + x s_{fg} \ kJ/kgK$$

If steam becomes dry and saturated, then x = 1.

$$s_g = s_f + s_{fg} \ kJ/kgK$$

- **Entropy of superheated steam**

Let the unit mass of dry saturated steam at temperature T_s be heated to T_{sup}, the superheated temperature. If specific heat C_{psup} is considered constant, then

$$s_{sup} = s_g + C_{Psup} \ln\left(\frac{T_{sup}}{T_s}\right) kJ/kgK$$

Property values from Steam Table

- **External Work Done During Evaporation**: The volume of saturated water (v_f) is very small in comparison to dry saturated steam (v_g).
- Since this process takes place at constant pressure and as volume increases, external work is done by the piston cylinder arrangement on the surroundings.
- The energy required for this external work comes from absorbing energy from the total heat of the steam which is called as external work done during evaporation

$$\text{external work of evaporation} = P(v_g - v_f)\ kJ/kg$$

since $v_f << v_g$, it can be neglected

$$\text{External work} = Pv_g \qquad \text{for dry saturated steam}$$

$$= xPv_g \qquad \text{for wet steam}$$

Property values from Steam Table

- **Internal Energy (u):** The energy stored in steam is called internal energy.
- The work of evaporation is not stored in the steam since it is used in carrying out the external work done.
- Therefore, the internal energy of steam can be defined as

$$\mathbf{h} = u + P(v_g - v_f)$$

$$\mathbf{u} = h - P(v_g - v_f)$$

Where, u is the internal energy of 1 kg of steam at pressure P

since $v_f << v_g$, it can be neglected

$$\mathbf{u} = h - Pv_g \quad \text{for dry saturated steam}$$

$$u = h - xPv_g \quad \text{for wet steam}$$

In case of superheated steam,

$$h_{sup} = h_f + h_{fg} + C_{PS}(T_{sup} - T_s) \ kJ/kg$$

$$\mathbf{u} = h_{sup} - Pv_{sup}$$

Numericals

Example 1: How much heat is required to convert 4 kg of water at 20°C into steam at 8 bar and 200°C. Take Cps= 2.1 kJ/kgK and Cpw = 4.187 kJ/kgK.

Solution Given: m = 4 kg, T_1 = 20°C P_1= 8 bar, T_2= 200°C

C_{ps}= 2.1 kJ/kgK , C_{pw} = 4.187 kJ/kgK

Data from the steam table at 8 bar pressure:

T_s= 170.41°C, h_f= 720.94 kJ/kg, h_g= 2767.5 kJ/kg

Since T_2 (200°C) > T_S (170.41°C), therefore, **steam is superheated.**

Enthalpy of steam which is superheated/kg = $h_g + C_{ps}(T_{sup} - T_S)$

= 2767.5 + 2.1(200 -170.41) = 2829.6 kJ/kg

Heat contained in water at 20°C=$C_{pw}(T_s$-0) = 4.187x20 = 83.74 kJ/kg

Amount of heat required for 1 kg of steam = 2829.6 - 83.74 = 2745.86 kJ/kg

Total amount of heat required = 4 x 2745.86 = 10983.44 kJ

Numericals

Example 2: Determine the enthalpy, volume, internal energy, and entropy of superheated steam at 14 bar pressure and 200°C. Neglect the volume of water and take specific heat of superheated steam equal to 2.1 kJ/kg.

Solution The steam properties at 14 bar pressure from steam tables:

v_g = 0.14084 m^3/kg, h_f = 830.29 kJ/kg,

h_g = 2790.0 kJ/kg, s_f = 2.2842 kJ/kgK,

s_g = 6.4692 kJ/kgK, h_{fg} = 1959.71 kJ/kg,

s_{fg} = 4.185 kJ/kgK, and T_{sat} = 195.07°C

Total heat or enthalpy of 1 kg of steam, $h_{sup} = h_f + h_{fg} + C_{PS}(T_{sup} - T_s)$

h = 830.29 + 1959.71 + 2.1 × (200 – 195.07) = 2800.35 kJ/kg

Volume of superheated steam , $v_{sup} = \frac{T_{sup} v_g}{T_s} = \frac{(200+273) * 0.14084}{(195.07+273)} = 0.1423\ m^3/kg$

Numericals

Internal energy of superheated steam is given by

$$u = h_{sup} - Pv_{sup}$$

$$u = 2800.35 - (1400 * 0.1423)$$

$$= 2601.13\ kJ/kg$$

The entropy of superheated steam is given by

$$s_{sup} = s_g + C_{Psup} \ln\left(\frac{T_{sup}}{T_s}\right)$$

$$s_{sup} = 6.4692 + 2.1\ln\left(\frac{200 + 273}{195.07 + 273}\right)$$

$$= 6.4912\ kJ/kgK$$

Numericals

Example 3: Determine the condition of steam at a pressure of 8 bar and volume of 0.22 m^3/kg.

Solution P= 8 bar, v= 0.22 m^3/kg

From the steam table for P = 8 bar

At 8 bar pressure, volume of dry steam, v_g= 0.24026 m^3/kg

Since, v (0.22 m^3/kg) < v_g (0.24026 m^3/kg)

