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Design and Velocity Distribution of Runner Blade for Axial Flow Turbine

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Abstract: Hydropower is a renewable resource that can satisfy an important percentage of the global energy demand. This paper intends to describe the design calculation of blade parameters and velocity distribution of blade for axial flow Kaplan turbine to produce electricity. The available head and flow rate for turbine are 31 m and 52 m3/sec in Sadawgyi Project away from the Sagging Township, Myanmar. The output power is 12.5 MW and turbine speed is 262 rpm. In designing blade, blade element theories are the main theories of blade parameter calculation. This paper includes selecting airfoil shape of the blade from NACA series and modeling the exact airfoil geometry by using Design Foil software. For the velocity distribution on runner blade, velocities from hub to tip due to the various radiuses and flow velocities through the blade are determined. Numerical simulation of velocity distribution on the blade is made by using SolidWorks software.

Keywords: Axial Flow Kaplan Turbine, Turbine Speed, Head And Flow Rate, Blade Element Theory, Solidworks.

I. INTRODUCTION

Renewable energy is energy generated from natural resources such as sunlight, wind, rain, tides, and geothermal heat which are renewable (naturally replenished). Of the renewable energy sources that generate electricity, hydro power is the one used most often. It is one of the oldest sources of energy and was used thousands of years ago. It is important to understand the water cycle in order to understand hydro power. In the water cycle, solar energy heats water on the surface, causing it to evaporate. This water vapour condenses into clouds and falls back onto the surface as precipitation. The water flows through rivers back into the oceans, where it can evaporate and begin the cycle all over again. The amount of available energy in moving water is determined by its flow or fall. Swiftly flowing water in a big river carries a great deal of energy in its flow. The water flows through a pipe, or penstock, then pushes against and turns the blades in a turbine, to spin a generator to produce electricity. The amount of electricity a hydro power plant produces is a combination of two factors: how far the water falls (head) and volume of water falling (flow rate) [1].

A turbine converts the energy of falling water into mechanical energy. Then an alternator converts the mechanical energy from the turbine into electrical energy. Alternatively, a turbine unit consists of a runner connected to a shaft that converts the potential energy in falling water into mechanical or shaft power. The turbine is connected either directly to the generator or is connected by means of gears or belts and pulleys, depending on the speed required for the generator. The choice of turbines depends mainly on the head and the flow rate. There are basically two types, reaction and impulse, the difference being in the manner of head conversion. In reaction turbines the water fills the blade passages and the head change or pressure drop occurs within the impeller. They can be of radial, axial or mixed flow types. In impulse turbines the high head is first converted through a nozzle into a high velocity jet which strikes the blades at one position as they pass by. Reaction turbines are smaller because water fills all the blades at one time [2].

TABLE I: CLASSIFICATION OF TURBINE TYPE

Type of turbine	High head	Medium head	Low head
Impulse turbine	Pelton Turgo	Cross flow Multi-jet turbine Turgo	Cross flow
Reaction turbine	-	Francis	Propeller Kaplan

II. BACKGROUND OF KAPLAN TURBINE

The Kaplan turbine is a great development of early 20th century. Invented by Prof. Viktor Kaplan of Austria during 1913 – 1922.The Kaplan is of the propeller type, similar to an airplane propeller. The difference between the Propeller and Kaplan turbines is that the Propeller turbine has fixed runner blades while the Kaplan turbine has adjustable runner blades. It is a pure axial flow turbine uses basic aerofoil theory. The Kaplan's blades are adjustable for pitch and will handle a great variation of flow very efficiently. They are 90% or better in efficiency and are used in place some of the old (but great) Francis types in a good many of installations. They are very expensive. The Kaplan turbine, unlike all other turbines, the runner's blades are movable. The application of Kaplan turbines are from a head of 2m to 40m.

A. Classification of Kaplan Turbines

The Kaplan turbine can be divided in double and single regulated turbines. A Kaplan turbine with adjustable runner blades and adjustable guide vanes is double regulated while one with only adjustable runner blades is single regulated. The advantage of the double regulated turbines is that they can be used in a wider field. The double regulated Kaplan turbines can work between 15% and 100% of the maximum design discharge; the single regulated turbines can only work between 30% and 100% of the maximum design discharge [3].

