



Design and Performance Analysis of a Low Head Propeller Turbine

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Abstract: Nowadays, using renewable energy to produce electricity is an essential role in all over the world. The generation of electricity from water is the most effective and the cheapest way to get energy. Low-head hydropower plants are expected to be implemented increasingly in the future. The main important part of propeller turbine such as guide vane, runner, casing and draft tube are designed. It can be used at sites which head is 3m and flow rate is $0.94\text{m}^3/\text{s}$. The turbine speed is 565 rpm and the specific speed for this turbine is 673 rpm to produce desired output power 15 kW. For the given capacity, the runner diameter is 481mm, hub diameter is 192 mm and the number of blade is four. The three dimensional blade profiles are drawn by SolidWorks Software. The velocity and pressure distributions acting on the propeller turbine are simulated by using SolidWorks Software.

Keywords: Guide Vane, Propeller Turbine, Runner Blade, Solidworks Software.

I. INTRODUCTION

The most important renewable sources are hydropower, biomass, geothermal, solar and wind but technical, economic and environmental benefits of hydroelectric power make it an important contributor to the future world energy mix. The demand for increasing the use of renewable energy has risen over the last few years due to environmental issues. Its present role in electricity generation is therefore substantially greater than any other renewable energy. Turbine is the main component of the hydro power plant over all generation of the plant depends on the performance of the hydro turbine. A hydraulic turbine converts the potential energy of the water into the rotational kinetic energy of the turbine. Investigation of flow condition of hydro turbine is very important to know the efficiency of the turbine. Furthermore, there is a possibility that such a design can directly drive a generator with the turbine runner fixed to a shaft extension, hence, increasing the mechanical efficiency of the system. Low-head hydro sites (2 to 10 m) have an even larger potential for providing electricity in rural areas of developing countries. Propeller turbines are one of the most cost-effective turbine options for low head hydropower.

II. TYPES OF HYDRAULIC TURBINE

Hydraulic turbines are classified into two categories which are being discussed below:

A. Impulse Turbines

Impulse turbine which available hydraulic energy is the first converted into kinetic energy by means of an efficient nozzle. Pressurized water from the penstock is converted to high-speed water jets that transfer the kinetic energy of the

jet by impacting the turbine blades or cups causing rotation. The pressure drop in the water flow occurs at the nozzle and the runner operates at atmospheric pressure. Examples of impulse turbines include the Pelton wheel, Turgo wheel, and Cross-flow turbines. Impulse turbines generally operate best with medium or high head (above 10 m).

B. Reaction Turbines

Reaction turbine which a part of the total available hydraulic energy is transformed into kinetic energy before the water is taken to the turbine runner. A substantial part remains in the form of pressure energy. Subsequently both the velocity and pressure change simultaneously as water glide along the turbine runner. The flow from inlet to outlet of the turbine is under pressure and, therefore, blades of a reaction turbine are closed passages sealed from atmospheric conditions. The flow is then redirected by the runner blades. The angular momentum of the water forces rotation in the runner. In contrast to impulse turbines, the water pressure drops at the stator and the runner. Examples of reaction turbines include propeller, Kaplan, and Francis. As shown in fig1 it is a necessary task to select a turbine for a hydro power site. The scales of hydropower schemes cover a broad range and are generally classified by power output. Larger schemes generally require damming to create storage capacity and regulate water flow. Given the greater amount of power generation, they are typically grid connected to supply high levels of demand. In India, depending on the capacities, hydropower projects are categorized as under given in Table I. Depending on the head, small hydropower plant may be further classified as low head (below 3 meters),

medium head (from 30-75 meters) and high head (above 75 meters).

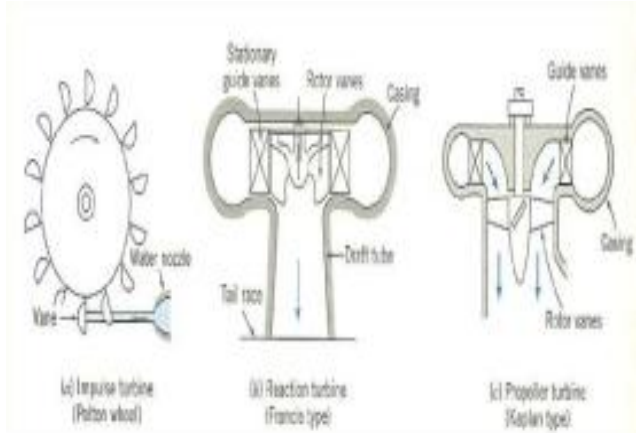


Fig. 1. Schematic diagrams of typical hydraulic turbines [2].