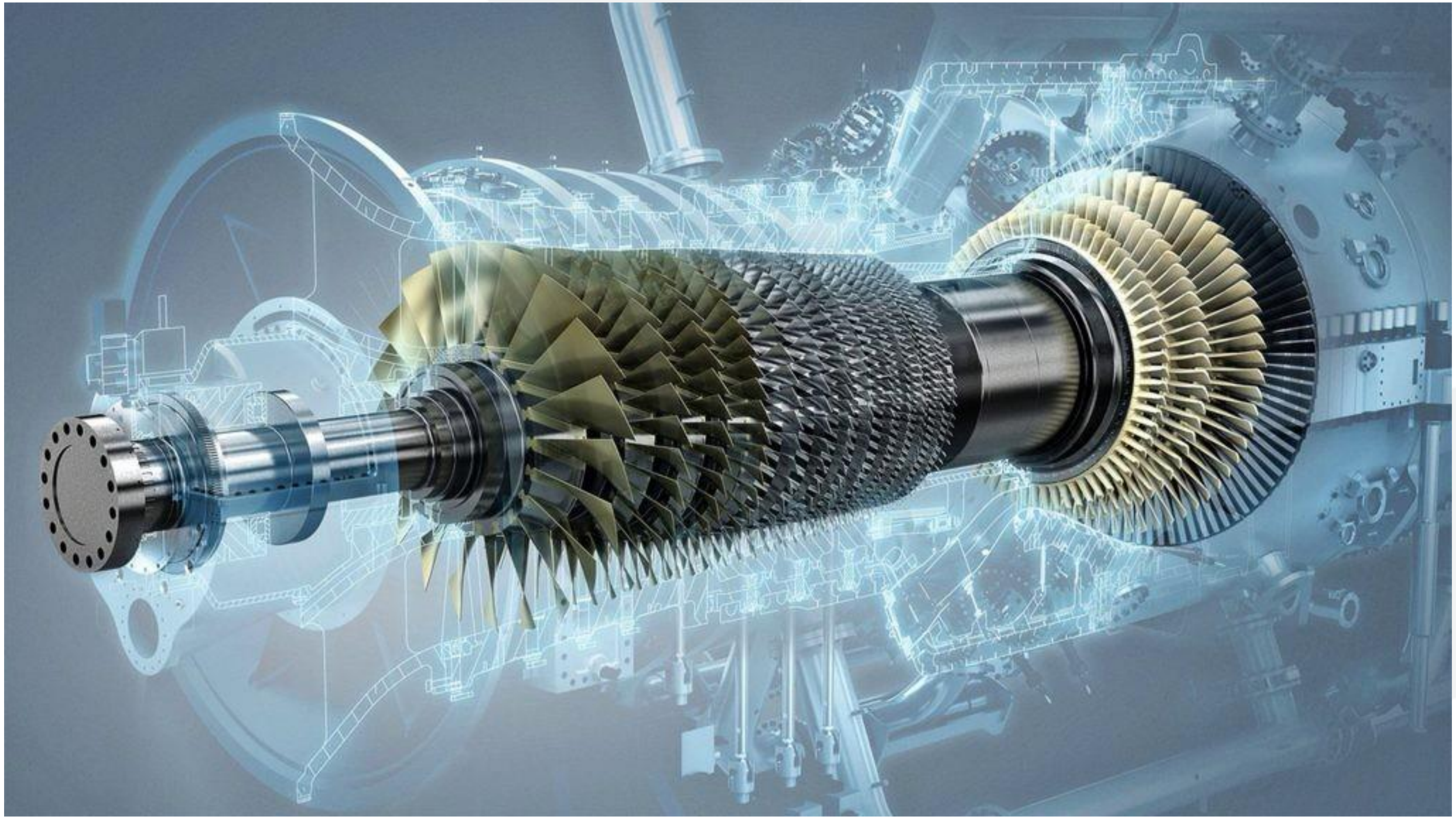
Therefore, steam *is* ***wet.***

Neglecting the volume of water,

$$V = x\, v_g$$

x = dryness fraction = V/v_g = 0.22 / 0.24026 = **0.91**

Steam Turbines

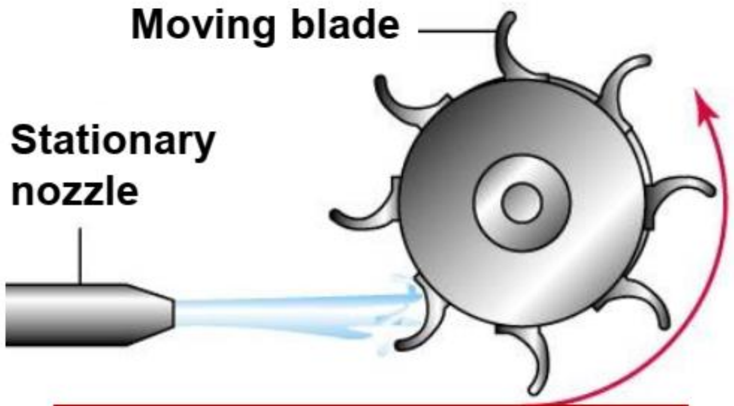


Steam Turbines - Introduction

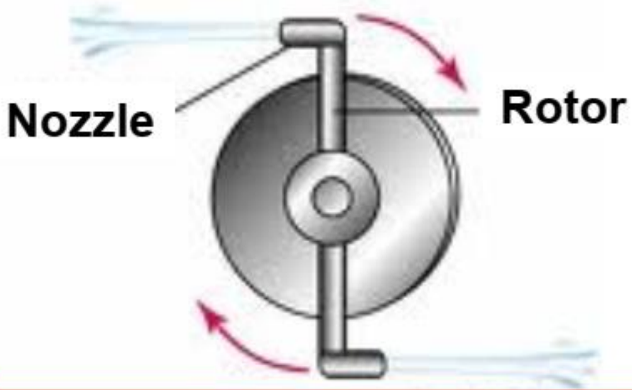
- A steam turbine is a power producing turbomachine in which energy of high pressure, high temperature steam supplied from a steam generator is converted continuously into shaft work and the lower pressure, lower temperature steam at its outlet is discharged.
- It is a prime mover working on **Rankine cycle** and its variants.
- It is basically an assemblage of nozzle and ring of moving blades mounted on a rotor shaft.
- The high pressure, high temperature steam first expands in a nozzle and comes out as ***high velocity jet*** because of the static pressure drop in the nozzle.
- The high velocity steam exiting the nozzle impinges on the rotor blades.
- The rate of change of momentum of a high velocity jet striking on a curved blade which is free to rotate determines the motive power of a steam turbine.

Impulse and Reaction Steam Turbine

- The conversion of energy of the steam in the blades to the driving thrust takes place by impulse, reaction or impulse reaction principle.
- Steam turbines are basically classified into:
  - Impulse turbines (De Laval, Curtis Turbine)
  - Reaction turbines (Parson Turbine)
- In an impulse turbine, all the pressure drop occurs across nozzles (or stationary blades) and there will be no pressure drop across the rotor blades (neglecting frictional loss)
- In a reaction turbine, there will be pressure drop across both stationary and moving blades.



Concept of impulse turbine

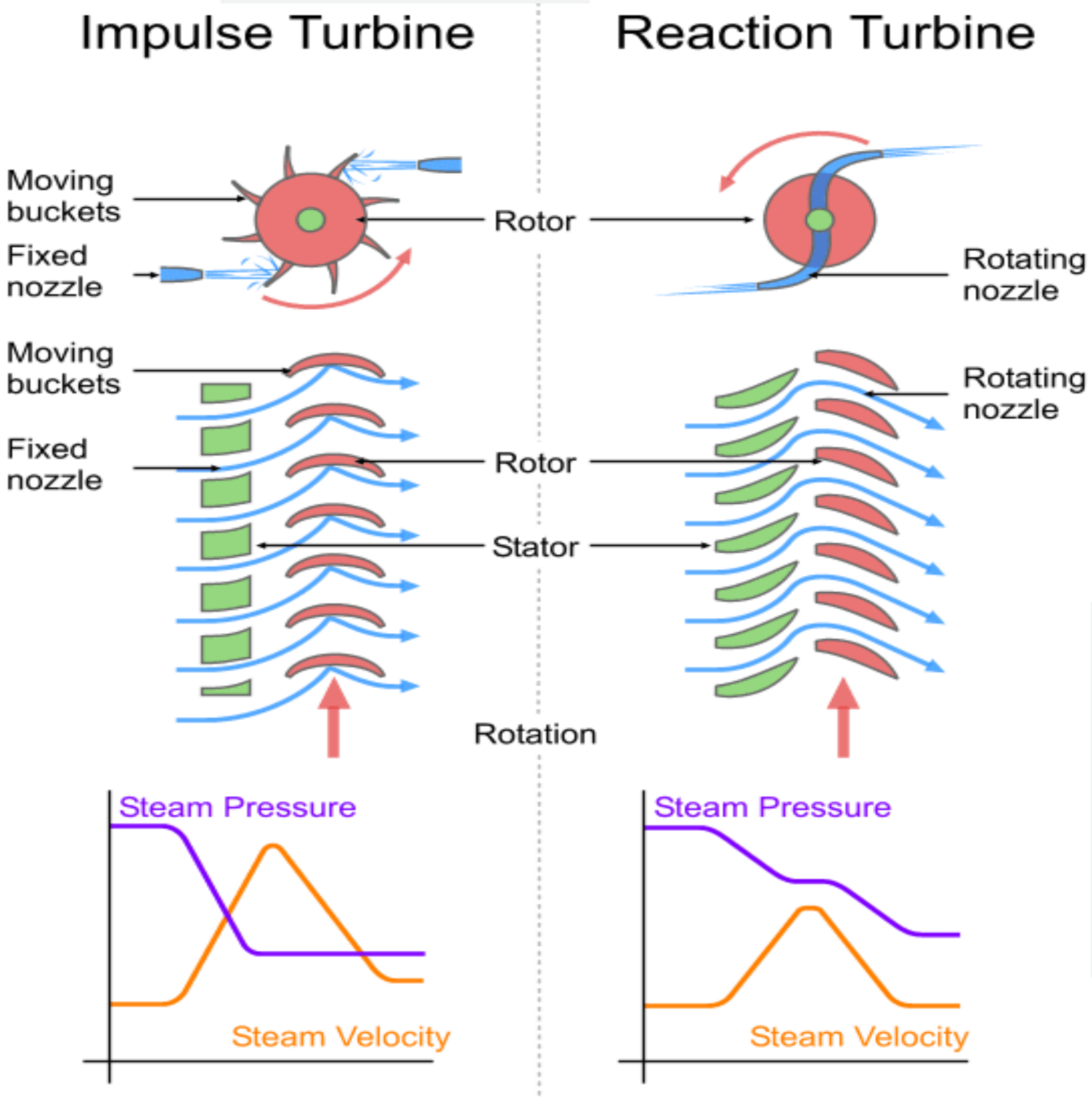


Concept of reaction turbine

Impulse and Reaction Steam Turbine

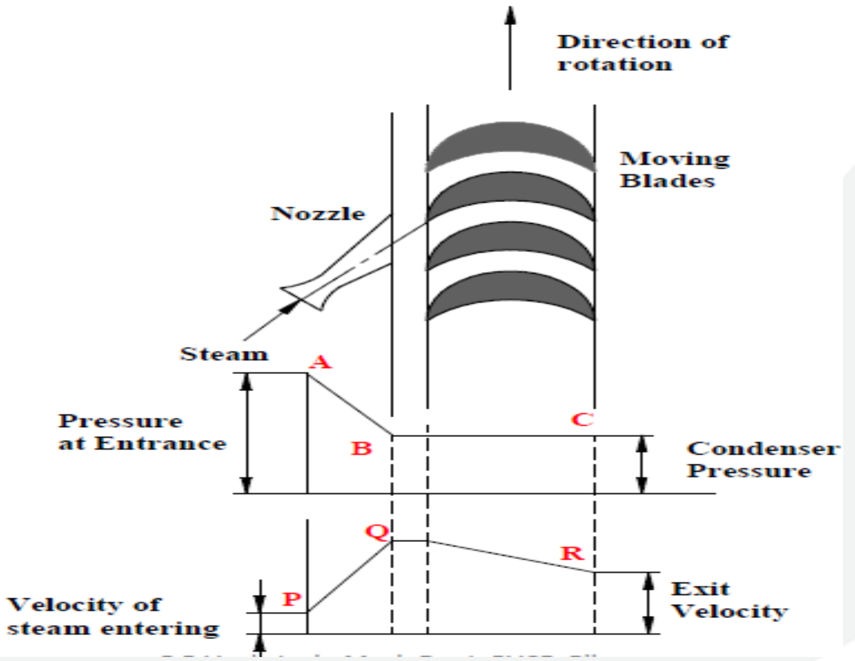
Impulse Steam turbine	Reaction Steam Turbine
Steam expands completely in nozzles. Pressure remains constant across rotor blades	Fixed blades act as nozzle. Steam expands partially in rotor and partially in stator blades
Driving thrust in case of impulse turbine is obtained due to *change of momentum because of change in the direction of steam velocity* (Impulse action) while flowing across the blade from inlet to outlet.	Driving thrust in reaction turbine consists of *reactive force and force corresponding to change of momentum because of the change in direction of steam velocity (Combined Impulse and reaction)*
Blade passage is of constant cross sectional area from inlet to outlet of rotor as P = const. across rotor blades	Blade passage is of variable cross sectional area (converging type) from inlet to outlet of rotor as pressure drops across rotor blades
Rotor blades are of symmetric profile and hence easier to manufacture.	Rotor blades are of airfoil shape and non-symmetric and are difficult to manufacture
It has got high rotational speed as it includes large pressure drop in nozzle, hence compounding is needed to reduce speed	It has got low rotational speed as it involves smaller pressure drops across stator. Hence no compounding is needed
Occupies less space per unit power.	Occupies more space per unit power
Suitable for lower power generation	Suitable for medium and larger power generation
E.g. De Laval, Curtis, Moore Turbine	E.g., Parson, Ljungstrom Turbine

