IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Comparative Structural And Modal Evaluation Of Pelton Wheel Buckets Using Gray Cast Iron, Inconel 625, And Stainless Steel

[1] M. Padmanabham, [2] Duvvari Bhujanga Rao

[1,2]Department of Mechanical Engineering, [1]Assistant Professor,[2] PG Student

[1,2] Sanketika Vidya Parishad Engineering college, Visakhapatnam, India

Abstract: This study focuses on designing and analyzing a Pelton wheel bucket using SolidWorks and ANSYS to evaluate its performance under realistic hydraulic loading. Three materials—Inconel 625, Gray Cast Iron, and Stainless Steel—were compared. Inconel 625 showed superior strength and fatigue resistance, Gray Cast Iron offered cost benefits but lower durability, and Stainless Steel provided balanced strength, corrosion resistance, and affordability. The study emphasizes CAD and FEA integration for optimizing Pelton wheel bucket design to enhance efficiency, durability, and sustainability in hydroelectric systems.

Keywordss - Pelton wheel, Finite Element Analysis (FEA), Material selection, ANSYS simulation, Hydroelectric power

I. Introduction

Hydroelectric power has emerged as one of the most reliable and sustainable sources of renewable energy, contributing significantly to the reduction of global dependence on fossil fuels. By harnessing the potential and kinetic energy of stored or flowing water, hydroelectric systems convert natural resources into clean electricity without generating greenhouse gas emissions during operation. This makes hydro power not only environmentally friendly but also highly efficient, with conversion efficiencies often exceeding 90%. Among the different types of turbines used in hydroelectric power plants, impulse turbines occupy a distinct place due to their suitability for high-head and low-flow conditions. The Pelton wheel, in particular, has been a breakthrough innovation in turbine engineering, designed specifically to capture the maximum energy from high-velocity water jets. Its operational principle makes it especially effective in regions with mountainous terrain and steep water gradients, where pressure heads are high but flow rates are relatively limited. Because of its adaptability and efficiency, the Pelton wheel has become a preferred choice for small-to-medium hydroelectric projects worldwide.

