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Design of Cross Flow Turbine (Runner and Shaft)

San San Yi, Aung Myo Htoo, Myint Myint Sein

***Abstract*— In Myanmar, there are many water resources. From these resources, hydropower can be produced to fulfill the requirements of the electrical energy needs. Cross flow turbines are used widely in such small hydropower plants due to their simple design, easier maintenance, low initial investment and modest efficiency. This research is to design cross flow turbine producing 90kW electric powers under a head of 13 m and the flow rate of 1 m^3/s. The detail design calculation of shaft that turbine is described in this research. The main aim of this study is to enhance and performance characteristics of cross flow turbine which is designed by using MATLAB program.**

Index Terms— **Cross Flow Turbine, Hydropower, Runner, Shaft.**

1) Introduction

The role of hydro plants becomes more and more important in today's global renewable energy. The small-scale renewable generation may be the most cost effective way to supply electricity to remote villages that are not near transmission lines. Hydropower traditionally represents the energy generated by damming a river and using turbine systems to generate electrical power. The reaction turbines require more sophisticated fabrication than impulse turbines because they involve the use of larger and more intricately profiled blades together with carefully profiled casings. Cross flow turbine is easiest turbine to make in home workshop [4].

The cross-flow turbine is a machine which provides shaft power by extracting energy from a moving fluid. The nozzle directs the water flow into the runner at a certain attack angle. The water jet leaving the nozzle strikes the blades at first stage. The water exits the first stage and was crossed to the second stage inlet after existing the runner completely. The portion of water that crosses the runner two times is known as cross flow and the name of the turbine is derived from this phenomenon. A cross flow turbine always has its runner shaft horizontal.

Nowadays, the cross-flow hydraulic turbine is gaining popularity in low head and small water flow rate establishments, due to its simple structure and ease of manufacturing in the site of the power plant. A typical cross-flow turbine consists of two main components namely the nozzle and the runner. A nozzle, which is rectangular shape that its width matches the width of runner. Its main function is to convert the total available head into kinetic energy and to convey water to the runner blades. The runner is the heart of the turbine. The function of the form of drum-shaped which consisting of two or more parallel discs connected together near their rims by a series of curved blades [4].

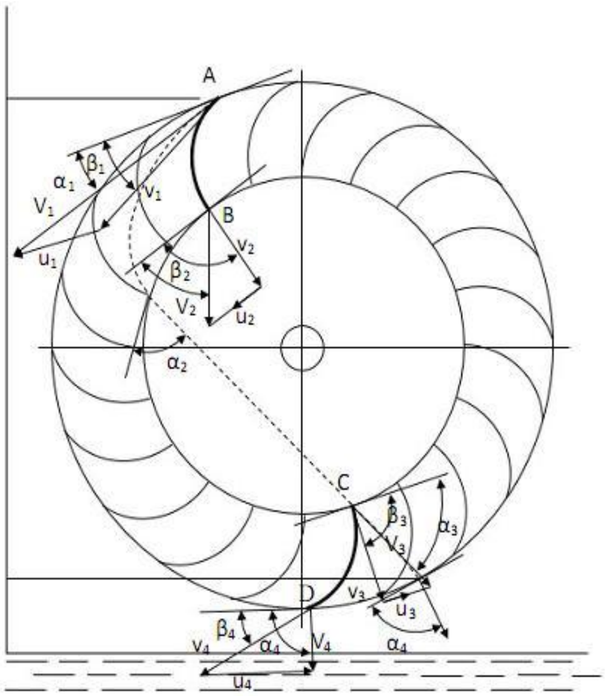

Figure 1. Path of water through turbine

The water starts enter from point A and strikes a blade AB. Then the water flow through the interior of the runner. The water strikes again to a blade CD and pass through the exit [2].

1.1) *Design Consideration of Shaft*

A shaft is the component of mechanical devices that is used to transmit power from hydraulic power to mechanical power, shaft is rotating machine element, usually of circular cross section having mounted upon it such elements as gears, pulleys, flywheel, crank, sprockets, and other power transmission elements. In the process of transmitting power at a given rotational speed, the shaft is inherently subject to a torsional moment or torque [8].

