Impulse Turbine

1. A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work.

2. Early turbine examples are windmills and waterwheels.

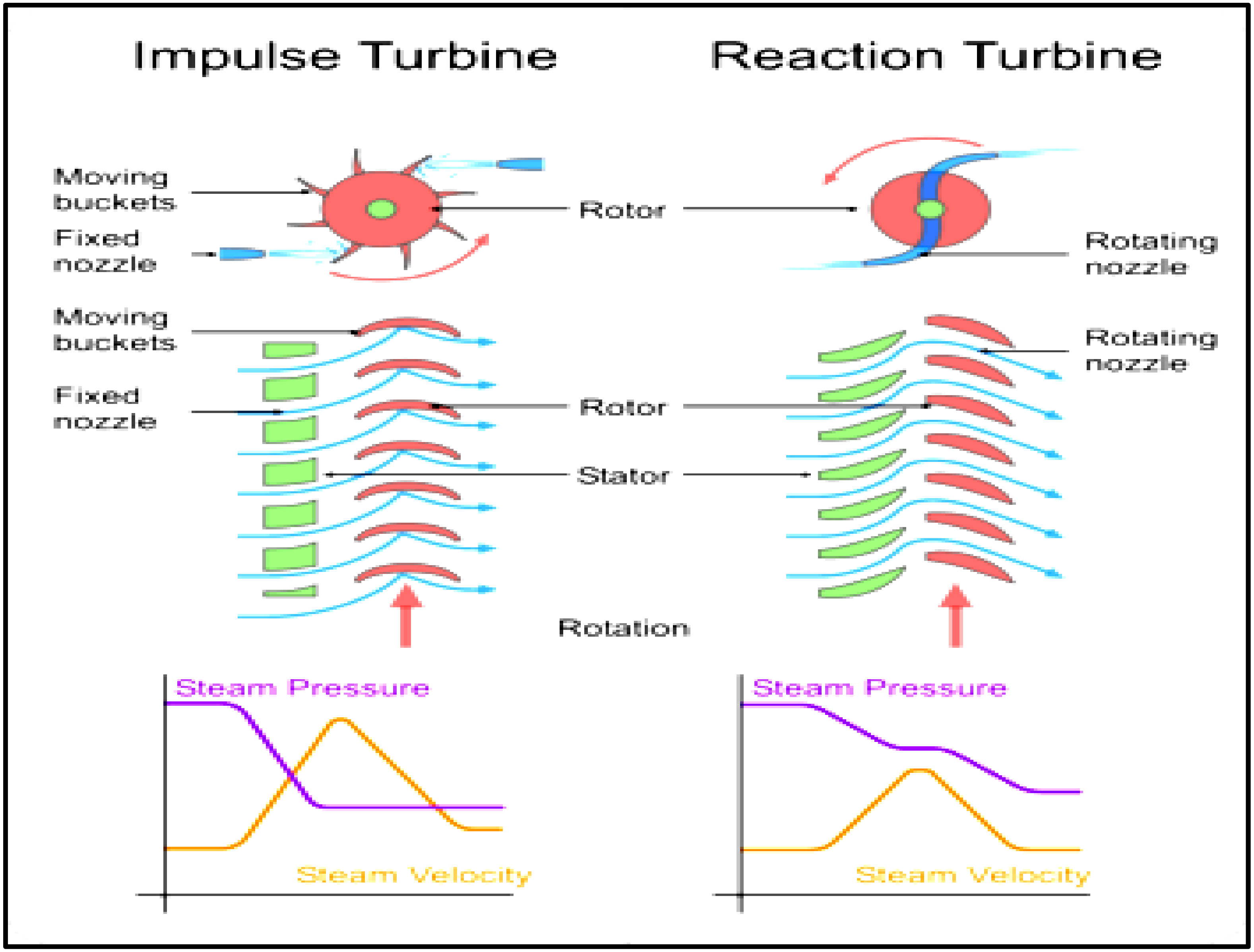
3. Gas, steam, and water turbines usually have a casing around the blades that contains and controls the working fluid.

Theory of operation

1. A working fluid contains potential energy (pressure head) and kinetic energy (velocity head).

2. The fluid may be compressible or incompressible.

3. Impulse turbines change the direction of flow of a high velocity fluid or gas jet.



Schematic of impulse and reaction turbines, where the rotor is the rotating part, and the stator is the stationary part of the machine.

Calculations for work, Power, and Efficiencies

Work and Power:-

From Newton's second law, the force F in the direction of moving blades is given by

F = Rate of change of momentum

= Mass flow rate of steam x Change in velocity of whirl

$$= m(\overrightarrow{C_{wi}} - \overrightarrow{C_{wo}})$$

Hence,

Work done on the moving blades = Force x Distance moved /sec

Or,

Power developed,

$$F = m(C_{wi} + C_{wo}) = m\,C_w$$

$$W = (m\,C_w)C_b$$

$$P = \frac{(m\,C_w C_b)}{1000}\,KW$$

Diagram or Blade Efficiency

The energy supplied per stage of an impulse turbine is equal to K.E given by $\frac{(mC_i^2)}{2}$ and assuming that the K.E leaving the stage is wasted.

Blade efficiency : $\eta_b = \frac{Work\ done\ on\ the\ blades}{K.E\ supplied\ to\ the\ blade} = \frac{(mC_w C_b)}{\frac{mC_i^2}{2}} = \frac{2C_w C_b}{C_i^2}$

Blade efficiency can also be defined as

$$\eta_b = \frac{Change\ in\ K.E\ of\ steam}{K.E\ supplied} = \frac{\frac{C_i^2}{2} - \frac{C_o^2}{2}}{\frac{C_i^2}{2}} = \frac{C_i^2 - C_o^2}{C_i^2}$$

Blade efficiency will be maximum when C_o is minimum, i.e when $\beta = 90^0$ or the discharge is axial.