TABLE I: CLASSIFICATION OF HYDRO PLANTS IN INDIA [8]

Classification	Power Output
Large	>25 MW
Small	2MW to 25 MW
Mini	100kW to 2 MW
micro	5kW to 100kW
Pico	<=5kW

C. Propeller Turbine

The axial flow turbines are the Kaplan turbine and propeller turbine. In propeller turbine the blades are fixed. In the Kaplan turbines the blades are mounted in the boss in bearings and the blades are rotated according to the flow conditions by a servomechanism maintaining constant speed. The propeller turbine is a reaction turbine which is particularly suited for low head and high flow rate installations. The main components of propeller turbine are shown in Fig.2. In a propeller, water enters the turbine laterally, gets deflected by the guide vanes and then flows through the propeller. It usually has four to six or at the most ten blades of air foil shape and known as fixed blade axial flow reaction turbine because the pitch angle of the rotor blades cannot be changed. The part flow efficiency of fixed-blade propeller turbines tends to be very poor. Large scale hydro sites make use of more sophisticated versions of the propeller turbine. The propeller turbine is a reaction turbine used for heads between 2m to 40m. If the head or the water flow rate tends to vary seasonally, as occurs in many river systems, an installation with only a few propeller turbines might have to operate all units at partial output under average flow and load conditions. The energy- conversion efficiency of a conventional propeller turbine decreases rapidly once the turbine load drops below 75 percent of its rating. This performance loss can be minimized by varying the inlet-blade angle of the runner to match the runner-inlet conditions more accurately with the water velocity for a given flow.

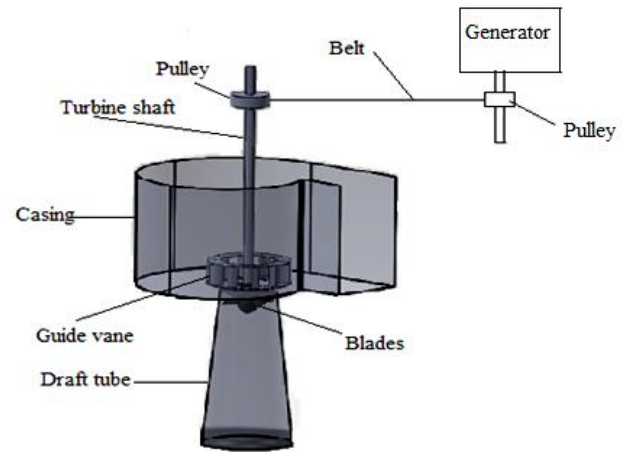


Fig.2. Components of Propeller Turbine.

III. DESIGN PROCEDURE OF PROPELLER TURBINE

After knowing the designed net head, the specific speed can be calculated from the following equation.

$$N_s = \frac{885.5}{H_d^{0.25}} \quad (1)$$

The speed of turbine,

$$N = \frac{N_s H_d^{1.25}}{\sqrt{P}} \quad (2)$$

Where,

H_d = Design head, m

P = required shaft power, Kw

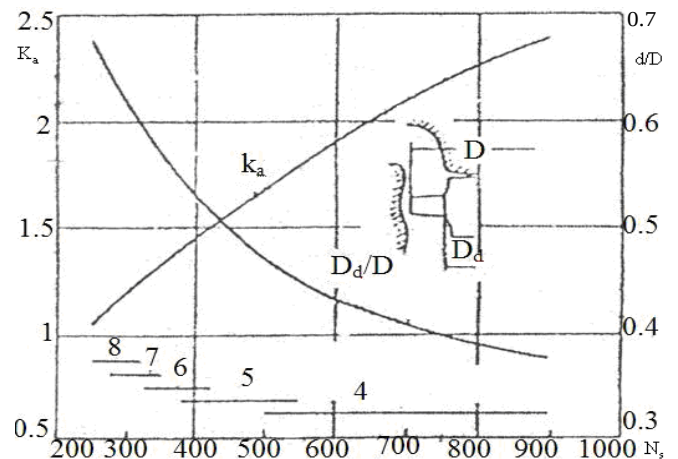


Fig.3. Relationship between Speed Ratio and Specific Speed[1].