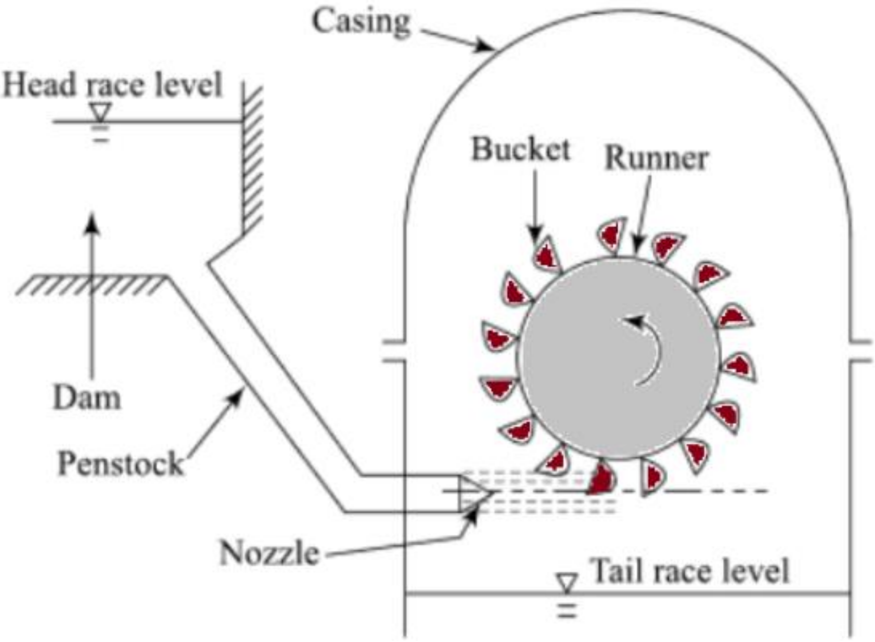

Fig: 1.1 Pelton wheel turbine

Pelton wheel Turbine

The Pelton wheel turbine is a type of impulse turbine specifically designed for high-head and low-flow hydroelectric power applications. Unlike reaction turbines that rely on pressure differences across blades, the Pelton turbine operates on the principle of impulse, where all the available water energy is converted into kinetic energy before striking the turbine. High-pressure water is directed through one or more nozzles, producing high-velocity jets that impinge on the turbine buckets mounted around the runner's periphery. The unique bucket design splits and redirects the water jet by nearly 180 degrees, ensuring maximum momentum transfer and high efficiency.

The Pelton wheel is characterized by its distinct double-cup bucket shape with a central splitter, which divides the incoming jet into two equal streams. This minimizes energy loss and prevents the jet from splashing, thereby improving power extraction. The runner is typically mounted on a horizontal or vertical shaft, depending on the installation, and multiple nozzles can be used to increase power output. The design is particularly efficient for heads ranging from 300 meters up to more than 1000 meters, with efficiencies often exceeding 90%. The bucket material and geometry are crucial, as they must withstand repeated high-velocity impacts while maintaining durability and smooth flow deflection.

Pelton wheel turbines are widely used in hydroelectric power stations located in mountainous regions where water is available at high heads but with limited flow rates. Their ability to harness high potential energy makes them ideal for small to medium-scale hydropower plants. Some advantages include high efficiency under varying loads, relatively simple construction, and long service life with proper maintenance. Additionally, the turbine's ability to operate effectively under partial load conditions makes it suitable for applications where water availability fluctuates throughout the year.

Water Turbines (Hydraulic Turbines)

Water turbines, also known as hydraulic turbines, are mechanical devices that convert the potential and kinetic energy of flowing or falling water into mechanical rotational energy. This energy is then used to drive electrical generators, making them the backbone of hydroelectric power plants. The working principle of a water turbine is based on fluid mechanics, where high-pressure water jets or streams strike specially designed blades or buckets, causing the turbine runner to rotate. The efficiency of these turbines largely depends on the water head, flow rate, and the design of the turbine components.

Hydraulic turbines are broadly classified into two main categories: **impulse turbines** and **reaction turbines**. Impulse turbines, such as the Pelton wheel, operate on high-head and low-flow conditions, where water jets strike the buckets at atmospheric pressure, imparting momentum. Reaction turbines, including Francis and Kaplan turbines, work under pressure differences across the runner blades, utilizing both kinetic and pressure energy of water. The choice of turbine depends on site conditions, such as head availability, water flow, and load requirements, ensuring maximum efficiency for specific applications.

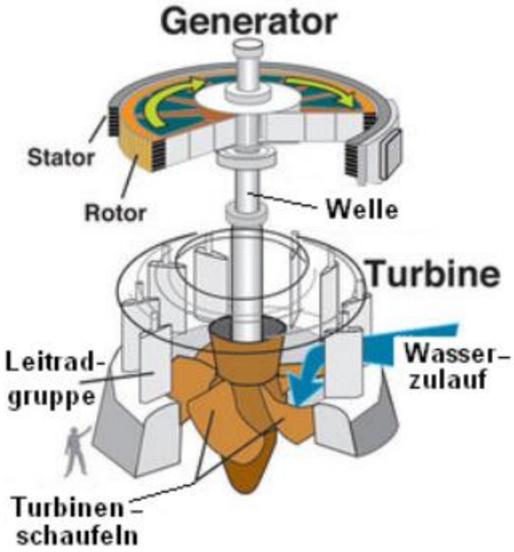

Fig:1.2 Water turbine

Pelton wheel turbines are a type of impulse hydraulic turbine specifically designed for **high-head, low-flow water sources**. They play a crucial role in hydroelectric power generation where water falls from great heights, converting its kinetic energy into mechanical energy with high efficiency. By directing high-velocity water jets onto spoon-shaped buckets, Pelton turbines achieve effective momentum transfer, making them highly suitable for mountainous regions and areas with steep river gradients. Their ability to harness energy from small water flows at high heads makes them invaluable for localized and remote power generation projects.