Stage efficiency

Stage is defined as the combination of a fixed blades and moving blades. The energy supplied corresponding to the isentropic heat drop ΔH in the nozzles.

$$\eta_s = \frac{Work\ done}{Energy\ supplied\ per\ stage} = \frac{(mC_w C_b)}{(\Delta H\ x\ 1000)} = \frac{C_w C_b}{(\Delta h\ x\ 1000)}$$

Where , ΔH is in KJ and it is equal to $m\Delta h$ where Δh is the isentropic enthalpy drop per Kg of steam in KJ/Kg.

The stage efficiency becomes equal to the blade efficiency if there are no friction losses in the nozzles.

$$\eta_s = \eta_n \, x \, \eta_b$$

Axial thrust

The axial thrust on the wheel is due to the force exerted as a result of the rate of change of momentum in axial direction.

Axial thrust, F_a = Mass of flow rate x Change in axial velocity

$$= m(\overrightarrow{C_{fi}} - \overrightarrow{C_{fo}})$$

Blade velocity Coefficient (K):-

In an impulse turbine if the friction is neglected, the relative velocity of steam C_{ro} at outlet of moving blades equal to relative velocity of steam C_{ri} at inlet to moving blades. i.e $C_{ro} = C_{ri}$.

Effect of friction is to reduce relative velocity of steam as it passes over the moving blades. The friction loss is 10 to 15 % . Therefore C_{ro} is less than C_{ri} .

Blade velocity coefficient , $K = \frac{Relative\ velocity\ at\ exit\ of\ moving\ blade, C_{ro}}{Relative\ velocity\ at\ inlet\ to\ moving\ blades, C_{ri}}$

$$C_{ro} = K C_{ri}$$

Blade speed ratio, (s) $s = \frac{Blade\ velocity, C_b}{Steam\ velocity\ at\ inlet,\ C_i}$

Condition for Maximum Discharge Efficiency for Impulse Turbine

From fig

Work done per Kg of steam $W = (C_{wi} + C_{wo})C_b$

$$= C_b[(C_{ri}\cos\theta + C_b) + (C_{ro}\cos\varphi - C_b)]$$

$$= C_b C_{ri}\cos\theta \left(1 + \frac{C_{ro}\cos\varphi}{C_{ri}\cos\theta}\right)$$

$$= C_b(C_i\cos\alpha - C_b)[1 + KC] \quad \ldots\ldots\ldots\ldots (1)$$

Where, $K = Friction\ factor = \frac{C_{ro}}{C_{ri}}$ and $C = \frac{\cos\varphi}{\cos\theta}$, $(a\ constant\ for\ given\ moving\ blades)$

and $Blade\ speed\ ratio, s = \frac{C_b}{C_i}$

$$\eta_b = \frac{Workdone\ per\ Kg\ of\ steam}{Energy\ supplied\ to\ blades\ per\ Kg\ of\ steam}$$

$$= \frac{C_b(C_i \cos\alpha - C_b)(1+KC)}{\frac{C_i^2}{2}}$$

$$= 2\left[\frac{C_b}{C_i}\cos\alpha - \frac{C_b^2}{C_i^2}\right](1+KC)$$

$$= 2\,[s\cos\alpha - s^2](1+KC) \qquad \ldots\ldots\ (A)$$

Effect of nozzle angle

From equation (1) above, it is evident that the work would be maximum if $\cos\alpha = 1, i.e, \alpha = 0^0$

Other parameters like $C_b, K, \theta, \emptyset, C_i$ are fixed.

For maximum efficiency, differentiating the expression for efficiency given by equation (A) with respect to s and equating to zero.

$$\frac{d(\eta_b)}{d(s)} = 0$$

$$2(1+KC)(cos\alpha - 2s) = 0$$

Optimum blade speed ratio, $(s)_{optimum} = \frac{cos\alpha}{2} = \frac{C_b}{C_i}$

Substituting S(optimum) in equation (A)

$$(\eta_b)_{max} = 2\left[\frac{cos\alpha}{2}cos\alpha - \left(\frac{cos\alpha}{2}\right)^2\right](1 + KC)$$

$$= \frac{cos^2\alpha}{2}(1 + KC)$$

For a De –Laval turbine neglecting friction , i.e K =1 and for symmetrical blades , i.e. θ = φ, hence, C =1.

$$(\eta_b)_{max} = cos^2\alpha$$

Expression for maximum work becomes $W_{max} = \frac{C_i cos\alpha}{2}\left(C_i cos\alpha - \frac{C_i cos\alpha}{2}\right)(1 + KC)$

$$= \frac{C_i^2 cos^2\alpha}{4}(1 + KC)$$

In case, K = 1 , C = 1(Blade symmetrical) and $C_i = \frac{2C_b}{cos\alpha}$, then

$$W_{max} = 2C_b^2$$

The algebraic sum of actual heat drops in stages i.e

$\left(A_1C_1 + A_2B_2 + A_3C_3 + ---- + \sum AB \right)$ is called the total useful heat drop.

The algebraic sum of isentropic heat drops in stages

$A_1B_1 + A_2B_2 + A_3B_3 + ------ = \sum AB$ is called the cummulative isentropic heat drop .

