A presentation on **Steam Turbines**

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Steam

Steam is a vapour used as a working substance in the operation of steam turbine.

Is steam a perfect gas?

Steam possess properties like those of gases: namely pressure, volume, temperature, internal energy, enthalpy and entropy. But the pressure volume and temperature of steam as a vapour are not connected by any simple relationship such as is expressed by the characteristic equation for a perfect gas.

Sensible heat – The heat absorbed by water in attaining its boiling point.

Latent heat – The heat absorbed to convert boiling water into steam.

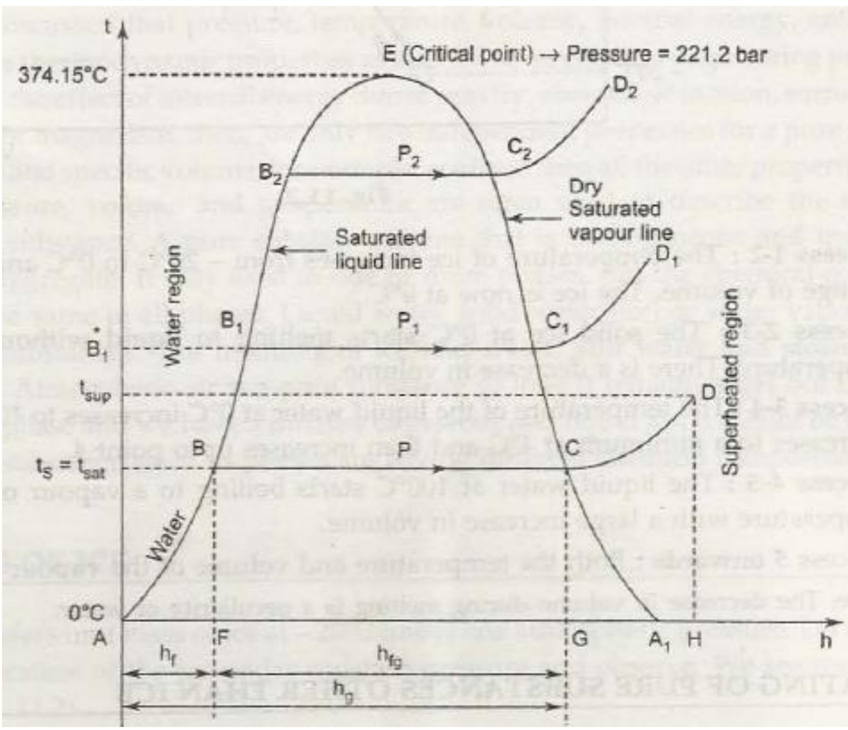
Wet steam – Steam containing some quantity of moisture.

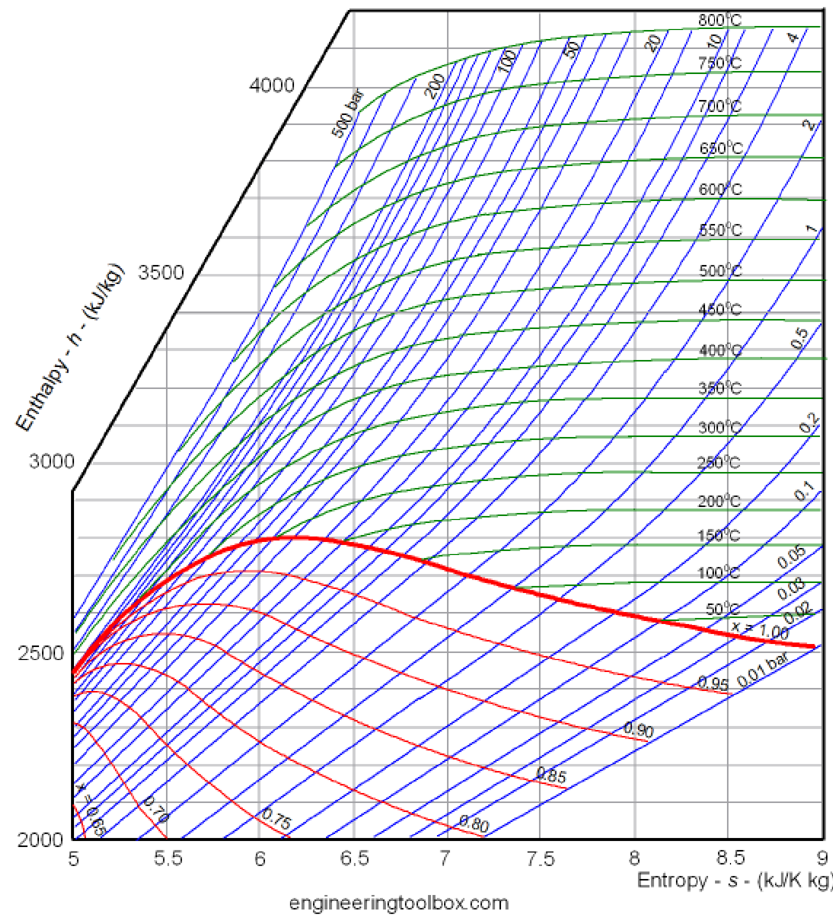
Dry steam – Steam that has no moisture content.

Superheated steam – Dry steam, when heated at constant pressure, attains superheat

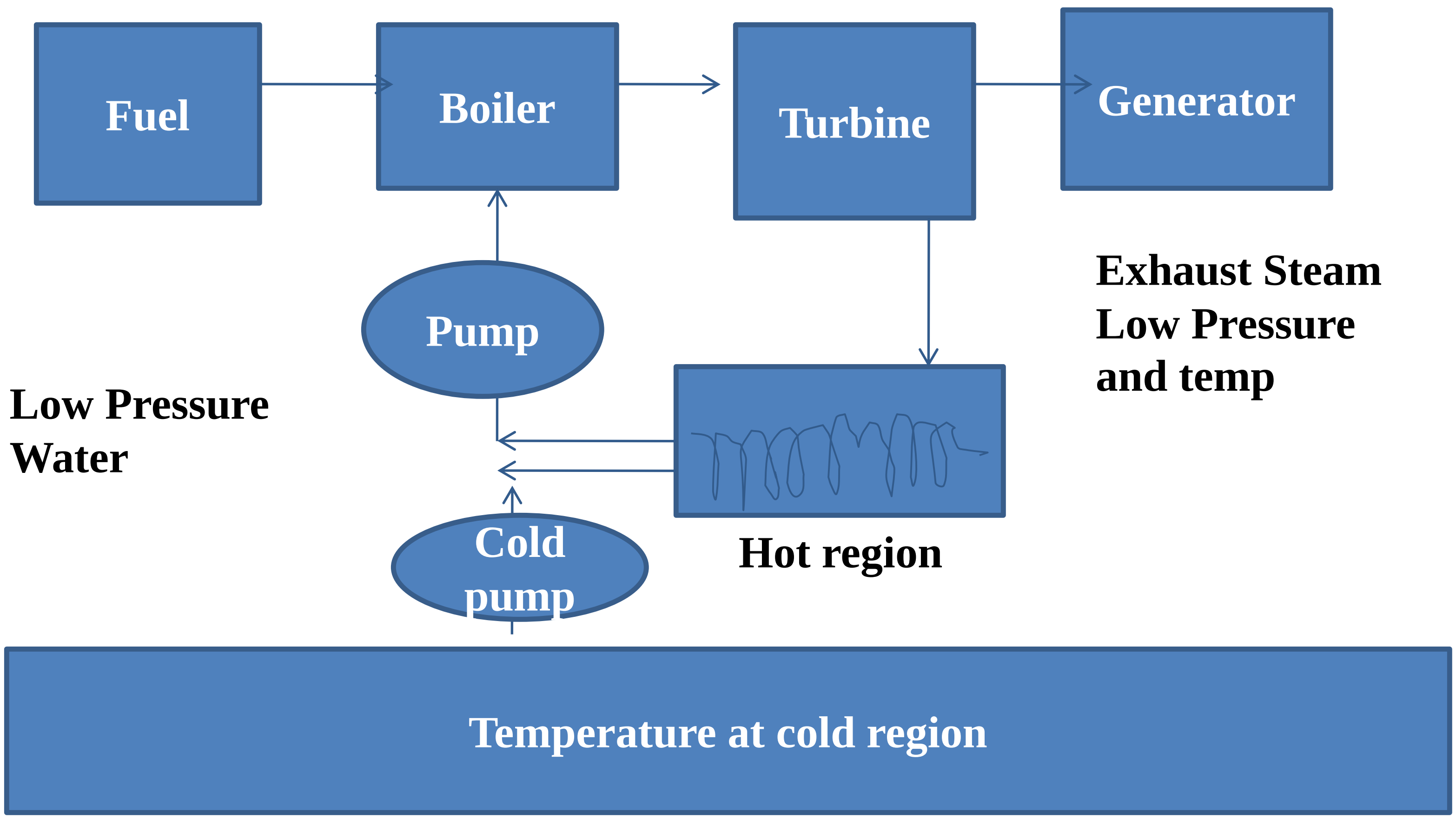
The properties of steam are dependent on its pressure

