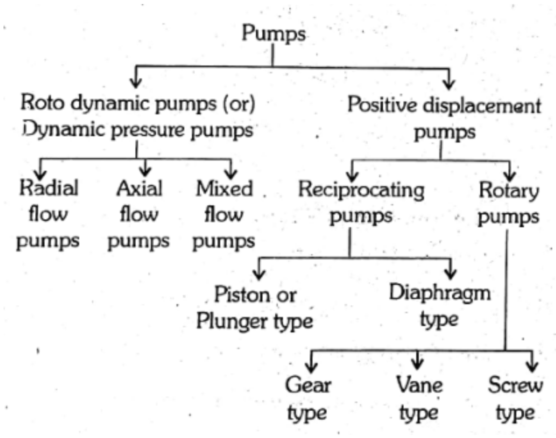
Pumps and Turbines Study Materials

Pumps:

Pump is a device which is used to convert mechanical energy into hydraulic energy. Here hydraulic energy refers to potential and kinetic energy of a liquid Hydraulic pumps are the energy-absorbing machines. Since, it requires mechanical power to run.

Classification of pumps



Reciprocating pumps:

The reciprocating pump is a positive displacement pump. It operates on a principle of actual displacement or pushing of liquid by a piston or plunger that reciprocates in a closely fitting cylinder. These pumps usually have one or more cylinders which are alternatively filled with liquid to be pumped and then emptied again. In this pump, the mechanical energy is converted into hydraulic energy by sucking the liquid into a cylinder in which a piston is reciprocating and exerts the thrust on the liquid and increases its hydraulic energy. The reciprocating pumps are generally employed for light at pumping, feeding small boiler condensate return and pneumatic pressure systems.

Classification:

According to the piston being in contact with piston or plunger.

a) Single acting pump
b) Double acting pump

According to the number of cylinders provided,

a) Single cylinder pump
b) Double cylinder pump
c) Triple cylinder pump
d) Duplux double acting pump
e) Quantiplex pump

Discharge work done and power required to drive Reciprocating pump:

Case (i): Single acting pump

Let D = Diameter of the cylinder

A = Area of cross section of the cylinder or piston = $\frac{\pi}{4} D^2$

r = Radius of crank

N = Speed of the crank in rpm

L = Length of the stroke (= 2r)

hs = Height of the axis of the cylinder from water surface in sump

hd = Height of the delivery outlet above the cylinder axis.

Volume of water delivered in one revolution = Area × Length of stroke

= A × L

Number of revolution per second = $\frac{N}{60}$

Discharge / sec = Q = $\frac{ALN}{60}$

Weight of water delivered per second

W = WQ = $\frac{WALN}{60}$

Work done per second = Weight of water lifted/sec × Total height through which liquid is lifted WALN

$= W(h_s+h_d) = \frac{WALN}{60}(h_s+h_d)$

where W = Weight density of liquid.

Case (ii) Double acting pump

Discharge, $Q = \frac{2ALN}{60}$

Work done per second $= \frac{2WALN}{60}(h_s+h_d)$

Power required to drive the pump

$$P = \frac{2WALN}{60}(h_s + h_d)$$

Slip of a Reciprocating pump:

The difference between the theoretical discharge and actual discharge is called slip of the pump.

Centrifugal pumps:

Centrifugal pumps are the devices which converts mechanical energy into hydraulic energy by means of centrifugal force acting on the fluid.

Centrifugal pumps are classified as roto dynamic type of pumps in which a dynamic pressure is developed to lift liquids from a lower to a higher level. The basic working principle of centrifugal pump is that when a certain mass of liquid is made to rotate by an external force, it is thrown away from the central axis of rotation and a centrifucal pressure is developed which raises the liquid to higher level.

Classification of centrifugal pumps:

1. Shape and type of casing
a) Volute or spiral casing
b) Vortex or whirlpool casing
c) Volute casing with guide blades
2. Working head
a) Low head (upto 15m)
b) Medium head (15m to 40m)
c) High head (over 40m)
3. Number of stages:
a) Single stage
b) Multistage
4. Liquid handled
a) closed impeller pump
b) semi-closed impeller pump
c) open impeller pump
5. Specified speed
a) Low specific speed pumps
b) Medium specific speed pumps
c) High specific speed pumps
6. Number of entrances to the impeller
a) Single suction pr single entry pump
b) Double suction or double entry pump

Workdone by the Impeller of a centrifugal pump:

Let

D_1 = Diameter of the impeller at inlet.

u_1 = tangential velocity of the impeller at inlet = $\frac{\pi D_1 N}{60}$

v_1 = Absolute velocity of water at inlet

v_{w1}= Velocity of whirl at inlet

v_{r1} = Relative velocity of liquid at inlet

v_{f1} = Velocity of flow at inlet

α = Angle made by v_1 at inlet with the direction of motion of vane

θ = Angle made by v_{ri} at inlet with the direction of motion of vane.

