

Design and Development of Kaplan Turbine Runner Blade

Aadilahemad Momin¹, Nairutya Dave², Parth Patel³, Karan Panchal⁴Bachelor Student, Department of Mechanical Engineering, Navrachana University, Vadodara, Gujarat, India¹Bachelor Student, Department of Mechanical Engineering, ITM Universe, Vadodara, Gujarat, India²Bachelor Student, Department of Mechanical Engineering, SVIT, Vasad, Gujarat, India³Bachelor Student, Department of Mechanical Engineering, GEC, Surat, Gujarat, India⁴

ABSTRACT: Use of renewable energy has been of great interest since last few years, especially the hydropower energy. Usually electricity is generated from hydropower energy, which is obtained from potential pressure heads, water discharge and hydro sites. Based on the location constraints, different types of hydro turbines can be designed and developed to generate electricity. The primary concern is to reduce the dependency on fossil fuels and increase the use of renewable power in rural areas such as ChotaUdepur (Amalwant check dam). In this paper, designing of Kaplan turbine runner mechanism for Amalwant Check Dam(Vadodara) which has a head of 17m for the generation of power upto 5MW is carried out. For thickness calculation, occurring forces are established which is followed by detailed drawings of the developed runner mechanism drawn in SolidWorks 2014.

KEYWORDS:Renewable Energy, Hydropower, Electricity, Kaplan Turbine, Check Dam, Design, Runner, SolidWorks

I. INTRODUCTION

Hydropower, generated mainly from hydroelectric dams, is a clear, green, and sustainable source of energy that produces cheaper electricity and lowers carbon emissions. Because of its high energy density, hydropower is the most efficient and most primarily available renewable power source to produce electricity [7]. In order to obtain greater efficiency, hydraulic turbines installed in the hydroelectric power plants have to be suitable, depending on the discharge of the site and head. There are a lot of hydraulic turbines available which are generally classified into two categories:

- 1] Impulse turbines
- 2] Reaction turbines

A hydraulic turbine in which all hydraulic energy of water gets converted into kinetic energy before the water reaches to the runner of the turbine is called impulse turbine. While in case of reaction turbine, some amount of available hydraulic energy is converted into kinetic energy before it strikes on the runner of the turbine. For flow head range available at the chosen site, reaction turbine is well suited. Reaction turbines include Propeller, Kaplan, and Francis turbine [2].

Table 1 Classification of the Turbines

Type	Head	Flow Rate	Specific Speed
Pelton Turbine	High	Low	Low
Francis Turbine	Medium	Medium	Medium
Kaplan Turbine	Low	High	High

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The Kaplan turbine and the Propeller turbine are relatively of smaller dimensions, and high specific speed and rational speed and hence the dimensions of the generator are quite smaller which results in low cost. In addition, both the turbines have a large overload capacity. Water comes through scroll casing into guide vanes in the radial direction, from where flow make a right angle turn and axially enters the runner. The design of runner differentiates Propeller turbine from the Kaplan turbine. The former has fixed blades, while runner blades of the latter can be adjusted according to the flow rate. Propeller turbines are more suitable for constant flow and head, while Kaplan turbine works under a broad range of flow rate [5].

There are two types of Kaplan turbines: single regulate and double regulated. The former has only adjustable runner blades, and the latter has flexible runner blade as well as adjustable guide vanes. Generally, Kaplan turbine is applicable for a head range of 2m - 40m. The double regulated Kaplan turbine works under a wider range of designed discharge (15% - 100%), while single regulated turbine operates under lower range (30% - 100%). It is the main advantage of double regulated turbine over the single regulated turbine [2,5].

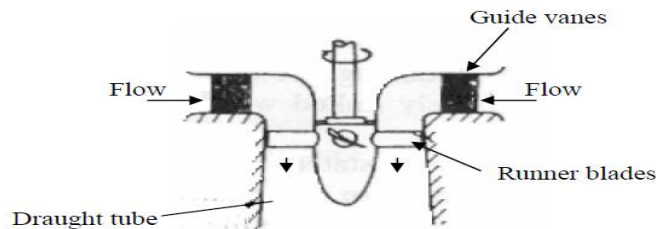


Figure 1 Kaplan Turbine

In this paper, low head Kaplan turbine runner is focused, because low-head schemes can be executed readily on the canals and run-off-rivers. The primary focus is on the development of Kaplan turbine runner blade for the Amalwant Check Dam (Vadodara). The main characteristics based on the site are calculated, which is followed by design methodology of the blade. The designed blade is drawn in SolidWorks software.

