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Experimental Evaluation on Performance of Novel Cross-flow Impulse Turbine for Water Stream in Hilly Areas of Pakistan

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Abstract- Pakistan is facing energy crisis due to dependence on fossil fuels having economical as well as environmental consequences. The hydropower plants make a low contribution to global warming and play a key role in the power sector. The identified hydroelectric resources in Pakistan has an overall potential of 60,000MW whereas, only approximate 11 % of the identified resources are operational, producing 7228MW of electric power. This paper presents a novel high-efficiency design of the cross-flow turbine at the low head of 6m by varying performance parameters i.e; tip speed ratio λ, power coefficient C_p and constraints affected by inlet guide vane angle. The proposed design of the cross-flow turbine was tested at guide vane angle starting from 20.5° to 40.5° with an interval of 5°. Power coefficients C_p for cross-flow turbine are calculated for different inlet guide vane angle and tip-speed ratios (TSR). The experimental setup is tested at the hilly waterfalls region and its uncertainty analysis performed. The maximum power output 8.9 KW at the head of 6m, flow rate of $0.21m^3/s$ and channel flow speed is 10.84m/s was produced. The maximum efficiency of 89 % was obtained at C_p is 0.78 and TSR 4.4 at the middle position and 30.5° guide vane angle. The experimental study verified that the proposed design of the cross-flow turbine is effective and practical for renewable energy applications in the power sector.

Keywords Hydro turbine; flow features; power coefficient; tip speed ratio; guide vane angle.

1. Introduction

The development of the world economy, the continuous succeed of human needs as well as technological growth has led to an increased demand for energy and consumption of conventional fuels [1]. Fossil fuels have been a major contributor to greenhouse gases [2]. The amounts of these gases can be reduced if the hydropower plant is used for electrical power generation. The cross-flow turbine mostly used for the domestic scale due to their higher efficiency, low initial investment and easier maintenance [3]. The cross-flow turbine is a superior option for hilly regions to generate electricity. Discs have grooves to keep the runner blades at a feasible position so that water can rotate the runner at desired rpm. The shaft is used for transmitting power and also support to the runner when couple it with the generator [4]. The working principle of the cross-flow turbine states that it works in two stages. In the first stage, water enters the nozzle and strikes with the blade surface. This crossing of water through the shaft before leaving the turbine is called cross flow [5].

Farooq [6] reviewed that Pakistan is investing a fair amount to build a hydropower plant in northern areas. The project is beneficial and can be used as a reference for the fabrication of a cross-flow impulse turbine to generate electricity on small scale. Sharma [4] designed a cross-flow water turbine to generate 5 KW electric power which works for a head of 12 m and a flow rate of 20 l/s. Patel [7] designed a cross-flow turbine having maximum efficiency after doing static and model analysis of it. Win [8] investigated nozzle guide vane at a middle position to generate 260 W electricity with a flow rate of 0.0091 m^3/s. Dhokiya [9] investigated to enhance the efficiency of the micro hydropower plant by varying the blade angles and fixing the head of water in the cross-flow turbine. Chitrakar [10] used cross-flow turbine with different sizes to enhance power output and efficiency. Muhammed [11] used multi-stage blade system of cross-flow turbine, in which water inlet velocity was kept 1.1 m/s, the velocity losses across blade was 25.6% and the turbine efficiency was 48.3 %. Adil [12] studied high efficient cross-flow turbine and use sewerage water to run the turbine of the domestic power plant to produce electricity.

Adhikari [13] experimentally investigated by using three-dimensional Navier-Stokes simulations on a 7 KW turbine and a 0.53 KW turbine. By converting head into kinetic energy and redesigning the nozzle, the maximum efficiency increased from 69 % to 87 %. Adhikari [14] studied experimentally and computational fluid dynamics (CFD) to designed a high efficiency cross-flow water turbine; with an efficiency range about 90 %. Aydin [15] analyzed double nozzle cross-flow turbine to determine turbine performance and fundamental flow parameters. Investigated that by using double nozzle turbine twice the power output as compared to the single nozzle turbine. Benzerdjeb [16] investigate that increased of the water velocity from 0.37 m/s to 0.73 m/s causes an increase in power output and efficiency from 16.92 % to 31.77 %.

