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Design of 50 kW Kaplan Turbine for Micro hydro Power Plant

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Abstract -- Low-head power plants are expected to be implemented increasingly in the future. The hydraulic and mechanical design will be detailed and compared to actual performance. In this paper, the generator power is 50kW and the water head is 8m. In Kaplan turbine design, the runner radius is 228.25mm, the runner speed is 826.12rpm, number of runner is four and the number of guide vane is eleven. In Kaplan design, the variable head is considered from 2m to 9m and the runner dimensions and the runner speed are as well as the Kaplan turbine output is 75.6082kW at the 8m water head. The double regulating system is considered and the hollow rotor shaft dimensions are outside diameter of 98mm and inside diameter of 78.4mm.

Indexed Terms: Low head power plant, hydropower system, Kaplan turbine, head, turbine output, hollow rotor shaft

I. INTRODUCTION

One of the most useful natural energy sources to fulfill the electricity requirement is hydro-electric power project. Therefore, natural source of water can provide that required power for farms, schools, hospitals and rural communities.

Moreover, it can develop many industrial zones and reduce dependency on scarce of fuel resources. The propeller turbines have the fixed blade so it is suitable for the constant head system and the Kaplan turbines have the adjustable blade so it is more suitable for the variable head system.

Hydropower plants can be equipped with different types of turbines depending on the head and discharge of the site to reach the highest possible efficiency. These turbines can be divided into three major types: Francis, Kaplan and Pelton turbines as shown in Fig 2 and also they can be classified as reaction and impulse types. Fig 2 shows the application areas of turbines depending on the head (H) and a dimensionless coefficient relating to specific speed (σ).

The head His difference between headwater and tail water. As shown in Fig. 2, Pelton turbines are used for high heads while Francis and Kaplan turbines are used for medium and low heads, respectively. The Kaplan turbine is a reaction type which is suitable for low pressure hydropower plants and can be used with big discharges. The Kaplan runner, similar to the Francis runner, also should be submerged in the water for proper operation. The water enters to the runner through regulated guide vanes which are radially mounted around the turbine inlet and hits with a certain angle of attack on the runner blades as shown in Fig. 1.

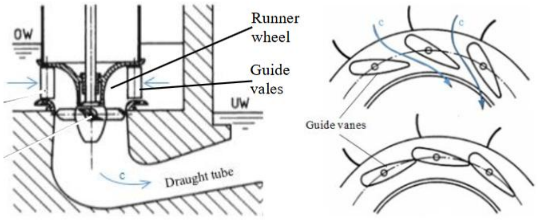

Fig. 1: A Kaplan turbine (runner wheel and guide vanes).

To achieve the highest possible efficiency at varying flow rates, the guide vanes and runner blades are adjustable and can be regulated by a controller. At a constant flow rate static blades are sufficient. The guide vanes can also be shut in case of a problem to protect the runner. As the water hits the blades it transmits its energy to the blades and streams out through the draught tube.

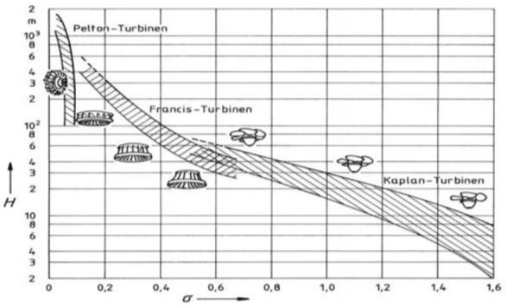

Fig.2: The use of turbines with varying head [4].

The runner can be positioned vertically as shown in Figure 1, otherwise horizontally or somewhere in between. If the cross section of the draught tube is assumed to be constant, the velocity does not vary from the inlet to outlet due to the continuity. Static pressure changes at the suction head does not affect the efficiency and hence the runner could be placed anywhere in the draught tube. When the runner is placed inside the tube, the guide vanes must be placed just in front of the runner for producing an accurate twist. But if the draught tube is quiet long, the risk of cavitations increases due to a high head [4, 8].

II. REACTION TURBINE

The reaction turbines considered here are the Francis turbine, bulb turbine, tubular turbine and the propeller turbine. A special case of the propeller turbine is the Kaplan. In all these cases, specific speed are high, i.e reaction turbines rotate faster than impulse turbines given the same head and flow conditions.