II. MATERIAL AND MAIN CHARACTERISTICS CALCULATIONS

(A) Material

Most of the parts involved in the Kaplan Turbine are generally high alloy steel (Stainless Steel) because most of the parts will be in continuous contact with water and thus they have to be corrosion resistant. Moreover, stainless steel (high Cr and Ni) possesses good weldability, high strength against bending and highly machinable. Thus looking at the above mentioned required properties, materials for various parts are selected as shown below [4]:

Table 2 Material Selection

Serial No.	Component	Material	Reason
1	Hub	X04Cr19Ni9	Hub material should be of weldable material since it is to be welded to the axle.
2	Blade	16Cr5Ni	The material should have high strength against bending and corrosive material. Also, the blade should be thin, and chosen material SS has high resistance against bending.
3	Pivot	X20Cr13	The material should be SS with high machinability.
4	Lever	X20Cr13	The material should be corrosion resistant since lever will be machined through milling.
5	Link	16Cr5Ni	The material should fulfill the requirement of corrosion resistance and withstand occurring forces.
6	Crosshead	X20Cr13	The Material with good machinability and conditional weldability is required which SS provides.

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(B) Main Characteristics Calculations

Runner blade is one of the most important components in the Kaplan turbine. And to begin with the designing part of the same, parameters like power, flow rate, and runner diameter first have to be determined. Depending upon the site selected, the calculations of these parameters are done in this section. The data on which the design of the runner is based is known as main characteristics. So for the calculation of forces on the blade, the main characteristics are to be obtained.

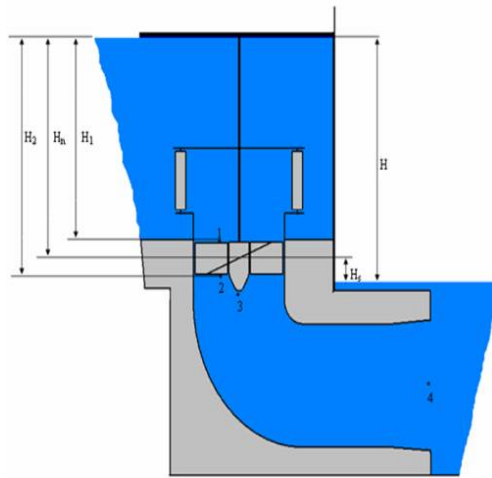


Figure 2 Various Heads involved in working of Kaplan Turbine

(I) Power

Multiplication of head of water and discharge through the turbine gives available Power [7]. The equation for the output power is as follow:

$$P = \rho * g * Q * H * \eta_h$$

Where,

ρ = Density of Water [Kg/m³] = 1000 Kg/m³

g = Gravitational Acceleration [m/s²] = 9.81 m/s²

Q = Discharge [m³/s]

H = Gross Head [m]

η_h = Hydraulic Efficiency [-]

Generally, according to the requirement of the power, and available head, other parameters are determined.

(II) Specific Speed

Usually, based on this parameter, hydraulic turbines are categorized. Specific speed is the speed of turbine which is identical in shape and other geometries and which works under the unit head and produces unit power. It is a dimensionless parameter.