One of the main advantages of Pelton wheel turbines is their **high efficiency under variable load conditions**. The design of the buckets and the arrangement of the nozzles allow the turbine to maintain performance even when water flow rates fluctuate. This adaptability ensures reliable electricity generation throughout seasonal variations, providing consistent energy supply for both industrial and residential applications. Consequently, Pelton turbines are often used in small hydroelectric plants and off-grid power systems where dependable energy output is critical.

Fig:1.8 Pelton wheel turbine

METHODOLOGY

3.1 Impulse Turbine - Pelton Wheel (Or) Pelton Turbine

The Pelton turbine is the most commonly used type of impulse turbine. This turbine is also called free jet or constant pressure (or) tangential flow impulse turbine

3.1.1 Characteristics of Pelton wheel turbine

- It is an impulse turbine.
- Only kinetic energy of water is available at inlet of turbine.
- It is working of high head and low discharge.
- Work is done only due to change in kinetic energy of water.
- Working pressure is equal and constant at atmospheric pressure.
- It is a Tangential flow and low specific speed turbine.

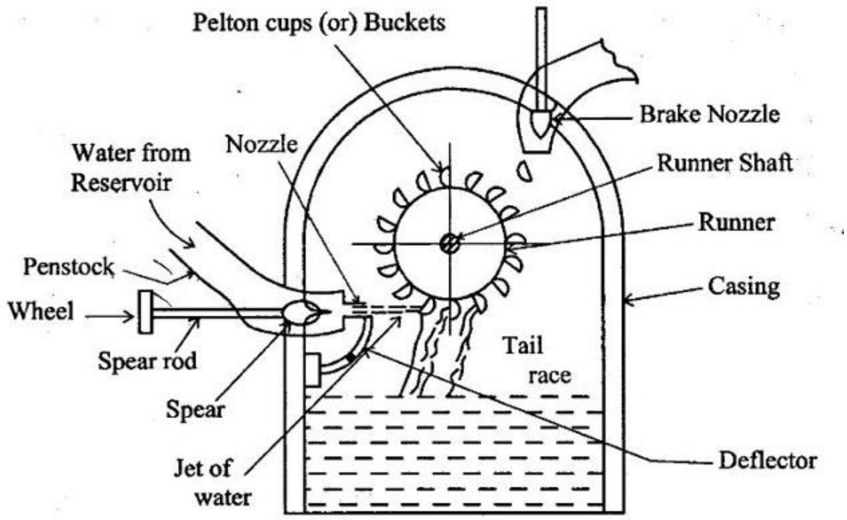

Fig: 3.1 Pelton Wheel Turbine

From figure 3.1 the main components of a Pelton wheel turbine are,

(a) penstock

(b) nozzle

(c) Spear

(d) Runner and buckets

(e) Deflector

(f) casing

(g) Brake nozzle.

(a) Penstock

It is a rigid pipe which is used to carries the water from reservoir through the dam gate valve to the turbine under the pressure. The penstock is provided with control valves for the regulation of water flow to the turbine.

(b) Nozzle

It is used to convert the net available pressure energy of the water into kinetic energy by the nozzle in the form of jet. The jet of water coming from the nozzle strikes the buckets with a high velocity and leaves the buckets with comparatively low velocity and produces impact on the buckets. Due to this impact, turning moment act on the runner which rotates the runner at a high speed.

(c) Spear

It is used to regulate the flow rate of water into the turbine. Due to linear movement of the spear, space between nozzle and spear increases (or) decreases in such a way, so flow rate of water also increases (or) decrease accordingly as shown in figure 3.2.