Verma [17] experimentally investigated of cross-flow turbine by changing its performance parameters. The inlet angle of the blade is changed between at 26º to 28º and outlet angle β2 as 90º to achieved efficiency 85 %. Mueller [18] experimentally verified the performance of economic cross-flow turbine which achieved high efficiency during a large range of water discharge. Jiyun [19] experimentally verified that cross-flow turbine performance can be improved by increasing flow velocity and pressure difference through the runner. The maximum output power of the turbine can achieve 136 W when the TSR is 1.2 and the effective head range from 3.45 m-3.75 m. Pujol [20] investigated the performance parameters of the cross-flow turbine and selected optimum working condition when the value of power coefficient is less than 0.2. Riglin [21] designed to enhance cross-flow turbine efficiency, optimized its performance parameters when power coefficient and TSR are 0.37 and 2.5

In the present work, we have evaluated different performance parameters of cross-flow turbine like tip speed ratio and power coefficient, by choosing the optimum inlet guide vane angle to enhance its efficiency and power output. To investigate the uncertainty analysis was conducted to identify the extend to which the experimental study was accurately performed. This work includes designing and fabrication of cross-flow turbine with power capacity of 10 KW, when kept under the low head of 6 meter with flow rate of 0.21 m^3/s.

2. Materials and Methods

The main components of cross-flow turbine are nozzle, guide vanes, draft tube and runner. The working procedure of novel cross-flow water turbine is shown in “Fig. 1”.

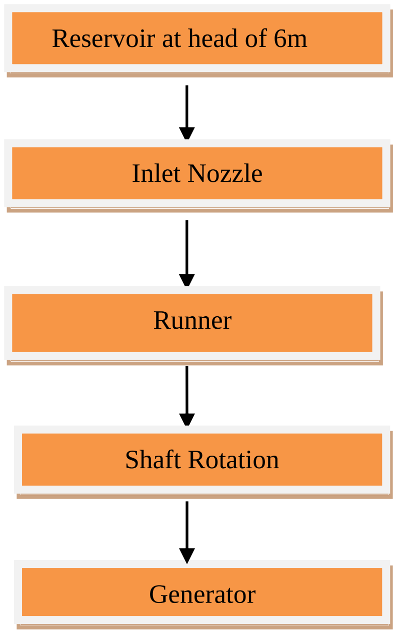


Fig. 1. Flow chart of cross-flow turbine

2.1 Components Description

In a cross-flow turbine, the nozzle increases the velocity and impinges water at a suitable angle to runner. Nozzle is motionless part of the turbine whose cross-sectional area is rectangular [9]**.** After nozzle water encounters to guide vane as the name suggests that it provides guidance to substance for obtaining maximum efficiency, Guide Vanes ensure that the substance is passed consistently and as easily as possible [16]. It is Prime part of cross flow turbine as output shaft is connected to it. It has two side disks to which number of blades are welded. The number of blades for CFT ranges from 18 to 37. At different blade angle and number of blades the efficiency effected for micro hydropower plant. It flushes out water from runner to downstream water level. The water may be recycled through the penstock [22].

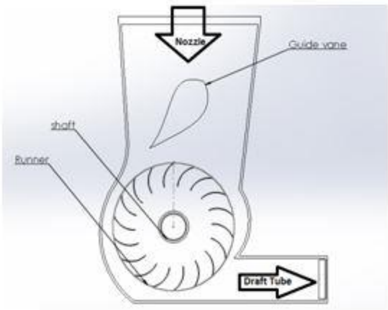


Fig. 2. Schematic diagram of the cross-flow water turbine

2.2 Design Methodology

Designing methodology consists of finding the different parameters associated with the turbine. The parameters considered for cross flow turbine involve the following steps [23].