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2) DESIGN PROCEDURE OF CROSS FLOW TURBINE

The calculations for design procedure of the cross flow turbine runner involve in the following steps.

TABLE I. PARAMETERS CONSIDERED FOR DESIGN

Generator Output Power (P)	90kW
Head (H)	13 m
Flow Rate (Q)	1 m^3/s
Overall Efficiency (η_o)	75%

Table I shows the parameters considered for designing 90 kW cross flow turbine.

3) *Calculation of output shaft power, P*

The output shaft power of the turbine in (Watt) can be calculated as

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

4) *Calculation of turbine efficiency, (η)*

The maximum efficiency can be calculated as [2]

$$\eta = \frac{1}{2} K_c^2 (1+\psi) \cos^2(\alpha_1) \tag{2}$$

where, ψ = an empirical coefficient (about 0.98)

K_c = coefficient of water velocity,

(0.98 ~ 0.95)

5) *Calculation of specific speed, (N_s)*

$$N_s = \frac{172.556}{H^{0.425}} \tag{3}$$

6) *Calculation of turbine speed, (N)*

$$N = \frac{N_s \times H^{1.25}}{\sqrt{P}} \tag{4}$$

7) *Calculation of the runner outer diameter, (D_1)*

Diameter of runner is selected depending upon the flow conditions. If there is larger flow through the turbine select a larger diameter of turbine and for the low water flow conditions, select a smaller diameter of turbine. The runner outer diameter (m) can be calculated as [7]

$$D_1 = \frac{K_u 60 K_c \sqrt{2gH}}{\pi N} \tag{5}$$

8) *Calculation of length of runner, (L)*

Runner length (width) is calculated using Eq (6):

$$L = \frac{Q}{K D_1 K_c \sqrt{2gH}} \tag{6}$$

9) *Calculation of radial rim width, (a)*

The radial rim width (m) can be calculated as [2]

$$a = 0.17 D_1 \tag{7}$$

10) *Calculation of radius of blade curvature, (r_c)*

The curvature of blade accounts a lot for the efficient working of the turbine. It is varying directly with the size of turbine. The following relation is used for the blade radius [7]:

$$r_c = 0.16 D_1 \tag{8}$$

11) *Calculation of radius of circle pitch of blade shape arc, (R_0)*

Pitch circle diameter is the circle from which the profile of the blade radius is drawn the side plates of the runner. It has the following relation: [7]

$$R_0 = 0.37 D_1 \tag{9}$$

12) *Calculation of spacing of blades, (t)*

Proper blade spacing allows the water to strike on the blades for maximum thrust production, the blade spacing depended upon the number of blades used in the turbine runner. Blade spacing can be calculated as: [2]

$$t = \frac{K D_1}{\sin \beta_1} \tag{10}$$

13) *Calculation of number of blades, (n)*

The selection of optimum number of blades is very important in the design of turbine runner, fewer numbers of blade may cause incomplete utilization of water available to the turbine and excessive number of blades may cause the pulsating power and reducing the turbine efficiency. The following relation exists for the number of blades in a turbine runner: [2]

$$n = \frac{\pi D_1}{t} \tag{11}$$

TABLE II. DESIGN RESULT DATA OF CROSS FLOW TURBINE RUNNER

Parameters	**Symbol**	**Results**	**Unit**
Angle of attack	α_1	16˚	-
Blade angle	β_1	30˚	-
Runner outer diameter	D_1	0.8	m
Runner length	L	1	m
Radius of outer circle	r_1	0.4	m
Radius of inner circle	r_2	0.27	m
Radius of pitch circle	R_0	0.3	m
Radius of blade curvature	r_c	0.128	m
Radial rim width	a	0.136	m
Number of blades	n	18	-

14) *Calculation of shaft diameter, (d_s)*

The diameter of shaft should have a value to bear the load on the turbine. It should not be too larger that water strike the shaft after passing through the first set of blades at the inlet:

$$d_s = 150 \times \sqrt[3]{\frac{P}{N}} \tag{12}$$

where, d_s = diameter of shaft (m)