Steam Properties





Steam Power Plant Process



Steam Turbine

- Steam turbine convert a part of the energy of the steam evidenced by high temperature and pressure into mechanical power-in turn electrical power

- The steam from the boiler is expanded in a nozzle, resulting in the emission of a high velocity jet. This jet of steam impinges on the moving vanes or blades, mounted on a shaft. Here it undergoes a change of direction of motion which gives rise to a change in momentum and therefore a force.

- The motive power in a steam turbine is obtained by the rate of change in momentum of a high velocity jet of steam impinging on a curved blade which is free to rotate.

- The conversion of energy in the blades takes place by impulse, reaction or impulse reaction principle.

- Steam turbines are available in a few kW(as prime mover) to 1500 MW Impulse turbine are used for capacity up to

Steam, Gas and Hydraulic Turbines

The working substance differs for different types of turbines.

- Steam turbines are axial flow machines (radial steam turbines are rarely used) whereas gas turbines and hydraulic turbines of both axial and radial flow type are used based on applications.
- The pressure of working medium used in steam turbines is very high, whereas the temperature of working medium used is gas turbine is high comparatively.
- The pressure and temperature of working medium in hydraulic turbines is lower than steam turbines.
- Steam turbines of 1300 MW single units are available whereas largest gas turbines unit is 530 MWand 815 MW

Merits and Demerits of Steam Turbine

Merits:

- Ability to utilize high pressure and high temperature steam.
- High component efficiency.
- High rotational speed.
- High capacity/weight ratio.
- Smooth, nearly vibration-free operation.
- No internal lubrication.
- Oil free exhaust steam.
- Can be built in small or very large units (up to 1200 MW).

Demerits:

- For slow speed application reduction gears are required.
- The steam turbine cannot be made reversible.
- The efficiency of small simple steam turbines is poor

Application

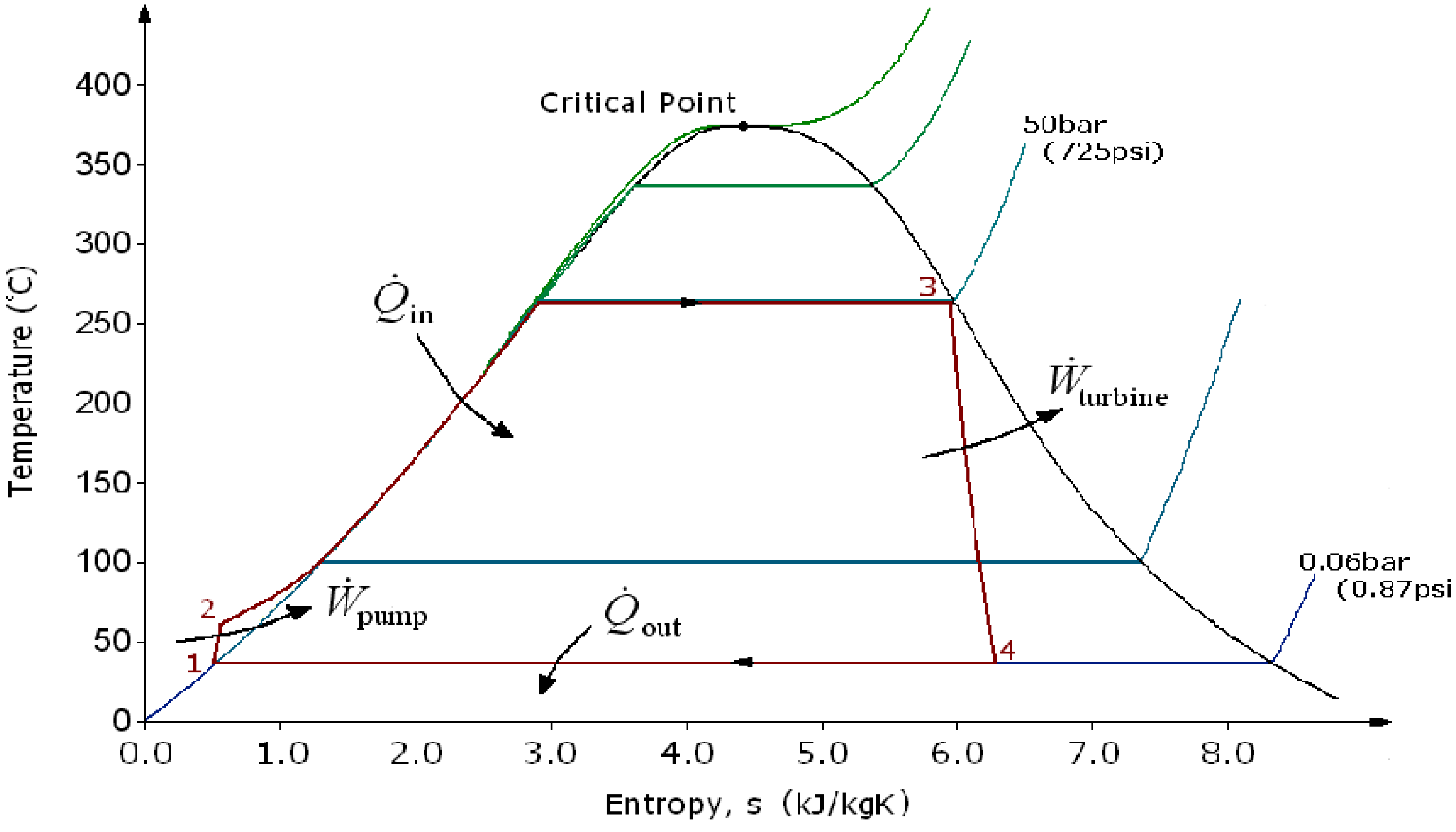
- Power generation
- Refinery, Petrochemical,
- Pharmaceuticals,
- Food processing,
- Petroleum/Gas processing,
- Pulp & Paper mills,
- Waste-to-energy

Turbine Selection

In all fields of application the competitiveness of a turbine is a combination of several factors:

- Efficiency
- Life
- Power density (power to weight ratio)
- Direct operation cost
- Manufacturing and maintenance costs