The ratio of cummulative isentropic heat drop to the Rankine heat drop is defined as the reheat factor (R.F). Hence,

$$Reheat\ factor = \frac{cummulative\ isentropic\ heat\ drop}{Rankine\ heat\ drop} = \frac{\sum AB}{A_1D}$$

Internal efficiency of turbine is defined as the ratio of total useful heat drop to the rankine heat drop. Accordingly

$$\eta_t = \frac{Total\ useful\ heat\ drop}{Rankine\ heat\ drop} = \frac{\sum AC}{A_1D} \qquad \ldots\ldots\ A$$

Stage efficiency for each stage is the ratio of actual heat drop to the isentropic heat drop .

Therefore the expression for stage efficiency for various stages is as follows:

Stage efficiency for first stage

$$\eta_{stage\ 1} = \frac{A_1C_1}{A_1B_1}$$

Similarly

$$\eta_{stage\ 2} = \frac{A_2C_2}{A_2B_2}$$

$$\eta_{stage\ 3} = \frac{A_3C_3}{A_3B_3}$$

If the stage efficiency is same for all the stages then,

$$\eta_{stage} = \frac{\sum AC}{\sum AB}$$

Equation A can be re-written as

$$\eta_t = \frac{\sum AC}{A_1D} x \frac{\sum AB}{\sum AB}$$

$$\eta_t = \frac{\sum AB}{A_1D} x \frac{\sum AC}{\sum AB}$$

$$\eta_t = (R.F)\, x\eta_{stage}$$

The reheat factor depends upon turbine stage efficiency, the condition of steam at entry and the exit pressure.

The value of R.F usually varies between 1.02 to 1.06.

Reaction Turbine

1. An impulse – reaction turbine usually called as reaction turbine.
2. Uses the principle of both the impulse and reaction turbine.
3. Due to this, the blade passages between consecutive blades are of converging types, like convergent nozzle.

Degree of reaction ,

The term degree of reaction as applied in case of reaction turbines is a measure of the proportion of the work done by reaction effect (due to pressure drop in moving blades and it is defined as

$$R_D = \frac{[Enthalpy\ drop\ in\ moving\ blades\ (\Delta h)_m]}{[Enthalpy\ drop\ in\ moving\ blades\ (\Delta h)_m + [Enthalpy\ drop\ in\ fixed\ blades\ (\Delta h)_f]]}$$

Enthalpy drop in moving blades $(\Delta h)_m$ is equal to increase in K.E of the steam corresponding to relative velocity while the steam passes over the moving blades, Therefore

$$(\Delta h)_m = \frac{C_{ro}^2 - C_{ri}^2}{2}$$

Enthalpy drop in fixed blade $(\Delta h)_f$ is given by

$$(\Delta h)_f = \frac{C_i^2 - C_o^2}{2}$$

Therefore, the total heat drop for the stage ($(\Delta h)_m$ $+(\Delta h)_f$) is equal to work done by the steam and it equals to

$$(\Delta h)_m + (\Delta h)_f = C_b\,(C_{wi} + C_{wo})$$

Hence, **degree of reaction** ,

$$R_D = \frac{C_{ro}^2 - C_{ri}^2}{2C_b(C_{wi} + C_{wo})} \quad \ldots\ldots\ldots\ldots \text{ A}$$

Velocity Diagram

$$C_{ro} = C_{fo}.\,cosec\varnothing$$

And $C_{ri} = C_{fi}.\,cosec\varnothing$

$$(C_{wi} + C_{wo}) = C_{fi}\cot\theta + C_{fo}\cot\varnothing$$

The velocity of flow is generally constant while the steam passes over the blade ring.

i.e $C_{fi} = C_{fo} = C_f (say)$

Substituting the values of C_{ro}, C_{ri}, and $(C_{wi} + C_{wo})$ in Equation A

Degree of reaction, R_D

$$R_D = \frac{(C_f cosec\phi)^2 - (C_f cosec\theta)^2}{2C_b C_f(cot\theta + cot\phi)}$$

$$= \frac{C_f\,(cosec^2\phi - cosec^2\theta)}{2C_b(cot\theta + cot\phi)}$$

$$R_D = \frac{C_f}{2C_b}\left[\frac{(cot^2\phi + 1) - (cot^2\theta - 1))}{(cot\theta + cot\phi)}\right]$$

$$= \frac{C_f}{2C_b}\left[\frac{(cot^2\phi - cot^2\theta)}{(cot\theta + cot\phi)}\right]$$

$$= \frac{C_f}{2C_b} x\,(cot\phi - cot\theta) \qquad \ldots\ldots\ldots\ldots (1)$$

For 50% degree of reaction turbine, called as Parson's reaction turbine, Equation (1) can be written as

$$\frac{1}{2} = \frac{C_f}{2C_b} x\,(\cot\emptyset - \cot\theta)$$

$$C_b = C_f.(\cot\emptyset - \cot\theta) \qquad \ldots\ldots (2)$$

From fig the value of C_b can also written as

$$C_b = C_f.(\cot\alpha - \cot\theta) \qquad \ldots\ldots\ldots (3)$$

$$C_b = C_f.(\cot\emptyset - \cot\beta) \qquad \ldots\ldots\ldots (4)$$

Comparing the equations (2), (3), and (4) we get

$$\alpha = \emptyset \text{ and } \theta = \beta$$

It follows that for a 50% reaction turbine the moving and fixed blades must be made symmetrical in shapes.