A. Propeller Turbine:

Propeller turbine is axial flow reaction turbine, generally used for low head. The basic propeller turbine consists of a propeller, similar to a ship's propeller, fitted inside a continuation of the penstock tube. The propeller usually has three to six blades, three in the case of very low head units and the water flow is regulated by static blades or swivel gates just upstream of the propeller. This kind of propeller turbine is known as a fixed blade axial flow turbine as shown in Fig. 3. The pitch angle of the rotor blades cannot be changed.

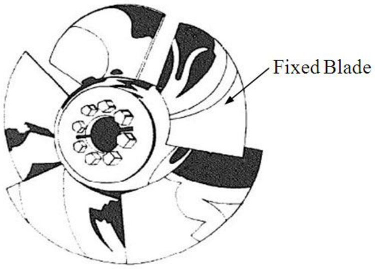

Fig. 3. Runner of Propeller Turbine [9]

B. Kaplan Turbine:

Kaplan turbines have been developed to be the most employed type of turbines for low heads and comparatively large discharges. The Kaplan turbines are fairly suitable for the purpose of three main reasons:

(1) relatively small dimensions combined with high rotational speed
(2) a favorable progress of the efficiency curve
(3) large overloading capacity

The runner has only a few blades radial oriented on the hub and without an outer rim. The water flows axially through. The runner blades have a slight curvature and cause relatively low flow losses.

Kaplan turbine is most appropriate for operation with a low head and a large amount of discharge. Owing to adjustable runner blades it offers the significant advantage to give high efficiency even in the range of partial load, and there is little drop in efficiency due to head variation or load.

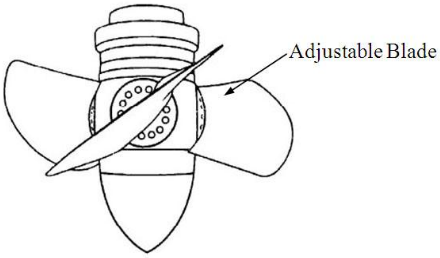

Fig. 4. Runner of Kaplan Turbine [11]

Kaplan turbine is axial-flow reaction turbines, generally used for low heads. The Kaplan turbine has adjustable runner blades as shown in Fig.4 and may or may not have adjustable guide vanes. If both blades and guide-vanes are adjustable it is described as double-regulated. If the guide-vanes are fixed it is single-regulated. Unregulated propeller turbines are used when both flow and head remain practically constant.

C. Main Components and Functions of Kaplan Turbine:

The main components of the Kaplan turbine are shown in Fig. 5. As having adjustable runner blades, the construction of Kaplan turbine becomes naturally a bit complicated. The runner blade operating mechanism consists of a pressure oil head, a runner servomotor, and the blade operating rod inside the shaft etc.

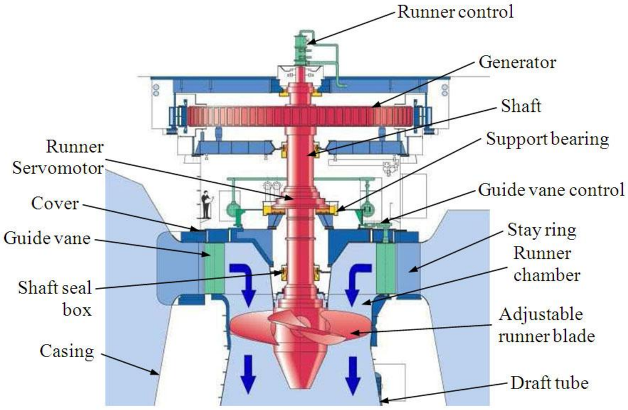

Fig. 5. Complete Assembly of Kaplan Turbine [2]

III. BASIC THEORIES OF KAPLAN TURBINE

The basic theories of Kaplan turbine are the same as well as in following.