Table 1. Parameters considered for 10kW cross-flow turbine

Parameters	Results
Generator output power(P)	10 KW
Head(H)	6 m
Radius(R)	0.08 m
Shaft speed	616 rpm
Flow rate(Q)	0.21 m^3/s
Turbine efficiency	86 %

2.3 Parameters Calculation

The net head is equal to difference of gross head and head losses in pipes, penstock, conduits:

$$H_n = H_g - H_l \quad (1)$$

The maximum turbine efficiency can be calculated by following formula: [7]

$$\eta = \frac{1}{2} C_c^2 (1 + \psi) \cos(\alpha)^2 \quad (2)$$

It is calculated from the measurement of velocity of water and cross-sectional area of the inlet of turbine:

$$Q = A \times V \quad (3)$$

The output electrical power in (Watts) can be calculated as [24]:

$$P = \eta \rho g Q H \quad (4)$$

It is the rotational speed of the runner shaft and can be calculated by formula:

$$N = \frac{513.25 \times H^{0.745}}{\sqrt{P}} \quad (5)$$

The shaft diameter has a value to transmit power of turbine:

$$d = 150 \times \sqrt{P} \div N \quad (6)$$

The water flow velocity can be calculated as:

$$V = \sqrt{2gh} \quad (7)$$

Tip speed ratio (TSR) of cross-flow turbine can be determined as follows:

$$TSR = \Omega R / U \quad (8)$$

Power coefficient of cross-flow turbine can be calculated as:

$$C_p = P/0.5\pi\rho U^3 R^2 \quad (9)$$

2.4 Design Model

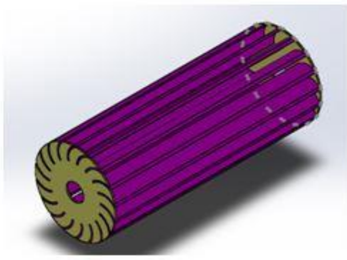
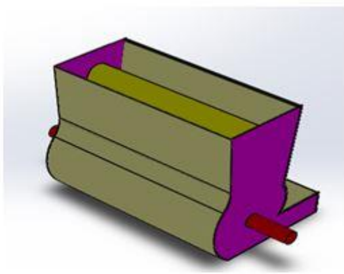


Fig. 3. Runner assembly mate with blades

Side runner discs are formed separately then in assembly mate them with blades. Perspective 3D view of cross- flow turbine is shown in “Fig. 4”



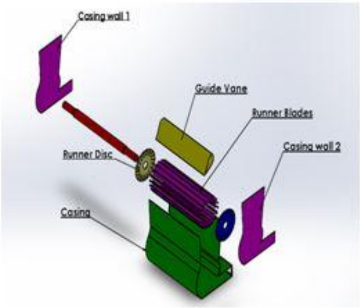


Fig. 4. 3-D model of novel cross-flow turbine

2.5 Construction of Cross-flow Turbine

The construction of turbine parts was 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 [25]. The cross-flow turbine is popular because it can be fabricated in any local metal workshop.

a. Blades

The number of blades for designed cross-flow was 18 blades with thickness 3 mm. We use the hydraulic press machine for the blades manufacturing.

b. Runner

We take the cast iron sheets for making the side discs of runner by using hydraulic press machine. The blades are fitted into slots of two side discs of 150 mm diameter with thickness 5 mm and weld it.

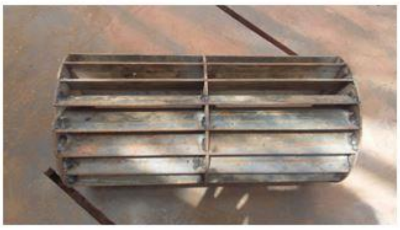


Fig. 5. Runner and its side disc

c. Casing and Nozzle

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. A nozzle in cross-flow turbine guides and controls the water flow into the runner. The water flow rate can be varied by changing the inlet guide vane in the nozzle.

Fig. 6. Casing and inlet guide vane

d. Generator

Permanent magnet generator is more efficient because no mechanical power is emaciated to generate the magnetic field. This generator is imported from China which is producing 10 KW output power. Then Connect dynamo motor of 10 KW with shaft and test the turbine for output power.

e. 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 fabricated Cross flow turbine is shown in “Fig. 7”.

Fig. 7. Assembled novel cross-flow impulse turbine

2.5 Uncertainity Analysis

An uncertainity analysis was conducted to identify the extend to which the experimental study was accurately performed.