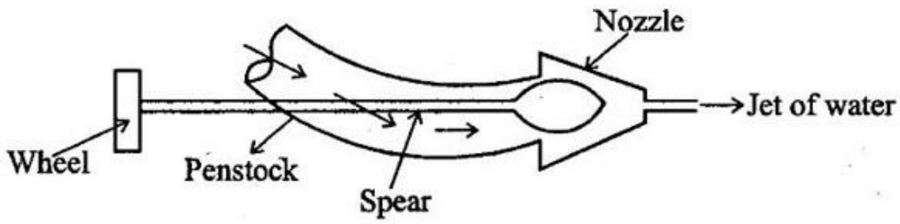

Fig: 3.2 Spear or Nozzle

(d) Runner and buckets

Runner of a Pelton turbine is a circular disc which is mounted on a horizontal shaft. The buckets are fixed to the periphery of the runner uniformly at equal distance. The shape of the bucket is like a double hemispherical cup. Each bucket is divided vertically into two part by a splitter. The splitter splits the jet of water into two equal parts without any shock. The two parts of the same jet move sideways in opposite direction.

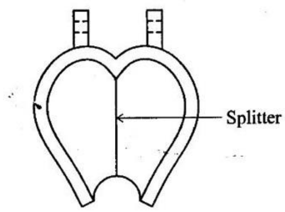

Fig: 3.3 Bucket with Splitter

The jet is deflected by the buckets through an angle of 160° to 170°. Average value is taken as 165°. The buckets are generally fastened by two (or) more both to the runner as shown in figure 3.3.

(e) Deflector

A deflector is provided which is hinged to the casing to deflect the set of water away from striking the buckets in case the load on turbine suddenly reduces.

It prevents the runner of turbine attaining unsafe speeds are called runaway speed.

(f) Casing

The casing of the Pelton wheel turbine do not perform any hydraulic function. It prevents the splashing of water and discharge the water into tail race. It can also be used as a safe guard against accidents.

(g) Brake nozzle

It is used to stop the rotation of the runner in a short period of time. When stopping the runner, firstly water supply to the turbine is stopped by operating the spear and then braking jet of water issuing from the brake nozzle will strike on the back of the buckets.

This braking jet exerts torque on the runner in opposite direction of motion of the runner. This opposite torque is known as brake torque and responsible to stops the runner in a short period of time.

3.2 Working

The penstock carrying water from the reservoir at high head to the turbine, it is connected to a branched pipe fitted with the nozzle at the end. The whole of the pressure energy of the water is converted into the kinetic energy with the help of nozzle before supply to the turbine runner. The water comes out of the nozzle in the form of a jet with very high velocity. This high velocity of jet is strike on a series of buckets mounted on the periphery of a wheel keyed to the turbine shaft. The impulsive force of the jet exerted on the series of buckets setup the wheel in rotation in the direction in which jet is impinging. The water as it flows over the buckets, the velocity of flow will be decrease and atmospheric pressure remain constant. This turbine in also called constant pressure turbine (or) velocity turbine (or) free jet turbine. Pelton wheel turbine is best suited for high head and low discharge.

3.3 Losses of Pelton turbine

(a) Head loss in the penstock:

Head loss due to friction between water and penstock is called head loss in the penstock. It is calculated by Darcy's formula.

$$h_f = \frac{4flv^2}{2g\,D}$$

(b) Head loss in the nozzle:

Pressure energy at the inlet of the nozzle does not completely converted into kinetic energy at the outlet, some of the energy lost due to friction inside the nozzle. This energy lost due to friction is called head loss in the nozzle.

(c) Hydraulic fosses:

These losses are due to bucket friction, eddy formation and kinetic energy of leaving water.

(d) Leakage losses:

The whole jet of water does not strike on the buckets. Therefore, some of energy of water go for waste. This loss is called as leakage loss.