A. *Specific Speed and Head Limitation*

The specific speed is a type of characteristic where all runners of a given specific speed are similar in form and vary only in size. This speed forms a basis for classification of turbines. The specific speed can be defined as the speed of a homologous turbine of that would develop one metric horse power at one meter head.

$$N = \frac{N_s \sqrt{P_t}}{H_d^{1.25}} \tag{1}$$

where

N_s = Specific speed (rpm)
N = Unit speed (rpm)
H_d = Design head (m)
P_t = power output of the turbine (kW)

Calculating the specific speed of the turbine after knowing the design net head (H_d). The specific speed can be calculated from the following equation. For head less than 18m – fixed blade propeller turbine,

$$N_s = \frac{885.5}{H_d^{0.25}} \tag{2}$$

Turbines with low specific speeds work under high head and low discharge conditions, while high specific speed turbines work under low head and high discharge conditions.

TABLE I.
Relationship Between Head and Turbine Type

Type of Turbine	Limit of Head	Specific Speed
Pelton turbine	300 to 2000 m	4 to 70
Cross flow		40 to 200
Francis	10 to 100 m	60 to 400
Kaplan, Propeller	2.5 to 450 m	300 to 1100
Fixed blade Propeller	1.5 to 70 m 1.5 to 30 m	) 1000

B. *Work done and Efficiency of the Turbine*

The expression for the power delivered to the shaft by passing water is the same for all types of reaction turbines. In this case, it is necessary to use velocity diagram and Euler’s Equation to calculate the power and efficiency of the turbine. Inlet and outlet velocity triangle of propeller turbine is indicated in Fig. 6.

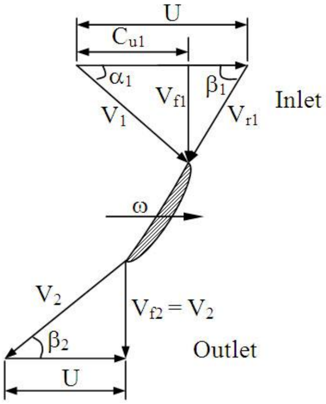

Fig. 6: Schematic Diagram of Automatic Transmission

where

U = runner tangential velocity (m/s)
ω = runner angular velocity (m/s)
V = fluid absolute velocity (m/s)
V_r = fluid relative velocity (m/s)
C_{u1} = fluid whirl velocity (m/s)
β = runner blade angle (deg)
α = guide vane angle (deg)

The runner tangential velocity,

$$U = \frac{\pi D n}{60} \qquad (3)$$

The runner angular velocity,

$$\omega = \frac{2U}{D} \qquad (4)$$

The hydraulic efficiency,

$$\eta_h = \frac{(C_{u1}U_1 - C_{u2}U_2)}{g\,H} \qquad (5)$$

where,

g = acceleration due to gravity (m/s)

H = design head (m)

C. Runner Blade

The outer diameter of the runner,

$$D = \frac{84.5 \times \phi \times \sqrt{H_d}}{N} \qquad (6)$$

$$\phi = 0.0242 \times N_s^{2/3} \qquad (7)$$

where

H_d = design head (m)

N = runner speed (rpm)

N_s = specific speed (rpm)

The inner diameter, d can be obtained by using the Fig. 7 depending on the specific speed, N_s.

D. Runner Blade Angle

The runner blade angle is between the tangential velocity of runner and the relative velocity of water.

It can be define by the following equations.

Inlet blade angle,

$$\tan \beta_1 = \frac{V_{f1}}{U - V_{w1}} \qquad (8)$$

Outlet blade angle,

$$\tan \beta_2 = \frac{V_{f2}}{U - V_{w2}} \qquad (9)$$

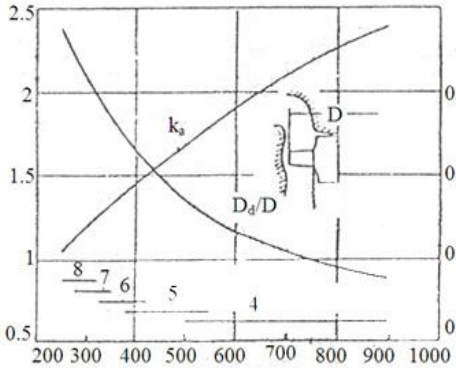

Fig. 7: Relationship between Speed Ratio and Specific Speed [7]

E. Guide Vane Angle

The main important is the correct design of the outlet blade angle, which must correspond to the velocity diagram. The angle of the outlet part in the one dimensional solution is given by the velocity at the outlet edge of the guide blade. The outlet blade angle of guide vane can be calculated.