Checking:

$$\frac{D_1}{d_s} > 4$$

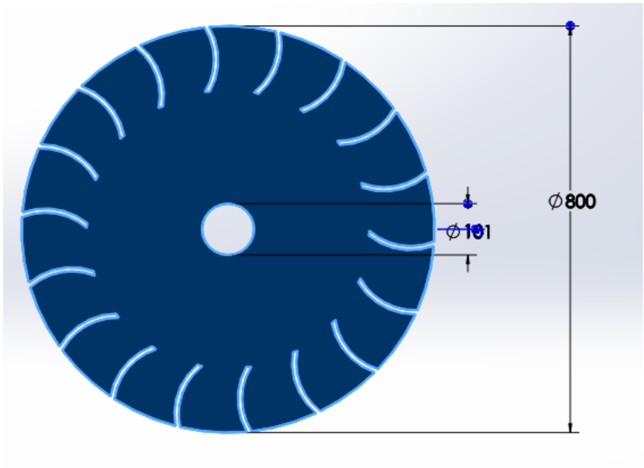

Figure 2. Cross flow turbine runner disc

Fig. 2 2D Autocad drawing consists of the radial rim width, outer diameter of cross flow turbine, inner diameter of cross flow turbine and diameter of shaft.

Fig. 3 shows the runner side disc with thickness 18 mm is cut and trim for 18 blades.The blades are fitted into slots of three discs of 800 mm diameter with thickness 18 mm and welded it.

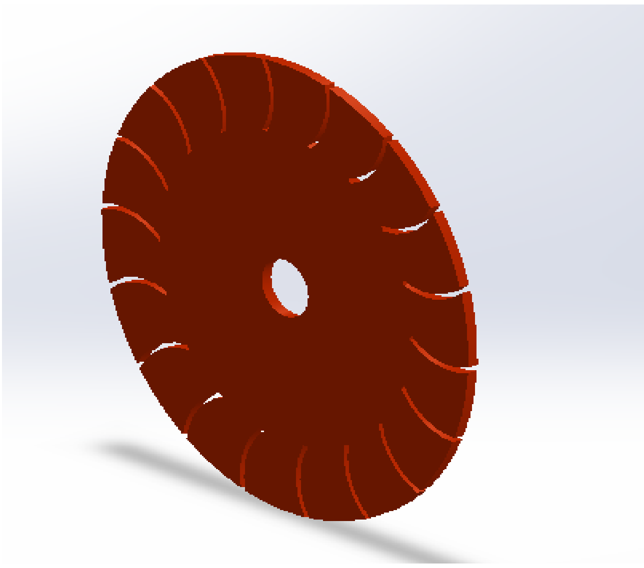

Figure 3. Cross flow turbine runner disc with 3D model

The shaft of 101 mm diameter is also welded to the rotor discs.The runner blades can be cut from a standard sheet metal or steel pipe and then be bent into the required blade profile.In some cases, to impove on the structural integrity of the runner, more than three equally spaced discs are employed.

The designed cross flow turbine rotor 3D model was generated with Solid Works software.

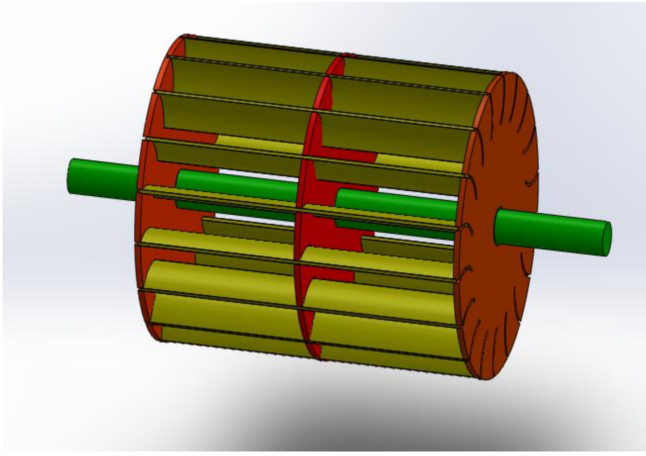

Figure 4. Cross flow turbine rotor

15) Design Calculation for Shaft

In this research, the suitable material is mild steel. Mild steel is especially desirable for construction due to its weld ability and machinability. Because of its high strength and malleability, it is quite soft.