B. Working principle of Kaplan Turbine

There are many essential parts in axial flow turbine such as guide vane, runner, casing and draft tube. Kaplan turbine was designed to have a minimum number of blades (4 to 6 in number) radial oriented on the hub (see fig 1). The runner in a Kaplan turbine is a very challenging part to design. Runner is the most important component of the turbine and its blade profile is designed at different section from hub to casing to get the best performance and efficiency. Runner blades have a slight curvature and cause relatively low flow losses. In Kaplan Turbine, the flow is entered through a spiral casing. Decreasing area of casing makes sure that flow is entered to the central portion almost at uniform velocity throughout the perimeter. Water after crossing the guide vanes passes over the runner. The water enters the blades in axial direction from one side and leaves through the other side so that a large quantity of water flows through the runner. The function of the runner is to convert the potential energy of pressure (head) and flow of water into mechanical energy or rotational horsepower. Finally, it leaves through a draft tube [4].

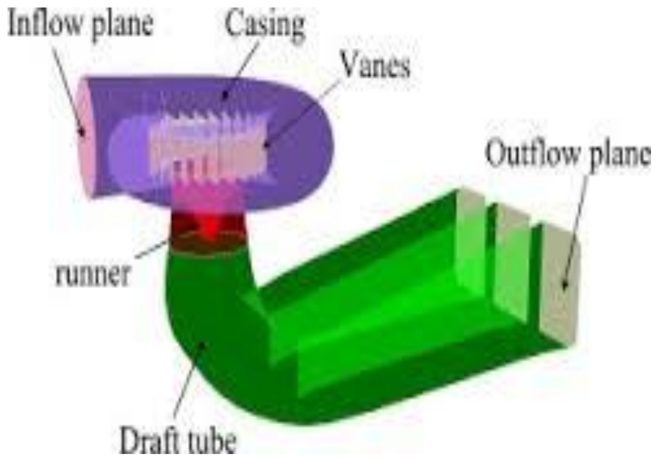

Figure.1.Working principle of Kaplan Turbine.

III. METHODOLOGY

A. Power and Speed of Turbine

The power available from turbine

$$P = \eta_o \times g \times \rho \times Q \times H_d \tag{1}$$

After knowing the design head and water flow rate for the expected output power, the specific speed can be specified by the following equation [5].

$$N_s = \frac{2.294}{H_d^{0.486}} \tag{2}$$

$$N = \frac{N_s \times (g \times H)^{\frac{3}{4}}}{\sqrt{Q}} \tag{3}$$

B. Diameter of Runner and Hub [6]

Diameter of runner

$$D = \frac{84.5 \times (0.79 + 1.602 \times N_s) \times \sqrt{H_d}}{60 \times N} \tag{4}$$

Diameter of hub

$$d = (0.25 + 0.0951/N_s) \times D \tag{5}$$

C. Flow Parameter for Kaplan Turbine

The expressions for the power delivered to the shaft by passing water are the same for all type of reaction turbines. Steady and one dimensional flow concept is used for calculation. The flow parameters at inlet and outlet velocity triangle of Kaplan turbine are defined in Fig2.The velocity triangle is drawn to get relative velocity at rotor inlet. At exit from the runner the flow is show leaving the runner without a whirl velocity and constant axial velocity [9].

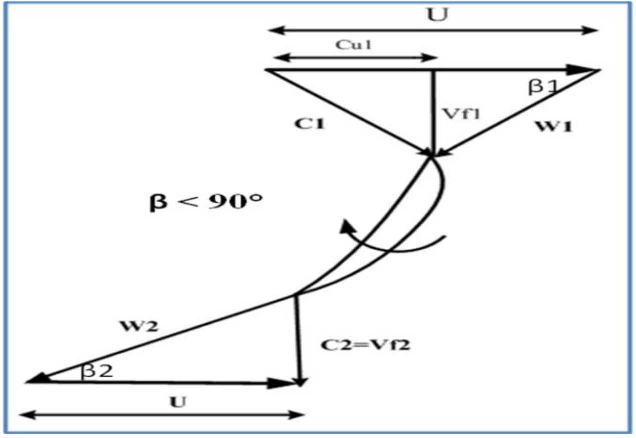

Figure.2. Inlet and Outlet Velocity Triangle of Kaplan Turbine.