It is given by the following equation:

$$N_s = \frac{885.5}{H_n^{\frac{1}{4}}}$$

Where,

N_s = Specific Speed [-]

H_n = Net Head [m]

Based on the available head, thenet head has to be calculated, which is calculated from the following equation

$$H_n = H * \eta_h$$

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(III) Speed of the Runner (N)

$$N = \frac{N_s * H_n^{1.25}}{\sqrt{P}}$$

(IV) Diameter of the Runner and Hub

To calculate the diameter of the runner D_e , following equation is used [3]:

$$Q = \frac{\pi}{4} * (D_e^2 - D_i^2) * V_f$$

Where,

V_f = Velocity of Flow [m/s]
 D_e = Diameter of Runner [m]
 D_i = Diameter of Hub [m]

A relation between runner diameter and hub diameter is $D_e = 0.4D_i$. Velocity of flow is unknown, which can be calculated from the equation given below[2]:

$$\Psi = \frac{V_f}{\sqrt{2 * g * H}}$$

Where,

Ψ = Flow ratio [-]

Table 3 Result Data of Main Characteristics

Parameter	Symbol	Value	Unit
Power	P	5	MW
Gross Head	H	17	m
Hydraulic Efficiency	η_h	0.9	-
Flow Rate	Q	33.31	m ³ /s
Net Head	H_n	15.3	m
Specific Speed	N_s	447	-
Runner Speed	N	191	rpm
Flow Speed	Ψ	0.6	-
Velocity of Flow	V_f	10.39	m/s
Runner Diameter	D_e	2.204	m
Hub Diameter	D_i	0.881	m

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III. DESIGN METHODOLOGY

The designing of the blade is mainly done in three parts. In the first part, the blade is considered to be a few sections. The radius of each section is to be calculated. Velocity diagram is drawn for each section, and involved velocities and blade angles of each section are calculated in the second part, While the thickness of the blade is calculated in the third part, once the occurring forces are established. In order to get a streamlined flow of water over the runner blade, the leading edge is designed thicker than the trailing edge. In addition, the cavitation characteristics can also be improved by keeping the blade as thin as possible; blade is designed so that thickness gradually reduces from the flange to the tip.

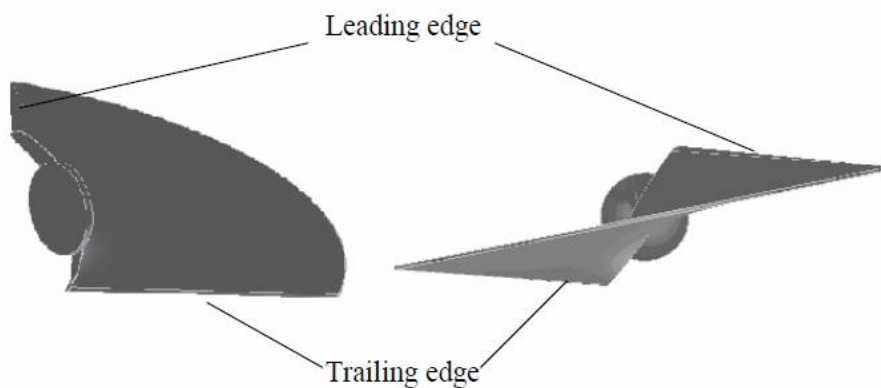


Figure 3 Runner Blade

(I) Distortion of the Blade

As per this theory, the blade is considered to be distorted into six sections. The velocity triangles of six different sections of the blade are determined. The angle β_∞ of each section gives conclusions on the distortion of the blade. Before beginning with the computation of the velocity triangle of each section of the blade, radiuses of each section needs to be determined.



Figure 4 Blade Sections

For Section 1,

R_1 and hub radius (R_h) are same. So using R_h , radiuses of all the blade sections are calculated from following equations.

$$R_1 = R_h$$

For Section 2,

$$R_2 = \frac{D_i}{2} + 0.0015 * D_e$$

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For Section 4,

$$R_4 = \frac{D_e}{2} * \sqrt{1 + \left(\frac{D_i}{D_e}\right)^2}$$

For Section 3,

$$R_3 = R_2 + \frac{R_4 - R_2}{2}$$

For Section 6,

$$R_6 = \frac{D_e}{2} - 0.015 * D_e$$

For Section 5,

$$R_5 = R_4 + \frac{R_6 - R_4}{2}$$

(II) Velocity Triangle

In order to know the blade angle of each section, velocity diagram is drawn for each section. Different velocities such as tangential velocity, flow velocity, and whirl velocity are shown in the figure. Gratings, as mentioned in the figure, occurs by a cylindrical cut (developed into drawing plane) at the runner. The first velocity triangle occurs when the water just enters into the runner (before the grating), and the other velocity triangle occurs at the time when water leaves the runner (after the grating). The vertical components w_{m1} and w_{m2} are flow velocities and are equal. The relative velocity w_∞ can be determined by taking an average of relative velocity at the inlet (w_1), and relative velocity at the outlet (w_2) and β_∞ shows its direction. The value of "t" indicates the distance between two adjacent blades and "l" denotes the length of the blade.