Impulse and Reaction Steam Turbine



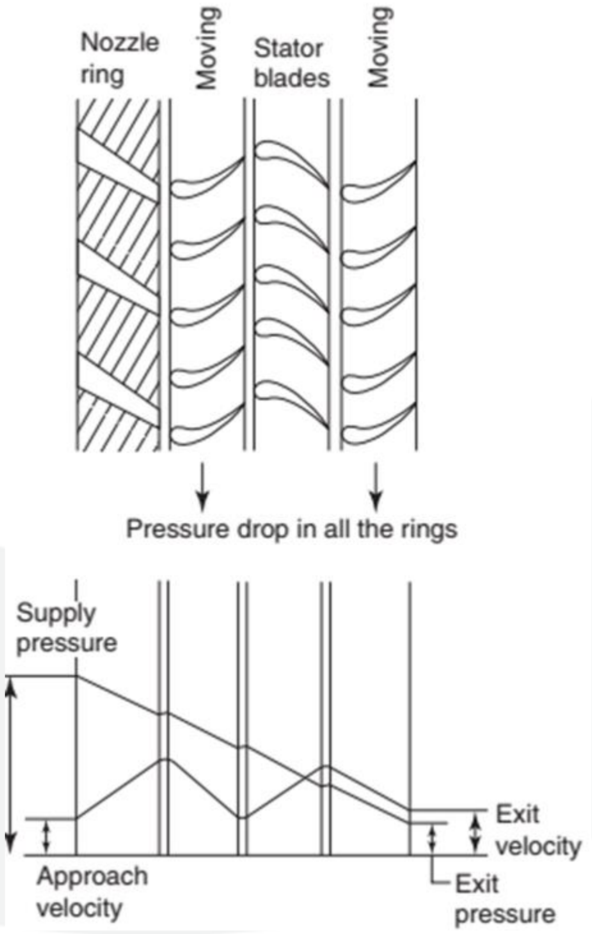
De Laval Turbine

- De Laval Turbine: *Single stage of an Impulse Turbine*
- Since, the expansion of the steam takes place in the nozzle, the pressure drop is represented by the curve AB, the corresponding rise in velocity in the nozzle is represented by the curve PQ.
- As there is no change in the pressure of steam that is passing over the blade, this flow is represented by the horizontal line BC.
- As the blades absorb the kinetic energy of the steam as it flows over it, the velocity decreases. This is represented by the curve QR.

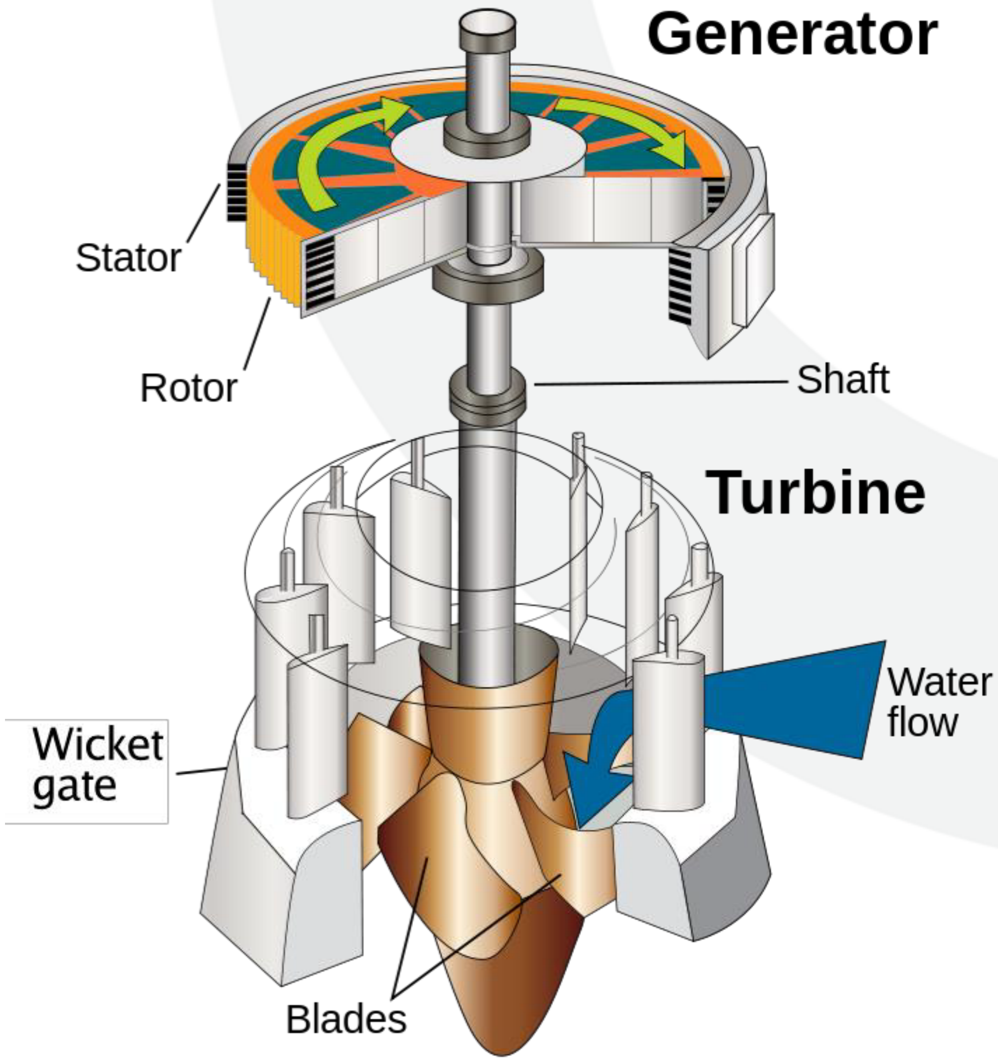


Parsons Turbine

- Parsons Turbine: *Pressure compounded Reaction turbine*
- In Parsons staging, pressure drop not only happens in stationary blades but also in moving blades.
- The cross-sectional area of the passages between the rotor blades is such that the passages act as nozzles, with expansion of steam occurring in the rotor blades also.
- These stages are repeated one after the other, each stage comprising one set of stator blades followed by one set of rotor blades



Hydraulic Turbines



Hydraulic Turbines - Introduction

- Hydraulic energy means the energy possessed by water in the form of *potential energy, kinetic energy and intermolecular energy*.
- The power transmitted by a rotating shaft is usually known as mechanical energy.
- The hydraulic machines are energy conversion devices in which hydraulic energy is either converted into mechanical energy or vice versa.
- The hydraulic machines which convert hydraulic energy (*potential energy, kinetic energy, intermolecular energy*) into mechanical energy by setting the rotor in motion through dynamic action of water are known as hydraulic turbines.
- The hydraulic machines which convert mechanical energy into hydraulic energy are known as pumps.

Hydraulic Turbines - Classification

1. According to the type of energy available at the inlet.

- **Impulse turbine:** At the inlet of the rotor of the turbine, the energy available is only in the form of kinetic energy of water.

  Example: Pelton wheel, Banki turbine and Jonval turbine

- **Reaction turbine:** At the inlet of the rotor of the turbine, the energy available is in the form of kinetic energy as well as pressure energy of water.