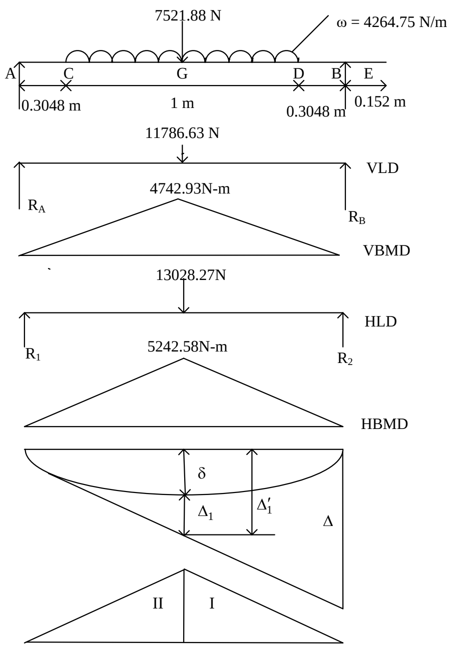

Figure 5. Loading and Bending Moment Diagram

Bending and torsional moments are the main factors influencing shaft design.

Torque of the runner exerted by the fluids on the runner, from the basic formula of the hydraulic turbine, the torque transmitted

$$T = \rho Q \begin{bmatrix} (r_1 v_1 \cos\alpha_1 - r_2 v_2 \cos\alpha_2) + \\ (r_3 v_3 \cos\alpha_3 - r_4 v_4 \cos\alpha_4) \end{bmatrix} \tag{13}$$

It is assumed that the velocity triangles are identical with each other in 2 and 3, while mutual speeds are identical with each other in 1 and 4.

$$T = \rho Q\left[r_1 v_1 \cos\alpha_1 - r_4 v_4 \cos\alpha_4\right] \quad (14)$$

The ASME code equation for solid shaft subjected to torsion and bending load (without axial load), [6]

$$d^3 = \frac{16}{\pi S_s}\sqrt{(k_b M_b)^2 + (K_t M_t)^2} \quad (15)$$

ASME code states for commercial steel shafting

S_s (allowable) = 55MN/m^2 for shaft without keyway

S_s (allowable) = 40MN/m^2 for shaft keyway

The critical speed (ω) of the shaft can be calculated by using Rayleigh-Ritz Equation,

$$\omega^2 = \frac{g\sum W\delta}{\sum W\delta^2} \quad (16)$$

δ = deflection due to weight (m)

16) PERFORMANCE CHARACTERISTIC OF TURBINE

Dimensional and non-dimensional design parameters are head coefficient, flow coefficient and power coefficient. These parameters are used to compare the performance characteristics of different turbine models.

Both the operating characteristics and non-dimensional characteristics are plotted by using MATLAB program.

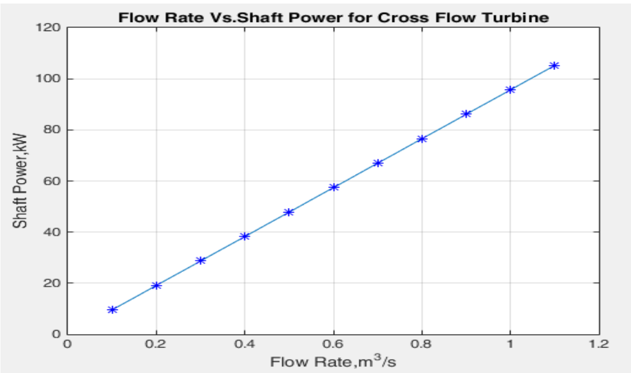

Figure 6. Performance curve of cross flow turbine (shaft power Vs flow rate)

