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Design Calculation of 40 MW Francis Turbine (Runner)

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ABSTRACT

A water turbine is one of the most important parts to generate electricity in hydroelectric power plants. The generation of hydroelectric power is relatively cheaper than the power generated by other sources. There are various types of turbines such as Pelton Turbine, Cross-flow Turbine, and Francis Turbine which are being used in Myanmar.

In this paper, one of the hydroelectric power plant which is used Vertical Francis Turbine type. The Francis turbine is one of the powerful turbine types. Francis Turbine is a type of water turbine that was developed by James Bicheno Francis. Hydroelectric Power Plant, Thaukyegat No.2, is selected to design the runner. This Vertical Francis Turbine is designed to produce 40 MW electric powers from the head of 65 m and flow rate of 70.10m3/s. The design parameters of 40 MW Vertical Francis Turbine runner's diameter, height, elevation, shaft, numbers of blades and blade angles are calculated. The initial value of turbine output is assumed as 94%. The number of guide blades and runner blades are also assumed. The detailed design calculations of the runner are carried out. Moreover, the selection of the turbine type according to the head, the flow rate and the power are also performed.

KEYWORDS: *Hydropower plant, Francis turbine, Head, Blade*

I. INTRODUCTION

Francis Turbines are almost mounted water from the shaft vertical to isolate water from the generator. Hydropower, also known as hydroelectric power, is a reliable, domestic, emission-free resource that is renewable through the hydrologic cycle and hardness the nature energy of flowing water to provide clean, fast and flexible electricity. It is a clean form of power generation. Water is a natural source of energy to produce electricity. Water flowing under pressure has to forms of energy: kinetic energy and potential energy. The water or hydraulic turbines convert this kinetic and potential energy into mechanical power. Hydraulic turbine runners can only be performed by numerical methods due to the complexity of these structures. The flow in hydraulic turbines of the Francis type is quite complicated due to its three-dimensional nature and the curvature of the passages between runner blades.

II. Design Consideration of Francis Turbine

The expression for the power delivered to the shaft by passing water is the same for all type of reaction turbines. In this case, it is necessary to use velocity diameter and moment of momentum equation (Euler's Equation) to calculate the power and efficiency of the inward flow turbine. It must be assumed that friction is neglected and fluid has the guidance through the turbine. That is the infinite number of vanes and relative velocity of the fluid. The expression for the power delivered to the shaft by passing water is the same for all type of reaction turbines. In this case, it is necessary to use velocity diameter and moment of momentum equation (Euler's Equation) to calculate the power and efficiency of the inward flow turbine. It must be assumed that friction is neglected and fluid has the guidance through the turbine. That is, the infinite number of vanes and relative velocity of the fluid is always tangent to the vane.

A. Hydropower Plants

A Hydropower Plant requires no fuel and it is much simpler to operate and maintain. Therefore the operating costs of the Hydropower Plant are much less than a thermal power plant. Hydropower plants can be classified by many different aspects. This classification is according to the working of hydropower plants, for example, they can by classified be the source of the water itself and by their construction or their turbine. Water power is one of the major sources of energy. The other sources of energy being developed by water power are one of the major sources of energy. The other sources of energy being developed by fuels such as coal, oil, etc., and nuclear power are used for energy. These are some of the conventional sources of energy.

B. Classification of Hydropower Plants

There are several classifications of related to the dimension of Hydropower Plants. Hydropower Plants can be classified into the following

1. Large Hydro: 100MW to 1000MW
2. Medium Hydro: 15MW to 100MW
3. Small Hydro: 1MW to 15MW
4. Mini Hydro: 100kW to 1MW
5. Micro Hydro: 5kW to 100kW
6. Pico Hydro: Fewer Watt to 5kW

C. Types of Hydropower Plants
There are different types of Hydro Power Plants based on types of facilities for the generation of hydropower. Construction of large Hydropower Plants is a practical and economically viable proposition as the capital costs of a project can be reduced with such installations. Hydropower Plants may be classified in different ways depending on the certain classification. They are
1. Reservoir or Storage Type
2. Run-of-River Type
3. Pumped Storage Type

D. Main Components of Francis Turbine
Francis Turbines are the medium head type of hydraulic turbines, having stationary (Spiral casing, Stay Vanes and Guide Vanes) and rotating component. There are several components of Francis Turbine.
They are
1. Spiral casing
2. Stay ring
3. Guide vanes
4. Runner
5. Draft tube
6. Shaft