Work, Power and Efficiency

W.D per Kg of steam = $(C_{wi} + C_{wo})C_b$

Power developed per stage = $\frac{m(C_{wi} + C_{wo})C_b}{1000}$ KW

Stage efficiency = $\frac{(C_{wi} + C_{wo})C_b}{(\Delta h)x1000}$

When (Δh) is the heat drop in KJ/Kg in a stage which can be determined with the help of Mollier's diagram. Also,

$$\Delta h = \frac{C_i^2}{2} + \frac{C_{ro}^2 - C_{ri}^2}{2}$$

Blade efficiency, $\eta_b = \frac{Work\ done}{Energy\ supplied} = \frac{C_b(C_{wi} + C_{wo})}{\left[\frac{C_i^2}{2} + \frac{C_{ro}^2 - C_{ri}^2}{2}\right]}$

$$= \frac{2C_b(C_{wi} + C_{wo})}{[C_i^2 + (C_{ro}^2 - C_{ri}^2)]}$$

Blade Height

Now it becomes necessary to determine the height of blade required at a particular stage, Let

N = Speed of turbine, rpm

D = drum diameter, m

h = blade height, m

Velocity of flow , $C_{fi} = C_{fo} = C_f \,(say)$

Mean drum diameter, $d_m = (d + h)$

Area of flow (neglecting the area of blades occupied)

$$A_f = (Mean\ circumference)\ x\ (Blade\ height)$$

$$= [\pi(d + h)]h$$

Volume flow rate of steam, Q = Area of flow x Velocity of flow

$$Q = [\pi(d + h)h]C_f$$

Mass flow rate of steam, $m = \dfrac{[\pi(d + h)h]C_f}{v}$

Where, v is the specific volume of steam in m^3/Kg at the given stage

Also, **Blade speed** , $C_b = \dfrac{[\pi(d + h)]N}{60}\ m/s$

Condition for Maximum Blade Efficiency in case of 50% Reaction Turbine

Work done per Kg of steam $W = (C_{wi} + C_{wo})C_b$

From previous fig.

$$C_{wi} = C_i \cos\alpha$$

$$C_{wo} = C_{ro}\cos\varphi - C_b = C_i\cos\alpha - C_b$$

$$W = C_b(2C_i\cos\alpha - C_b)$$

$$W = C_i^2\left[\frac{2C_bC_i\cos\alpha}{C_i^2} - \frac{C_b^2}{C_i^2}\right] \quad \text{........ (a)}$$

Let, the ratio of blade velocity to steam velocity called Blade velocity ratio, be represented by 's', i.e

$$Blade\ velocity\ ratio, s = \frac{Blade\ velocity, C_b}{Steam\ velocity, C_i}$$

Using definition of blade velocity ratio from above equation , the equation (a) becomes

Then,

$$W = C_i^2(2\,s\cos\alpha - s^2)$$

Energy supplied /Kg of steam becomes,

$$= \frac{C_i^2}{2} + \frac{C_{ro}^2 - C_{ri}^2}{2}$$

$$= C_i^2 - \frac{C_{ri}^2}{2}, (Since\ C_i = C_{ro})$$

But, from ΔABC , $C_{ri}^2 = C_i^2 + C_b^2 - 2C_bC_i\cos\alpha$

Energy supplied per Kg of steam becomes $= C_i^2 - \frac{C_i^2 + C_b^2 - 2C_bC_i\cos\alpha}{2} = \frac{C_i^2 + 2C_bC_i\cos\alpha - C_b^2}{2}$

$$= \frac{C_i^2}{2}(1 + 2\ s\ cos\alpha - s^2)$$

The **blade efficiency for the stage**

$$\eta_b = \frac{Work\ done}{Energy\ supplied} = \frac{C_i^2(2\ s\ cos\alpha - s^2)}{\frac{C_i^2}{2}(1 + 2\ s\ cos\alpha - s^2)}$$

$$= \frac{2(2\ s\ cos\alpha - s^2)}{(1 + 2\ s\ cos\alpha - s^2)} = \frac{2(1 + 2\ s\ cos\alpha - s^2) - 2}{(1 + 2\ s\ cos\alpha - s^2)}$$

$$= 2 - \frac{2}{(1 + 2\ s\ cos\alpha - s^2)} \qquad \text{…………. (A)}$$

Therefore, η_b becomes maximum when factor $(1 + 2\,s\,cos\alpha - s^2)$ becomes maximum

The required condition is $\frac{d}{d(s)}(1 + 2\,s\,cos\alpha - s^2) = 0$

$$(2cos\alpha - 2s) = 0, s = cos\alpha$$

I.E condition for maximum efficiency $s = \frac{C_b}{C_i} cos\alpha$ .... (B)

Substituting the value of 's' from equation (B) in equation (A)

$$(\eta_b)_{max} = 2 - \frac{2}{(1 + 2\,cos\alpha cos\alpha - cos^2\alpha)} = \frac{2\,cos^2\alpha}{(1 + cos^2\alpha)}$$

Governing of Impulse Turbines

1. The function of a governor is to control the fluctuation of speed of prime mover which the prescribed limits with the variations of load on it.

2. output according to the load on the alternator with very small fluctuations in speed called governor.