Flow velocity

$$V_F = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}\left(D^2 - d^2\right)} \tag{6}$$

Tangential velocity

$$U = \frac{\pi\, DN}{60} \tag{7}$$

Whirl velocity

$$C_{u1} = \frac{\eta_h \times g \times H}{U} \tag{8}$$

The blade inlet angle

$$\tan\beta_1 = \frac{V_f}{U - C_{u1}} \tag{9}$$

The blade outlet angle

$$\tan\beta_2 = \frac{V_f}{U} \qquad \textbf{(10)}$$

D. Radius for Each Blade Section

In the space of the runner, it can be divided into five cylindrical sections (as shown in fig 3).

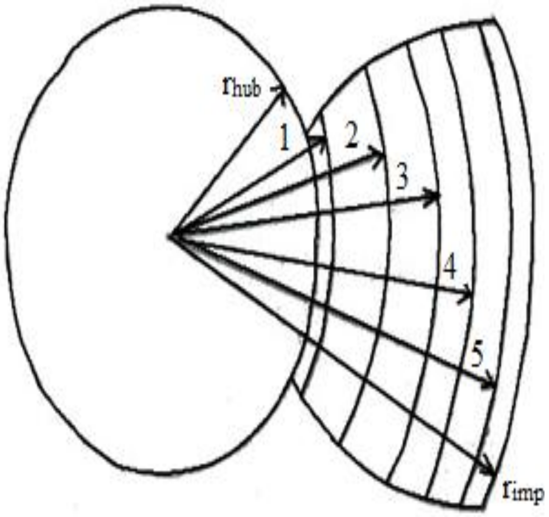

Figure.3.Blade divides into five sections.

Section I,

$$r_1 = \frac{d}{2} + 0.015d \qquad \textbf{(11)}$$

Section III,

$$r_3 = \frac{D}{2}\sqrt{\frac{1+(d/D)^2}{2}} \qquad \textbf{(12)}$$

Section II,

$$r_2 = r_1 + \frac{r_3 - r_1}{2} \qquad \textbf{(13)}$$

Section IV,

$$r_4 = r_3 + \frac{r_5 - r_3}{2} \qquad \textbf{(14)}$$

Section V,

$$r_5 = \frac{D}{2} - 0.015D \qquad \textbf{(15)}$$

E. Geometric Characteristics of Airfoils

The most important geometric characteristics of the airfoil are indicated in Fig 4. It is taken from the profile N.A.C.A (National Advisory Committee for Aeronautics) 2412. In this series, the geometric characteristics are shown in the following [8].

$$\frac{m}{l} = 0.02, \frac{L}{l} = 0.40, \frac{t}{l} = 0.12$$

Where, m is maximum deflection of the central curve of the airfoil, L is distance of maximum deflection of the central curve from the leading edge, 1 is length of chord and t is maximum thickness of the blade. The following equation of coordinates unsymmetric NACA Four-Digit Series

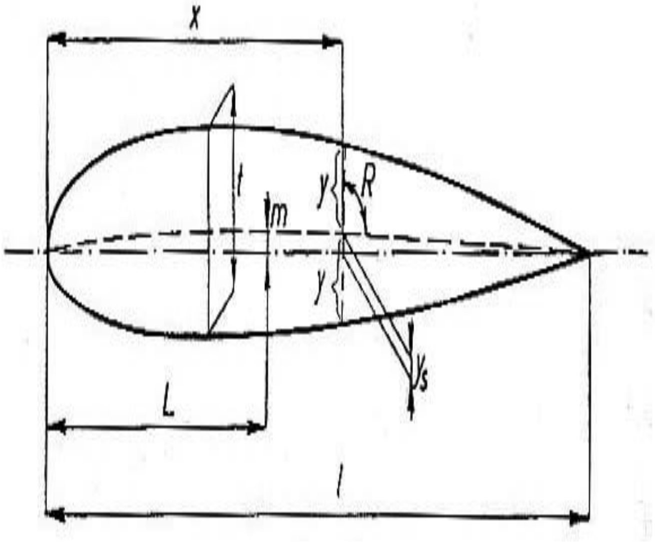

Figure.4. Geometric Characteristics of Airfoils.