And then, the value of periphery coefficient can be calculated by the following equation.

$$\phi = 0.0242 \times N_s^{2/3} \quad (3)$$

The runner discharge diameter,

$$D_3 = \frac{84.5 \times \phi \times \sqrt{H_d}}{N} \quad (4)$$

Where,

ϕ = periphery coefficient

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N = Speed of turbine, rpm

According to the specific speed, the number of runner blades and the ratio d/D between the diameter of the hub and runner can be read from Fig. 3.

A. Calculation of Flow Rate and Guide Vane Angle

The power developed by a turbine is given by the following equation.

$$P = \gamma Q H_d \eta_o \quad (5)$$

Where,

Q = Flow rate, m^3/s

H_d = Design head, m

η_o = Overall efficiency of the turbine

γ = Specific weight of water, kN/m^3

The flow velocity with the runner can be determined from the following continuity equation.

$$Q = A V_f \quad (6)$$

Where,

A = Flow area, m^2

V_f = Flow velocity, m/s

$$A = \frac{\pi}{4} (D_3^2 - d^2) \quad (7)$$

Where,

D_3 = Runner discharge diameter, m

d = Runner hub diameter, m

$$\eta_h = \frac{\eta_o}{\eta_m} \quad (8)$$

Where,

η_h = Hydraulic efficiency

η_o = Overall efficiency

η_m = Mechanical efficiency

B. Guide Vane Design

The tangential velocity at outer diameter of runner blade,

$$U = \frac{\pi D_3 N}{60} \quad (9)$$

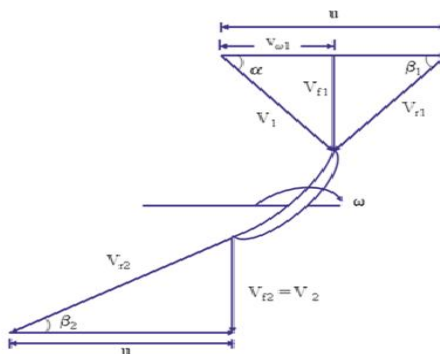


Fig.4. Inlet and outlet velocity triangle of propeller turbine[5].

For one unit mass flow and no whirl velocity at outlet, the guide vane angle can be determined from the velocity triangle (see fig 4),

$$\alpha = \tan^{-1} \frac{V_f}{V_{\omega 1}} \quad (10)$$

Where,

α = Guide vane angle, degree

$V_{\omega 1}$ = tangential component of absolute velocity, m/s

V_f = Flow velocity, m/s

The number of guide blade,

$$z_1 = \frac{1}{4} \sqrt{D_3} + 4 \quad (11)$$

The length of the guide blade,

$$L = \frac{1.5 \frac{D_3}{2} - \frac{D_3}{2}}{\sin \alpha} \quad (12)$$

C. Draft Tube Design

As shown in fig 5 draft tubes can be calculated by the following equation. These dimensions are related to the runner discharge diameter.

$$T = D_3 \quad (13)$$

$$Y = 3D_3 \quad (14)$$

Outlet diameter of draft tube,

$$D_d = D_3 + 2 (\tan 6^\circ \times Y) \quad (15)$$

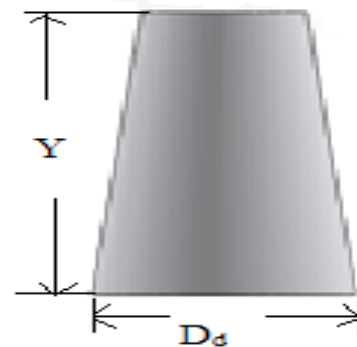


Fig. 5. Draft Tube.