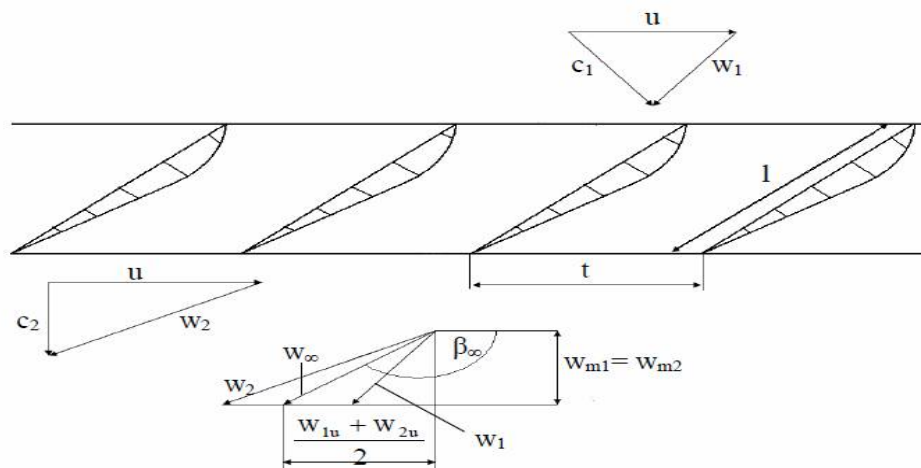


Figure 5 Velocity Triangles of Kaplan Turbine Blade

Where,

w = Relative Velocity [m/s]

c = Absolute Velocity [m/s]

u = Tangential Velocity [m/s]

Drawing velocity triangle at each section of the blade and using following equations, tangential velocity, inlet velocity, outlet velocity, Relative velocity and blade angle at each section are calculated.

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Tangential Velocity,

$$u = \pi * d * n$$

Absolute Velocity,

$$c_u = \frac{H_n * g}{u}$$

Whirl Velocity,

$$w_u = c_u - u$$

Flow Velocity,

$$w_m = \frac{Q}{A}$$

Relative Velocity,

$$w = \sqrt{w_u^2 + w_m^2}$$

Blade Angle,

$$\beta_\infty = \arccos \frac{w_u}{w}$$

(III) Thickness of Blade Sections

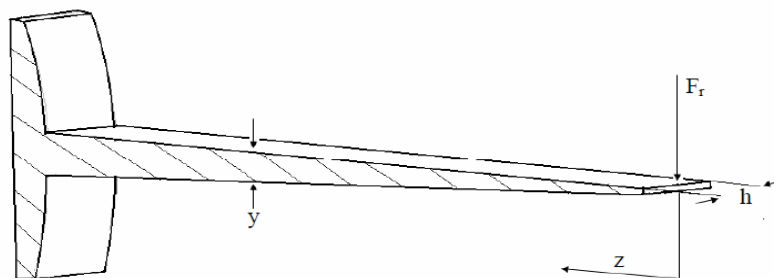


Figure 6 Blade Section

It is assumed that resultant force acts on the tip of the blade and not on the center of pressure of the blade. A safety factor of 1.5 is considered, so the blade does not fail in bending. To calculate the thickness using bending stress, following equation is used:

$$y = \sqrt{\frac{6 * F_r * z}{h * \sigma_{bpermissible}}}$$

Where,

$\sigma_{bpermissible}$ = Allowable Stress

y = Blade Thickness

z = Distance between tip of the blade and top of the section of the blade

$$\sigma_{bpermissible} = \frac{\sigma_{yield}}{FOS}$$

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For the chosen material of the blade (16Cr5Ni), $\sigma_{yield} = 750 \text{ MPa}$ and factor of safety is taken as 1.5. So from above equation, $\sigma_{bpermissible}$ yields out to be **500MPa**. Distance z is found from the following equation:

$$z = R_e - R_n$$

Resultant Force,

$$F_r = \sqrt{F_t^2 + F_a^2}$$

Where,

F_t = Tangential Force [N]

