DESIGN, CONSTRUCTION AND PERFORMANCE TEST OF CROSS-FLOW TURBINE

[1]ZAR NI TIN WIN, [2]HTAY HTAY WIN, [3]MYINT THEIN

[1,2,3]Department of Mechanical Engineering, Mandalay Technological University, Mandalay, Myanmar
E-mail: [1]zarnitinwin@gmail.com, [2]htayhtayw@gmail.com, [3]minmyintthein2008@gmail.com

Abstract- Myanmar is a developing country that has perennial rivers and topographies that are mountainous. Electricity is the main component to develop a country. Currently, 80% of the electricity is produced from the hydropower by using hydro turbines. For hilly regions, cross-flow turbine is the suitable type for producing electricity. The objective of this paper is to test the performance of the constructed cross-flow turbine and verify that all parts and systems installed in the cross-flow turbine are working fine and performing their functions correctly. Cross-flow turbines can be applied over a head range from less than 2 m to more than 100 m. A cross-flow turbine has been considered, designed and constructed based on design specification. The designed cross-flow turbine is capable of producing up to 300 W AC power at the head of 6 m and flow rate of 0.0091 m^3/s. The performance test conducted at selected site location by changing the water flow rate and nozzle guide vane. Maximum efficiency was at middle position of nozzle guide vane with flow rate 0.0091 m^3/s and producing 260W with efficiency 86%.

Index Terms- construction, cross-flow turbine, design, hydropower, performance test

I. INTRODUCTION

Hydropower is an ancient technology that has been used throughout the world as a natural source of energy for several hundreds of years. 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. There are various types of turbines for hydro power plants. The selection of the best turbine for any particular hydro site depends on the site characteristics, the dominant ones being the head and flow available. Selection also depends on the desired running speed of the generator or other device loading the turbine. Cross-flow turbine is the best type for hilly regions with low head and high flow rate.

The cross-flow turbine is a machine which provides shaft power by extracting energy from a moving fluid. The fluid is guided into the rotor by inlet jet or nozzle. The fluid is then flows through the first rotor, through the interior, then the second rotor and through the exit. Due to the change in angular momentum of the fluid across the exit, a torque is applied to the output power shaft. The output power shaft can be used to drive a water pump, an electric generator or a compressor. A typical cross-flow turbine consists of two main components namely the nozzle and the runner. The power transfer process takes place on the surface of the runner blades. The blades are assembled on a disc that is supported by a shaft; the whole assembly is technically known as runner. A nozzle, which converts the potential energy to kinetic energy of water in the form of a high velocity jet. 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. Due to the forces of water strikes to the blades, the blades must be strong enough to withstand the forces of water [2].

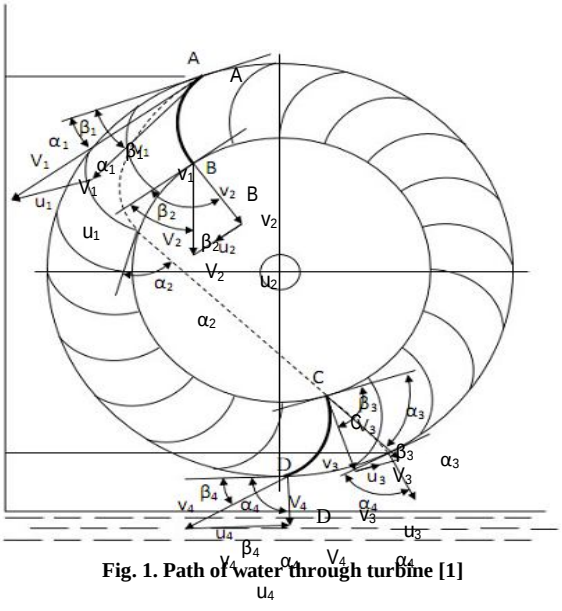


Fig. 1. Path of water through turbine [1]

Figure 1 illustrates the path of water through turbine. The water starts enter from point A and strikes a blade AB. Then through the interior of the runner. The water strikes again to a blade CD and pass through the exit.

II. DESIGN PROCEDURE OF THE CROSS-FLOW TURBINE RUNNER

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

TABLE I. Parameters Considered for Design

Generator Output Power (P)	300 W
Head (H)	6 m
R.P.M (N)	650 rpm
Generator efficiency (η_g)	0.75
Turbine Overall efficiency (η_o)	0.75

Table I shows the parameters considered for designing 300 W cross flow turbine.