The methods used for governing of impulse turbines are:-

1. Throttle governing

2. Nozzles governing

3. By-pass governing

4. Combined throttle and nozzle governing

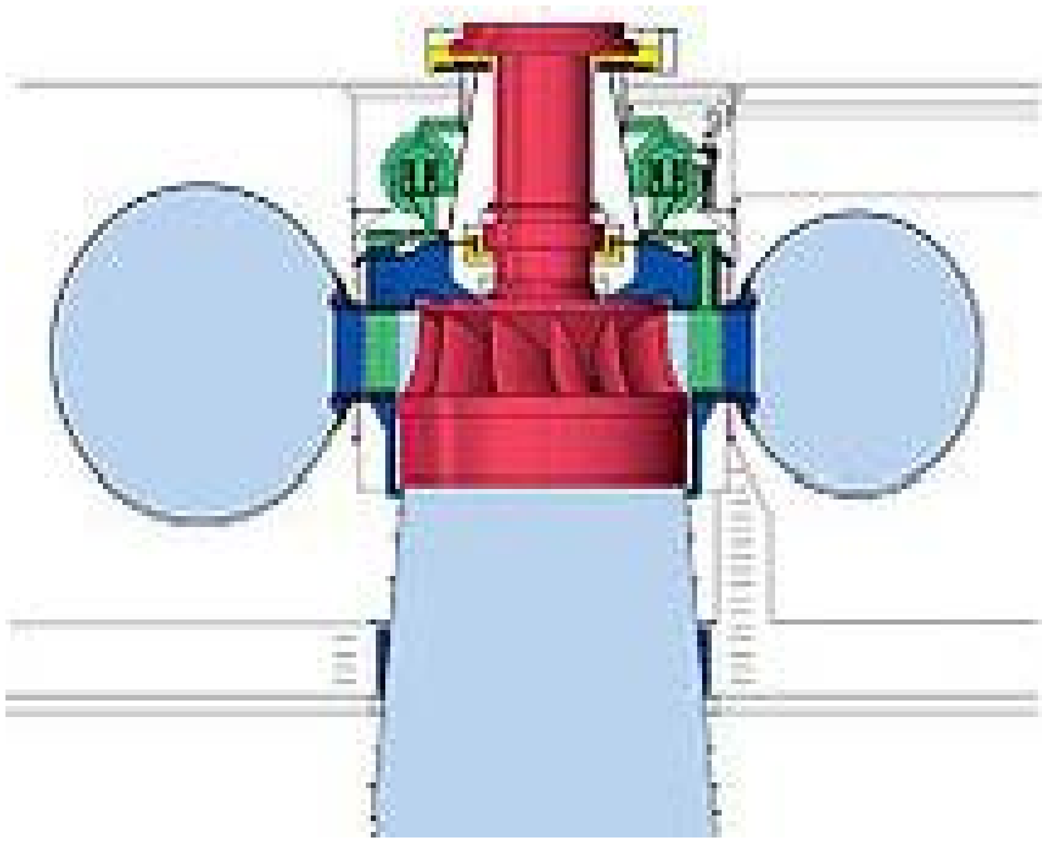
5. Combined throttle and by-pass governing.

FrancisTurbine

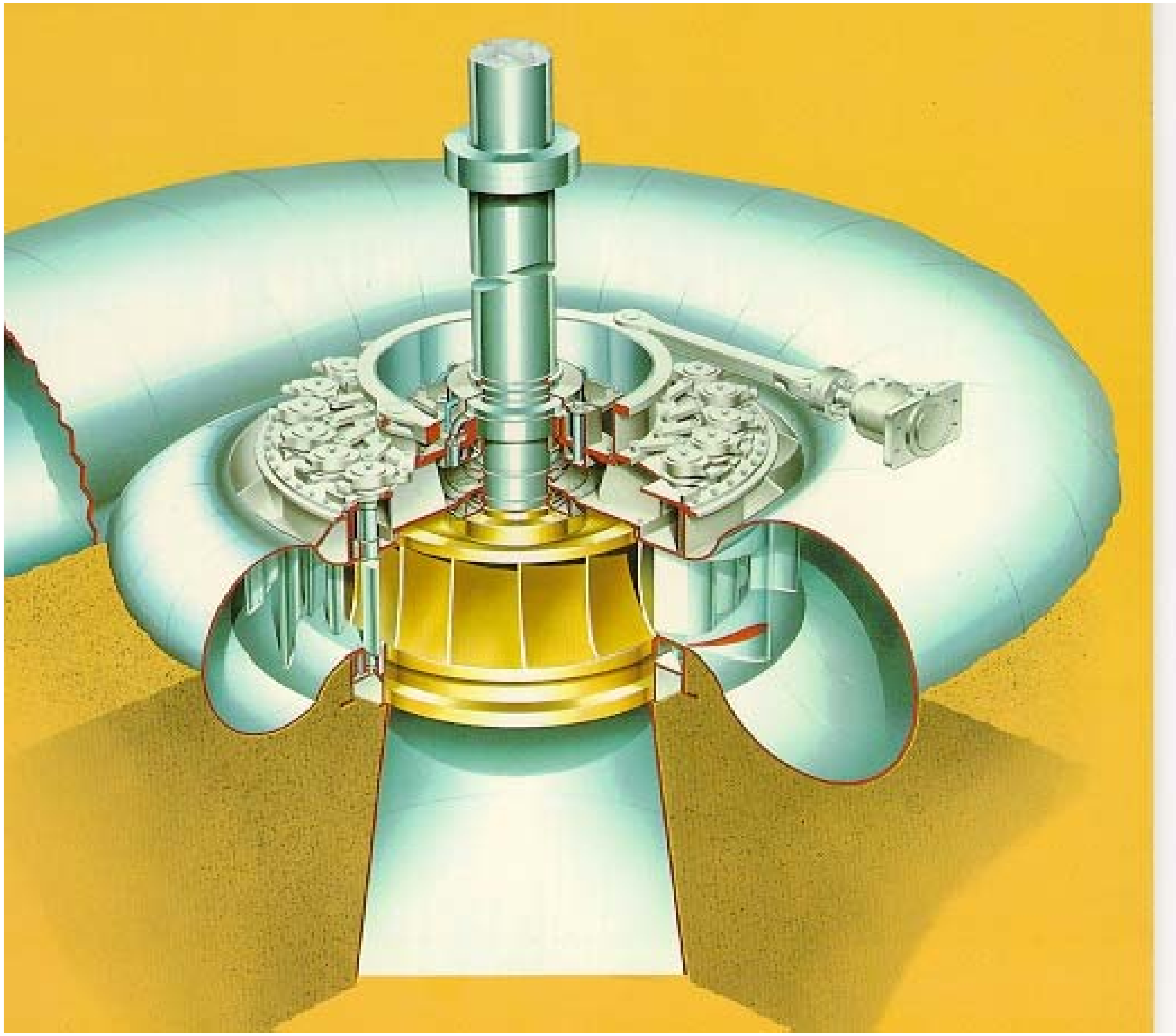
1. Francis Turbine is the first hydraulic turbine with radial in flow.