$$y_t = \frac{t}{0.2}(0.2969\sqrt{x} - 0.126x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4)$$

$$y_c = \frac{m}{p^2}(2px - x^2) \qquad \text{from } x = 0 \text{ to } x = p$$

$$y_c = \frac{m}{(1-p)^2}[(1-2p) + 2px - x^2] \quad \text{from } x = p \text{ to } x = c$$

$$\tan\theta = \frac{dy_c}{dx}$$

$$y_u = y_c + y_t \times \cos\theta$$

$$y_l = y_c - y_t \times \cos\theta$$

TABLE II: The Coordinate of X and Y for Naca Turbine

x	y_u	y_l
0	0	0
1.25	2.15	-1.65
2.5	2.99	-2.27
5	4.13	-3.01
7.5	4.96	-3.46
10	5.63	-3.75
15	6.61	-4.10
20	7.26	-4.23
30	7.88	-4.12
40	7.80	-3.80
50	7.24	-3.34
60	6.36	-2.76
70	5.18	-2.14
80	3.75	-1.50
90	2.08	-0.82
100	.13	-.13

F. Required Parameters to Design Blade Profile

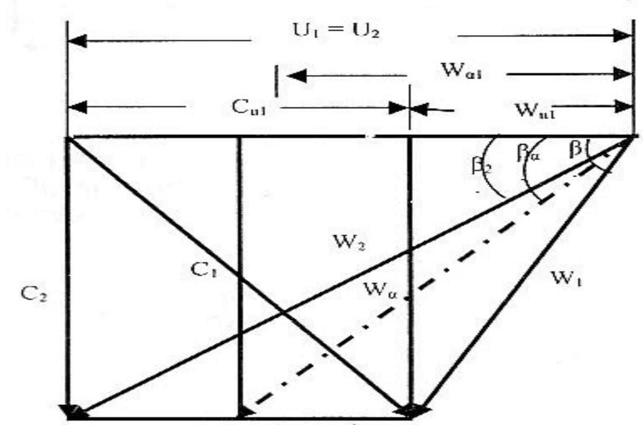

Figure.5. Velocity Triangle of Axial Turbine.

Average blade angle, β_α

$$\tan\beta_\alpha = \frac{V_f}{W_{\alpha 1}} \tag{16}$$

Average relative velocity

$$W_\alpha = \frac{W_{\alpha 1}}{\cos\beta_\alpha} \tag{17}$$

The specific relative velocity

$$w_\alpha = \frac{W_\alpha}{\sqrt{2g \times H_d}} \tag{18}$$

G. Circulation

The circulation around the blade of turbine is shown in Fig6. The water approaches the blade at the velocity C1which incorporate a certain peripheral component C_{ul}. That is in the form of a whirl with its axis in the turbine axis and the circulation [7]; The circulation in front of the runner is

$$\Gamma_1 = 2\pi r C_{ul} \tag{19}$$

The circulation in back of the runner is

$$\Gamma_2 = 2\pi r C_{u2} \tag{20}$$

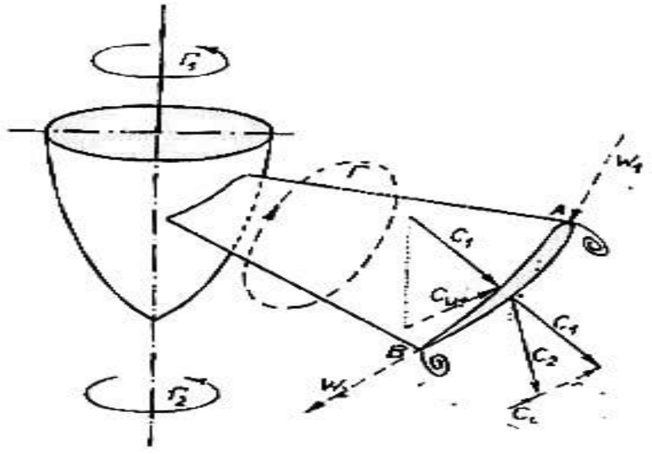

Figure.6. Circulation around the Blade.