  Example: Francis turbine, propeller and Kaplan turbines

2. Based on the head under which the turbine works

- High head, impulse turbine: H > 250 m E.g., Pelton wheel
- Medium head, reaction turbine: 60 < H < 250 m E.g., Francis turbine
- Low head, reaction turbine: H < 60 m E.g. Kaplan turbine, Propeller turbine

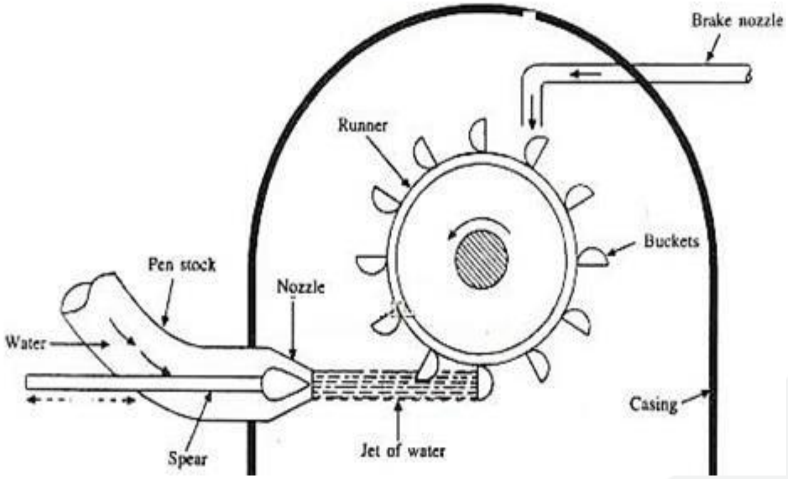
Hydraulic Turbines - Classification

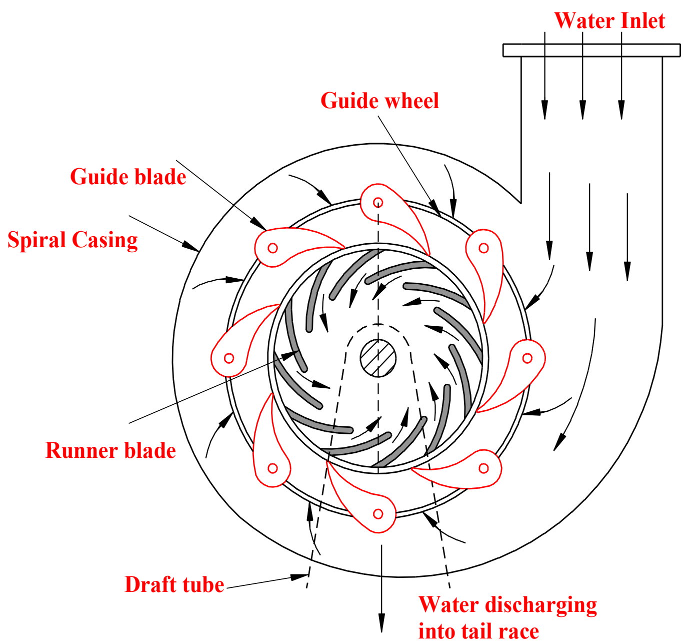
3. According to the direction of flow through the rotor or runner.

- Tangential flow : Water flows in a direction tangential to the path of rotation of rotor, i.e., normal to both axial and radial directions. E.g. *Pelton wheel*
- Radial inward flow: Water flows in a radial direction from larger diameter to smaller diameter of runner. E.g. *Old Francis turbine*
- Radial outward flow: Water flows in a radial direction from smaller diameter to larger diameter of runner. E.g. *Fourneyron turbine*
- Axial flow : Water flows parallel to the axis of the turbine rotor. E.g. *Kaplan turbine*
- Mixed flow : Water enters the rotor radially at outer periphery and leaves axially. E.g. *Modern Francis turbine*

Impulse and Reaction Hydraulic Turbine

- Impulse Turbine: The pressure of water does not change during the flow through a turbine rotor.
- At the rotor inlet, only KE of water is available.
- The pressure change occur only in the nozzles. The jet impingement takes place at P = 1 atm.
- E.x. Pelton Wheel
- Reaction Turbine: Water pressure changes while it flows through the rotor of the turbine.
- The change in water velocity and reduction in its pressure causes a reaction on the turbine blades.
- The flow passages are under pressure and the rotor has to be encased in an airtight casing.
- E.x. Francis Turbine and Kaplan Turbine



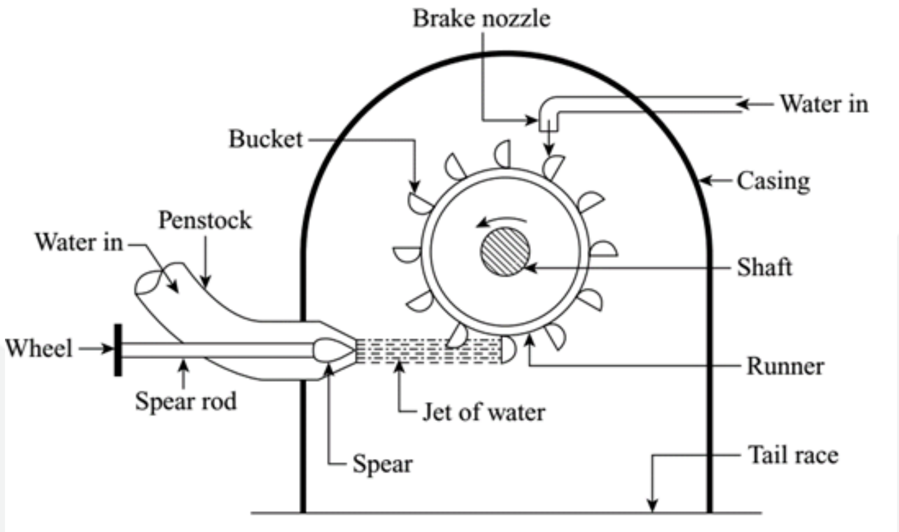


Impulse and Reaction Hydraulic Turbine

Impulse Hydraulic turbine	Reaction Hydraulic turbine
All the available hydraulic energy is converted into kinetic energy by a nozzle.	Only a part of the available hydraulic energy is converted into kinetic energy before the water enters the runner of the turbine.
Impulse turbines operate under atmospheric conditions and thus, the pressure remains constant throughout the action of water on the runner.	Reaction turbines operate under varying pressures different from the atmospheric pressure and the water pressure drops partly in the rotor blades and partly in the stator blades.
It is not essential to have a casing as it does not perform any hydraulic function.	Air and water tight casing is quint-essential which maintains the pressure in the turbine passage.
Water may be allowed to enter a part or whole of the wheel circumference.	Water is admitted over the whole circumference of the wheel.
Air has free access to the runner as it does not run full.	Air has no access to the runner as all the passages are completely filled by water.
It is always installed above the tail race and it does not require any draft tube.	It is connected to the tail race through a draft tube and it may be installed above or below the tail race.
These turbines are suitable for high head, low discharge and low specific speed conditions	These turbines are suitable for low to medium head and specific speed, and high discharge.
Ex: Pelton wheel	Ex: Propeller and Kaplan turbine, Francis turbine

Pelton Wheel

- Named after *L. A. Pelton, an American Engineer. It is a high head, low flow rate, tangential flow, impulse hydraulic turbine.*

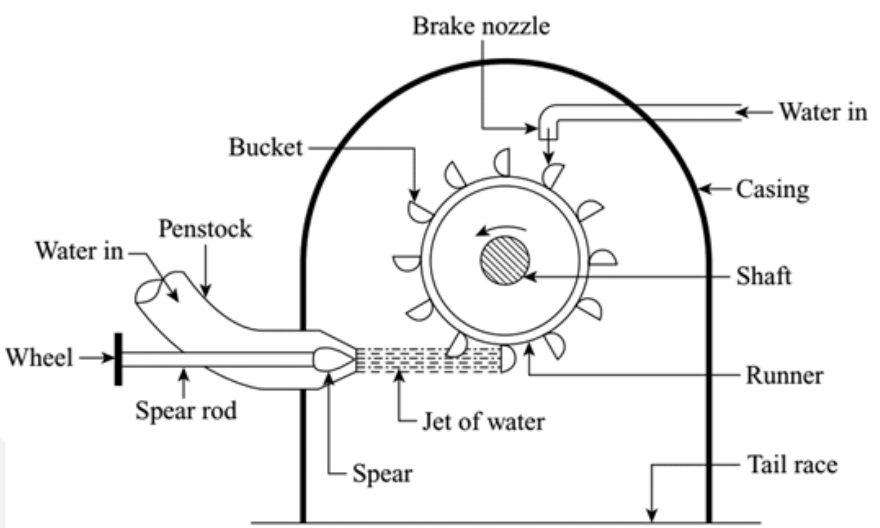


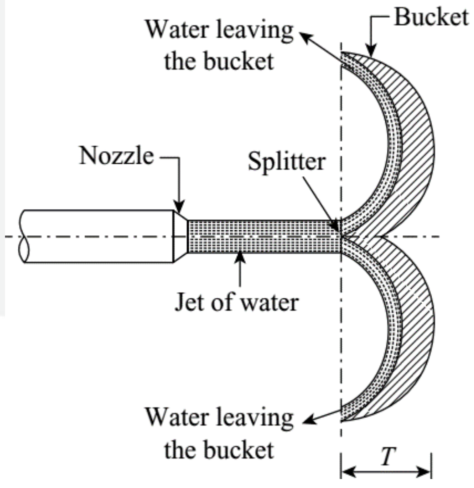
The main parts of the Pelton wheel are

- Penstock: A large sized pipe through which water flows from the reservoir to the turbine.
- For regulating the flow from the reservoir to the turbine, the penstocks are fitted with control valves.
- Spear and nozzle arrangement: The nozzle fitted at the end of the penstock is provided with a spear which controls the quantity of water striking the buckets of runner.
- When the spear moves in forward direction, the flow area decreases and thus, the amount of water striking the runner is reduced and vice-versa.