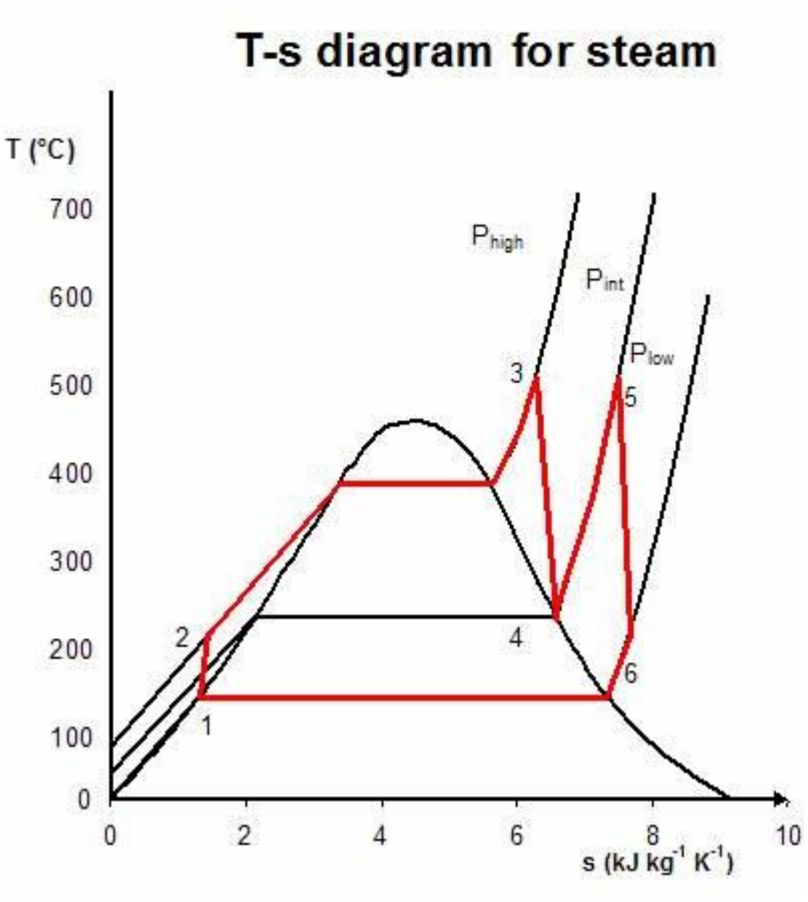
Rankine Cycle



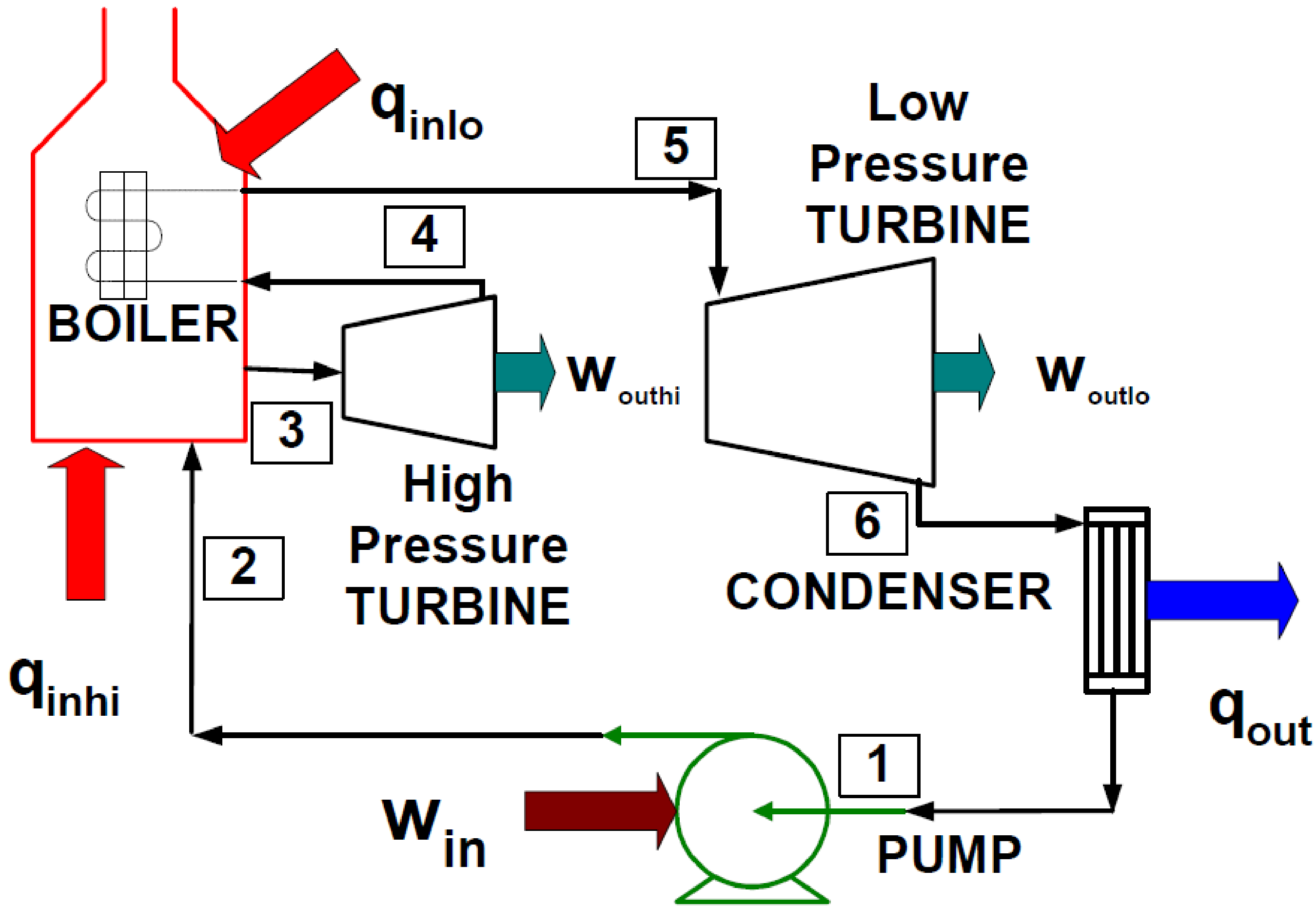
Reheat on T-s diagram

Note that T5 < T3. Many systems reheat to the same temperature (T3=T5)

Reheat is usually not in 6 out offered for turbines less than 50 MW.



Schematic of Rankine Reheat Cycle



Steam Turbine Classification

Steam turbines can be classified in several different ways:

1. By details of stage design
   - Impulse or reaction.
2. By steam supply and exhaust conditions
   - Condensing, or Non-condensing (back pressure),
   - Automatic or controlled extraction,
   - Mixed pressure
   - Reheat
3. By casing or shaft arrangement
   - Single casing, Tandem compound or Cross compound
4. By number of exhaust stages in parallel:
   - Two flow, Four flow or Six flow.
5. By direction of steam flow:
   - Axial flow, Radial flow or Tangential flow
6. Single or multi-stage
7. By steam supply

Steam Turbine Stage

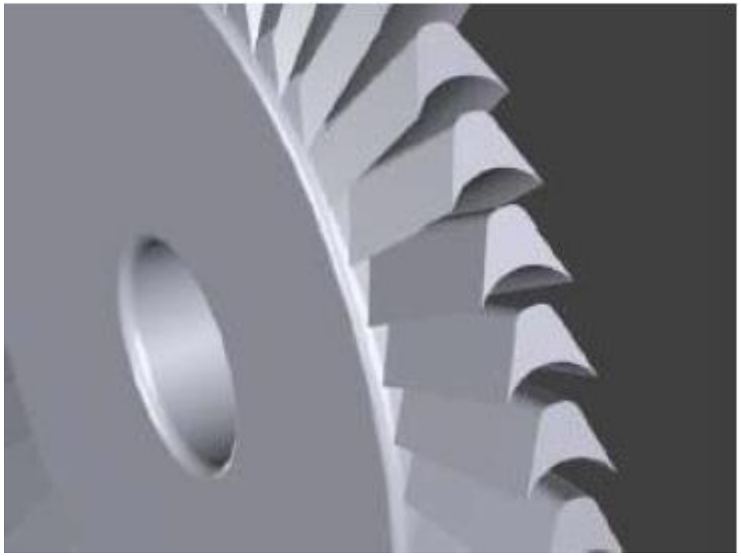
- A turbine stage consists of stationary stator row (guide vanes or nozzle ring) and rotating rotor row.
- In the guide vanes high pressure, high temperature steam is expanded resulting in high
- The guide vanes direct the flow to the rotor velocity
- The blades at an appropriate angle.
- In the rotor, the flow direction is changed and

  kinetic energy of the working fluid is absorbed by

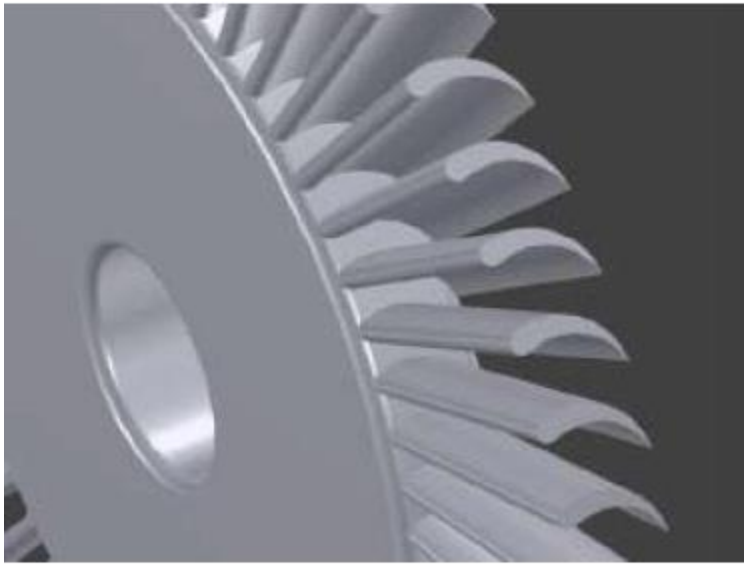
  the rotor shaft producing mechanical energy