The uncertainity of the experiment was evaluated from measured parameters using the following general equation:

$$\frac{\alpha_E}{E} = \left[\sum_{i=1}^{n} \left(\frac{1}{E}\frac{\partial E}{\partial e_i}\alpha_{ei}\right)^2\right]^{\frac{1}{2}} \tag{10}$$

Table 2. Measurement Range, accuracies and uncertainty in the measurements

Parameters	Measurement Range	Accuracy	Uncertainties (%)
Speed	250-650 rpm	±5 rpm	±0.01
Torque	0-30 Nm	±0.2 Nm	±0.01
Power	0-10 KW	±0.1 W	±0.1
Head	0-6 m	±0.1mm	±0.1
Flow Rate	0-0.21 m^3/s	±0.5 mm^3/s	±0.01

$$\alpha_{Exp} = \left[(Speed_\alpha)^2 + (Power_\alpha)^2 + (Torque_\alpha)^2 + (Head_\alpha)^2 + (FlowRate_\alpha)^2\right]^{\frac{1}{2}}$$

$$\alpha_{Exp} = [(0.01)^2 + (0.01)^2 + (0.1)^2 + (0.1)^2 + (0.01)^2]^{1/2}$$

$\alpha_{Exp} = 0.2\%$

Table 2 shows the percentage uncertainties in different parameters including speed, torque, power, head, flow rate etc. The total percentage uncertainty of the experimental study α_{Exp} came out to be 0.2% which is in satisfactory range.

3. Results and Discussion

3.1 Observation of Experiment

The cross-flow turbine prototype has been designed and tested for the head of 6 m and flow rate 0.21 m^3/s in hilly areas of Pakistan. The revolutions of shaft are measured with the help of tachometer. The voltage and amperes are calculated with the help of digital clamp multimeter [26]. We record the readings and compare the experimental output with that of theoretical.

Table 3. Observation of Experiment

Parameters	Theoretical Reading	Experimental Reading
Head (m)	6	6
Flow rate (m^3/s)	0.21	0.21
Output power (KW)	$P = \eta\rho gQH$ =0.89x1000x9.81x0.2x6 P = 10 KW	8.94

3.2 Effect of flow rate on shaft power

The output power of cross-flow turbine is strongly affected by flow rate. The output power of the turbine increases as well as flow rate increase. In this research required 8.94 KW electric power is produced; when we used flow rate 0.21 m^3/s at optimum guide vane angle 30.5°. During optimum guide vane angle 30.5° maximum amount of inlet water strike the runner blade and vortex doesn't produce. The graph between flow rate and shaft power is shown in "Fig. 8"

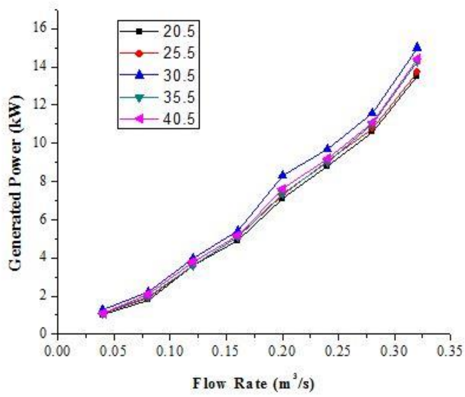


Fig. 8. Performance curve of cross-flow turbine (shaft power Vs flow rate)

3.3 Effect of Head and Runner Speed on Shaft Power

The output power of turbine is strongly affected by effective head of reservoir. Shaft power of the turbine increases as well as effective head of reservoir increases. In our study the value of effective head of reservoir is 6 m which produced 8.94 KW of electricity. Runner speed (rpm) increased with effective head and flow rate. It can be observed that the required 8.94 KW output electric power of turbine achieved when we used guide vane angle 30.5° and runner turns at 616 rpm.