$$\tan \alpha = \frac{V_f}{C_{u1}} \qquad (10)$$

where

V_f = Flow velocity (m/s)

C_{u1} = Component of absolute velocity (m/s)

F. Circulation

The water approaches the blade at the velocity C_1 which incorporate a certain peripheral component C_{u1}. That is in the form of a whirl with its axis in the turbine axis and the circulation can define as follow;

$$\Gamma_1 = 2\,\pi\, r\, C_{u1} \qquad (11)$$

where

Γ = circulation (m^2/s)

t = spacing of the blade (m)

C_u = tangential component of absolute velocity (m/s)

The spacing of the blade

$$t = \frac{2\pi\ r}{z} \qquad (12)$$

IV. DESIGN OF 50KW KAPLAN TURBINE

In design consideration of a turbine, the hydraulic efficiency, the best speed for maximum efficiency and synchronous speed are necessary in design calculation. In this thesis, overall efficiency and mechanical efficiency are assumed such as 68% and 85%.

To obtain 50 kW for four pole generator, the turbine speed to drive the generator must be about 826.12 rpm. The design head is selected 8m to design the runner diameters and the number of runner and calculate the adjustable discharge and the inlet and outlet angle of the runner blade. The designed Kaplan turbine is the double regulated type because both blade and guide-vane angle are adjusted. The data specifications are as followed.

The required generator output power, P_g = 50 kW
Generator efficiency, η_g = 0.8
Generator speed, N_g = 1500 rpm
Design head of turbine, H_d = 8m
Mechanical efficiency , η_m = 0.85

The results data of the Kaplin Turbine is as shown in Table 1.

TABLE 1.Results Data 50kW with 8m Head

Item	Result Data
Turbine power, P	73.529 kW
Turbine speed, N	826.12 rpm
Flow rate, Q	1.17 m^3/s
Runner outer diameter, D	456.5mm
Hub diameter, d	209.9mm
Height of the hub or boss	356.7mm
Length of guide vane, L	126.6mm
Height of guide vane, B	182.6mm
Number of guide vane, N_g	11
Number of runner, z	4
Guide vane inlet angle, α_1	64.33°
Runner inlet angle, β_1	42.03°
Runner outlet angle, β_2	32.16°
Water circulation, Γ	47 ^{2}/s

A. *Variable Head in Kaplin Turbine*

The propeller turbine is not adjusted the runner blade and guide vane angles, so the output power and discharge will increase when the head is increase. The relatives of power and discharge are shown in Fig. 8 and Fig. 9.

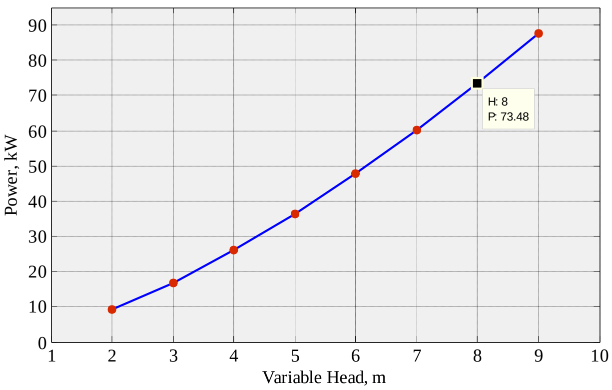

Fig. 8. Relations of Head and Power of Kaplin Turbine

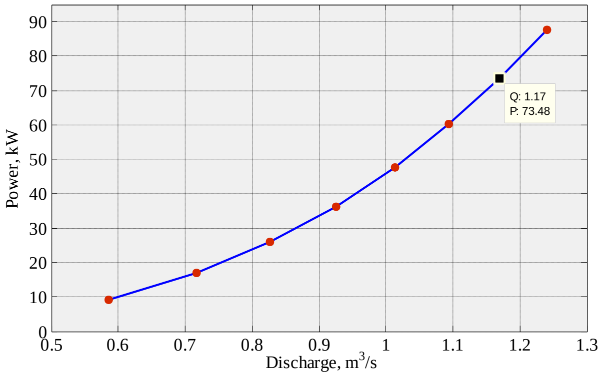

Fig. 9. Relations of Discharge and Power of Kaplin Turbine

The runner dimensions and the rotor speed are not changed. So, the runner blade angles and the guide vane angles must be adjusted to be the highest efficiency of turbine. The adjustable blade angles and relative values are displayed as below by using MATLAB program.