A. Calculation of the design output of turbine (P_G)
The electrical power of the turbine in (Watt) can be calculated as

$$P_G = \frac{P_T}{\eta_g} \quad (1)$$

B. Calculation of the water flow rate (Q)
The water flow rate can be calculated by

$$Q = \frac{P_{out}}{\rho g H \eta_0} \quad (2)$$

C. Calculation of the mass flow rate, $\dot{m}$
The mass flow rate can be calculated from water flow rate 10.63 m^3/s, an available hydraulic head 6m, and turbine overall efficiency 75%.

$$\dot{m} = \rho Q \quad (3)$$

D. Calculation of the velocity of water before entering, V_1
The velocity of water before entering can be calculated as

$$V_1 = C\sqrt{2gH} \quad (4)$$

E. Calculation of the runner Outer Diameter, D_1
The runner outer diameter in (m) can be calculated as

$$D_1 = 39.85\frac{\sqrt{H}}{N} \quad (5)$$

F. Calculation of the length of runner, L
The length of runner in (m) can be calculated as

$$L = \frac{Q}{kD_1C\sqrt{2gH}} \quad (6)$$

Where k=0.075

G. Calculation of pitch of the circle, ρ
The pitch of the circle can be calculated as

$$\rho = 0.326\, r_1 \quad (7)$$

H. Calculation of the spacing of blades in wheel, t
Where blade inlet angle, =30, then the blade spacing t can be calculated as

$$t = \frac{kD_1}{\sin\beta_1} \quad (8)$$

I. Calculation of radial rim width, a
The radial rim width can be calculated as

$$a = 0.17D_1 \quad (9)$$

J. Calculation of number of blades, n
The number of the runner blades can be determined as

$$n = \frac{\pi D_1}{t} \quad (10)$$

K. Calculation of shaft diameter, d_s
The diameter of shaft can be calculated by using ASME equation

$$d_s^3 = \frac{16}{\pi s_s}\sqrt{(K_bM_b)^2 + (K_tM_t)^2} \quad (11)$$

TABLE II. Design Result Data for Cross-flow Turbine Runner

	Symbol	Results	Unit
Angle of attack	α_1	16°	-
Blade angle	β_1	30°	-
Runner diameter	D_1	0.150	m
Runner length	L	0.071	m
Number of blades	n	20	-
Radius of outer circle	r_1	0.075	m
Radius of inner circle	r_2	0.050	m
Radius of pitch circle	r_0	0.055	m
Radius of blade curvature	ρ	0.024	m
Radial rim width	a	0.026	m
Diameter of shaft	d_s	0.016	m

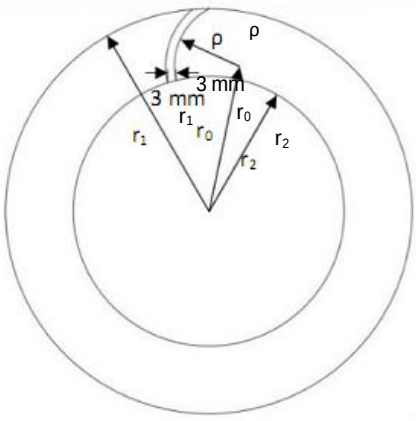


Fig. 2. Curvature of blades

Table II shows the design result data for 300W cross-flow turbine runner. Figure 2 shows the curvature of blades with result parameters.

I. SELECTION OF MATERIAL FOR CROSS-FLOW TURBINE BLADE

The designed cross-flow turbine runner blade 3D model was generated with AutoCAD software and analyze in ANSYS 14.5. Comparative study on static structure analysis has been carried out on turbine blade made of different materials which are suitable for turbine blade. Depending on the type of material, size and geometry of the object, and the force applied, various type of deformation result. Figure 3 shows the von-Mises stress on runner blade using structural steel.

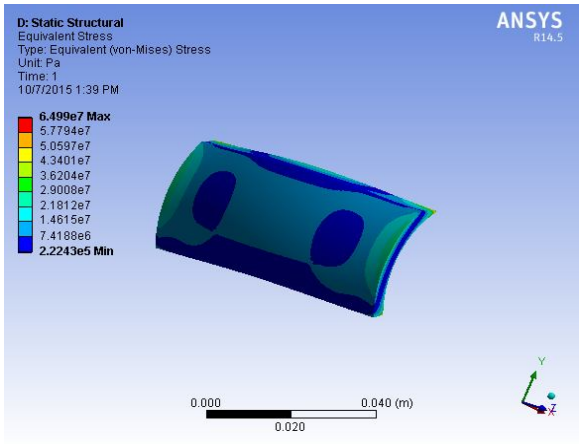


Fig. 3. The von-Mises on runner blade using structural steel

Figure 4 shows the deformation on runner blade using structural steel.