The circulation around the blade

$$\Gamma = \frac{2\pi r}{z}(C_{ul} - C_{u2}) \tag{21}$$

Since t is the spacing of the blade, $t_s = \frac{2\pi\ r}{z}$ **(22)**

Therefore, $\Gamma = t_s(C_{ul} - C_{u2})$ **(23)**

H. Angle of Attack

An airfoil shaped body moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion is called lift. The component parallel to the direction of motion is called drag. Angle of attack is the angle between the body's reference line and the oncoming flow. Therefore, angle of attack is

$$\alpha_\alpha = \alpha - 57.3\frac{c_z}{6\pi} \tag{24}$$

The lattice angle is

$$\beta = 90 - \beta_\alpha + \alpha_\alpha \tag{25}$$

I. Shaft Diameter

Bending moment is neglected because of vertical shaft

$$d_s = \sqrt[3]{\frac{16 \times k_t \times M_t}{\pi \times S_S}} \tag{26}$$

The torsional moment

$$M_t = \frac{60 \times P}{2\pi \times N} \tag{27}$$

IV. RESULT AND DISCUSSION

A. Theoretical Result for Parameters of Turbine

The parameters of the Kaplan Turbine are listed in Table III.

TABLE III: Parameters of Kaplan Turbine

Parameters	Data
Output power	12.5 MW
Runner diameter	2.6628m
Hub diameter	1.2515 m
Shaft diameter	387 mm
Specific speed	0.4323
Rotational speed	262 rpm
Number of runner blades	5
Flow velocity	11.9852 m/s

B. Theoretical Result for Blade Profile

The calculated results which are based on net head 31m and water flow rate, 52 m^3/s, are shown in Table IV.

TABLE IV: Result Data for Blade Profile

Parameters	I	II	III	IV	V
R (m)	0.645	0.842	1.04	1.166	1.291

U (m/s)	17.68	23.11	28.53	31.98	35.43
V_f (m/s)	11.98	11.98	11.98	11.98	11.98
β_1 (degree)	82	48	33	27	24
β_2 (degree)	34	27	24	21	19
Cu1 (m/s)	15.99	12.24	9.91	8.84	7.98
$W_{\alpha_1}(m/s)$	9.68	16.98	23.58	27.56	31.43
β_α (degree)	51	35	27	24	21
$W\alpha(m/s)$	15.41	20.79	26.45	30.05	33.64
t_s(m)	0.81	1.06	1.31	1.46	1.62
Γ (m^2/s)	12.96	12.96	12.96	12.96	12.96
l/t_s	1.45	1.225	1.1	1.05	0.9
l (m)	1.17	1.29	1.44	1.54	1.46
β (degree)	52	61	66	69	71
α_α	13.44	6.49	3.40	2.25	1.47

1. Runner Geometry

It is necessary to get the airfoil shape for the various chord length of each blade section from Design Foil software. Then, isometric view of runner blade is drawn with calculated data by using SolidWorks software.

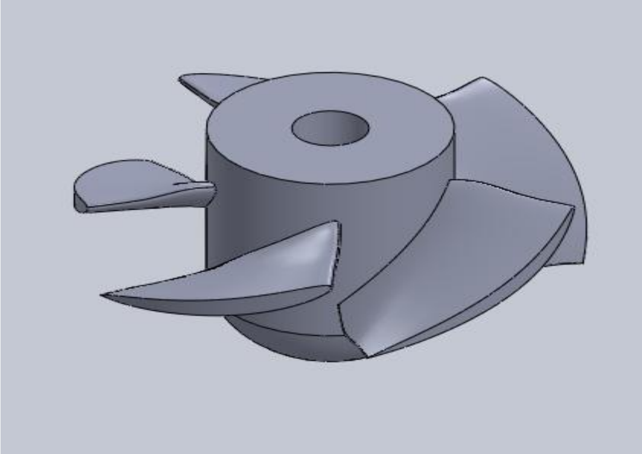

Figure.7. Isometric View of the Runner Blade.