2. It was designed by an American scientist James Francis

3. Francis turbine is a reaction turbine as the energy available at the inlet of the turbine is a combination of kinetic and pressure energy



Side-view cutaway of a vertical Francis turbine. Here water enters horizontally in a spiral shaped pipe (penstock) wrapped around the outside of the turbine's rotating *runner* and exits vertically down through the centre of the turbine.



Vertical Francis turbine.

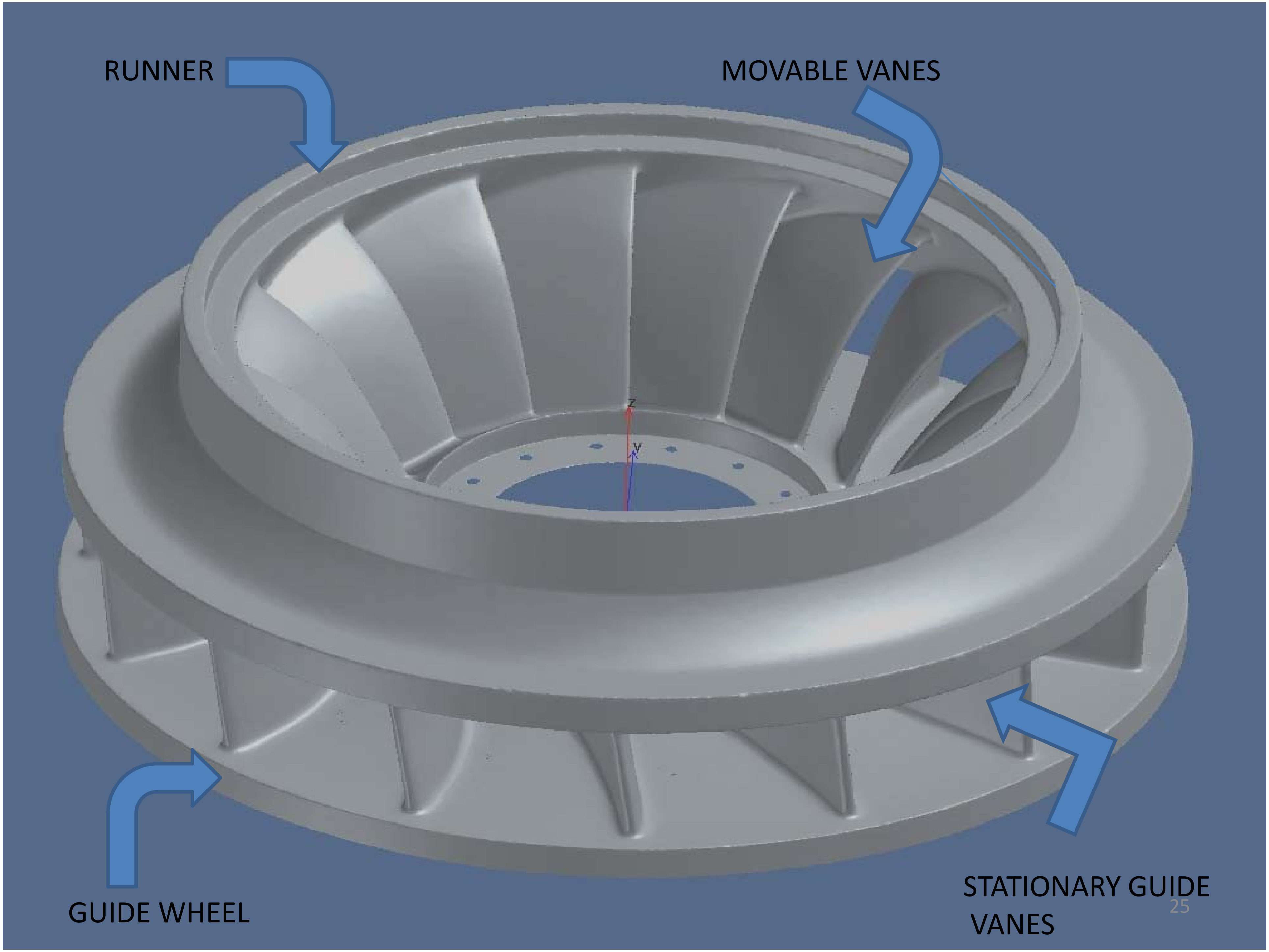
- **Main parts of Francis Turbine**

- **CASING**: The runner is completely enclosed in an air-tight spiral casing. The casing and runner are always full of water.

- **GUIDE MECHANISM**: It consists of a stationary circular wheel on which stationary guide vanes are fixed. The guide vanes allow the water to strike the vanes of the runner without shock at inlet

- **RUNNER**: It is a circular wheel on which a series of curved radial guide vanes are fixed.

- **DRAFT TUBE**: It is used for discharging water from the outlet of the runner to the tail race.