(e) Mechanical losses:

The power available at shaft is always less than power produced by the runner because some power is consumed in overcoming friction in bearing and some in overcoming friction in bearing and some in overcoming the windage losses. So the losses due to bearing friction and windage are called mechanical losses.

(f) Generator losses:

In generator, complete input shaft power (or) mechanical power is not converted into electrical power, some input shaft power can be lost in generator, is called generator loss.

3.4 Velocity triangle of Pelton turbine and work done

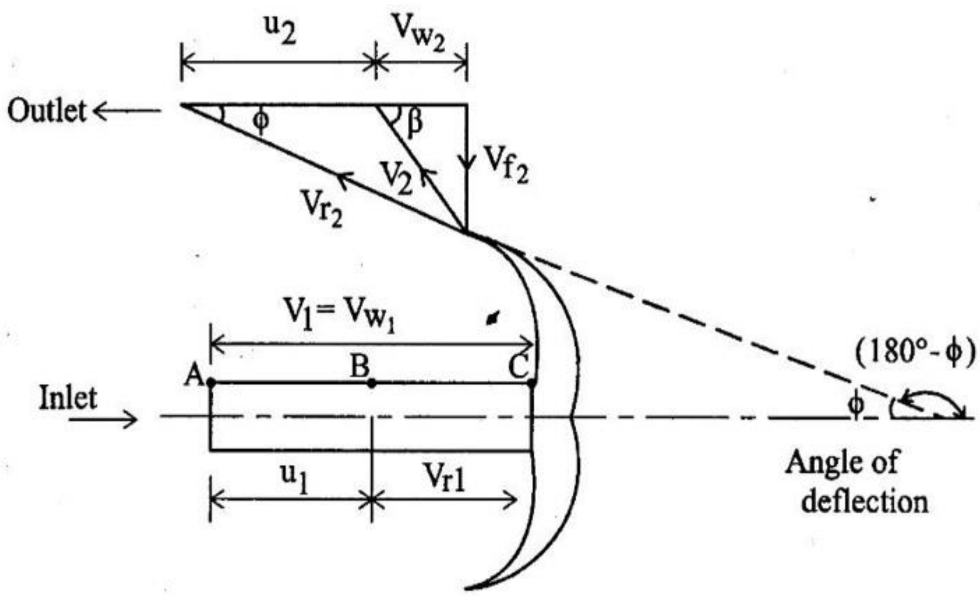

Fig: 3.4 Velocity Triangles as the Inlet & Outlet

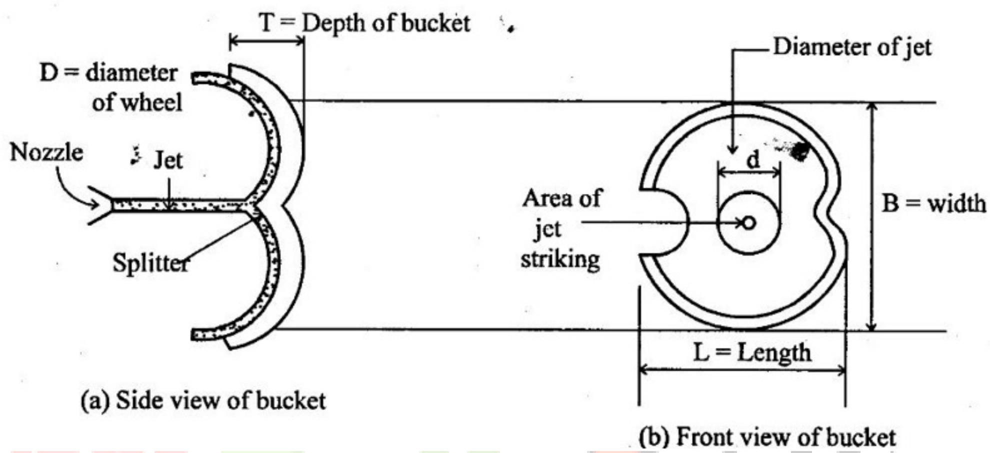

Fig: 3.5 Views of Bucket

Consider a water jet striking at the splitter of a bucket as shown in figure 3.5. The velocity triangles of the water jet are drawn at the inlet and outlet of the bucket as shown in figure 3.4. The symbols used for determining work done by jet from velocity triangles are

N - Speed of the wheel (or) turbine.