Pelton Wheel

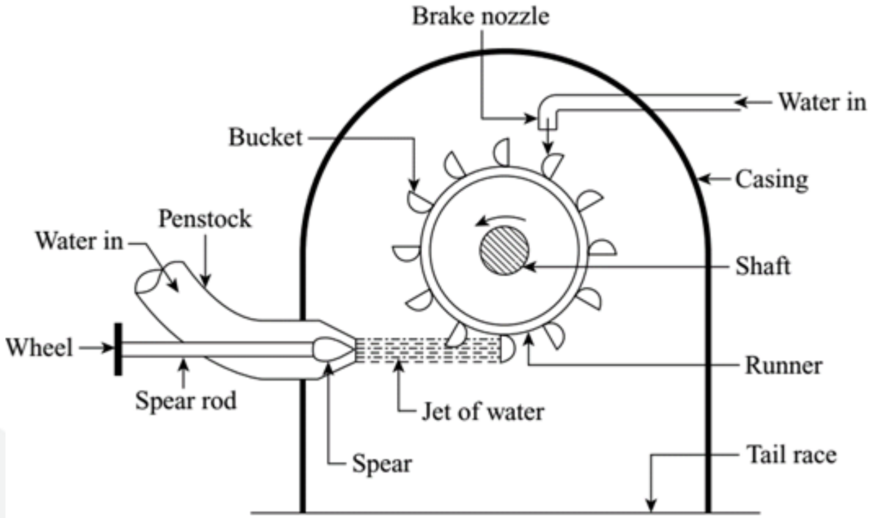
- Runner with buckets: Runner consists of a large circular disc in which a number of buckets (≥ 15) are evenly spaced round its periphery.
- The buckets take a shape of double hemispherical cup or bowl.
- Each bucket is divided into two symmetrical parts by a sharp edged ridge called a **splitter.**
- The jet of water strikes on the splitter, which divides the jet into two equal parts, each of which after flowing round the inner smooth bucket surface leaves at its outer edge.
- The buckets are so shaped that the jet of water gets deflected through **160° to 170°.**

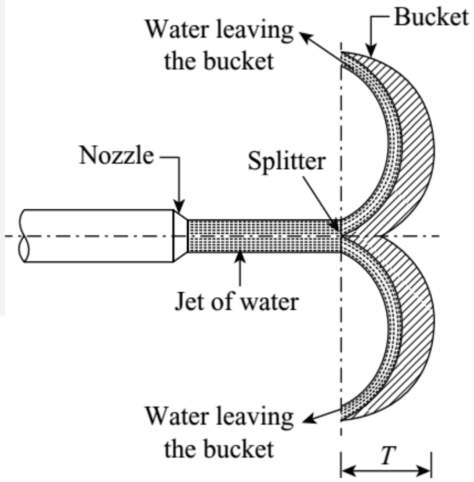




Pelton Wheel

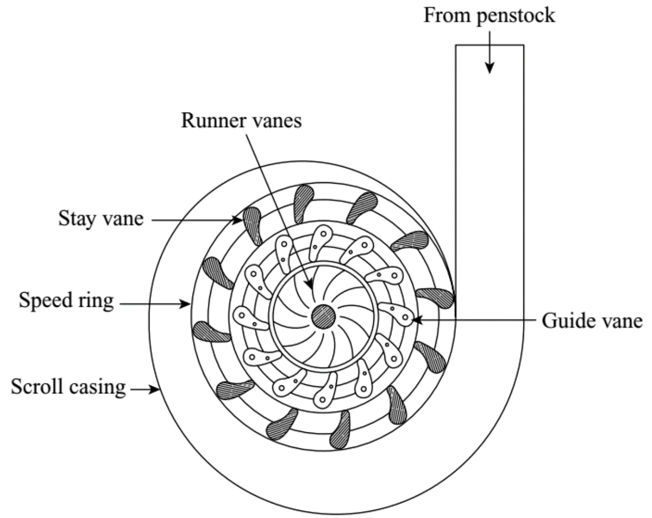
- ***Casing:*** In Pelton turbine, the casing does not perform any hydraulic function.
- It is provided only to prevent splashing of water and to guide it to the tail race.
- It also acts as a safeguard against accidents.
- **Braking jet:** In order to shut down the turbine, the nozzle is completely closed by moving the spear in the forward direction.
- However, the runner still goes on revolving for a long time due to inertia.
- To stop the runner in a short time, a small brake nozzle is provided which directs the jet of water on the back of the buckets.

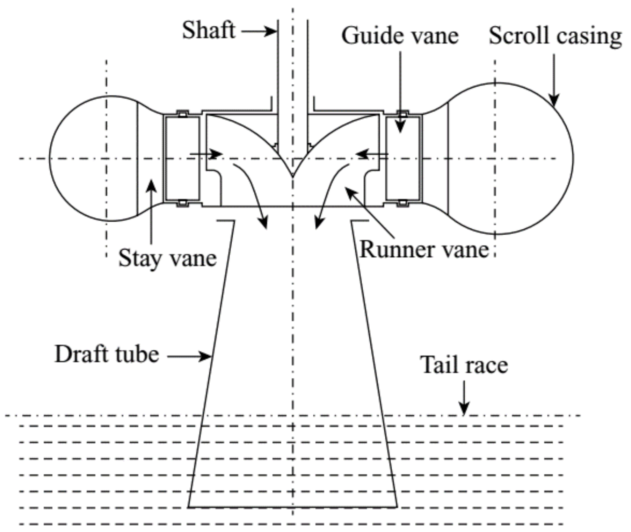




Francis Turbine

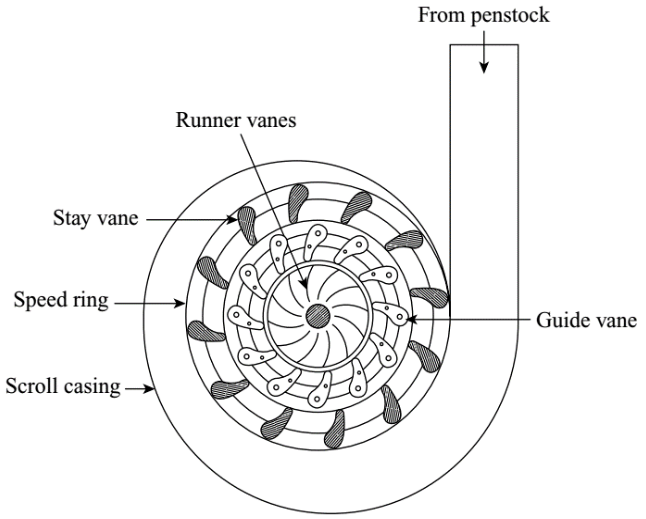
- Named in the honour of *J. B. Francis, an American engineer. It is a* ***medium head, medium flow rate, mixed flow, reaction hydraulic turbine***.
- The main parts of a Francis turbine are (1) penstock, (2) scroll casing, (3) guide mechanism, (4) runner, (5) draft tube.
- Penstock: It is a large sized conduit which conveys water from reservoir to the runner.
- Trash racks are commonly provided at the inlet of penstock to obstruct the entry of debris and other foreign matter into the turbine.
- In Francis turbines, large size penstocks are required due to large volume of water flow.

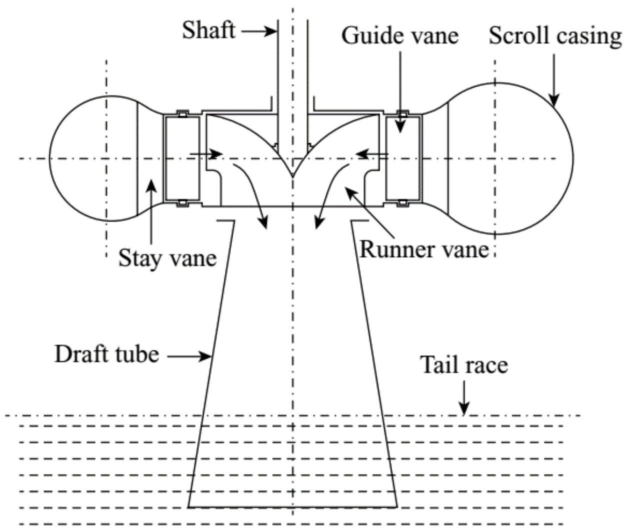




Francis Turbine

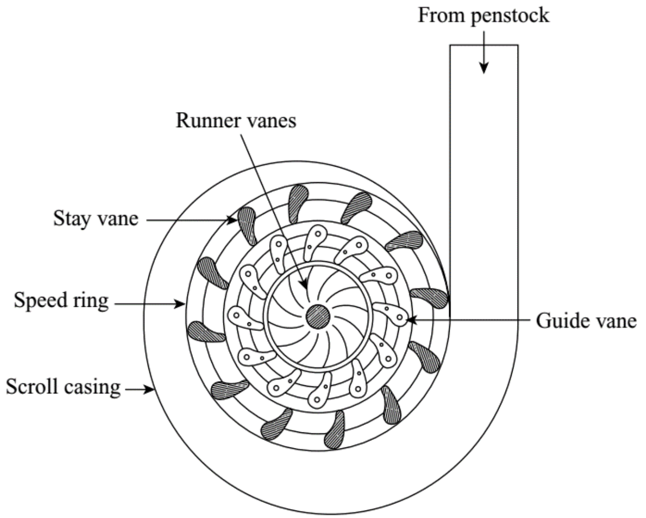
- **Scroll casing:** The water from the penstock enters the scroll casing which is of spiral shape. It completely surrounds the runner of the turbine and maintains the even distribution of water around the circumference of the runner.
- **Guide mechanism:** Water from the casing flow through a stay ring having fixed stay vanes which direct the water to the guide vanes. Generally, the number of stay vanes is taken as half of the number of guide vanes.
- The guide vanes are adjustable and are also known as wicket gates. The guide vanes are airfoil shaped so that the flow remains smooth without any separation. The guide vanes behave like nozzles.