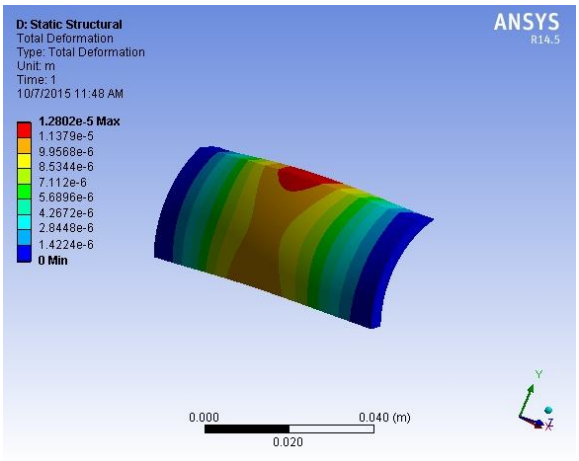


Fig. 4. The deformation on runner blade using structural steel

TABLE III. Total Deformation and von-Mises Stress for Three Types of Materials

Materials	Structural steel	Aluminium alloy	Copper alloy
Total deformation (displacement)	0.0128 m	0.0361 m	0.0233 m
Von-mises stress	64.99 MPa	64.86 MPa	64.79 MPa

Table III shows the total deformation and von-Mises stress on blade for three types of materials. Minimum deformation of blade occurs in structural steel. From the obtained results, it is clear that the stresses on turbine blades with three types of materials were not exceed the yield strength. In this research, the suitable material is structural steel because three types of blade materials has nearly the same von-Mises stresses on blade but structural steel has lowest deformation on blades.

So, the cross-flow turbine blade was constructed with structural steel to get the best performance with longer life time.

III. CONSTRUCTION PROCEDURE OF CROSS-FLOW TURBINE

The construction of cross-flow turbine parts were carried out after completing of design work. All the manufacturing activities were carried out at local workshop except standard parts such as bearings, bolts and nuts etc. which were purchased from the market. The results of the research ensure availability of a model and documented procedures for designing, constructing and testing of cross-flow turbine in Myanmar.

i. Blades

The number of blades for designed cross-flow was 20 blades with thickness 3 mm. The blades in this experiment were cut out of hollow steel pipes with thickness 3 mm corresponding to the blade angle as calculated by Banki theory. Figure 5 shows the blade profile with designed data.

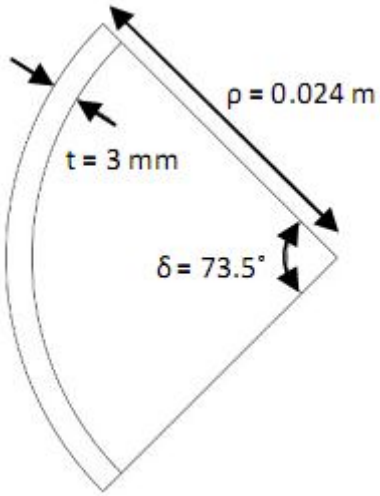


Fig. 5. blades profile

ii. Runner

The runner side discs with thickness 5 mm is cut and trim for 20 blades using CNC lathe machine as shown in Figure 6.

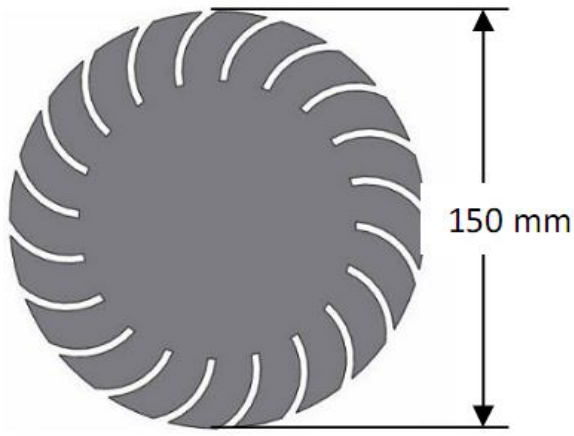


Fig. 6. Side disc for runner

The blades are fit into slots of two side discs of 150 mm diameter with thickness 5 mm and weld it. The central shaft of 25.4 mm diameter is also welded to the rotor discs. Figure 7 shows the constructed cross-flow turbine runner with pulley and flywheel.



Fig. 7. Constructed cross-flow turbine runner

iii. Casing

The casing was made up of 5 mm in thick mild steel, having 25.4 mm diameter steel shaft with the runner mounted on it passed through along with the bearings. The nozzle was attached on top of the casing. The side covers are screwed together for easy set-up and dismantling, and hence to facilitate the fast and easy replacements for various tests.