Specified data from design point,
N = 826.12rpm
g = 9.81 m/s^2
ρ = 1000 kg/m^3
A = 0.1291 m^2
U = 14.4127 m/s
Head variable, H_v = 2 to 9 m
For design head, H_v = 8 m
Guide vane angle, α = 55°

Runner blade angle, β = 40°

TABLE 2.Results of Table Design

Head	α	β	Q	Γ	η	Power
2	75	20	0.6171	0.0790	94.08	11.3899
3	71	24	0.7183		93.82	19.8343
4	67	28	0.8072	0.1182	97.48	30.8746
5	64	31	0.8646		95.98	40.7060
6	61	34	0.9135	0.1637	96.04	51.6407
7	58	37	0.9533		96.84	63.3920
8	55	40	0.9835	0.2015	97.96	75.6082
9	52	43	1.0038		99.17	87.8858
				0.2420		
				0.2847		
				0.3291		
				0.3748		

G. *Design of Shaft*

Specification of shaft are given as follow,

Shaft material = 40C8 Carbon Steel
Allowable shear stress, $s_{sal\,l}$ = 96 MPa
Turbine power, P_t =75.6082 kW
Shaft speed, N_s = 826.12rpm
Number of runner = 4
Turbine tangential force, F_t= 1942.67×4 = 7770.68 N
Turbine axial force, F_n = 1469.24×4 = 2210.52 N
Shaft length, L_1 = 500 mm
Shaft length, L_2 = 1000 mm
Runner mean radius, r_m = 166.6 mm
Moment factor, k_b = 3
Torque factor, k_t = 3

The main shaft of the Kaplan turbine must transmit the full torque of the runner the maximum head conditions at which the turbine will operate. The shaft of the turbine is mainly subjected to torsional stress by the driving torque. The shaft of Kaplan turbine is hollow and the axial load is applied. So, the applied stress on the shaft is defined as,

$$s_s = \frac{16}{\pi d_o^3\left(1-K^4\right)}\sqrt{\left[k_b M_b + \frac{\alpha F_a d_o\left(1+K^2\right)}{8}\right]^2 + \left(k_t M_t\right)^2} \qquad (13)$$

where
d_o = outside diameter, m
d_i = inside diameter, m
K = inside and outside diameter ratio
α = axial load factor
N = the speed of turbine, rpm
M_b = bending moment, N m
M_t = torsional moment, N m

The design data of shaft in variable diameter assumption are as shown in Table 3.

TABLE 3. Results of Table Design

Outside Diameter (m)	Inside Diameter (m)	Actual Shear Stress (Pa)
0.0950	0.0760	237.9497
0.1000	0.0800	204.0197
0.1050	0.0840	176.2464
0.1100	0.0880	153.2944
0.1150	0.0920	134.1612
0.1200	0.0960	118.0845
0.1250	0.1000	104.4775
0.1300	0.1040	92.8836
0.1350	0.1080	82.9438
0.1400	0.1120	74.3733
0.1450	0.1160	66.9443
0.1500	0.1200	60.4728

The shaft outside diameter of 0.135m is selected, so the actual applied stress, s_s is 86 MPa. Therefore, it is less than the allowable shear stress, s_{sall} of 96 MPa. The assumed diameter is satisfied for design.

V. CONCLUSION

The generator output is 50 kW at the runner speed of 826.12 rpm. The considered design head is 8m and the variable head range is 2m to 9m. The runner and guide vane angle of the propeller turbine are 42.03° and 64.33°. The runner dimensions of the propeller turbine are 0.4565m outside diameter and 0.2099m inside diameter. The number of runner is four and the number of guide vane is eleven. In Kaplan turbine, the runner blade inlet angle must be adjusted 20° and the guide vane angle is also must be adjusted 75° at 2m head. The angles at 9m are 43° and 52°. The diameters of rotor shaft are 135mm outside and 108mm inside. In this research paper, the efficiency of propeller turbine is constant because the runners and guide vanes angles are not adjusted as much as the Kaplan turbine.

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