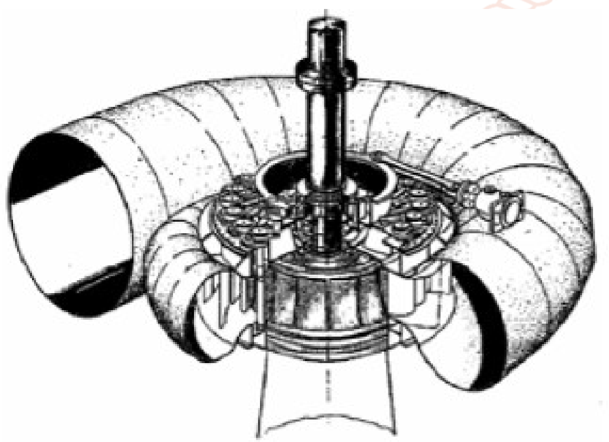

Figure1. Francis Turbines

III. Design Theory of Francis Turbine
Francis Turbines can be arranged in two ways; with vertical shaft and horizontal shaft. The vertical shaft arrangement requires the minimum space for installation and therefore permits the smallest area powerhouse.

It is not only more economical in space, but in many cases, it is the only practical solution for large machines, especially when the topographical nature of the site limits the size of the powerhouse.

By setting of the turbine is meant the location with respect to the head and tailwater level. Referring to Figure3.4 and equating the energies of flow at the exit end of the runner to the energy of flow at the exit end of the draft tube. The result of the various condition of head, speed and capacity are that runner of low speed and capacity are generally demanded under the high head, while runner of high speed and capacity are necessary under the low head.

$$\frac{P_2}{W}+\frac{V_2^2}{2g}+Z+Hs = \frac{P_a}{W}+\frac{V_f^2}{2g}+Z-H_1$$

Table1.Turbine Selection (Head-Output)

Turbine Types	Effective Head(m)	Power Output(kW)
Horizontal Shaft Pelton	Over 75	100 ~ 5000
Vertical Shaft Pelton	Over 200	Over 4000
Horizontal Shaft Francis	17 ~ 300	400 ~ 5000
Vertical Shaft Francis	40 ~ 300	2000 ~ 20000
Cross Flow	7.5 ~ 100	50 ~ 1000
Kaplan	10 ~ 70	Over 100
Conduit Type Bulb	5 ~ 20	Over 1000
Package Type Bulb	5 ~ 18	150 ~ 4000

Table2. Relation between Water Temperature and Standard Stream Pressure

Water Temperature (°C)	Saturated Steam Pressure (m)
0	0.05
5	0.09
10	0.13
15	0.17
20	0.24

Table3. The relation between Elevation and Atmospheric Pressure

Elevation(m)	Pressure (Atm)
0	10.33
100	10.21
200	10.09
300	9.97
400	9.35
500	9.73
600	9.52
700	9.50
800	9.39
900	9.27
1000	9.16
1100	9.05
1200	8.94

A. The efficiency of Francis Turbine
The expression for the power delivered to the shaft by passing water is the same for all type of reaction turbines. In this case, it is necessary to use velocity diameter and moment of momentum equation (Euler's Equation) to calculate the power and efficiency of the inward flow turbine. As an assumption, it must be assumed that friction is neglected and fluid has the guidance through the turbine. That is, the infinite number of vanes and relative velocity of the fluid is always tangent to the vane, Steady and one-dimensional flow concept is used for calculation.

P = Elemental mass x Tangential velocity

$P = d_m \times V_1 \cos\alpha_1 \times r_1$

Similarly,

$T_2 = d_m \times V_2 \cos\alpha_1 \times r_2$

$T_m = d_m (V_2 \cos\alpha_1 r_1) \times r_2$

$T_t = m^\circ (V_1 \cos\alpha_1 r_1 - V_2 \mathrm{cos}\cos\alpha_2 r_2)$

Power equation is

Power = Torque $\times$ Angular Velocity

Power $= m^\circ(V_1\cos\alpha_1 r_1 - V_2\cos\alpha_2 r_2)\omega$

$V_1\cos\alpha_1 = V_{w1}$ & $V_2\cos\alpha_2 = V_{w2}$

$U_1 = r_1\omega_1$ & $U_2 = r_2\omega_2$

From above the relations, the equation of power is

Power $= m^\circ(V_{w1}U_1)$

Above equation can be changed by

$$\eta_m = \frac{UV_{w1}}{gH_d}$$

Where, η_h is hydraulic efficiency of turbine.

$$\eta_h = \frac{B.P}{\frac{W}{g}\times UV_{w1}}$$

Further the overall efficiency is,

$$\eta_0 = \eta_m \times \eta_h$$

$$\eta_0 = \frac{B.P}{\frac{W}{g}\times UV_{w1}} \times \frac{U_1V_{w1}}{gH_d}$$

$$\eta_0 = \frac{B.P}{WH_d}$$

$$W = \gamma.Q$$

$$\eta_0 = \frac{B.P}{\gamma QH_d}$$

Where,

B.P = Power of the turbine in kW

η_0 =Overall efficiency

Q = Flow rate through the turbine in m^3/sec

λ = Specific weight of water in kN/ m^3

H_d = Design head in m

B. Runner Design as Affected by Speed and Capacity

Head and available rate of flow varies widely among power plant. Generally, large flow rates accompany with low head relatively small rates of flow are available at high heads. Because of the difference in flow rates, low head usually requires runner of large water capacity and high head required runner of low capacity. Accordingly, the runner may be again classified as being of high, low and medium capacity, and the term may refer to either the discharge rate or the power output since the latter is a function of the discharge.