Types of Steam Turbine

Impulse turbine



Reaction turbine



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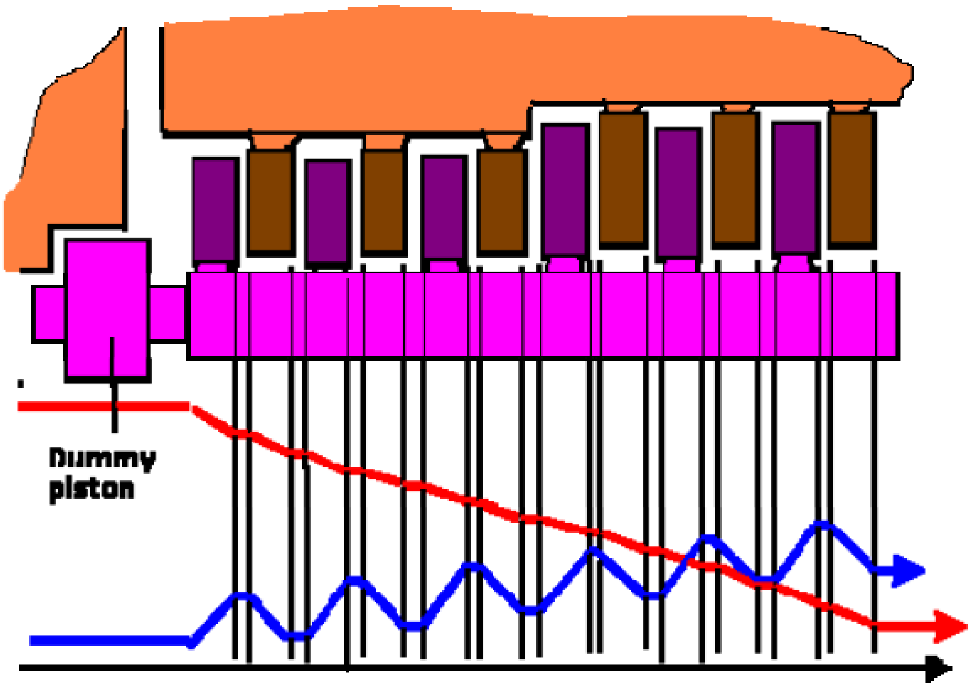
Impulse turbine

- Process of complete expansion of steam takes place in stationary nozzle and the velocity energy is converted into mechanical work on the turbine work turbine blades.

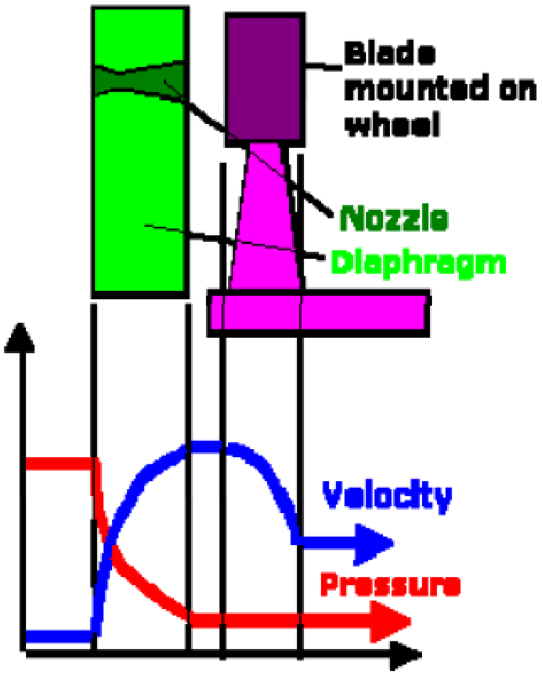
Reaction turbine

- Pressure drop with expansion and generation of kinetic energy takes place
  in the moving blades

Types of Steam Turbine



Parsons Reaction Turbine



De Laval Impulse Turbine.

Impulse Reaction Turbine

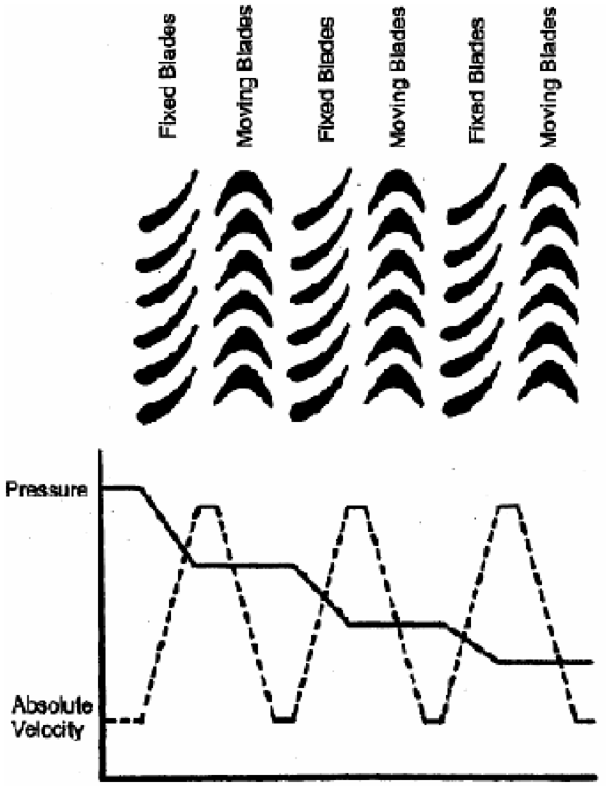
- Modern turbines are neither purely impulse or reaction but a combination of both.
- Pressure drop is effected partly in nozzles and partly in moving blades which are so designed that expansion of steam takes place in them.
- High velocity jet from nozzles produce an impulse on the moving blade and jet coming out from still higher velocity from moving blades produces a reaction.
- Impulse turbine began employing reaction of upto 20% at the root of the moving blades in order to counteract the poor efficiency incurred from zero or even negative reaction.
- Reaction at the root of reaction turbines has come down to as little as 30% to 40% resulting in the reduction of the number of stages required and the sustaining of 50% reaction at mid point.
- It may be more accurate to describe the two design as

  Disc and diaphragm turbine using low reaction blading

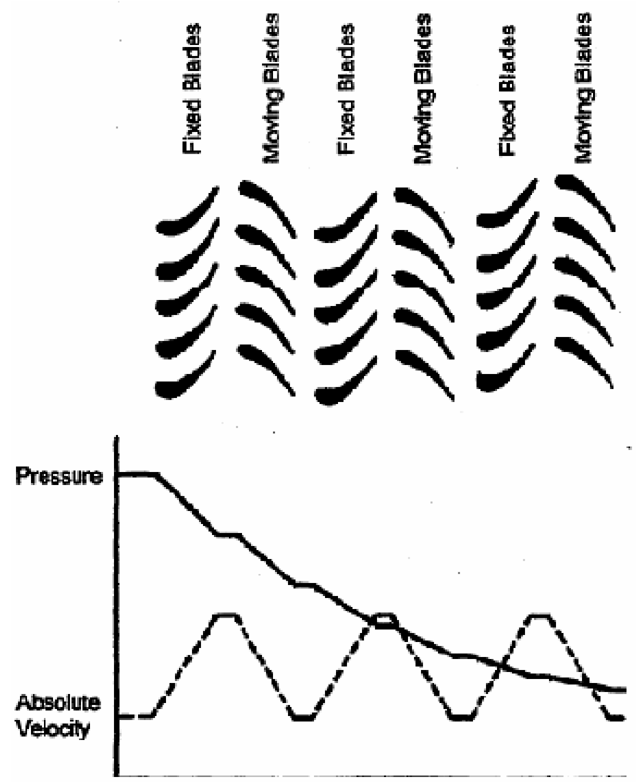
  Drum rotor turbine using high reaction blading

Flow Through Steam Turbine Stage

Distance through turbine(impuls turbine)



Distance through turbine(reaction turbine)



Compounding of Steam Turbines

- This is done to reduce the rotational speed of the impulse turbine to Compounding of Steam Turbines practical limits.
- Compounding is achieved by using more than one set of nozzles, blades rotors in a series keyed to a common shaft; so that either the steam pressure or the jet velocity is absorbed by the turbine in stages.