Wor'kdone $= \frac{w}{g}\left(V_{w_1} \pm V_{w_2}u_2\right)$

where w = weight of the liquid per second that passes through the impeller = ρgQ

θ = Volume of liquid $= \pi D_1 B_1 \times V_{f_1}$

$= \pi D_2 B_2 \times 2$

where B_1 and B_2 are the width of the impeller at inlet and outlet respectively.

Since α=90° and V_{w_1} =0

Workdone by the impeller on water per second

$= \frac{W}{g}(V_{w_2}u_2)$

Head and Efficiencies of a pump

i) Suction head (hs):

It is the vertical height of the centre line of the pump shaft above the liquid surface in the sump from which the liquid is being raised.

Delivery head (h_d):

It is the vertical height of the liquid surface in the tank/ reservoir to which the liquid is delivered above the centre line at the pump shade.

Static head (H_{stat}):

The sum of suction and delivery head is known as static head.

$H_{start} = hs + hd$

Manometric head (Hm):

It is the head against which a centrifugal pump has to work. It is given by the following expressions.

H_m = Head imparted by the impeller to liquid loss of head in the pump

$$H_m = \frac{V_{w_2}u_2}{g} - (h_{Li} + h_{Lc})$$

where h_{Li} ⇒ Loss of head in the impeller

h_{Lc} ⇒ Loss of head in the casing

$H_m = \frac{V_{w_2}u_2}{g}$ → if there is no loss in the

b) $H_m = H_{stat} +$ Losses in pipes$+\frac{V_d^2}{2g}$

$$H_m = h_s + h_d + h_{is} + h_{id} + \frac{V_d^2}{2g}$$

where

h_{fs} ⇒frictional loss in the suction pipe

h_{fd} ⇒ frictional loss in the delivery pipe v_d ⇒ velocity of liquid in the delivery pipe

c) H_m = Total head at outlet of the pump - Total head at the inlet of the pump

$$= \left(\frac{p_2}{w} + \frac{v_2^2}{2g} + z_2\right) - \left(\frac{p_1}{w} + \frac{v_1^2}{2g} + z_1\right)$$

where

$\frac{p_1}{w}$ ⇒ Pressure head at inlet of the pump = h_s

$\frac{v_1^2}{2g}$ ⇒ Velocity head at inlet of the pump

Z_1 = Vertical height of the pump inlet from the datum line

$\frac{p_2}{w} + \frac{v_2^2}{2g}$ and Z_2 are corresponding values of pressure head, velocity head and datum head at outlet of the pump.

Efficiencies of a pump:

i) Manometric efficiency (η_{mano}):

$$\eta_{mano} = \frac{\text{Manometric head}}{\text{Head imparted by impeller}}$$

$$= \frac{H_m}{\left(\frac{V_{w_2}u_2}{g}\right)} = \frac{gH_m}{V_{w_2}u_2}$$

$$\eta_{mano} = \frac{\text{Power actually delivered by the pump}}{\text{Power imparted by the impeller}}$$

or

$$\eta_{mano} = \frac{\text{Output of the pump}}{\text{Power imparted by the impeller}}$$

Volumetric efficiency (η_n):

It is defined as the ratio of quantity of liquid discharged per second from the pump to the quantity passing per second through the impeller.

Mechanical Efficiency (η_{mech}):

$$\eta_{mech} = \frac{\text{Power at the impeller}}{\text{Power at the shaft}}$$

$$\eta_{mech} = \frac{\frac{W}{g}\left(\frac{V_{w_2}u_2}{1000}\right)}{\text{Shaft power in kW}}$$

Output efficiency (h_0):

$$\eta_0 = \frac{\text{Power output of the pump}}{\text{Power input to the pump}}$$

$$= \frac{WQH_m}{P}$$

$$\eta_0 = \eta_{mano} \times \eta_v \times \eta_{mech}$$

Impeller Blade Profiles:

Backward curved vanes:

The blade angle $\phi < 90°$

Radial vane:

$\phi = 90°$

Forward curved vanes:

$\phi > 90°$

Specific speed for a pump (N_s):

The specific speed of a centrifugal pump is defined as the speed of a geometrically similar pump which will deliver unit quantity (i.e. 1 litre of liquid per second) against a unit head (i.e. 1 meter)

Specific speed, $N_s = \frac{N\sqrt{Q}}{H_m^{3/4}}$

The above equation gives the specific speed in terms of discharge and manometric head. Sometimes another definition of the specific speed may be used which is based on unit power.