C. Numerical Result

In this study, the Solid Works flow simulation is used to simulate the design of Kaplan Turbine. This analysis states velocity distribution of Kaplan Turbine.

1. Boundary Condition

Water flow rate inlet and environmental pressure outlet are set as boundary condition; no slip condition is enforced on wall surface .Water flow rate having uniform velocity profile with vectors parallel to the turbine's axis.

2. Results

From Fig (8) it can be seen clearly that for axial flow turbine, the flow velocity gradually increases from inlet to blade and from blade to outlet of rotation region. But the flow velocity on runner blades is equal. So, theoretical result and simulation result is nearly equal. Fig(9) show clearly the velocity distribution on the runner blade surface . It can be seen clearly that the velocity of the end of runner blade greater than the velocity near the hub. It is found that the tangential velocity values are within the theoretical calculation result.

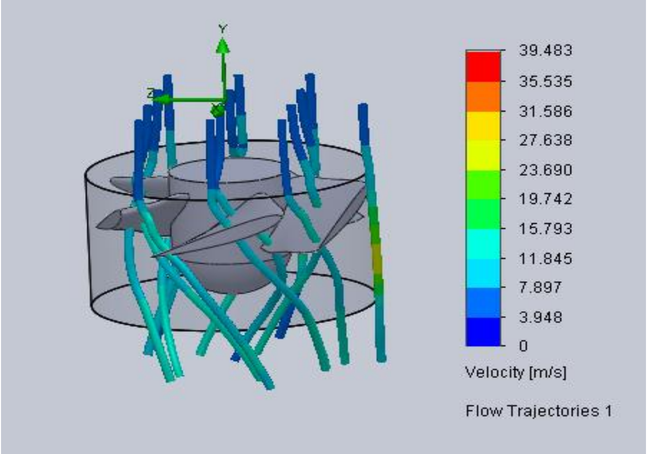

Fig.8. Velocity Distribution on Kaplan Turbine Blade.

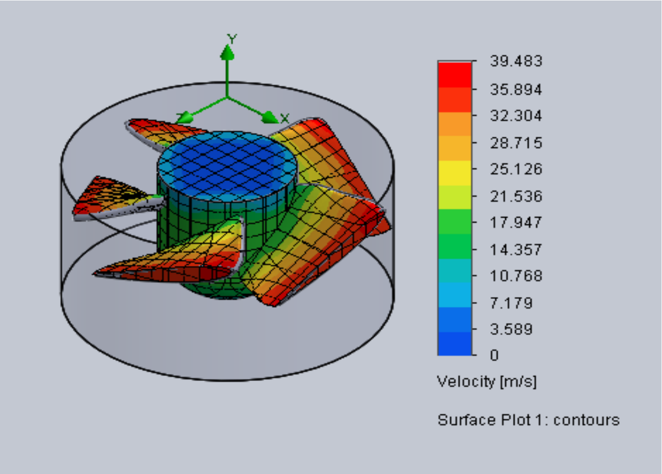

Fig.9. Flow Velocity Distribution over the Runner Blade Surface.

V. CONCLUSIONS

In hydropower plant, turbine is one of the most important parts to generate electricity. The output power of turbine depends upon the head and flow rate. So Kaplan turbine type is chosen for 31 m head and flow rate 52 m^3/s to generate 12.5 MW power. To meet the required power from the turbine, the blade design is the most important. In this paper, the detailed design of blade that is divided in five cylindrical sections is presented. Then, the dimensional data of runner blade is calculated by using MATLAB program and Microsoft Office Excel Software. In this study, the SolidWorks flow simulation is used to simulate the design of Kaplan turbine. The theoretical analysis is checked by simulations by SolidWorks software and the velocity distribution is also mentioned.

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