Three main types of compounded impulse turbines are:

- a. Pressure compounded
- b. Velocity compounded
- c. Pressure and velocity compounded impulse turbines.

Pressure compoundind

Involves splitting up of the whole pressure drop

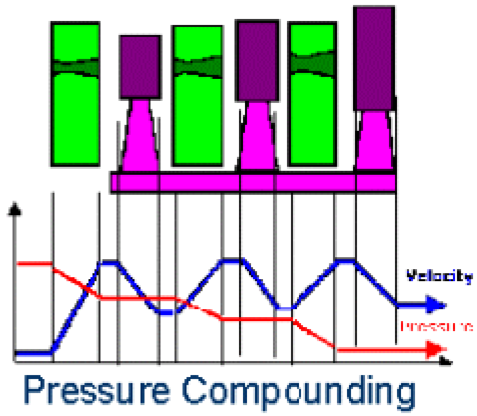
into a series of smaller pressure drops across

several stages of impulse turbine.

The nozzles are fitted into a diaphragm locked in

separates one wheel chamber from

the casing that another. All rotors are mounted on the same shaft.



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Pressure velocity compounding gives the advantage of

producing a shortened rotor compared to pure velocity

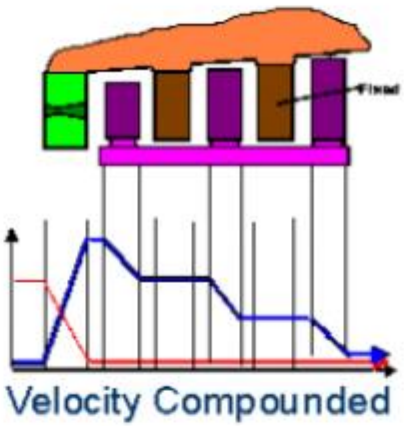
compounding.

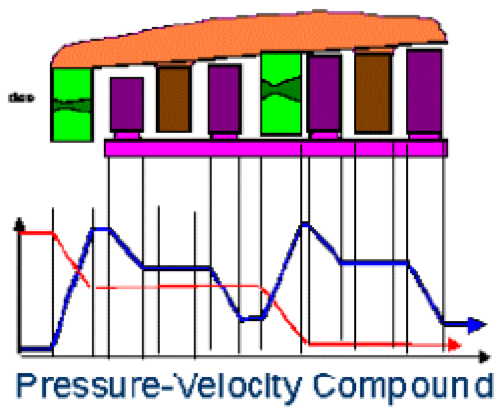
In this design steam velocity at exit to the nozzles is kept

reasonable and thus the blade speed (hence rotor rpm)

reduced.

Velocity drop is achieved through many moving rows of blades instead of a single row of moving blades. It consists of a nozzle or a set of nozzles and rows of moving blades attached to the rotor or the wheel and rows of fixed blades attached to the casing





Comparison between Impulse & Reaction Turbine

Impulse turbine

- An impulse turbine has fixed nozzles that orient the steam flow into high speed jets.
- Blade profile is symmetrical as no pressure drop takes place in the rotor blades
- Suitable for efficiently absorbing the high velocity and high pressure
- Steam pressure is constant across the blades and therefore fine tip clearances are not necessary
- Efficiency is not maintained in the lower pressure stages (high velocity cannot be achieved in steam for the lower pressure stages)

Reaction turbine

- Reaction turbine makes use of the reaction force produced as the steam accelerates through the nozzles formed by the rotor
- Blades have aerofoil profile (convergent p drop occurs partly in the rotor Blades passage) since pressure
- Efficient at the lower pressure stages
- Fine blade tip clearances are necessary due to the pressure leakages
- Inefficient at the high pressure stages due to the pressure leakages around the blade tips
- Fine tip clearances can cause damage to the tips of the blades

Losses in Steam Turbine

- **Profile loss:** Due to formation of boundary layer on blade surfaces. Profile loss is a boundary layer phenomenon and therefore subject to factors that influence boundary layer development. These factors are Reynolds number, surface roughness, exit Mach number and trailing edge thickness.
- **Secondary loss**: Due to friction on the casing wall and on the blade root and tip. It is a boundary layer effect and dependent upon the same considerations as those of profile loss.
- **Tip leakage loss:** Due to steam passing through the small clearances required between the moving tip and casing or between the moving blade tip and rotating shaft. The extend of leakage depends on the whether the turbine is impulse or reaction. Due to pressure drop in moving blades of reaction turbine they are more prone to leakages.
- **Disc windage loss**: Due to surface friction created on the discs of an impulse turbine as the disc rotates in steam atmosphere. The result is the forfeiture of shaft power for an increase in kinetic energy and heat energy of steam

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- **Lacing wire loss**: Due to passage blockage created by the presence of lacing wires in long blade of LP Stages.
- **Wetness loss**: Due to moisture entrained in the low pressure steam at the exit of LP turbine. The loss is a combination of two effects; firstly, reduction in efficiency due to absorption of energy by the water droplets and secondly, erosion of final moving blades leading edges.
- **Annulus loss**: Due to significant amount of diffusion between adjacent stages or where wall cavities occur between the fixed and moving blades. The extent of loss is greatly reduced at high annulus area ratios (inlet/outlet) if the expansion of the steam is controlled by a flared casing wall.
- **Leaving loss**: Due to kinetic energy available at the steam leaving from the last stage of LP turbine. In practice steam does slow down after leaving the last blade, but through the conversion of its kinetic energy to flow friction losses.
- **Partial admission loss**: Due to partial filling of steam, flow between the blades is considerably accelerated causing a loss in power.

TURBINE

- **FEATURES OF TURBINES**

  We shall consider steam as the working fluid

  Single stage or Multistage

  Axial or Radial turbines

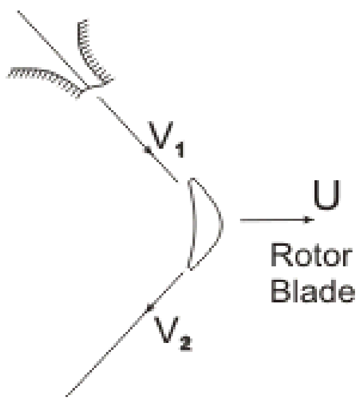
  Atmospheric discharge or discharge below atmosphere in condenser

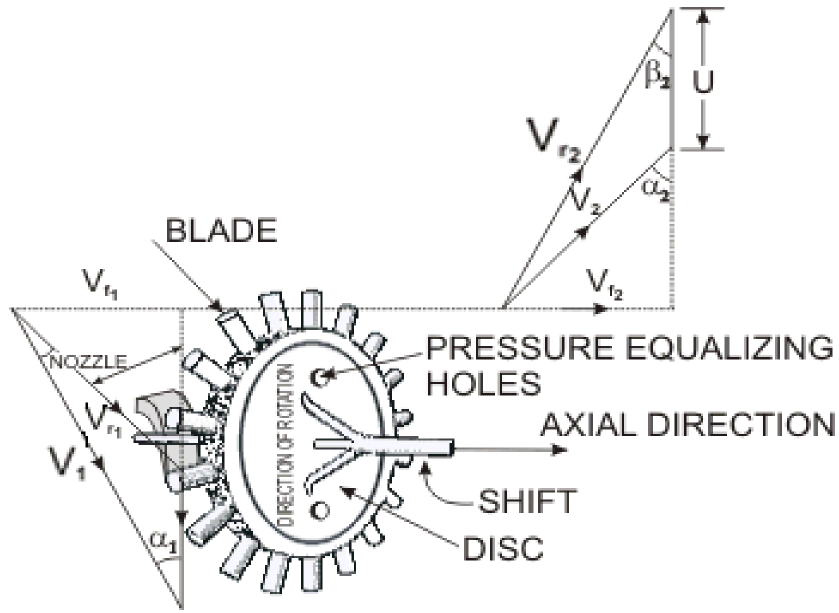
  Impulse/and Reaction turbine

- **Impulse Turbines**

  Impulse turbines (single-rotor or multi-rotor) are simple stages of the turbines. Here the impulse blades are attached to the shaft. Impulse blades can be recognized by their shape. They are usually symmetrical and have entrance and exit angles respectively, around 20 ° . Because they are usually used in the entrance high-pressure stages of a steam turbine, when the specific volume of steam is low and requires much smaller flow than at lower pressures, the impulse blades are short and have constant cross sections

