Subject: FLUID MECHANICS -II

Topic: Hydraulic Machines
Module 2 (Turbines)
Part - I

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INTRODUCTION

A hydraulic turbine is a prime mover that uses the energy of flowing water and converts it into the mechanical energy.

(Or) A machine which uses the raw energy of a substance and converts it into mechanical energy.

The mechanical energy is used in running an electric generator which is directly coupled to the shaft of the hydraulic turbine; from this electric generator, we get electric power which can be transmitted over long distance by means of transmission lines and transmission towers. The hydraulic turbines are also known as ‘water turbines’ since the fluid medium used in them is water.

The factors that are major obstacles in the utilization of hydropower resources:

i. Large investments,  
ii. Long gestation period, and  
iii. Increased cost of the power transmission.

Classification of Hydraulic turbines:

1. **According to the head and quantity of water available:**
   a) Impulse turbine... requires high head and small quantity of flow.  
   b) Reaction turbine... requires low head and high rate of flow.

2. **According to the action of water on moving blades:**
   - Impulse turbine - Pelton turbine  
   - Reaction turbine  
   - Francis turbine  
   - Kaplan and propeller turbines
3. According to the name of the originator:
(i) Pelton turbine ... named after Lester Allen Pelton of California (U.S.A). It is an impulse type of turbine and is used for high head and low discharge.
(ii) Francis turbine ... named after James Bichens Francis. It is a reaction type of turbine from medium high to medium low heads and medium small to medium large quantity of water.
(iii) Kaplan turbine ... named after Dr. Victor Kaplan. It is a reaction type of turbine for low heads and large quantities of flow.

4. According to direction of flow of water in the runner:
(i) Tangential flow turbines (Pelton turbine)
(ii) Radial Flow turbine (no more used)
(iii) Axial flow turbine (Kaplan turbine)
(iv) Mixed (radial and axial) flow turbine (Francis turbine).

• In tangential flow turbine of Pelton type the water strikes the runner tangential to the path of rotation.
• In axial flow turbine water flows parallel to the axis of the turbine shaft. Kaplan turbine is an axial turbine. If the runner blades of the axial flow turbine are fixed, these are called “propeller turbines.”
• In mixed flow turbines the water enters the blades radially and comes out axially, parallel to the turbine shaft. Modern Francis turbines have mixed flow runners.

5. According to the disposition of the turbine shaft:
Turbine shaft may be either vertical or horizontal. In modern practice, Pelton turbines usually have horizontal shafts whereas the rest, especially the large units, have vertical shafts.
6. According to specific speed:
The specific speed of a turbine is defined as the speed of a geometrically similar turbine that would develop 1 kW under 1 m head. All geometrically similar turbines-(irrespective of the sizes) will have the same specific speeds when operating under the same head.

\[ N_s = \frac{N\sqrt{P}}{H^{5/4}} \]

Where  
\( N \) = the normal working speed,  
\( P \) = power output of the turbine, and  
\( H \) = the net or effective head in metres.

• Turbines with low specific speeds work under high head and low discharge conditions. high specific speed turbines work under low head and high discharge conditions.
• The following table gives the comparison between the impulse and reaction turbines with regard to their operation and application.
Construction and working of Pelton wheel/turbine

\[ \frac{L}{d} = 2 \text{ to } 3, \quad \frac{B}{d} = 3 \text{ to } 4, \quad \frac{D}{d} = 11 \text{ to } 16, \quad \frac{T}{d} = 0.8 \text{ to } 1.2, \text{ Notch (width) } = 1.1d + 5 \text{ mm} \]
WORK DONE AND EFFICIENCY OF A PELTON WHEEL

Work done and efficiency of a Pelton wheel

Fig. 1 shows the velocity triangles.

Let $N =$ speed of wheel in r.p.m.,
$D =$ diameter of the wheel,
$d =$ diameter of the jet,
$u =$ peripheral (or circumferential) velocity of runner. It will be same at inlet and outlet of the runners at the mean pitch. \(i.e.\ u = u_1 = u_2\)

\[\frac{\pi DN}{60}\]

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Fig. 1 velocity triangles.
\( V_1 \) = absolute velocity of water at inlet,
\( V_{r1} \) = jet velocity relative to vane/bucket at inlet,
\( \alpha \) = angle between the direction of the jet and direction of motion of the vane/bucket (also called guide angle),
\( \theta \) = angle made by the relative velocity \( (V_{r1}) \) with the direction of motion at inlet (also called vane angle at inlet),
\( V_{w1} \) and \( V_{f1} \) = the components of the velocity of the jet \( V_1 \), in direction of motion and perpendicular to the direction of motion of the vane respectively,
\( V_{w1} \) is also known as velocity of whirl at inlet,
\( V_{f1} \) is also known as velocity of flow at inlet,
\( V_2 \) = velocity of jet, leaving the vane or velocity of jet at outlet of the vane,
\( V_{r2} \) = relative velocity of the jet with respect to the vane at outlet,
\( \phi \) = angle made by the relative velocity \( V_{r2} \) with the direction of motion of the vane at outlet and also called vane angle at outlet,
\( \beta \) = angle made by the velocity \( V_2 \) with the direction of motion of the vane at outlet,
\( V_{w2} \) and \( V_{f2} \) = components of the velocity \( V_2 \), in the direction of motion of vane and perpendicular to the direction of motion of vane at outlet,
\( V_{w2} \) is also called the velocity of whirl at outlet,
\( V_{f2} \) is also called the velocity of flow at outlet.