D. Design of Blade Profiles

In the space of the runner, it can be divided into five cylindrical sections. These sections can be calculated by the following equations.

$$\text{Section I, } r_1 = \frac{d}{2} + 0.015D_3 \quad (16)$$

$$\text{Section III, } r_3 = \frac{D_3}{2} \sqrt{1 + \left(\frac{d}{D}\right)^2} \quad (17)$$

$$\text{Section II, } r_2 = r_1 + \frac{r_3 - r_1}{2} \quad (18)$$

$$\text{Section IV, } r_4 = r_3 + \frac{r_5 - r_3}{2} \quad (19)$$

$$\text{Section V, } r_5 = \frac{D_3}{2} - 0.015 D_3 \quad (20)$$

To find tangential component of absolute velocity,

$$C_{u1} = \frac{\eta_h g H_d}{U} \quad (21)$$

The blade inlet angle,

$$\tan\beta_1 = \frac{V_{f1}}{U - C_{u1}} \quad (22)$$

The blade outlet angle,

$$\tan\beta_2 = \frac{V_{f2}}{U} \quad (23)$$

The spacing of the blade,

$$t = \frac{2r\pi}{z} \quad (24)$$

The average tangential component of relative velocity,

$$W_{\alpha 1} = U - \frac{C_{u1}}{2} \quad (25)$$

The average angle,

$$\tan\beta_\alpha = \frac{V_f}{W_{\alpha 1}} \quad (26)$$

The average relative velocity,

$$W_\alpha = \frac{W_{\alpha 1}}{\cos\beta_\alpha} \quad (27)$$

Circulation,

$$\Gamma = t(C_{u1} - C_{u2}) \quad (28)$$

The angle of attack,

$$\alpha = \alpha^0 - 57.3 \frac{C_z}{6\pi} \quad (29)$$

The lattice angle,

$$\beta = 90 - \beta_\alpha + \alpha \quad (30)$$

TABLE II: RESULT DATA FOR BLADE PROFILE

Parameters	I	II	III	IV	V
R_1 (m)	0.1032	0.1436	0.184	0.2085	0.233
U (m/s)	6.106	8.496	10.88	12.33	13.78
β_1	75.62	49.55	36.37	31.34	27.56
β_2	45.19	35.89	29.45	26.49	24.03
C_{u1} (m/s)	4.53	3.26	2.54	2.24	2.006
$W_{\alpha 1}$ (m/s)	3.841	6.866	9.617	11.21	12.78
β_α	58	41.84	32.59	28.73	25.68
W_α (m/s)	7.25	9.21	11.41	12.79	14.18
t (m)	0.162	0.226	0.29	0.33	0.366
Γ (m ² /s)	0.734	0.734	0.734	0.734	0.734
l/t	1.1	1.012	0.925	0.84	0.74
l (m)	0.178	0.229	0.268	0.277	0.27
β	45.44°	56.94°	63.1°	65.4°	68.08°
α	13.44°	8.80°	5.72°	4.17°	3.79°

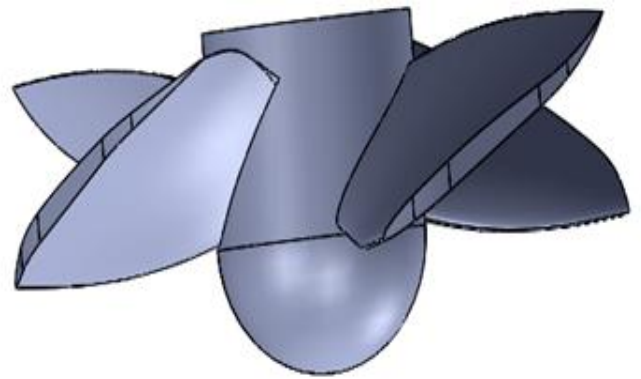


Fig.6. Runner Blade.

After calculating the blade profile, three dimensional runner blades are drawn by solid works software (see fig 6).

IV. SIMULATION RESULTS

The result of simulation for efficiency prediction of 15 kW capacities of propeller turbine with spiral casing is presented. The rated head and discharge for the turbine were 3 m and 0.94 m³/s respectively.

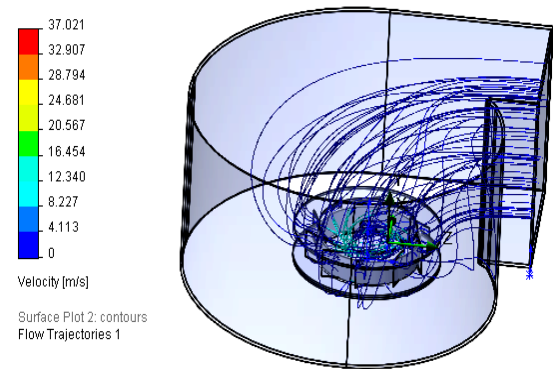


Figure7. Variation of Velocity Components from Casing to Guide Vane.