IMPULSE TURBINE





Blade efficiency or Diagram efficiency or Utilization factor is given by

$$\eta_b = \frac{\dot{m} \cdot U \cdot \Delta V_w}{m(V_1^2 / 2)} = \frac{\text{Workdone}}{\text{K.E supplied}}$$

$$\eta_b = \frac{2U\Delta V_w}{V_1^2}$$

TO BE CONTINUE

$$\text{stage efficiency} = \eta_s = \frac{Work\ done\ by\ the\ rotor}{Isentropic\ enthalpy\ drop}$$

$$\eta_s = \frac{\dot{m} U \Delta V_w}{\dot{m}(\Delta H)_{isen}} = \frac{\dot{m} U \Delta V_w}{\dot{m}\left(\frac{V_1^2}{2}\right)} \cdot \frac{\dot{m}(V_1^2/2)}{\dot{m}(\Delta H)_{isen}}$$

or,

or, $\eta_s = \eta_b \times \eta_n \qquad [\eta_n = Nozzle\ efficiency]$

The maximum value of blade efficiency

$$(\eta_b)_{max} = 2(\rho\cos\alpha_1 - \rho^2)(1 + kc)$$

$$= \frac{\cos^2\alpha_1}{2}(1 + kc)$$

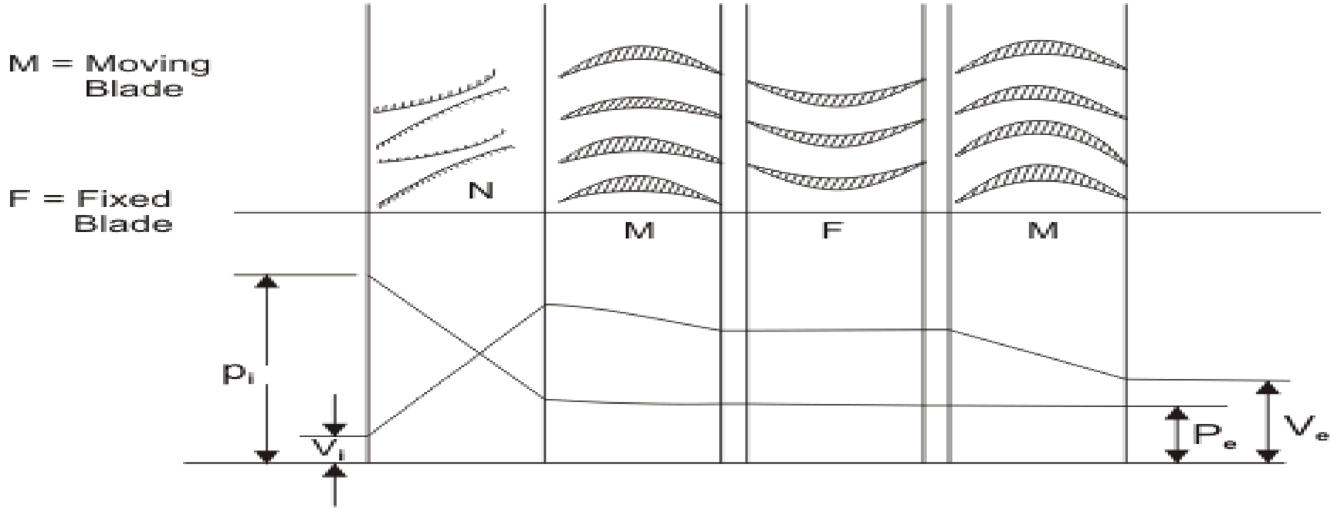
For equiangular blades

$$(\eta_b)_{max} = \frac{\cos^2\alpha_1}{2}(1 + k)$$

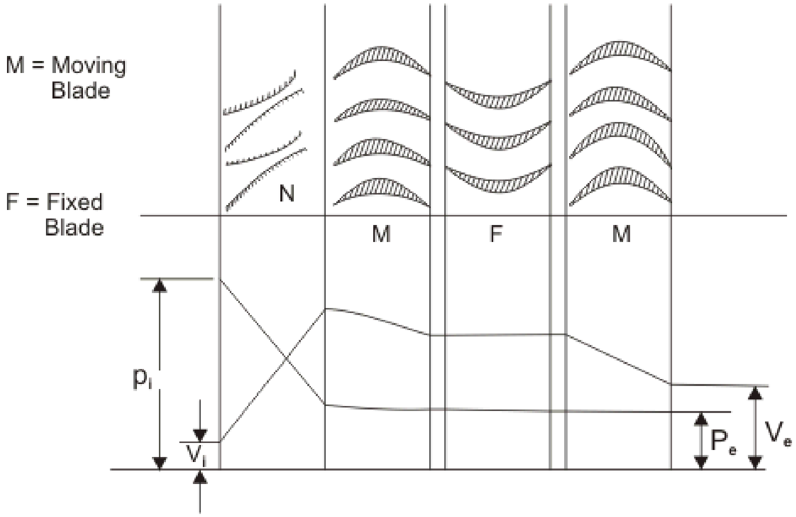
If the friction over blade surface is neglected $(\eta_b)_{max} = \cos^2\alpha_1$

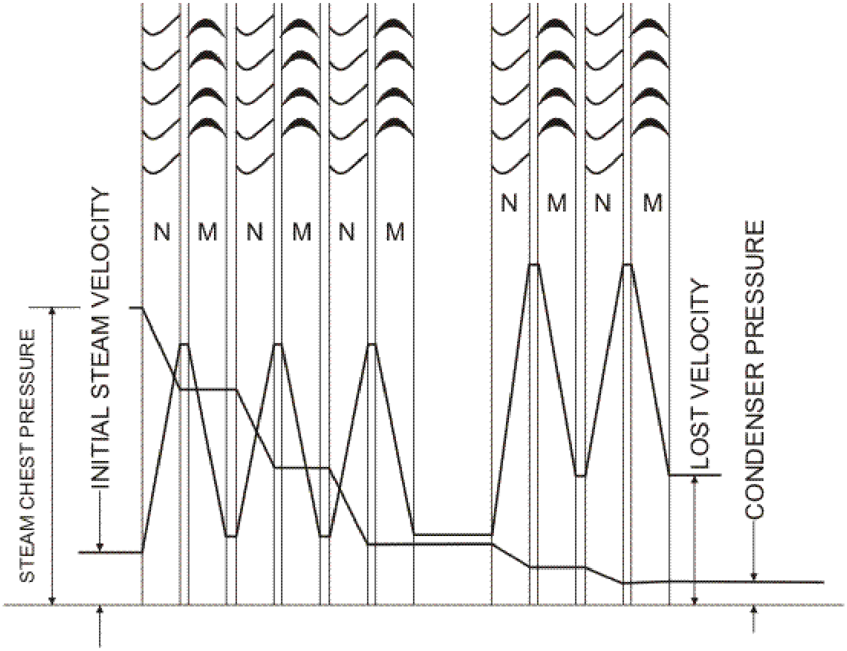
Compounding in Impulse Turbine

- If high velocity of steam is allowed to flow through one row of moving blades, it produces a rotor speed of about 30000 rpm which is too high for practical use.
- It is therefore essential to incorporate some improvements for practical use and also to achieve high performance. This is possible by making use of more than one set of nozzles, and rotors, in a series, keyed to the shaft so that either the steam pressure or the jet velocity is absorbed by the turbine in stages. This is called compounding. Two types of compounding can be accomplished: (a) velocity compounding and (b) pressure compounding