RUNNER
MOVABLE VANES
GUIDE WHEEL
STATIONARY GUIDE
VANES

Francis Turbine (exterior view) attached to a generator

Working Principle

1. The Francis turbine is a type of reaction turbine, a category of turbine in which the working fluid comes to the turbine under immense pressure

2. At the exit, water acts on the spinning cup-shaped runner features, leaving at low velocity and low swirl with very little kinetic or potential energy left.

3. The turbine's exit tube is shaped to help decelerate the water flow and recover the pressure.

The velocity triangle at inlet and outlet of Francis Turbine are drawn in the same way as in case of inward flow reaction turbine.

As in case of Francis turbine the discharge is radial at outlet, the velocity of whirl at outlet will be zero.

Hence, the work done /sec on the runner by the water given by = $\rho Q \; V_{w1} u_1$

And the work done /sec/ unit weight of water striking/s $= \dfrac{V_{w1} u_1}{g}$

Hydraulic efficiency will be given as $\eta_H = \dfrac{V_{w1} u_1}{Hg}$

- **Applications**

a) Francis turbines may be designed for a wide range of heads (head range from 20 to 700 meters (100 to 2,300 feet) and flows.

b) This, along with their high efficiency, has made them the most widely used turbine in the world.

c) They may also be used for pumped storage, where a reservoir is filled by the turbine (acting as a pump) driven by the generator acting as a large electrical motor.

Kaplan Turbine

a) Kaplan turbine is an axial flow reaction turbine.

b) The water flows through the runner of the turbine in an axial direction and the energy at the inlet of the turbine is the sum of kinetic and pressure energy .

c) If the vanes are adjustable then it is known as *kaplan Turbine* and

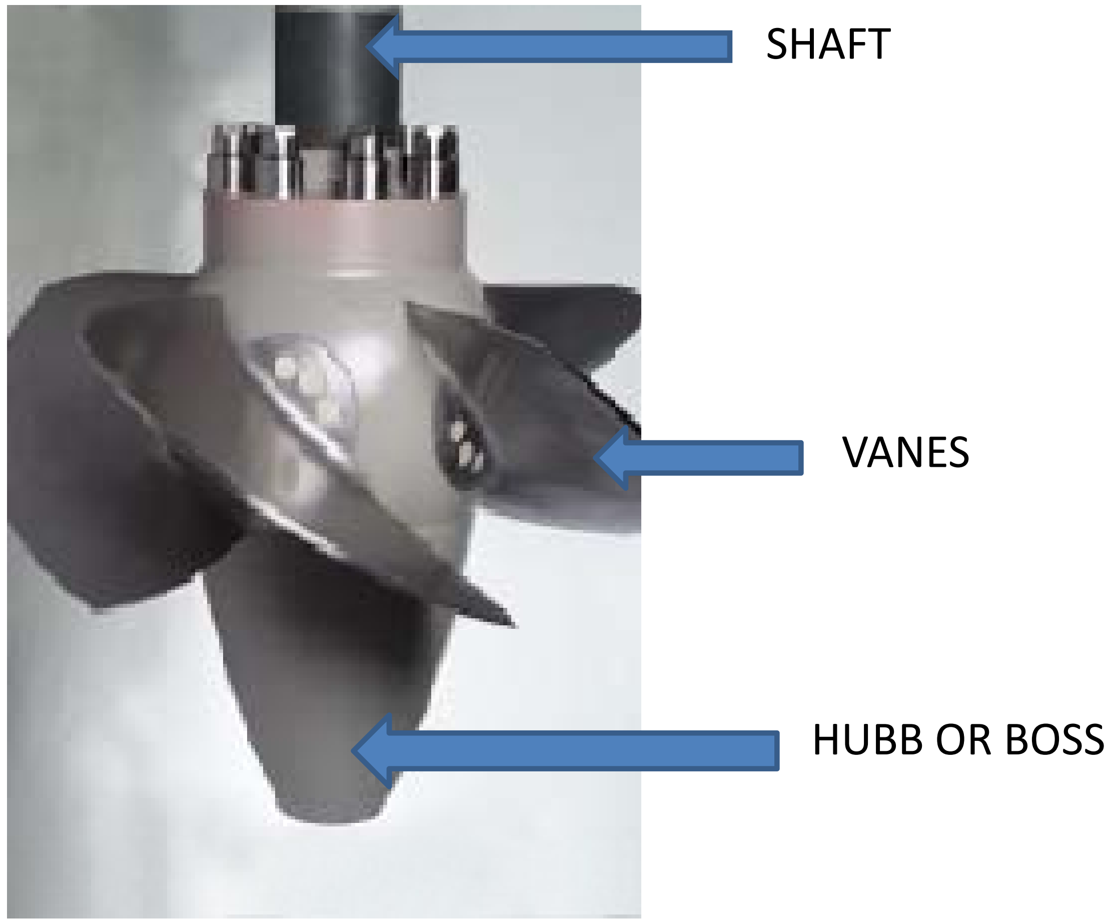
d) if the vanes are non adjustable then it is known as *Propeller Turbine*.

Kaplan turbine is best suited where large quantity of low head water is available.