**Inlet.** The velocity triangle at inlet will be a straight line where
\[
V_{r1} = V_1 - u_1 = V_1 - u, \quad V_{w1} = V_1 \quad (\because u_1 = u_2 = u)
\]
\( \alpha = 0 \) and \( \theta = 0 \)

**Outlet:** From velocity triangle at outlet, we have
\( V_{r2} = KV_{r1} \),
where \( K = \) blade friction co-efficient, \( \textit{slightly less than unity.} \) Ideally when bucket surfaces are \textit{perfectly smooth} and energy losses due to impact at splitter are \textit{neglected,} \( K = 1 \)

\[ V_{w2} = V_{r2} \cos \phi - u_2 = V_{r2} \cos \phi - u \quad (\because \ u_1 = u_2 = u) \quad \text{(when} \ \beta < 90^\circ) \]

and

Depending upon magnitude of the peripheral speed \((u)\), the unit may have a slow, medium or fast runner and the angle \( \beta \) and \( V_{w2} \) will vary as follows:

(i) Slow runner \( \beta < 90^\circ \) (\( V_{w2} \) is \(-\text{ve}\))

(ii) Medium runner \( \beta = 90^\circ \) (\( V_{w2} = 0 \))

(iii) Fast runner \( \beta > 90^\circ \) (\( V_{w2} \) is \(+\text{ve}\))

The force exerted by the jet of water in the direction of motion is given as:

\[ F = \rho a V_1 (V_{w1} + V_{w2}) \]

\( \rho \) and \( a \) are the mass density and area of jet \( \left( a = \frac{\pi}{4} d^2 \right) \) respectively.

Now work done by the jet on runner per second

\[ = F \times u = \rho a V_1 (V_{w1} + V_{w2}) \times u \]

Work done per second per unit weight of water striking

\[ = \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{\text{weight of water striking}} = \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{\rho a V_1 \times g} \]

\[ = \frac{1}{2} (V_{w1} + V_{w2}) \times u \]

The energy supplied to the jet at inlet is in the form of K.E and is equal to \( \frac{1}{2} m V_1^2 \)

\[ \therefore \text{Kinetic energy (K.E.) of jet per second} = \frac{1}{2} \rho a V_1 \times V_1^2 \]

\[ \therefore \text{hydraulic efficiency,} \ \eta_h = \frac{\text{work done per second}}{\text{K.E. of jet per second}} = \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{\frac{1}{2} \rho a V_1 \times V_1^2} \]

or

\[ \eta_h = \frac{2 (V_{w1} + V_{w2}) \times u}{V_1^2} \]

From inlet and outlet velocity triangles we have
\[ V_{w1} = V_{r1} = V_1 - u_1 = V_1 - u \\
V_{w2} = V_{r2} \cos \phi - u_2 = V_{r2} \cos \phi - u = KV_{r1} \cos \phi - u = K (V_1 - u) \cos \phi - u \]

Substituting the values of \( V_{w1} \) and \( V_{w2} \) in eqn (18.3), we have

\[ \eta_h = \frac{2 [V_1 + K (V - u) \cos \phi - u]u}{V_1^2} = \frac{2 [(V_1 - u) (1 + K \cos \phi)]u}{V_1^2} \]

The hydraulic efficiency will be maximum for given value of \( V_1 \) when

\[ \frac{d}{du} \eta_h = 0 \]

i.e.,

\[ \frac{d}{du} \left( \frac{2(V_1 - u)(1 + K \cos \phi)u}{V_1^2} \right) = 0 \]

or

\[ \frac{2(1 + K \cos \phi)}{V_1^2} \times \frac{d}{du} (V_1u - u^2) = 0 \]

since

\[ \frac{2 (1 + K \cos \phi)}{V_1^2} \neq 0, \quad \therefore \quad \frac{d}{du} (V_1u - u^2) = 0 \]

or

\[ V_1 - 2u = 0 \quad \text{or} \quad u = \frac{V_1}{2} \]

\[ (\eta_h)_{\text{max}} \]

The above equation states that hydraulic efficiency of a Pelton wheel is maximum when the velocity of the wheel is half the velocity of jet of water at inlet. The maximum efficiency can be obtained by substituting the value of \( u = \frac{V_1}{2} \) in eqn. (18.4).

\[ (\eta_h)_{\text{max}} = \frac{2 \left( V_1 - \frac{V_1}{2} \right) \left( 1 + K \cos \phi \right) \frac{V_1}{2}}{V_1^2} = \frac{2 \times \frac{V_1}{2} (1 + K \cos \phi) \times \frac{V_1}{2}}{V_1^2} \]

or

\[ (\eta_h)_{\text{max}} = \frac{(1 + K \cos \phi)}{2} \]

If friction \( f(\eta_h)_{\text{max}} = 1 \) (i.e., assuming no friction), we have

\[ (\eta_h)_{\text{max}} = \frac{1 + \cos \phi}{2} \]