D - Diameter of the Pelton wheel.

D - diameter of jet.

u - peripheral velocity of runner.

V_1 - absolute velocity of jet at inlet.

V_2 - absolute velocity of jet at outlet.

V_{rl}= Relative velocity of the jet to the bucket at inlet.

V_{r2} = Relative velocity of the jet to the bucket at outlet.

V_{wl} = Component of velocity of jet V_1 in the direction of motion of bucket at inlet (or) Whirl velocity at inlet.

V_{w2} = Component of velocity V_2 in the direction of motion of bucket at inlet (or) Whirl velocity at outlet.

V_{f1} = Component of velocity of jet V_1 in the direction perpendicular to the motion of buckets (or) Flow velocity at inlet.

V_{f2} = Component of velocity V_2 in the direction perpendicular to the motion of buckets (or) Flow velocity at outlet.

α = Angle between the direction of jet and direction of motion of the bucket at inlet (or) Guide blade angle at inlet.

β = Angle made by absolute velocity V_2 with the direction of motion of bucket at outlet (or) Guide blade angle at outlet.

θ = Angle made by the relative velocity V_{r1} with the direction of motion of bucket at the inlet (or) vane angle at inlet.

ϕ = Angle made by the relative velocity V_{r2} with the direction of motion at outlet (or) Vane angle at the outlet.

(i) From Inlet velocity triangle

The velocity triangle at inlet will be a straight line because the jet of water is entering the bucket in same direction in which bucket is moving.

So $V_{f1} = 0$

$V_{\omega 1} = V_1$

$V_{r1} = v_1 - u_1 = v_1 - u$ $(u = u_1 = u_2)$

Inlet angles α & θ = 0

(ii) From outlet velocity triangle

As the water passes over the curved surface of bucket V_{r2} becomes less than V_{r1} due to frictional loss therefore,

$V_{r2} = k\, V_{r1}$ [K= co-efficient of friction k < 1]

For general purpose these frictional losses are neglected and k is taken as unity.

Therefore

$$V_{r2} = V_{r1}$$

$$\cos\phi = \frac{V_{w2} + u_2}{V_{r2}} \quad \text{[From triangle]}$$

$$V_{w2} + u_2 = V_{r2}\cos\phi$$

$$V_{w2} = V_{r2}\cos\phi - u_2$$

$$V_{w2} = V_{r2}\cos\phi - u$$

V_{w2} depends upon angle β.

(i) For slow speed runner $\beta < 90°$ V_{w2} is negative.

(ii) For medium speed runner $\beta = 90°$ $V_{w2} = 0$.

(iii) For high speed runner $\beta > 90°$ V_{w2} in positive.