Fig. 8. Combination of casing, runner and nozzle

Figure 8 shows the assembly of casing, runner and nozzle. Two bearings (NSK 6205 DU) are used for runner mounted on casing.

iv. Nozzle

A nozzle in the cross-flow turbine guides and control the water flow into the runner. The water flow rate can be varied by changing the guide vane in the nozzle. Its shaft is parallel to the rotor shaft; it fits neatly inside the nozzle to keep leaks. It guides water to the runner and controls the amount of water entering the runner. The guide vane is controlled by using a hand wheel.

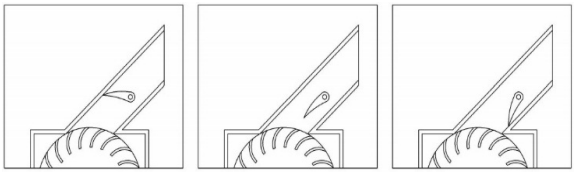


Fig. 9. Cross-flow turbine nozzle with three positions of guide vane

Figure 9 shows the cross-flow turbine nozzle with three positions of guide vane to test the performance of turbine with different flow rate.

v. Adapter

At the entry of the nozzle, the square parts of the nozzle need to transmit to the circular shape of the 50.8 mm penstock pipe. So, adapter is used to change the circular inlet to square outlet as shown in Figure 10.

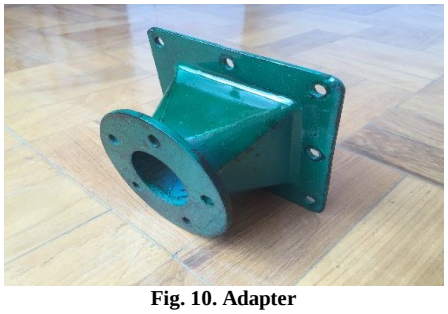


Fig. 10. Adapter

vi. Selection of generator

Hydro systems use AC generator either induction or synchronous to supply AC electrical appliances. Permanent magnet generator is selected as it is much cheaper and has smaller overall size. This type of generator is more efficient because no power is wasted to generate the magnetic field. This generator is imported from China which is producing 300 W output power.



Fig. 11. Generator for water turbine

Figure 11 shows the 300 W output permanent magnet generator

vii. Assembly of cross-flow turbine

Each designed part is constructed and combined into a set of cross-flow turbine to test the performance at the selected site location. The cross-flow turbine is connected with generator by using pulley and belt system which increase the speed ratio from 1:3 to the generator. A-36 v-belt type is used for this pulley and belt system.

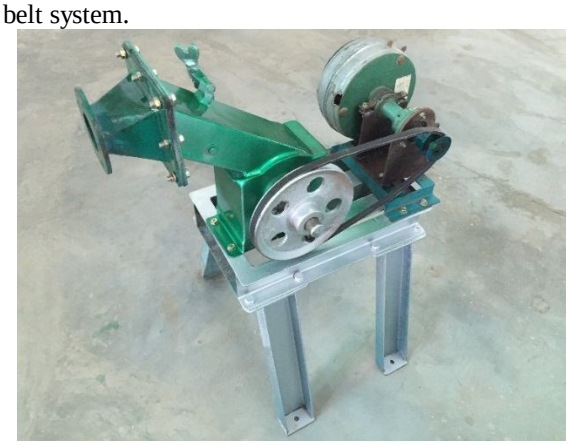


Fig. 12. Complete assembly of cross-flow turbine

Figure 12 shows the complete assembly of cross-flow turbine to test the performance at the selected site location

IV. TESTING PROCEDURE OF CROSS-FLOW TURBINE

The selected site is located at the Mya Kha Nauk Mountain near Mandalay Technological University. The water is free flowing from the site location to the

bottom of the mountain. There is a water fall at site location and reservoir is located at the base of waterfall. A 50.8 mm diameter penstock pipe is connected between reservoir and the turbine. The maximum flow rate is 0.0091 m^3/sec and head is 6 m. The water flow rate is controlled by changing the gate valve angle from 0 degree to 90 degree full opening. The nozzle guide vane is also adjusted to test the speed of runner shaft. The turbine speed and generator speed was measured at different position of guide vane using tachometer. Water flow rates are measured by using bucket method. The voltage and ampere are measured with digital clamp multimeter.

II. RESULTS

Two tests were conducted. In the first test, gate valve opened at 90˚ full opening and the rotating speeds of the runner shaft (not connecting with generator) is measured with tachometer by changing three positions of guide vane (top, middle, and bottom). The results of which are shown in Table IV.