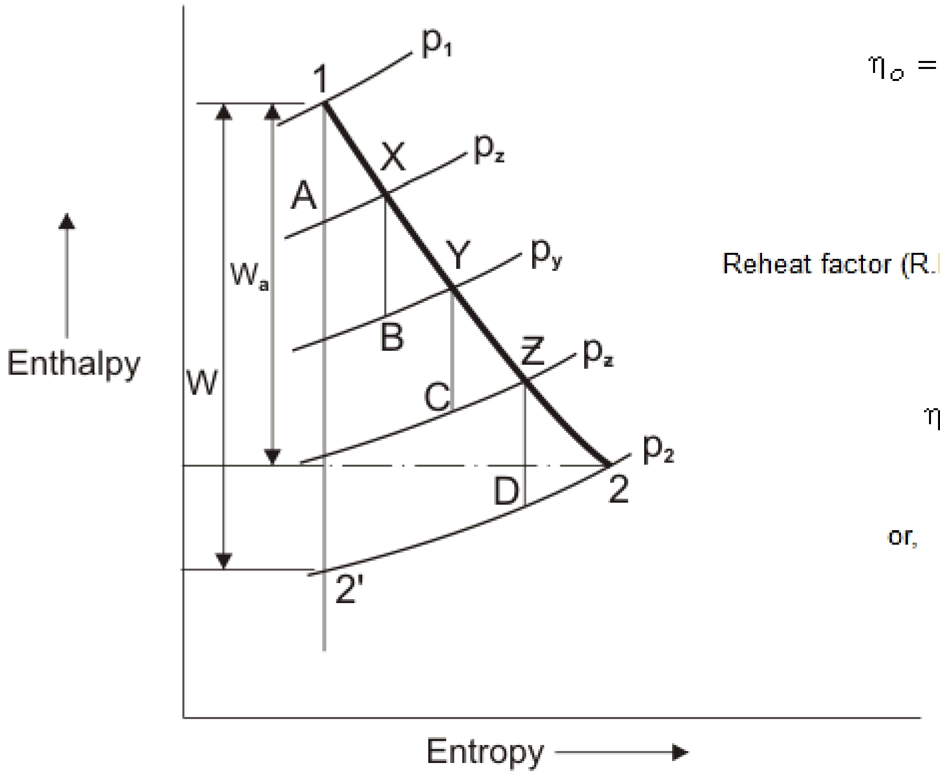
Velocity And Pressure Compounding





Stage Efficiency and Reheat factor

The Thermodynamic effect on the turbine efficiency can be understood by considering a number of stages between two stages as shown in Figure



$$\eta_o = \frac{Wa}{W} = \frac{actual\ \ enthalpy\ drop\ \ (1-2)}{isentropic\ \ heat\ \ drop\ \ (1-2')}$$

$$\text{Reheat factor (R.F.)} = \frac{Cumulative\ \ enthalpy\ drop\ \ (isentropic)}{Isentropic\ \ enthalpy\ \ drop\ \ (overall)}$$

$$\eta_s = \frac{\Delta h_{1x}}{\Delta h_{1A}} = \frac{\Delta h_{xy}}{\Delta h_{xB}} = \frac{\Delta h_{yz}}{\Delta h_{yc}} = \frac{\Delta h_{z2}}{\Delta h_{zD}}$$

or,

$$\eta_s = \frac{\Delta h_{1x} + \Delta h_{xy} + \Delta h_{yz} + \Delta h_{z2}}{\Delta h_{1A} + \Delta h_{xB} + \Delta h_{yc} + \Delta h_{zD}}$$

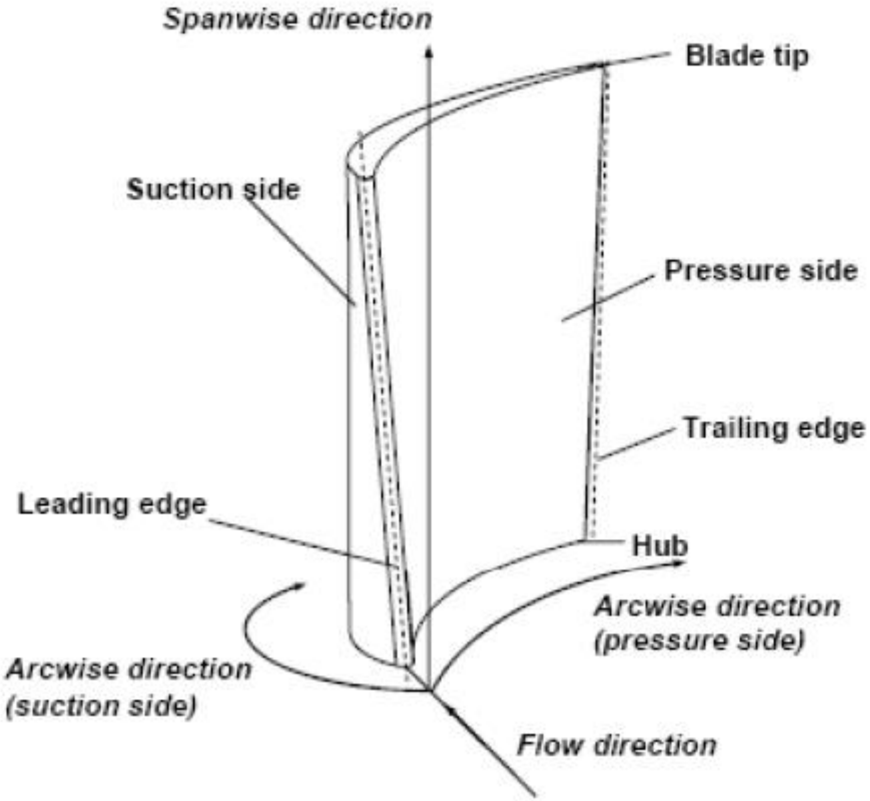
$$= \frac{actual\ \ \ enthalpy\ \ \ drop}{Cumulative\ enthalpy\ drop\ \ (isentropic)}$$

$$\eta_0 = \eta_s \times R.F$$

Velocity Triangles

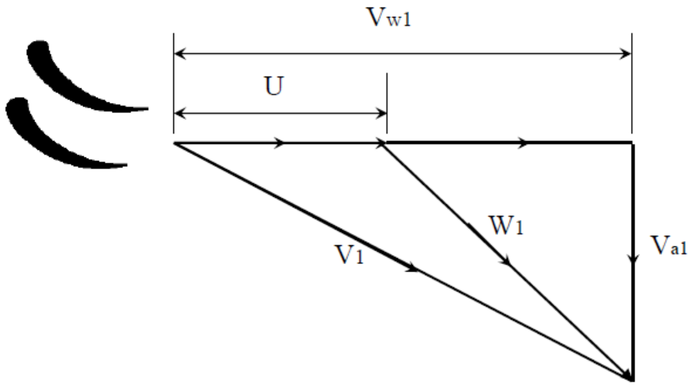
- The three velocity vectors namely, blade speed, absolute velocity and relative velocity in relation to the rotor are used to form a triangle called velocity triangle.
- Velocity triangles are used to illustrate the flow in the bladings of turbo machinery.
- Changes in the flow direction and velocity are easy to understand with the help of the velocity triangles.
- Note that the velocity triangles are drawn for the inlet and outlet of the rotor at certain radii.