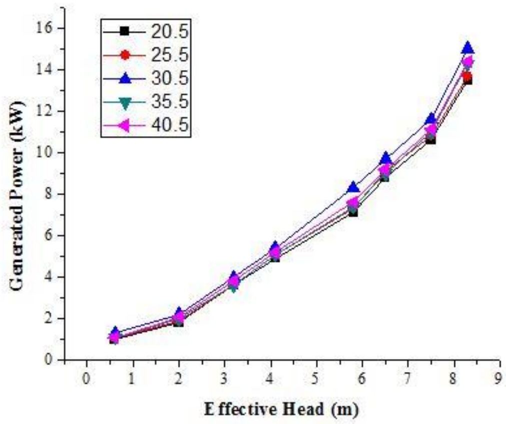


Fig. 9. Performance curve of cross-flow turbine (shaft power Vs effective head)

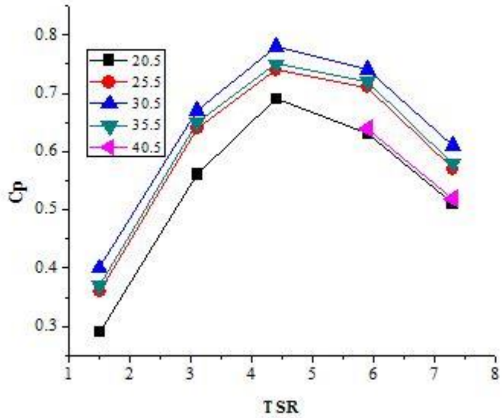


Fig. 10. Performance curve of cross-flow turbine (C_p Vs TSR)

3.4 Effect of Guide Vane Angle on Shaft Power:

Maximum performance of the turbine is calculated to be at the tip speed ratio corresponding to the angle of the inlet guide vane. The effect of modifying the inlet guide vane angle of the blades has also been investigated. Results are shown in Table 2. Maximum value of C_p achieved for different guide vane angle and TSR as shown in Table 3.

Table 3. C_P as a function of TSR. All cases use a 18-blade rotor with U=10.84ms^{-1}

Guide Vane Angle	C_P	TSR
20.5º	0.4	1.5
25.5º	0.67	3.1
30.5º	0.78	4.4
35.5º	0.74	5.9
40.5º	0.61	7.3

For all the cases evaluated, the power coefficient is maximum for the guide vane angle 30.5º, with a 12 % increase in comparison with the 20.5◦ case (TSR = 4.4, angular revolutions equal to 616 rpm). When increased guide vane angle above 30.5º then vortex produced on low pressure side of runner and also power loss factor increased. Similarly, when reduced guide vane angle below 30.5º, then all the water is not utilized to strike the runner blades. From above graph, it can be seen that optimum efficiency of cross-flow turbine (89 %) is achieved when C_p is 0.78, TSR reaches 4.4 and guide vane angle is 30.5º.

4. Conclusion

Experimental investigation and theoretical calculations regarding the integration of a novel cross-flow turbine for electricity production system were achieved, and conclusions were made as follows:

1. In this paper, the design of novel cross flow turbine has been discussed in detail along with the uncertainty analysis to investigate that experimental study was accurately performed.

2. The prototype is designed and fabricated at a head of 6 m, flow rate of 0.21 m^3/s and turbine shaft speed is 616 rpm to generate output power of 8.94 KW.

3. In this novel cross-flow turbine, maximum efficiency of 89 % is obtained at inlet guide vane of 30.5º. Also, the value of TSR is 4.4 and power coefficient is 0.78 at this point due to high pressure difference through the runner resulting in maximum efficiency. The recommendations suggest that the present design could be implemented easily at domestic as well as commercial scale where availability of effective head is low or medium.

4. Using artificial intelligence (AI) and internet of things (IoT) technologies, guide vane angle and rotor blades angle can be varied according to the water flow rate (Q) conditions that results in enhanced efficiency and power output.

Abbreviations

Λ	Tip Speed Ratio (TSR)
C_p	Power Coefficient
B	Blade Angle (degree)

CFD	Computational Fluid Dynamics
D	Outer Diameter of runner (mm)
P	Density of Water (kg/m^3)
η_o	Overall Efficiency (%)
Ψ	Blade Roughness Coefficient
G	Gravity (ms^{-2})
H	Head (m)
L	Length of Runner (mm)
N	Turbine Speed (r.p.m)
P	Power Generated (KW)
Q	Water Discharge (m^3/s)
U	Water Flow Velocity (m/s)
C	Nozzle Roughness Coefficient

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