The main parts of a kaplan Turbine are:

1. Scroll Casing
2. Guide vane Mechanism
3. Hub with Vanes
4. Draft Tube

Kaplan Turbine Runner



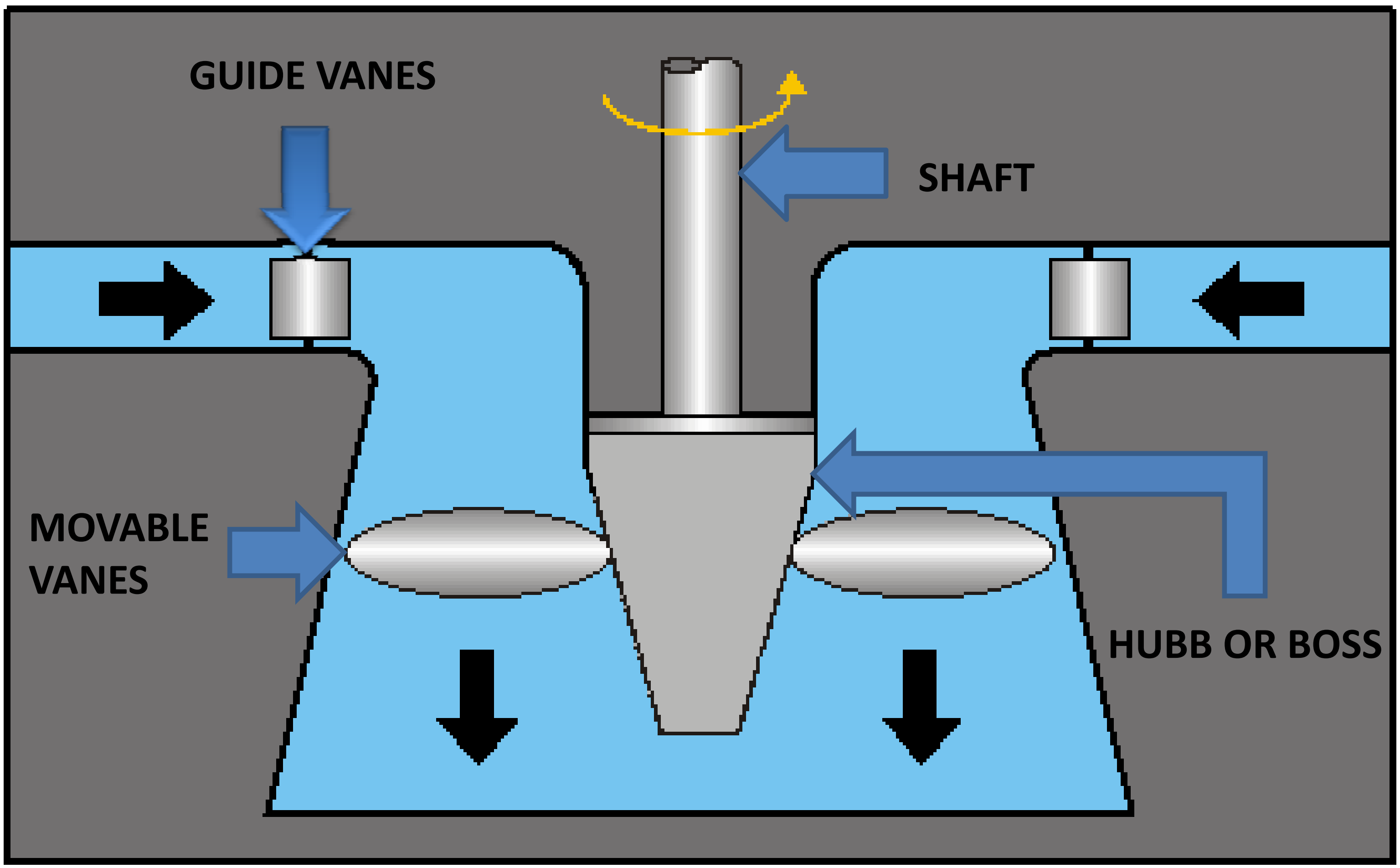
Working Principle

1. The water enters the turbine through the guide vanes which are aligned such as to give the flow a suitable degree of swirl.

2. The flow from guide vanes pass through the curved passage which forces the radial flow to axial direction.

3. The scheme for production of hydroelectricity by Kaplan Turbine is same as that for Francis Turbine.

Schematic View

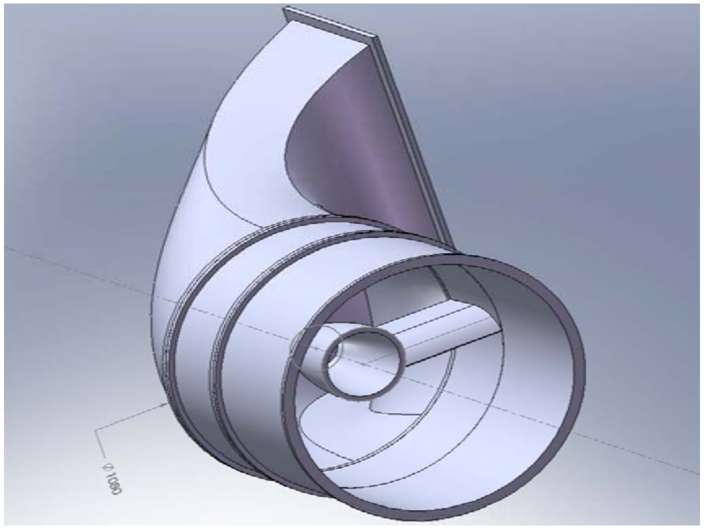


Draft Tube

1. The draft tube is a pipe of gradually increasing area which connects the outlet of the runner with the tailrace.

2. One end of the draft tube is connected to the outlet of the runner while the other end is submerged below the level of water in the tail race.

3. It converts a large proportion of rejected kinetic energy into useful pressure energy



Elbow-Type Draft Tube

Governing of Turbines

1. It is the operation by which the speed of the turbine is kept constant under all conditions of working load.

2. This is done automatically by a governor which regulates the rate flow through the turbines according to the changing load conditions on the turbine.

3. Governing of a turbine is absolutely necessary if the turbine is coupled to an electric generator which is required to run at constant speed under all fluctuating load conditions.