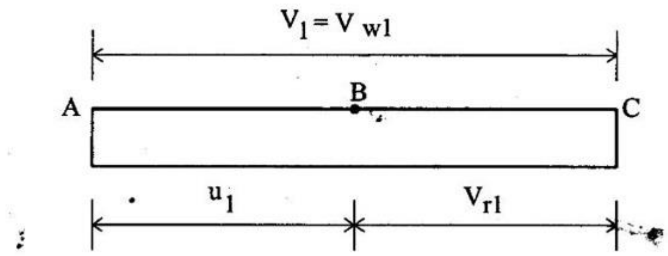

Fig: 3.6 Inlet Velocity Diagram

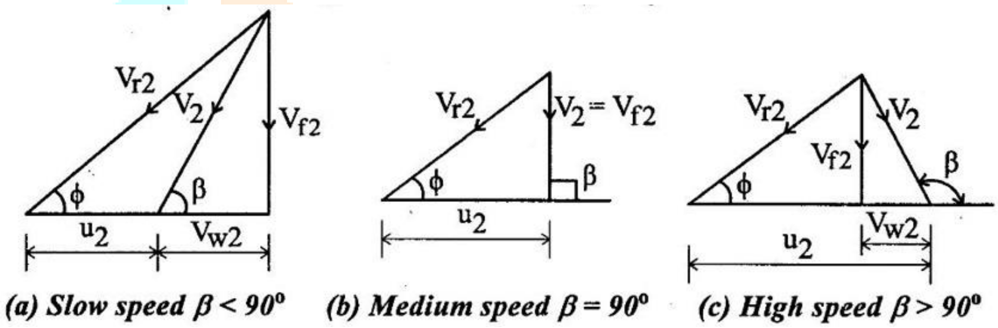

Fig: 3.7 Outlet Velocity Diagram

From the above three cases, commonly used slow speed runner, so take the value of V_{w2} is negative sign.

(iii) Force exerted by the jet of water in the direction of motion

F_x = Mass flow rate x change in whirl velocity

$= \rho a V_1 \times [V_{wl} (+ V_{w2})]$

∴ [β > 90 For fast runner] so V_{w2} is positive sign (+ve)

(i) $F_x = \rho a V_1 (V_{wl} - (+V_{w2}))$ ∴ V_{w2} is positive sign (+ve)

$F_x = \rho a V_1 (V_{wl} - V_{w2})$ [β > 90° - Fast runner]

(ii) $F_x = \rho a V_1 (V_{wl} - (-V_{w2}))$ ∴ V_{w2} is negative sign (-ve)

$F_x = \rho a V_1 (V_{wl} + V_{w2})$ [β < 90° - Slow runner]

(iii) $F_x = \rho a V_1 (V_{wl})$ ∴ $V_{w2} = 0$ [β = 90° - Medium speed-runner]

Commonly used V_{w2} is negative, assume runner is slow speed and $\beta < 90°$, so,

$$F_x = \rho a V_1 (V_{w1} + V_{w2})$$

$$a = \text{area of the jet} = \pi/4 \times d^2$$

$$\rho = \text{Density of the liquid.}$$

(iv) Work done by the jet on the runner/sec = Force × Velocity

$$\rho a V_1 (V_{w1} + V_{w2}) \times u \text{ in N } m/s$$

(v) Power produced by the Pelton wheel (P) = (Work done/sec) / 1000

$$= \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{1000} \ kw$$

(vi) Work done per unit weight of water striking/sec = (Work done/sec) / Unit weight of water striking

$$= \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{\rho a V_1 \times g}$$

$$= \frac{(V_{w1} + V_{w2}) \times u}{g}$$

(vii) Hydraulic efficiency (h_h) = (Work done/sec) / kinetic energy supplied by the jet of inlet

$$= \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{\frac{1}{2}(\rho a V_1) \times V_1^2} \qquad \left(\therefore K.E = \frac{1}{2} m V^2 = \frac{1}{2}(\rho a V_1) \times V_1^2\right)$$

$$\boxed{\eta_h = \frac{2 \times (V_{w1} + V_{w2}) \times u}{V_1^2}} \qquad \text{...(i)}$$

above equation (i) is also called blading efficiency (or) bucket efficiency (η_b).