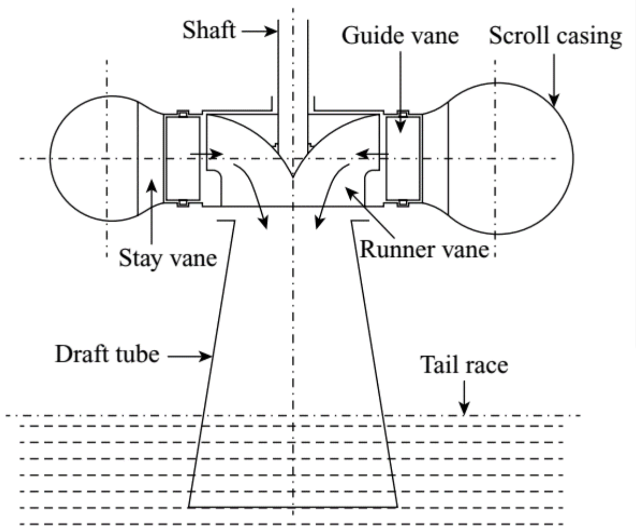




Francis Turbine

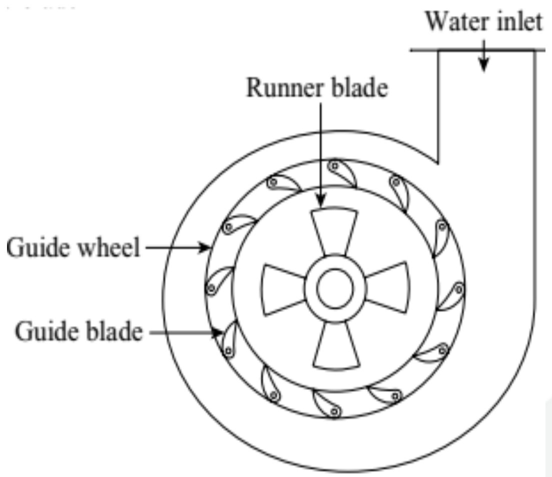
- **Runner:** It is also known as rotor.
- Runner is a circular wheel in which a series of radial curved vanes are evenly fixed. Usually, the number of vanes varies between 16 to 24.
- The radial curved vanes are so shaped that water enters the ***runner radially at the outer periphery and leaves axially*** at the inner periphery without shock.
- **Draft tube:** A draft tube is a pipe of gradually increasing cross-sectional area.
- One end of the draft tube is connected to the runner exit, while the other end is submerged deep into the tail race.



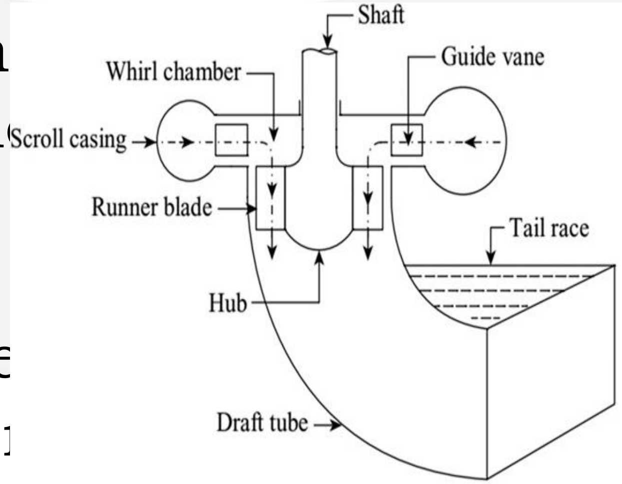


Kaplan Turbine

- Named after an *Austrian Engineer, Victor Kaplan*. It is an *axial type, low head (2.5 m to 50 m), high specific speed, reaction turbine* which handles large volume flow rate of water.



- The main parts of a Kaplan turbine are (1) Scroll casing, (2) Guide vanes, (3) Whirl chamber, (4) Propeller-shaped runner (with adjustable blades), (5) Draft tube and (6) Governor mechanism.
- **Scroll Casing:** Its function is very similar to scroll casin in Francis turbine. It reduces the eddies formation an hence minimizes the eddy loss.
- **Guide vanes**: The function is similar to Francis turbine.
- **Whirl Chamber**: Space between the guide-vane outle and the inlet of the runner is known as whirl chamber. I this, the flow changes from radial orientation to axial direction



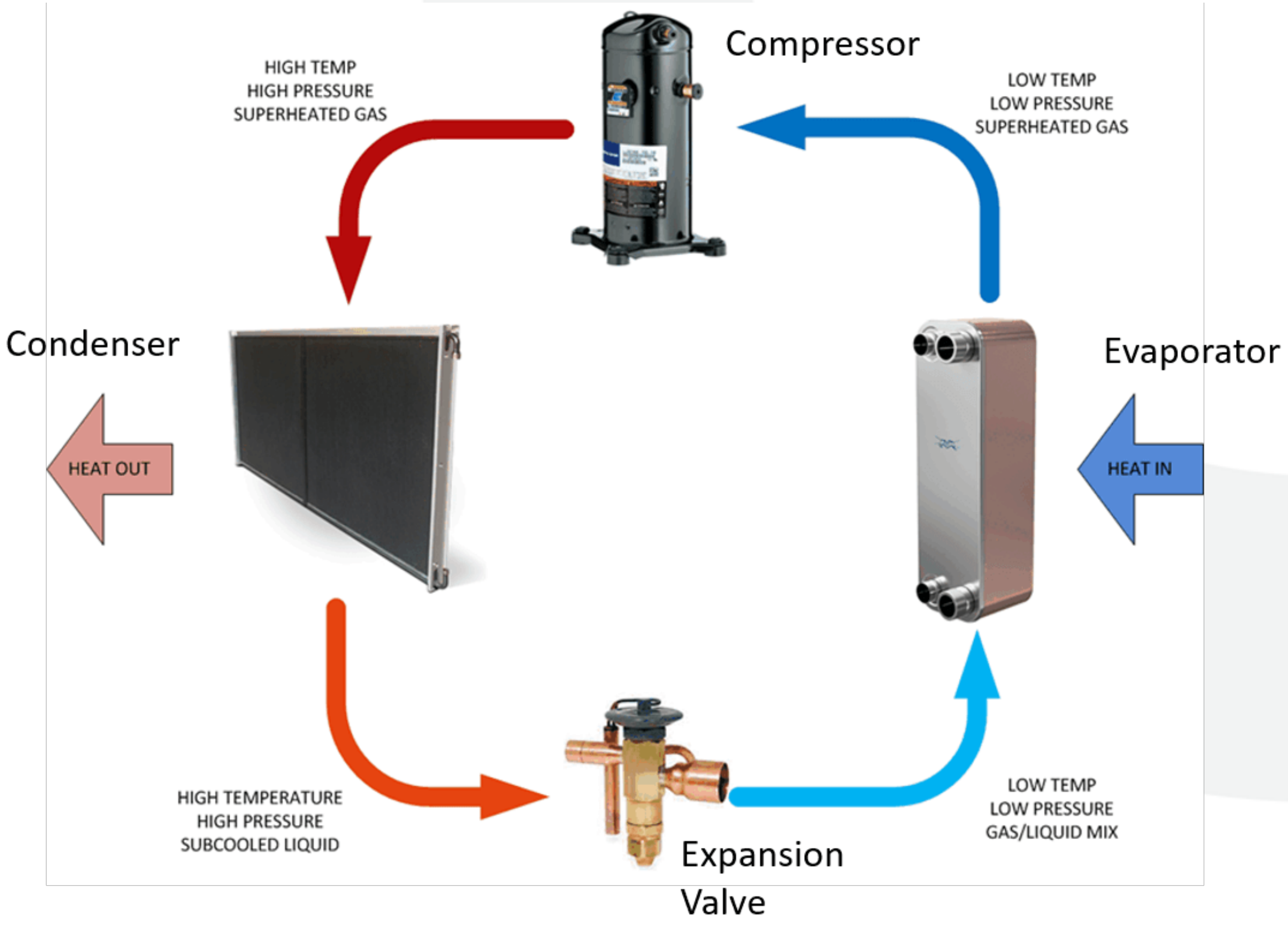
Kaplan Turbine

- **Runner:** The runner in a Kaplan turbine is a set of specially designed blades that give the appearance of a ship's propeller.
- The blades are connected to the drive shaft at the hub.
- The number of blades varies from 3 to 8 and the blades
- In a Kaplan turbine, the pitch of the blades are adjustable.
- **Draft Tube:** The hydraulic aspects relating to draft-tube installation are the same as described in connection with Francis turbines.
- **Governor Mechanism:** The governor is an essential, integral component of the Kaplan turbine. It does two functions:

a. Controls the guide-vane openings and thereby regulates the discharge into the turbine.