$N_s = \frac{N\sqrt{p}}{H_m^{5/4}}$

Centrifugal pumps with the corresponding ranges of specific speeds.

S.No.	Types of impeller	Specific Speed, N_s
1.	Slow speed radial flow	10 - 30
2.	Medium speed	30 – 50
3.	High speed radial	50 – 80
4.	Mixed flow	80 – 160
5.	Axial flow	160 – 500

Design Aspects of a centrifugal pump:

I) Speed ratio (K_u):

It is the ratio of peripheral speed at outlet (u_2) to the theoretical velocity of jet corresponding to manometric head H_m.

$$K_u = \frac{u_2}{\sqrt{2gH_m}}$$

K_u varies from 0.95 to 1.25

ii) Flow ratio (K_f):

It is the ratio of the velocity of flow at exit (V_{f2}) to the theoretical velocity of the jet corresponding to manometric head (H_m).

$$K_f = \frac{u_{f2}}{\sqrt{2gH_m}}$$

Value of K_f varies from 0.1 to 0.25

Outlet diameter of impeller (D_2):

$$D_2 = \frac{84.6K_u\sqrt{H_m}}{\pi N}$$

Inlet diameter of impeller (D_1):

$D_1 = 0.5\ D_2$

Least diameter of impeller:

$$D_2 = \frac{97.68\sqrt{H_m}}{N}$$

Diameter of suction pipe (D_s):

$$D_s = \sqrt{\frac{4Q}{\pi V_s}}$$

Diameter of delivery pipe $D_d: \sqrt{\frac{4Q}{\pi V_d}}$

Pumps in series:

A number of impeller are mounted on the same shaft in series to obtain a high head. If n identical impellers are mounted on the same shaft in series, then the total head developed will be

$H_{total} = n \times H_n$

The discharge passing through each impeller is same. Pipes in series are employed for delivering a relatively small quantity of liquid against very high head.

Pumps in parallel:

A number of pumps are connected in parallel for obtaining high discharge. Here the impellers are mounted on separate shafts. Each unit works separately and the discharge from various impellers are collected in common delivery pipe.

If Q is the discharge capacity for one impeller and there is ~ identical impellers arranged in parallel then totai discharge will be $Q_{total} = n \times Q$

when a large quantity of liquid is required to be pumped against a relatively small head, then pump in parallel arrangement is used.

Pump characteristics:

i) Main characteristics curves (H, p, η, VSQ)

ii) Operating characteristic curves (H, p, η VSQ)

iii) Constant efficiency or Muschel curves (H VS Q)

iv) Constant head and constant discharge curves (Q VS N, H=const ; H VS N, Q = const)

Cavitations in Hydraulic Machines:

Hydraulic machines subjected to cavitations are reaction turbines and centrifugal pumps.

Cavitation is defined as the phenomenon of formation of vapour bubbles of a flowing liquid in a region where the pressure Of the liquid falls below its vapour pressure and the sudden collapsing of these vapour bubbles in a region of higher pressure. The collapsing pressure of bubbles may be as high as 100 atmospheres and this may cause a local mechanical failure of the solid surface. The ultimate effect may be the breakdown of the machine itself due to severe pitting and erosion of blade surfaces in the region of cavitation. The cavitation in a pump can be noted by a sudden drop in efficiency, head and more power requirement.

Harmful effects of cavitation are:

- Pitting and erosion of surface due to continuous hammering action of the collapsing bubbles.
- Sudden drop in head, efficiency and the power delivered to the fluid.
- Noise and vibrations produced by the collapse of vapour bubbles.

Priming of a centrifugal pump:

The operation of filling liquid (which is to be pumped) in the suction pipe, casing of the pump and a portion of the delivery pipe upto delivery valve before starting the pump is called priming of a centrifugal pump.

Turbines:

Hydraulic turbines are the machines which convert the energy of flowing water into mechanical energy. The mechanical energy developed by a turbine is used in running an electric generator which directly couples to the shaft of the turbine. Thus the mechanical energy is converted into electrical energy. This electrical power is known as hydroelectric power.