F_a = Axial Force [N]

Tangential force,

$$F_t = \frac{P}{2 * \pi * N * Z * r_{cp}}$$

Where,

N = Rotational Speed [rpm]

Z = Number of Blade [-]

r_{cp} = Radius of the center of pressure [m]

Centre of pressure is a point on the blade on which the entire resultant force can be assumed to be acted and distance of which is calculated from the following equation:

$$r_{cp} = \sqrt{\frac{R_e^2 + R_t^2}{2}}$$

Axial Force,

$$F_a = \rho * g * H_n * A_b$$

Where,

A_b = Area of the Blade

$$= \frac{\pi * \alpha * (R_e^2 - R_t^2)}{360^\circ}$$

Table 4 Result Data of Blade Profile

Parameter	Unit	1	2	3	4	5	6
R	m	0.473	0.656	0.839	0.954	1.068	1.102
L	m	0.844	0.980	1.226	1.374	1.414	1.414
u	m/s	9.50	13.16	16.83	19.13	21.43	20.86
w _m	m/s	10.39	10.39	10.39	10.39	10.39	10.39
w _u	m/s	15.79	11.39	8.91	7.84	7.00	6.83
c _u	m/s	18.90	15.42	17.81	13.02	14.78	12.45
w ₁	m/s	12.15	10.54	13.06	15.34	17.78	19.37
w ₂	m/s	14.08	16.77	19.78	21.77	23.82	25.29
w _∞	m/s	13.11	13.66	16.42	18.56	20.80	22.33
β _∞	°	127.55	130.42	140.71	145.92	150.01	152.00
180-β _∞	°	52.44	49.57	39.28	34.07	29.98	28.00

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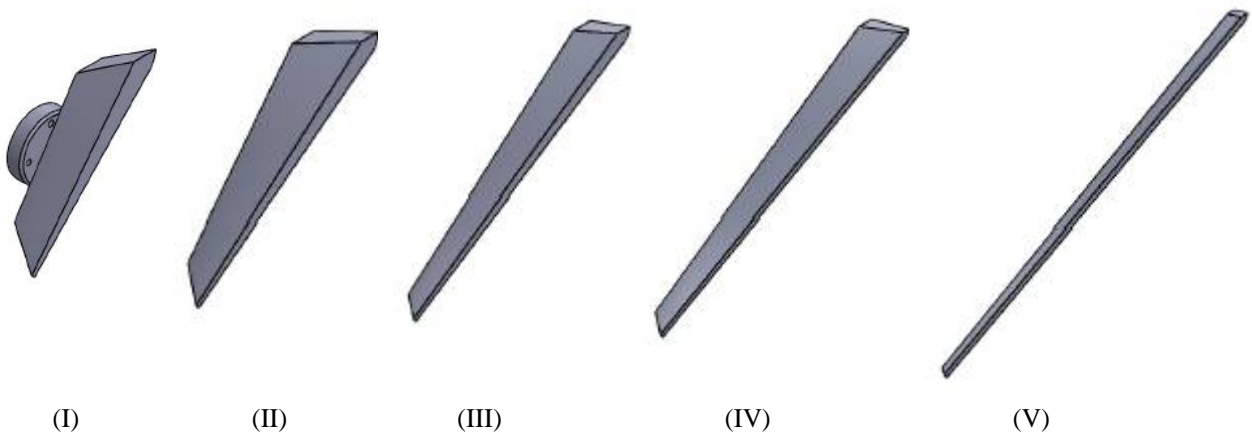
Table 5 Result Data of Forces acting on Blade