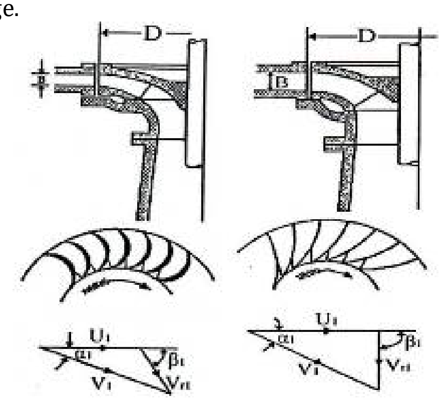

Figure2. Types of Runner

A. Low-Speed Runner
B. Medium Speed Runner
C. High-Speed Runner
D. High Speed- High Capacity Runner

C. The setting of Turbine Draft Head

By setting of the turbine is meant the location with respect to the head and tailwater level. Referring to and equating the energies of flow at the exit end of
the runner to the energy of flow at the exit end of the draft tube.

$$\frac{P_2}{W} + \frac{V_2^2}{2g} + Z + Hs = \frac{P_a}{W} + \frac{V_f^2}{2g} + Z - H_1$$

Where,

H_1 = Energy lost in friction during the passage of water through the draft tube

H_1 = Elevation of existing of the runner through the draft tube

Z = height of runner bottom above any assumed datum

P_2 =Pressure of exit section of runner

P_a = Atmospheric pressure

Since the flow through the draft tube is turbulent, the friction in the draft tube is proportional to V_2^2. Also, velocities at the various section of the draft tube are proportional to V_2 since the profile of flow is fixed.

Thus,

$$\frac{p_2}{W} = \frac{P_a}{W} - H_s - \frac{V_2^2}{2g}(1-K)$$

Where,

$$K = \frac{H_1 + (V_2^2/2g)}{(V_2^2/2g)}$$

η_d = efficiency of the draft tube

$$H_2 = H_a - H_s - \eta_d V_2^2/2g$$

Where,

σ = Thoma's cavitation coefficient

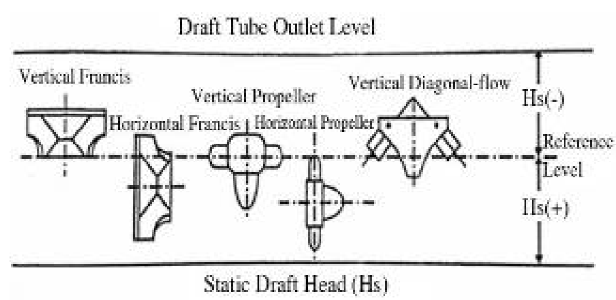

Figure3. Static Draft Head and Various Type of Turbines

D. Specific Speed

Limit of Specific Speed,

$$N_{sl} \leq \frac{21000}{H+25} + 35$$

Calculate Specific Speed, after decided the rated speed, Specific Speed,

$$N_s = \frac{N \times P_{t(i)}^{1/2}}{H^{5/4}}$$

E. Normal Efficiency

$$\eta_n = -1.172 \times \left(\frac{N_s}{100}\right) + 4.344 \times \left(\frac{N_s}{100}\right) + 82.321$$

Maximum Efficiency, $\eta_{max} = \eta_{th} + 2.08 \log P_{t(i)} - 4.61$

Speed factor, $_u$= $-4.4 \times (N_s/100)^2 + 0.039 \times (N_s/100) + 0.69$

Runner inlet diameter, $D_1 = 84.6 \times K_u \times \frac{H^{1/2}}{N}$ Runner outlet diameter,

$$D_2 = D_1 \times [-1.7 \times 12^{-2} (N_s/100)^2 + 0.44 \times (N_s/100) + 0.321]$$

Runner inlet height,

$$B_1 = D_1 \times [8.7 \times 10^{-3} (N_s/100)^2 + 0.15 \times (N_s/100) - 0.028]$$