Classification of Turbines:

1. According to the action of the-water flowing.

a) Impulse turbine - Pelton wheel

b) Reaction turbine - Francis turbine, Kaplan turbine

2. According to the main direction of flow of water.

a) Tangential flow turbine - Pelton wheel.

b) Radial flow turbine - Old Francis turbine.

c) Axial flow turbine - Kaplan turbine

d) Mixed flow turbine - Modern Francis turbine

3. According to the head and quantity of water required:

a) High head (above 250 m) - Pelton wheel.

b) Medium head (60 m - 250 m) - Modern Francis turbine

c) Low head turbine (less than 60 m - Kaplan turbine)

4. According to the specific speed:

a) Low specific speed (10 to 35) - Pelton wheel

b) Medium specific speed (60 to 400) - Francis turbine

c) High specific speed (300 to 1000) - Kaplan turbine

Impulse turbine:

In an impulse turbine, all the energy available by water is converted into kinetic energy by passing it through a nozzle. The high velocity jet coming out of the nozzle then impinges on a series of buckets fixed around the aim of a wheel. Thus, the runner revolves freely in air.

Ex: Pelton wheel

Reaction turbine:

In a reaction turbine, the runner utilizes both potential and kinetic energies. Here only a portion of a potential energy is transformed into kinetic energy before the fluid enters the turbine runner. As the water flows through the runner, remaining part of potential energy goes on changing into kinetic energy.

Ex: Francis turbine and Kaplan turbine.

Head and Efficiencies of Pelton wheel:

1. **Gross head (H_g)**

The gross head is the difference between the water level at the reservoir and the level at the tailrace.

2. **Effective or Net Head (H):**

The head available at the inlet of the turbine is known as effective or net head.

$H = Hg - H_f - h$

where h_f = head loss due ,o friction in penstock.

$= \frac{4fLV^2}{2gD}$

h = height of the nozzle above the tailrace.

3. **Water and Bucket Power:**

The power supplied by the water jet is known as water power (wp) power supplied by the jet=WQH = ρgQH

where Q - Discharge supplied by the water jet m^3/s

H - Effective or net head.

The power developed by the bucket wheel is known as bucket or actual power, B P

4. **Hydraulic efficiency (η_b):**

It is defined as the ratio of power developed by the runner to the power supplied by the water jet

$$\eta_h = \frac{\left(V_{w_1} \pm V_{w_2}\right)u}{gH} = \frac{H_r}{H}$$

The parameter, $H_r = \frac{1}{g}\left(V_{w_1} + V_{w_2}\right) \times u$ represents the energy transfer per unit weight of the water and is referred to the 'runner head' or Euler head.

Hydraulic loss within the turbine,

$\Delta H = H - H_r$

5. **Mechanical efficiency (h_m):**

$\eta_m = \frac{\text{Shaft power}}{\text{Water power}}$

$$\eta_m = \frac{P}{WQ_a H_r}$$

6. **Volume efficiency:**

$\eta_v = \frac{Q_a}{Q} = \frac{Q-q}{Q}$

7. **Overall efficiency (h_0)**

$\eta_0 = \frac{\text{Shaft power}}{\text{Water power}} = \frac{P}{W\,QH}$

$\eta_0 = \eta_v \times \eta_n \times \eta_m$

Design Aspects of Pelton wheel:

1. **Velocity of jet**

$V_1 = C_v\sqrt{2gH}$

where C_v = Co-efficient of velocity = 0.98 -0.99

H = Net head on turbine

2. **Velocity of wheel**

$u = K_u\sqrt{2gH}$

where K_u - speed ratio = 0.43 to 0.48

3. **Mean diameter of wheel (D)**

$u = \frac{\pi DN}{60} \Rightarrow D = \frac{60\,u}{\pi\,N}$

The mean diameter is also known as pitch diameter.

4. **Jet ratio (m):**

It is defined as the ratio of mean diameter (D) of the pelton wheel to the diameter of the jet (d).

$m = \frac{D}{d}$

m varies b/w 11 to 15. Normally, m = 12 is adopted.

5. **Number of jets:**

Normally, Pelton wheel has one nozzle or one jet. When more power is to be produced, No. of nozzles or jets may be employed with the same wheel. Theoretically six nozzles can be used with one Pelton wheel.

Number of jet is obtained by dividing the total rate of flow through the turbine by the rate of flow of water through a single jet.

Bucket dimensions:

Axial width, B = 4d to 5d

Radial length, L = 2d to 3d

Depth, T=0.8d to 1.2d

Angle, ϕ = 10° to 20°

Number of buckets (z):

The number of buckets is decided mainly on the following two principles.

1. The number of buckets should be as few as possible so that there is little loss due to friction.
2. No water escapes without striking the buckets.

The number of buckets is usually more than 15.

$Z = \frac{D}{2d} + 15 = 0.5m + 15$

Francis Turbine:

Francis turbine in an inward flow reaction turbine. It is developed by the American Engineer James B. Francis. In the earlier stages, Francis turbine had a purely radial flow runner. But the modern Francis turbine is a mixed flow reaction turbine in which the water enters the runner radially at its outer periphery and leaves axially at its centre. This arrangement provides a larger discharge area with the prescribed diameter of the runner.