b. Regulates through servo control mechanism, the disposition of the blades to the flow and achieves high efficiencies at part loads

Refrigeration

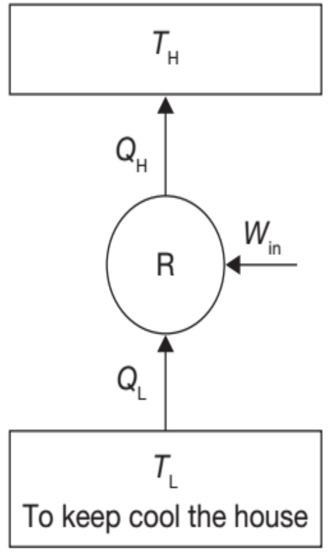


Refrigeration - Introduction

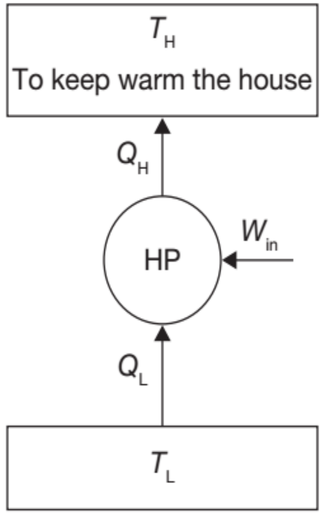
- American Society of Refrigerating Engineers defines refrigeration as "*the science of providing and maintaining temperature of the system below that of the surrounding atmosphere*"
- The melting of ice or snow was one of the earliest methods of refrigeration and is still employed.
- Another medium of refrigeration is solid carbon dioxide or dry ice. At atmospheric pressure, CO_2 cannot exist in a liquid state, and consequently, when solid CO_2 is exposed to atmosphere, it sublimates, by absorbing the latent heat of sublimation from the surroundings.
- In the above example, it is observed that the refrigeration effect has been accomplished by non-cyclic processes.
- In closed cycle or cyclic process, the refrigerant flows inside tubes while refrigerating the space and does not get contaminated.

Refrigeration and Heat Pump

- Clausius statement of the Second Law of Thermodynamics says "*It is impossible to construct a device that operating in a cycle, has no effect other than the transfer of heat from a cooler to a hotter body*".
- It means that heat will not flow from cold to hot regions without the assistance of outside agents.
- The devices that provide this assistance are called **refrigerators** and **heat pumps**.
- The refrigeration unit transfers heat from cold to hot regions for the *purpose of cooling the region* while the heat pump does the same thing with the intent of *heating the region*.



Refrigerator



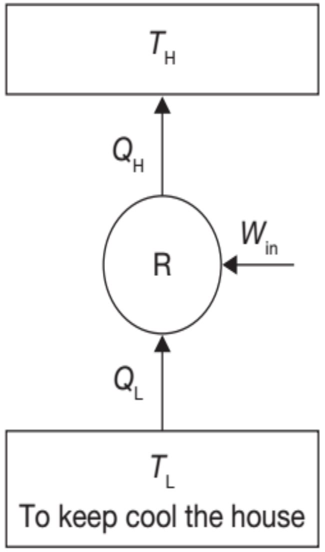
Heat Pump

Refrigeration and Heat Pump

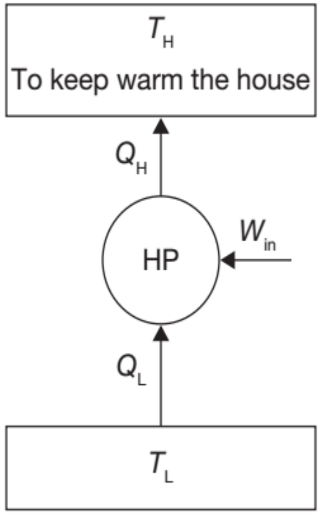
- The performance of the refrigerators and the heat pump is expressed in terms of the quantity known as Coefficient of Performance (COP).
- <u>Coefficient of Performance (COP):</u>

$$COP_R = \frac{Desired\ Output}{Required\ Input} = \frac{Refrigeration\ \ Effect}{Work\ Input} = \frac{Q_L}{W_{in}}$$

$$COP_{HP} = \frac{Desired\ Output}{Required\ Input} = \frac{Heating\ Effect}{Work\ Input} = \frac{Q_H}{W_{in}}$$



Refrigerator



Heat Pump

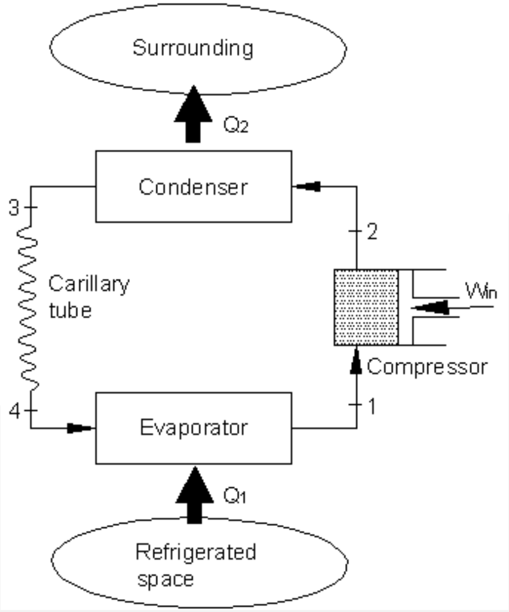
Unit of Refrigeration

- Refrigeration effect is the amount of heat extracted from the refrigerated space per unit mass flow of the refrigerant.
- The higher the capacity of refrigerator means higher shall be the refrigeration effect. Refrigeration effect is defined by the unit of refrigeration called '**Ton**' of refrigeration.
- One '**Ton**' of refrigeration can be defined by the amount of heat being removed from one ton of water at 0°C to form one ton of ice at 0°C within 24 hours.
- Latent heat of solidification from water to ice at 0°C = 334.5 kJ/kg
- 1 Ton of refrigeration = (m_{water} × latent heat of fusion of water)/24 hrs

  = (1000 × 334.5)/(24 × 3600) = *3.87 kJ/s = 3.87 kW*
- One ton or ton or tonne of refrigeration is SI units is often taken approximately equivalent to the heat removal rate of *3.5 kW* or *210 kJ/min* or 12,600 kJ/h

Components of Refrigeration System

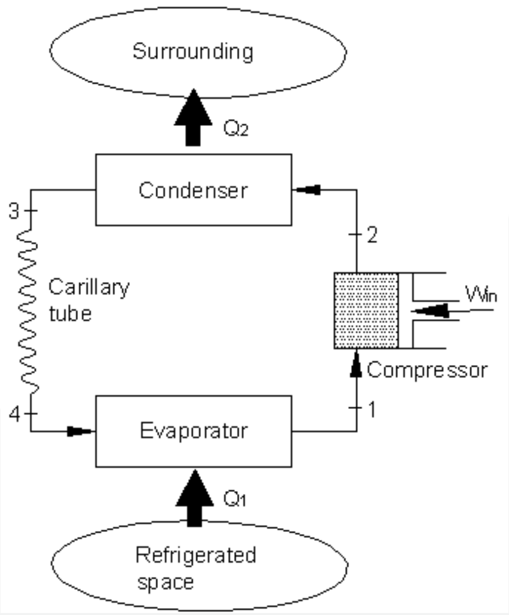
- There are four basic components of a refrigeration system: *Compressor, Condenser, Expansion valve or capillary tube and Evaporator*.
- Evaporator: The purpose of the evaporator is to remove unwanted heat from the space that needs to be cooled Q1 with the help of **liquid** refrigerant.
- When leaving the evaporator coil the liquid refrigerant is in **vapour** form.
- Compressor: The purpose of the compressor is to draw the *low-temperature, low-pressure vapour* from the evaporator via the suction line. Once drawn, the vapour is compressed.
- Therefore, the compressor transforms the vapour from a *low-temperature vapour to a high-temperature vapour, high pressure vapour.*



Simple Refrigeration system

Components of Refrigeration System

- Condenser: The purpose of the condenser is to extract heat from the refrigerant to the outside air. The temperature of the high-pressure vapour determines the temperature at which the condensation begins.
- As heat has to flow from the condenser to the air, the condensation temperature must be higher than that of the air.
- Expansion valve or Capillary Tube: The high-pressure liquid reaches the expansion valve from the exit of condenser.
- The valve then reduces the pressure of the refrigerant as it passes through the orifice (or the capillary tube reduces the pressure of refrigerant as it passes through smaller diameter and long tube).



Simple Refrigeration system

Desirable Properties of Refrigerants

- Refrigerants have to be physiologically nontoxic and non-flammable.
- The selection of a refrigerant depends on certain thermodynamic, chemical and physical properties.
- **Thermodynamic Properties**
- Evaporation and Condensing Pressure: The pressure in the evaporator should be positive and a little above the ambient pressure so that the atmospheric air and moisture do not leak into the system.
- The pressure in the condenser should not be high so as to necessitate heavy construction of equipment and high cost.
- Critical Pressure and Temperature: Fluids have a better heat-transfer rate at temperatures below critical temperature. So the critical temperature should be as high as possible. This would give a high COP. The critical pressure should be low so as to give lower condensing pressure.