Runner outlet height,

$$B_2 = D_2 \times [0.2875 + 0.0175 \times (N_s/100)^2]$$

Runner shaft diameter,

$$D_s = 2 \times \sqrt{\frac{P_t}{(863 \times N)}}$$

Inlet peripheral velocity,

$$U_1 = \frac{\pi D_1 N}{60}$$

Inlet absolute velocity,

$$V_1 = 0.6\sqrt{2 \times g \times H}$$

Inlet flow velocity,

$$V_{f1} = \frac{Q}{\pi D_1 B_1}$$

Outlet peripheral velocity,

$$U_2 = \frac{\pi D_2 N}{60}$$

Runner inlet angle,

$$\tan \alpha_1 = \frac{V_{f1}}{V_{w1}}$$

Guide vane inlet angle,

$$B_1 = 180° - \beta_1$$

$$\tan \beta = \frac{V_{f1}}{U_1 - V_{w1}}$$

Theoretical Output Power,

$$P_{theo} = \rho g Q H$$

F. Design Input Data

The required design data must be known from Thautyegat No.2 Hydroelectric Power Plant, in Bago Division (Myanmar).

Table4 .Input Data

Descriptions	Symbols	Value	Unit
Effective Head	H	65	m
Discharge	Q	70.10	m^3/s
Overall efficiency	η_o	94	%
Output Power of Turbine	P	44.7	kW

IV. Result Data

Table5. Result Data

Descriptions	Symbols	Values	Units
Inlet tangential velocity	U_1	27.48	m/s
Outlet tangential velocity	U_2	40.05	m/s
Inlet absolute velocity	V_1	21.42	m/s
Outlet absolute velocity	V_2	5.61	m/s
Inlet flow velocity	V_{f1}	10.95	m/s
Outlet flow velocity	V_{f2}	5.61	m/s
Inlet whirl flow velocity	V_{w1}	18.4	m/s
Outlet whirl flow velocity	V_{w2}	0	m/s
Inlet relative velocity	V_{r1}	13.3	m/s
Outlet relative velocity	V_{r2}	40.41	m/s
Runner inlet angle	α_1	3075	Degree
Runner outlet angle	α_2	90	Degree
Guide vane inlet angle	β_1	130	Degree
Guidae vane outlet angle	β_2	7.97	Degree
Turbine output power	P_t	42.75	MW
Generator Output power	P_G	42	MW
Inlet diameter of Runner	D_1	2.1	m
Outlet diameter of Runner	D_2	3.1	m
Inlet high of Runner	B_1	0.97	m
Outlet high of Runner	B_2	1.3	m
Runner discharge diameter	D_3	3.22	m
Runner shaft diameter	D_s	0.8	m
No: of Runner blades	Z	16	
No: of guide blades	-	24	
Runner elevation	H_s	-6	m
Turbine speed	N	250	rpm
Specific speed	N_s	280	m-kW
Runaway speed	N_r	486	rpm
Critical speed	N_c	972	rpm
Efficiency	η_t	94	%

Table 6.Comparison of Theory and Actual Data

Descriptions	Theory	Actual	Units
Runaway Speed	486.4	432.8	rpm
Turbine of Power	42.7	41.24	MW
Outlet Runner Diameter	3.06	2.94	m
Generation Power	41.89	40	MW
Runner Discharge Diameter	3.22	3.04	m
Shaft Diameter	0.8	0.7	m
Runner Outlet Height	1.3	1	m

Figure4. Two Dimensional View of Runner

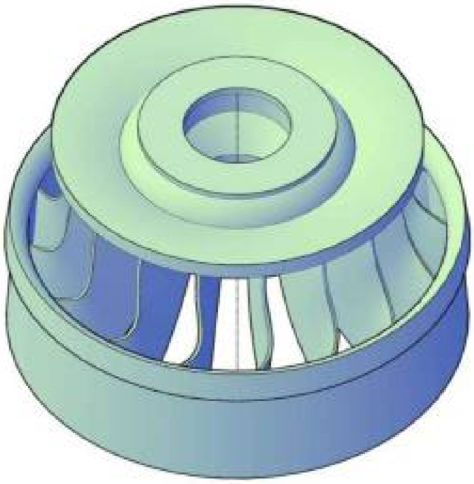

Figure5. Three Dimensional View of Runner

Discussions and Conclusions

Hydropower is contained of two main portions as the mechanical and electrical system. Generally, Francis Turbines are placed in Vertical Francis Turbines configuration. Vertical Francis Turbine is very widely used in the world for large hydroelectric Power plant.

The runner design is very important for any type of turbine. In this paper, the design calculation of the runner of 40 MW Vertical Francis Turbine which is taken from Thaukyegat No.2 Hydroelectric Power Plant is carried out. This runner is designed in the maximum power output conditions. Any type of turbine, runner blade design is very important. In this paper, the runner blade design of 40MW Francis Turbine is calculated.

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