Parts

1. Penstock
2. Scroll or spiral casing
3. Speed lins or stay ring
4. Guide vanes or wicket gates
5. Runner and runner blades
6. Draft tube

Workdone and Efficiencies of Francis turbine:

$\text{Workdone} = \rho Q\left(V_{w_1}u_1 \pm V_{w_2}u_2\right)$

$= \frac{WQ}{g}\left(V_{w_1}u_1 \pm V_{w_2}u_2\right)$

where Q = discharge through the runner

V_{w_1} and V_{w_2} = velocity of whirl at inlet and outlet respectively

u_1 and u_2 = tangential velocity of wheel at inlet and outlet

Hydraulic efficiency (η_h):

$\eta_h = \frac{V_{w_1}u_1}{gH}$

Mechanical efficiency (η_m):

$\eta_m = \frac{P}{\frac{WQ}{g}(V_{w_1}u_1)}$

Overall efficiency (η_0):

$\eta_0 = \frac{P}{W\,Q_a H}$

Or $\eta_0 = \eta_m \times \eta_n$

Design Aspects of Francis Turbine:

1. Ratio of width to diameter $\left(\frac{B}{D}\right)$ is represented by

$n = \frac{B}{D}$

2. **Flow ration (K_f):**

Ratio of the velocity of flow at inlet $\left(V_{f_1}\right)$to the theoretical velocity $\left(\sqrt{2gh}\right)$ is known as flow ratio.

$K_f = \frac{V_{f_1}}{\sqrt{2gH}}$

value of K_f varies from 0.15 to 0.3.

Speed ratio (K_u):

It is the ratio of the peripheral speed at inlet to the theoretical jet velocity, u

$K_u = \frac{u}{\sqrt{2gH}}$

Kaplan Turbine:

A Kaplan turbine is an axial flow reaction turbine which was developed by Austrian engineer V. Kaplan. It is suitable for relatively low heads. Hence it requires a large quality of water to develop large power.

Main components of a Kaplan turbine:

1. Scroll casing
2. Stay ring
3. Guide vanes
4. Runner
5. Draft tube

Working properties of Kaplan turbine:

1. In case of Kaplan turbine, the ratio n= $\frac{D_b}{D_o}$

   ` where D_b = Diameter of the hub or boss.

   D_o = outside diameter of the runner.
2. Discharge Q = Area of flow × Velocity of flow

   $Q = \frac{\pi}{4} D_0^2 (1 - n^2) \times K_f \sqrt{2gH}$
3. The peripheral velocity u of the runner is dependent on the radius of the point under consideration and thus varies from section to section along the blade.
4. Velocity of flow (V_f) remains constant throughout.

Performance of Turbines:

Unit Speed (N_u)

Unit speed is the speed of a turbine when working under a unit head (i.e. 1m).

We know that u=wr=w $\frac{D}{2}$

$\therefore u \propto N$

Since the diameter D is constant for a given turbine.

Unit discharge (Q_u):

It is the theoretical discharge of a turbine when working under a unit head.

$Q_u = \frac{Q}{\sqrt{H}}$

Unit power:

It is the theoretical power of a turbine when working under a unit head.

$P_u = \frac{P}{H^{3/2}}$

Specific speed (N_s):

Specific speed is the speed of a geometrically similar turbine (i.e. a turbine identical in shape, dimensions, blade angles and gate openings etc.) which will develop unit power when working under a unit head.

The specific speed is used in comparing the different types of turbines as every type of turbine has different specific speed.

Specific Speed = $N_s = \frac{N\sqrt{P}}{H^{5/4}}$

Note:

- Specific speed is proportional to the speed of rotation Evidently the high speed Kaplar turbines are expected to have high specific speed than Pelton wheel.
- Specific speed is inversely proportional to head obviously, the high head Pelton wheel has a low value of specific speed than Kaplar turbine which operates at low heads.

Turbine characteristics:

The curves which are plotted from the results of the tests performed on the turbine under different working conditions are known as characteristic curves. The purpose of these curves is to predict the behaviour and performance of a furbine under different working condtions.

1. **Main or constant head characteristic curves:**

These curves are obtained by maintaining a constant head and a constant gate opening. The speed of the turbine is varied by allowing a variable quantity of water to flow through the inlet.

2. **Operating or constant speed characteristic curves:**

These curves are obtained by keeping speed as constant for each gate opening. The dischange, Q and head H may vary according to their availability.