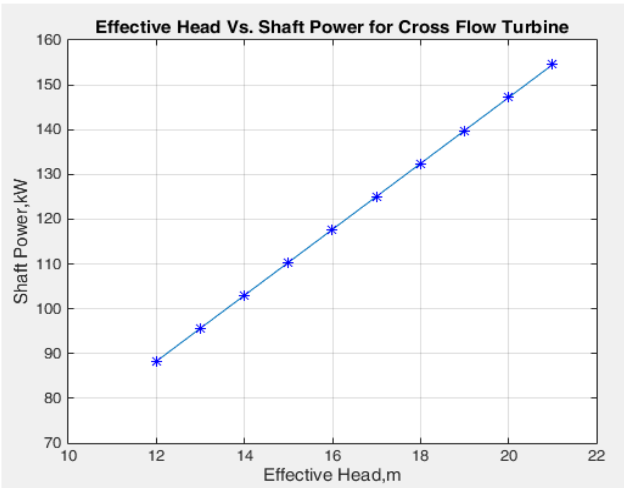

Figure 7. Performance curve of cross flow turbine (shaft power Vs effective head)

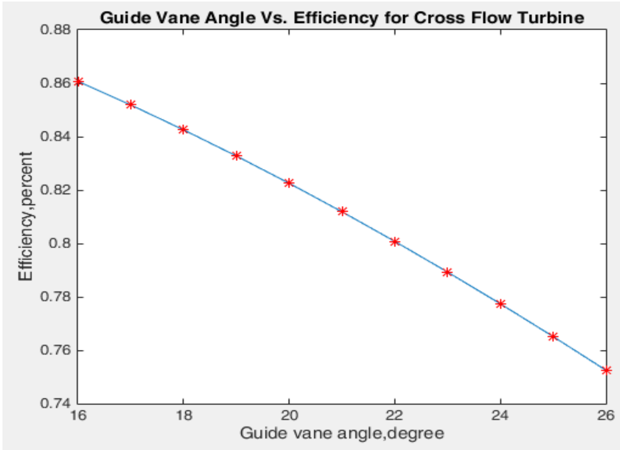

Figure 8. Performance curve of Cross Flow Turbine(Guide Vane Vs Efficiency)

Fig. 6 shows the variation of shaft power with flow rate.According to the Fig. 7 effective shaft power and effective head are directly proportional, as the shaft power increase the possible effective head also increase. And then performance curve of cross flow turbine (guide vane angle and efficiency) is inversely proportional as the guide vane angle increase efficiency produced is going to decrease.

17) CONCLUSION

A complete design of cross-flow turbines is presented in this research. The cross flow turbine is designed at a head of 13 m and flow rate of 1 m^3/s to generate output power of 90 kW. It is applicable to wide range of flow rate adjusting the runner length. In this research, runner diameter 0.8 m and runner length 1 m are used. According to the length of runner and three discs, benefits are to ensure sufficient strength of blade and to prevent the bending blades. The speed of turbine shaft is 150 rpm which is less than calculated critical speed of 104.8 rad/s (1000rpm). Therefore, the shaft design is satisfied. From the performance result, it is clear that the cross flow turbine need more flow rate to get higher power output. The recommendations are suggested that the present design could be implemented easily because it can be installed with locally available materials and technology.

APPENDIX

TABLE III. RUNNER DIAMETER AND BLADE THICKNESS

Runner Diameter, mm	200	300	450	700	800	1000
Blade Thickness, mm	3.2	4.5	6	9	10	12

TABLE IV. VALUE OF BENDING MOMENT FACTOR K_B TORSIONAL MOENT K_T

For stationary shafts:	**K_b**	**K_t**
Load gradually applied	1.0	1.0
Load suddenly applied	1.5 to 2.0	1.5 to 2.0

For rotating shafts:	**K_b**	**K_t**
Load gradually applied	1.5	1.0
Load suddenly applied (minor shock)	1.5 to 2.0	1.0 to 1.5
Load suddenly applied (heavy shock)	2.0 to 3.0	1.5 to 3.0

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