Parameter	Symbol	Value	Unit
Yield Stress	σ_{yield}	750	MPa
Factor of Safety	FOS	1.5	-
Allowable Stress	$\sigma_{bpermissible}$	500	MPa
No. of Blades	Z	4	-
Radius of Center of Pressure	r_{cp}	0.839	m
Tangential Force	F_t	74.26	kN
Area of Blade	A_b	0.711	m ²
Axial Force	F_a	106.84	kN

Table 6 Result Data of Blade Thickness

Parameter	Unit	1	2	3	4	5	6
R_n	m	0.473	0.656	0.839	0.954	1.068	1.102
z	m	0.628	0.445	0.262	0.147	0.033	0.005
y	mm	127.85	107.66	82.69	62.04	29.33	20.00

IV. DRAWINGS



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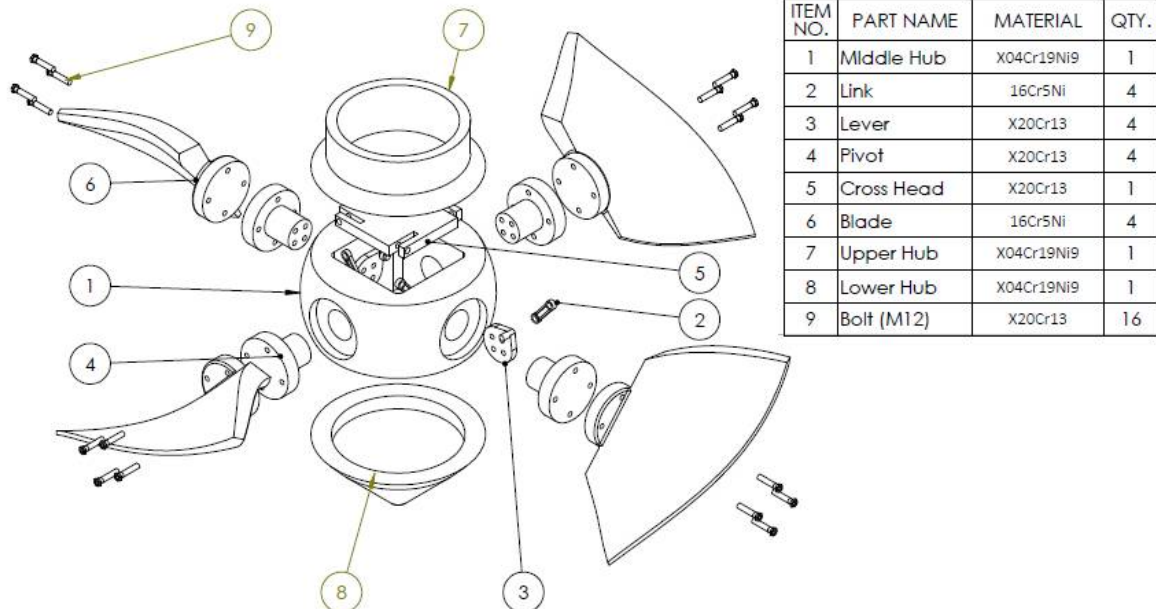


Figure 7 Runner Assembly Exploded View

V. SUMMARY AND CONCLUSION

The main characteristics play the primary role in selecting the type of turbine for the chosen site. At Amalwant Check Dam, the available head is 17m, the flow rate is 33.31 m³/s, and desired power output is 5MW. So Kaplan turbine is selected based on the main characteristics. The diameter of the hub is 0.881m, and diameter of the runner is 1.102m. There are four blades in the runner. The specific speed is 447, and runner speed is 191 rpm. The blade is designed in six different sections. For each section, velocities and blade angles from velocity diagram are calculated. Thickness is calculated by assuming the blade as a beam. For these calculations, Microsoft office excel is used, and SolidWorks software is used for modeling. Velocity distribution on the blade can be known by performing flow simulation on the blade in SolidWorks software.

Looking at the current scenario of increasing greenhouse gases, usage of conventional energy resources is not favorable. And since India is facing the coal issues, the increasing electricity demand will need to be fulfilled in the near future and for that necessary steps have to be taken. In Gujarat state, about 1,66,082 check dams with water storage capacity of 28,408 million cubic feet have been built so far, and this hydropower can be utilized to generate pollution free electricity.

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