From velocity triangles $V_{w1} = V_1$

$$V_{w2} = V_{r2} \cos\phi - u_2$$

$$V_{r2} = K(V_{r1})$$

$$V_{r2} = K(V_1 - u_1) \qquad [V_{r1} = V_1 - u]$$

$$V_{r2} = K(V_1 - u) \qquad [u = u_1]$$

So

$$V_{w2} = K(V_1 - u)\cos\phi - u \qquad [u_2 = u]$$

on substituting the values of V_{w1} and V_{w2} in equation (i)

$$\boxed{\eta_h = \frac{2\times[V_1 + k(V_1 - u)\cos\phi - u]\times u}{V_1^2}} \qquad ...(ii)$$

(viii) Maximum hydraulic efficiency

Absolute velocity of jet (V_1) and hydraulic efficiency depends upon the peripheral velocity (u) of the runner. Hence, for obtaining maximum efficiency condition is

$$\frac{d}{du}(\eta_h) = 0$$

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

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

But the term $\frac{2(1 + K\cos\phi)}{V_1^2}$ cannot be zero, so neglect that from the above equation.

$$\frac{d}{du}\left[V_1 u - u^2\right] = 0$$

$$V_1 - 2u = 0$$

$$V_1 = 2u$$

$$\boxed{u = \frac{V_1}{2}}$$

The above shows that a Pelton wheel will have maximum efficiency when velocity of wheel (*u*) is half of the velocity of the jet (V_1) at inlet of the turbine. Hence the value of u is applying in equation (ii).

$$\eta_h = \frac{2\left(V_1 - \frac{V_1}{2}\right)(1 + K\cos\phi)\times\frac{V_1}{2}}{V_1^2} = \frac{2\times\frac{V_1}{2}(1 + K\cos\phi)\times\frac{V_1}{2}}{V_1^2}$$

$$\eta_h = \frac{1 + K\cos\phi}{2}$$

In case neglect the frictional losses then,

$$\boxed{\eta_{h\max} = \frac{1 + c\cos\phi}{2}} \qquad ...(iii)$$

Conclusion:

The structural and modal analyses of the Pelton wheel bucket using Gray Cast Iron, Stainless Steel, Aluminium Alloy, and Inconel 625/718 revealed key performance differences. Inconel 625 showed the lowest stress and excellent vibration resistance, while Stainless Steel exhibited the least deformation and strain, indicating superior stiffness and dimensional stability. Gray Cast Iron, though economical, showed higher deformation and lower modal frequencies, making it less suitable. Aluminium Alloy, being lightweight, suffered from lower stiffness. Overall, Inconel 625 emerged as the best material due to its outstanding stress resistance, fatigue strength, and vibrational stability, ensuring durability in hydropower applications.

To summarize:

- Stainless Steel is the best performer in terms of deformation and strain resistance.
- Inconel 625/718 provides excellent stress resistance and outstanding vibrational stability.
- Gray Cast Iron, while cost-effective, performs poorly in both deformation and modal behavior.

REFERENCES

1. Xiao, Y., Li, X., Zhang, H. & Wang, J., 2014. Numerical and experimental analysis of the hydraulic performance of a prototype Pelton turbine. *Renewable Energy*, 63, pp.142-152.
2. Nigussie, T., Gebremedhin, K. & Asfaw, A., 2017. Design, modeling, and CFD analysis of a micro-hydro Pelton turbine runner for site-specific conditions. *International Journal of Renewable Energy Research*, 7(2), pp.567-578.
3. Solemslie, B., 2016. Experimental methods and design of a Pelton bucket. *Master's Thesis*, Norwegian University of Science and Technology, Trondheim.
4. Ishola, O., Adewale, F. & Adepoju, O., 2019. Design and performance analysis of a pico-size Pelton wheel turbine. *Journal of Mechanical Engineering Research*, 11(3), pp.45-56.
5. Liji-Qing, L. & Moe Saw, K., 2019. Fatigue analysis of Pelton turbine buckets using numerical approaches. *Engineering Structures*, 198, pp.109510.
6. Atthanayake, A., 2016. Dynamic analysis of Pelton wheel turbines: Vibrational characteristics and operational reliability. *International Journal of Mechanical Engineering*, 5(4), pp.234-242.