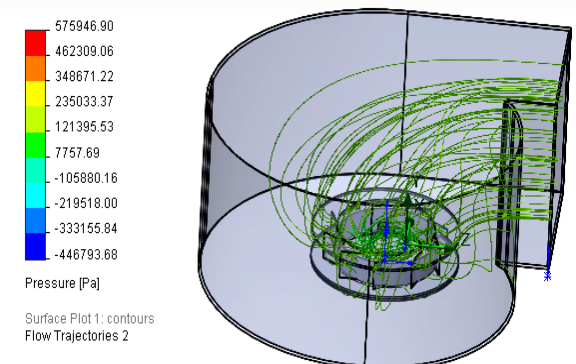


Figure 8. Variation of Pressure Components from Casing to Guide Vane.

For set of boundary conditions mass flow rate was specified at casing inlet and pressure outlet was specified at

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draft tube outlet. Grid interface was defined between casing and runner as well as between runner and guide vane. The figures 7, 8, 9 and 10 are shown the results of simulation in which blade material is using cast-iron. Simulation was carried out of propeller turbine with design parameters, which are the discharge is $0.94 \text{ m}^3/\text{s}$ and turbine speed 565 rpm. The velocity variations obtained through the numerical simulation are shown in the form of velocity contours. The total velocity variation is high near the outlet of the runner.

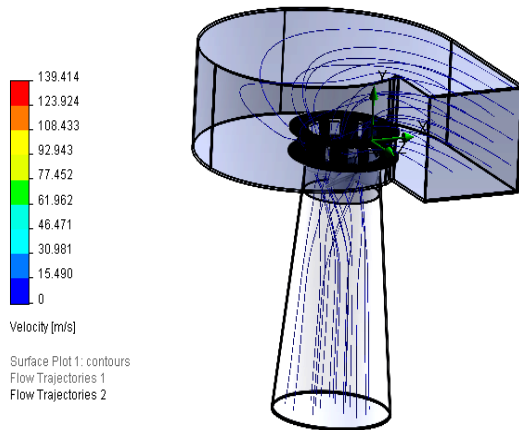


Figure 9. Variation of Velocity Components in Propeller Turbine.

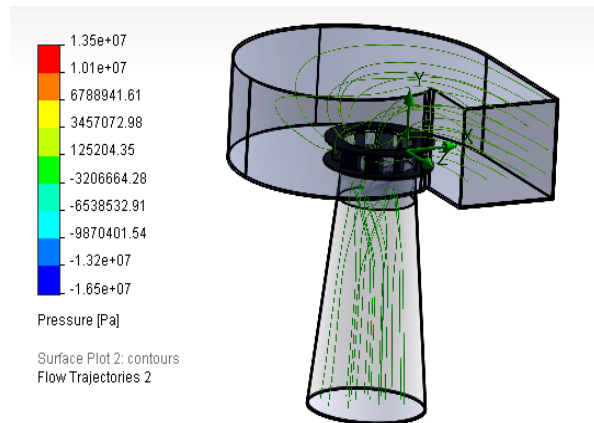


Figure 10. Variation of Pressure Components in Propeller Turbine.

TABLE III: FLOW SIMULATION OF PROPELLER TURBINE

Unit system	SI
Analysis type	Velocity and Pressure
Physical features	Rotation: Type: Local rotating, Rotational Speed = 565 rpm
Wall Conditions	Adiabatic wall, default smooth walls
Initial Conditions	Default conditions

TABLE IV: INLET AND OUTLET BOUNDARY CONDITIONS

Type	Inlet Volume Flow	Type	Environment Pressure
Faces to apply	Casing Inlet	Faces to apply	Draft Tube Outlet

V. CONCLUSION

In hydropower plant, turbine is one of the most important parts to generate electricity. The output power of turbine depends on the head and flow rate. The turbine having rated capacity of 15kW at rated head and discharge of 3m and $0.94 \text{ m}^3/\text{s}$ respectively. In this paper, the detailed design of blade that is divided in five cylindrical sections is presented. Then, SolidWorks Software is used to draw blade profile. The velocity and pressure distributions acting on the propeller turbine are simulated by using SolidWorks software. According to reaction turbine theory, the inlet velocity is less than the outlet velocity and the outlet pressure rejected from the draft tube will fall down approximately equal to atmospheric pressure as shown in figures.

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