TABLE IV. Speed of Runner at Different Position of Guide-Vane with No Load

Head, m	Vane Adjustment	Runner Speed, rpm
6	top	425
6	middle	475
6	bottom	430

At this experiment, the best guide-vane position is at middle producing runner speed 475 rpm.

In the second test, the turbine is connected with generator by using pulley and belt system. The penstock pipe is connected with gate valve to control the flow rate of water and test the performance of the turbine with gate valve angle 30˚, 60˚ and 90˚ (full opening). From the graph in Figure 13, the generator shaft speeds are compared with three position of guide-vane angle depending on the inlet flow rate.

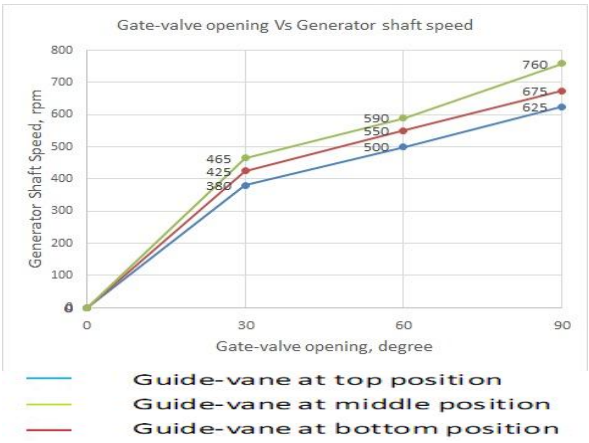


Fig. 13. Graph showing the relationship between gate valve opening, degree and generator shaft speed, rpm

The graph showing the relationship between flow rate and power output are shown in Figure 14. Finally, the flow rate vs efficiency are shown in Figure 15.

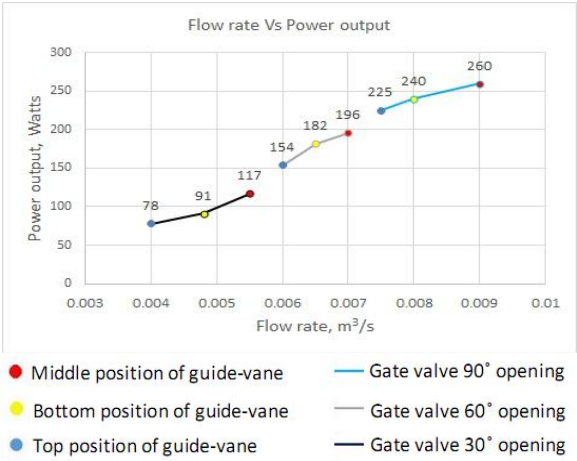


Fig. 14. Graph showing the relationship between flow rate, m^3/s and power output, watts

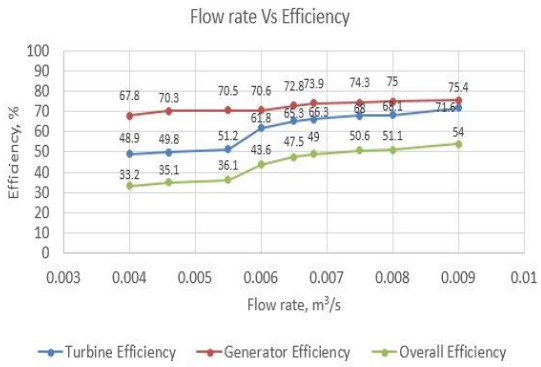


Fig. 15. Graph showing the relationship between water flow rate, m^3/s and efficiency, %

CONCLUSIONS

The cross-flow turbine is suitable for small scale hydro power production in case of low head and flow rate. A complete design of cross-flow turbines has been presented in this paper. The complete design parameters of runner diameter, runner length, blades number, runner speed, radius of blades curvature, water jet thickness and turbine power were determined at maximum turbine efficiency.

Comparative study on static structure analysis has been carried out on turbine blade made of different materials which are suitable for turbine blade by using ANSYS. In this research, the suitable material is structural steel because three types of blade materials has nearly the same von-Mises stress on blade but structural steel has lowest deformation on blades.

The performance test is conducted with three position of water flow rate by changing the angle of gate valve. In each position of gate valve, the guide-vane position in the nozzle with top, middle and bottom position are changed and tested the generator shaft speed, output voltage, ampere, power output and efficiency. From the performance result, it is clear that the cross-flow turbine need more flow rate to get higher power output as shown in Figure 14. The designed cross-flow

turbine can produce highest power output 260 watts by using flow rate 0.0091 m^3/sec at 90˚ full opening from the gate valve and at middle position of nozzle guide-vane.

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