Desirable Properties of Refrigerants

- **Freezing Point:** The freezing-point temperature should be as low as possible so that the refrigerant can operate freely at higher temperatures in the cycle without freezing anywhere in the cycle.
- **Latent Heat and Specific Heat:** A higher latent heat of vaporization at the working pressure would permit a greater amount of heat extraction in the evaporator. The specific heat of the liquid should be small so that less liquid flashes into vapour during expansion and there is higher refrigerating effect.
- **Liquid and Vapour Density:** Refrigerants must have a high density (low specific volume) at evaporator pressure so as to have smaller suction and discharge lines and the displacement volumes.
- **COP and kW per Ton of Refrigeration:** The refrigerant should have a high COP and low power input to compressor per ton of refrigeration.

Desirable Properties of Refrigerants

- **Chemical Properties**
- Inflammability: The refrigerant should not be inflammable and explosive as far as possible.
- Toxicity: Toxic refrigerants should not be used in domestic refrigerating systems and comfort air conditioning.
- Solubility in Water: Refrigerants should have poor affinity for water, since the presence of moisture would lead to formation of ice and choking of the capillary tube.
- Action on Material of Construction: Refrigerants must not react chemically or corrode materials of construction. If a refrigerant, e.g., attacks copper and copper alloys, then pipes, fittings, valves, etc. are to be made with ferrous materials.

Desirable Properties of Refrigerants

- **Physical Properties**
- Thermal Conductivity: For better heat-transfer rate, the refrigerant should have a high value of thermal conductivity.
- Viscosity: A low viscosity is desirable for low pumping power and high heat-transfer rate.
- Leak Tendency: The tendency for leakage of the refrigerant should be low and the detection of leak should be easy.
- Besides these, the refrigerant should be cheap in cost and readily available. It should be chemically stable at all conditions of operating pressures and temperatures.
- It should not allow the lubricating oil to be carried over into the evaporator and condenser to cause fouling and reduce the rate of heat transfer.

Commonly Used Refrigerants

The refrigerants can be classified into following classes:

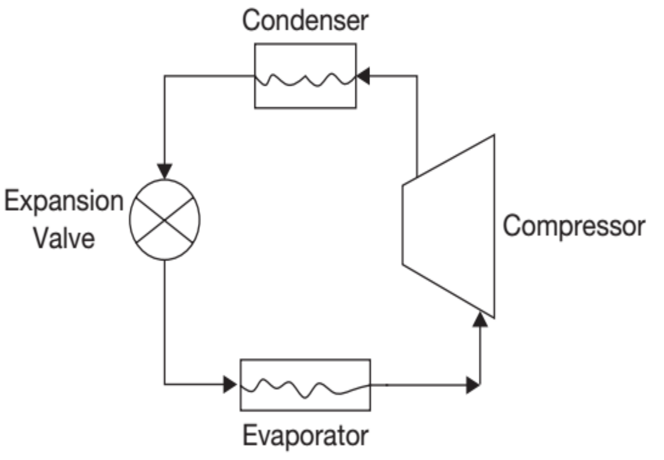
- HaloCarbons: These refrigerants are all synthetically produced and were developed as the Freon family of refrigerants.
- *Freons* are a series of fluorinated hydrocarbons, generally known as fluorocarbons, derived from methane and ethane as bases.
- Some of the refrigerants in this class are given below:
  a. CFC's: Fully halogenated ones with chlorine in their molecule are *chloro fluoro carbons*, referred to as CFCs *E.g. R11, R12, R113, R114, R115*
  b. HCFC's: These contain H atoms in the molecule along with Cl and F, called *hydro chloro fluoro carbons*. *E.g. R22, R123*
  c. HFC's: These contain H atoms in the molecule along with F, called *hydro fluoro carbons*. *E.g. R134a, R404a, R407C, R410a*

Commonly Used Refrigerants

- Inorganic Refrigerants: Following refrigerants are used as inorganic refrigerants: *Carbon Dioxide, Water, Ammonia, Air, Sulphur dioxide*
- Hydrocarbon Refrigerants : Following hydrocarbon gases have been used as refrigerants in industrial, commercial and domestic applications: *R170-Ethane (C_2H_6), R290-Propane (C_3H_3)R600-Butane (C_4H_{10}) and R600a-Isobutane (C_4H_{10})*

Vapour Compression Refrigeration System

- A simple vapour compression refrigeration system consists of the following equipments: Compressor, Condenser, Expansion valve and Evaporator.
- The low-temperature and low-pressure vapour is compressed by a compressor to high temperature and high-pressure vapour.
- This vapour is then condensed into condenser at constant pressure and then passes through the expansion valve.
- The vapour is then throttled down to a low-pressure liquid and passed through an evaporator, where it absorbs heat from the surroundings and vaporizes into low-pressure vapour.
- The cycle then repeats again and again.

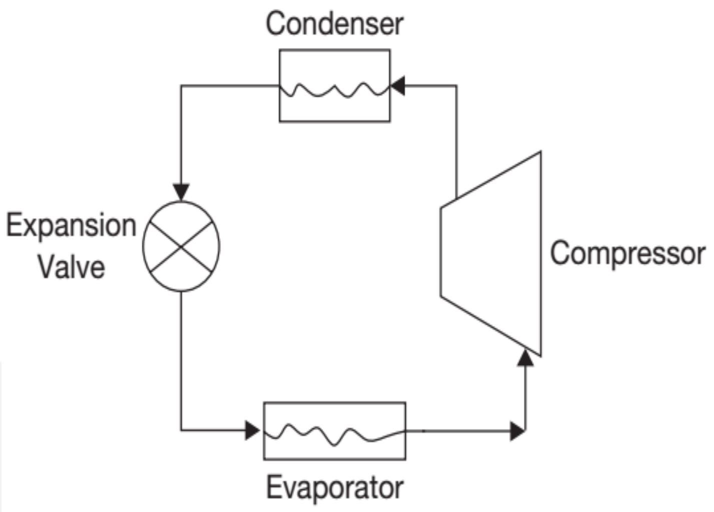


Schematic of VCR system

Vapour Compression Refrigeration System

Heat and work interaction in VCR

- Compressor requires work (W). The work is supplied to the system.
- During condensation, heat Q_H the equivalent of latent heat of condensation is removed from the refrigerant.
- During evaporation, heat Q_L equivalent to the latent heat of vaporization is absorbed by the refrigerant.
- There is no exchange of heat during throttling process through the expansion valve as this process occurs at constant enthalpy.

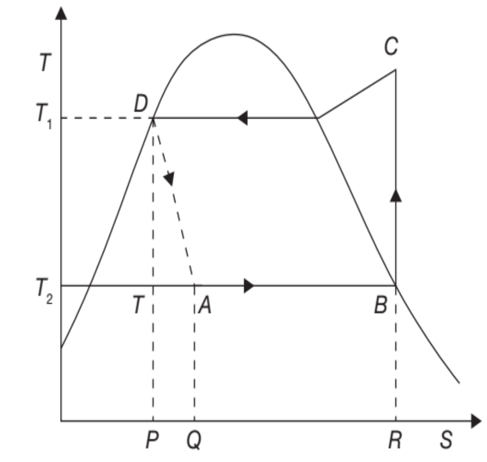


Schematic of VCR system

Vapour Compression Refrigeration System

T-s diagram of VCR

- The cycle works between temperatures T_1 and T_2 representing the condenser and evaporator temperatures, respectively. The thermodynamic process of the cycle A–B–C–D is given as:
- (i) Process B–C: Isentropic compression of the vapour from state B to C.
- (ii) Process C–D: Heat rejection in condenser is at constant pressure.
- (iii) Process D–A: An irreversible adiabatic expansion of vapour through the expansion value. The process is shown by dotted line.
- (iv) Process A–B: Heat absorption in the evaporator at constant pressure.



T-S Diagram

Vapour Compression Refrigeration System

COP of VCR

$$COP_R = \frac{Desired\ Output}{Required\ Input} = \frac{Heat\ Extracted\ at\ low\ temp.}{work\ supplied\ to\ compressor}$$

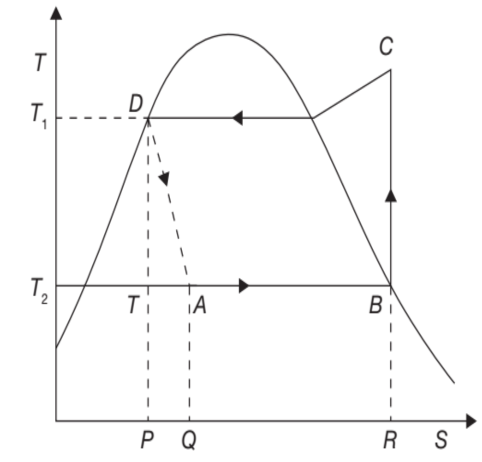
Heat extracted from the system = Heat transfer during the process, A–B = refrigerating effect.

$$Q_L = h_B - h_A$$

Work of compression,

$$W = h_C - h_B$$

$$\boldsymbol{COP_R = \frac{Q_L}{W} = \frac{h_B - h_A}{h_C - h_B}}$$



T-S Diagram

END