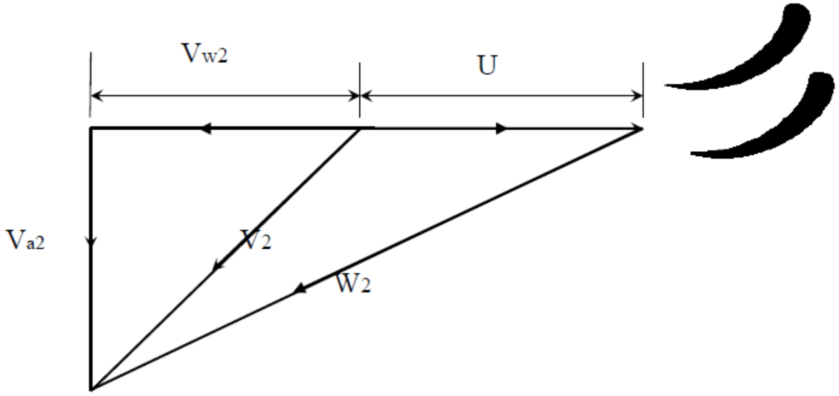
Steam Turbine Blade Terminology



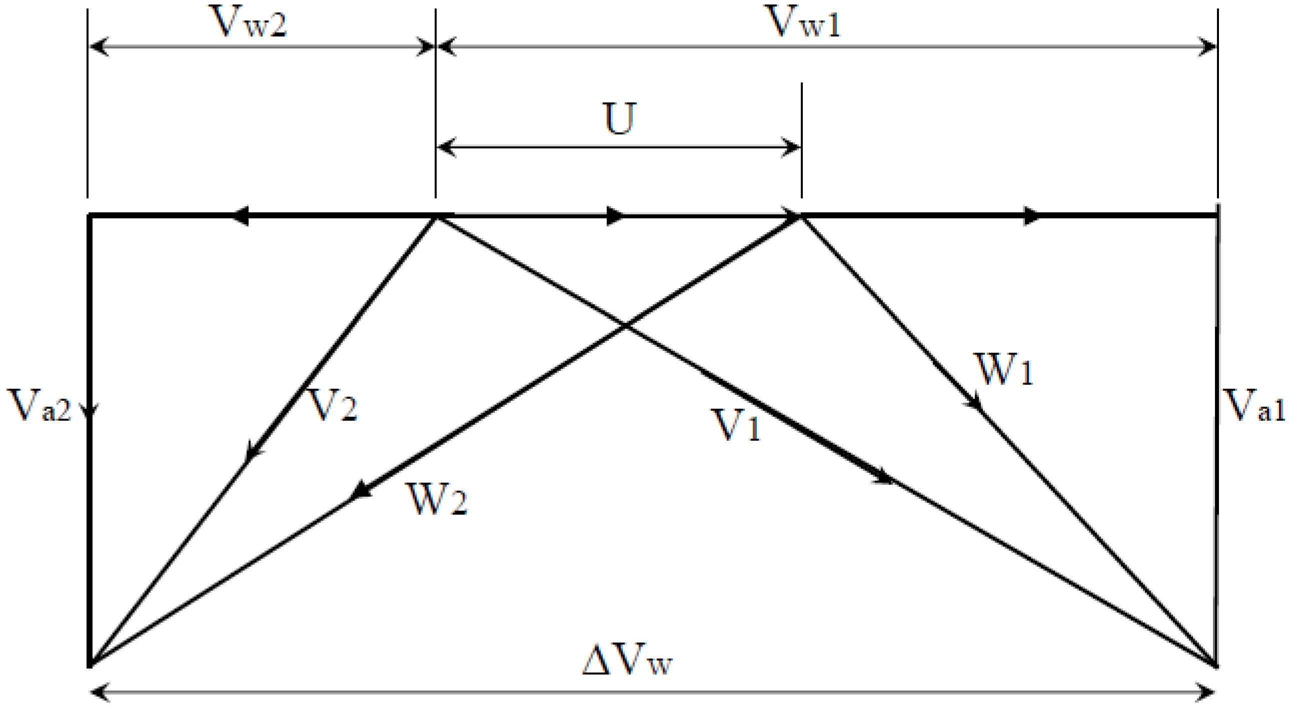
Velocity triangle

Inlet Velocity Triangles **Outlet Velocity Triangles**





Combined velocity triangle



Work Done – Impulse Steam Turbine

If the blade is symmetrical then $\beta 1 = \beta 2$ and neglecting frictional effects of the blades on the steam, W1 = W2.

In actual case, the relative velocity is reduced by friction and expressed by a blade velocity coefficient k.

Thus k = W2/W1

From Euler's equation, work done by the steam is given by;

$$Wt = U(Vw1 \pm Vw2) \quad (1)$$

Since Vw2 is in the negative r direction, the work done per unit mass flow is given by,

$$Wt = U(Vw1+Vw2) \quad (2)$$

If $Va1 \neq Va2$, there will an axial thrust in the flow direction. Assume that Va is constant then,

$$Wt = UVa\,(\tan\alpha 1+ \tan\alpha 2) \quad (3)$$

$$W\ UV\ (t\ \beta + t\ \beta\ ) \quad (4)$$

Wt = UVa tanβ1+ tanβ2) Equation (4) is often referred to as the diagram work per unit mass flow and hence the diagram efficiency is defined as

$$\eta_d = \frac{\text{Rate of work performed per unit mass flow}}{\text{Energy supplied per unit mass of steam}}$$

$$\eta_d = (U\Delta V_w) x \frac{2}{V_1^2} = \frac{2U\Delta V_w}{V_1^2}$$

maximum diagram efficiency

$$= \frac{4\cos\alpha_1}{2}\left(\cos\alpha_1 - \frac{\cos\alpha_1}{2}\right)$$

or $\eta_d = 4\cos^2\alpha_1$

Work Done – Impulse Steam Turbine

$$\eta_d = \frac{\text{Rate of work performed per unit mass flow}}{\text{Energy supplied per unit mass of steam}}$$

$$\eta_d = (U\Delta V_w)x\frac{2}{V_1^2} = \frac{2U\Delta V_w}{V_1^2} \qquad (10)$$

Using the blade velocity coefficient ($k=W_2/W_1$) and symmetrical blades ($\beta_1= \beta_2$),

then; $\Delta V_w = 2V_1 \cos\alpha_1 - U$

Hence $\Delta V_w = 2(V_1 \cos\alpha_1 - U)U$ (11)

And the rate of work performed per unit mass $= 2(V_1 \cos\alpha_1 - U)U$

Therefore; $\eta_d = 2(V_1 \cos\alpha_1 - U)U \times {}^{2}\!/\!{}_{V_1^2}$

$$\eta_d = \frac{4(V_1 \cos\alpha_1 - U)U}{V_1^2} = \frac{4U}{V_1}\left(\cos\alpha_1 \frac{U}{V_1}\right)$$

where $\frac{U}{V_1}$ is called the blade speed ratio (12)

Degree of reaction

- **Degree of reaction** is a parameter that describes the relation between the energy transfer due to the static pressure change and the energy transfer due to dynamic pressure change.
- **Degree of reaction** is defined as the ratio of static pressure drop in the rotor to the static pressure drop in the stage. It is also defined as the ratio of static enthalpy drop in the rotor to the static enthalpy drop in the stage

Degree of reaction

$$\Lambda = \frac{(h_1 - h_2)}{\left(h_{00} - \frac{V_0^2}{2C_p}\right) - \left(h_{02} - \frac{V_2^2}{2C_p}\right)}$$

Zero reaction stage

Let us first discuss the special case of zero reaction. According to the definition

of reaction, When Λ = 0, equation (upper) reveals that h1 = h2 and equation (lower) that

β1 = β2.

$$\Lambda = \frac{1}{2} + \frac{V_a}{2U}(\tan\beta_2 + \tan\alpha_2)$$

Putting Λ = 0 in equation we get

$(\beta_2 = \beta_1)$ And $V_1 = V_2$ and for Λ = 0.5, $(\beta_2 = \alpha_1)$

Fifty percent reaction stage

From equation (16) for Λ = 0.5 α1 = β2 and the velocity diagram is symmetrical Because of symmetrical. symmetry, it is also clear that α2 = β1. For Λ=1/2,

the enthalpy drop in the nozzle row equals the enthalpy drop in the rotor.

h0 - h1 = h1 - h2

Blade Height in Axial Flow turbine

The continuity equation $\dot{m} = \rho AV$ may be used to find the blade height 'h'. The annular area of flow = πDh. Thus the mass flow rate through an axial flow turbine is

$$\dot{m} = \rho \pi D h V_a$$

$$h = \frac{\dot{m}}{\rho \pi D V_a}$$

Blade height will increase in the direction of flow in a turbine and decrease in the direction of flow in a compressor.

THANK YOU