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ORIGINAL RESEARCH ARTICLE

DEVELOPMENT OF HYDROPOWER TURBINES POWERED BY DAM OVERFLOW

O. O. Oyebode[1*] and J. O. Olaoye[2]

([1]Department of Food, Agricultural and Biological Engineering, Kwara State University, Malete, Kwara State, Nigeria
[2]Department of Agricultural and Biosystems Engineering, University of Ilorin, Ilorin, Kwara State, Nigeria)
** Corresponding author's email address: oyebodeoyetayo@yahoo.com*

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ABSTRACT

The epileptic power supply in most rural areas in Nigeria and its attendant negative impact on the economy of the Nation, Agricultural productivity and huge rural emigration, is a serious source of concern. This necessitated the development of two hydro-power turbines powered by the overflow (which was rather considered a waste) from University of Ilorin (UNILORIN) dam. A portion of the overflow was channeled into a Polyvinyl Chloride (PVC) pipe and the flow rate was calculated to be 0.017m^3/sec using the bucket method. The change in elevation between the overflow and the point of usage was reported to be 4m. The flow (Q) and Head (h) were typical values for many streams and rivers in different rural areas of Nigeria, hence its suitability and adoption for this study. Two turbines viz: Pelton Wheel (PW) and Cross Flow (CF) were developed and tested. The PW generated a speed of 538.4rpm and a torque of 46.2kNm at off load condition while the CF generated a speed of 330.1rpm and a torque of 39.07kNm at the same condition. During loading – when the alternator had been connected to the turbine - the PW turbine speed and torque became 392.0rpm and 36.5kNm respectively, while that of the CF became 197.7rpm and 25.0kNm respectively. A belt and pulley mechanism was used to deliver the rotational speed to the alternator and this increased the alternator speed from the PW and CF turbines to 1768.6rpm and 879.24rpm respectively. The speed from the PW was enough to power the alternator as the alternator only requires 1500rpm to function optimally. The PW was thus adjudged the most suitable for use.

1.0 Introduction

The use of renewable energy is not new and its impact on world's energy economy is significant. The six renewable sources of energy used most often include hydropower, solar energy, biomass, wind energy, geothermal and tidal wave or ocean energy. Hydropower is however the most often used of the renewable energy sources that generate electricity. It is one of the oldest sources of energy and was used thousands of years ago to turn paddle wheels for purposes such as grinding grain and water lifting. Hydropower plants use the motion of water from sources such as the ocean, rivers and waterfalls to move vane-like blades in a turbine which turns a shaft connected to a generator. The generator has a powerful electromagnet (a rotor) which is turned inside a coil of copper bars (a starter). This produces an electromotive force or the process of exciting electrons to jump from atom to atom. When electrons flow along a wire or any other conductor, jumping from atom to atom, they create an electric current or a flow of electricity.

The estimated long-term power demand of Nigeria was 25GW for the year 2010 to sustain industrial growth (Okpanefe and Owolabi, 2001). According to Ezennaya et al. (2014), this demand is said to be expected to increase geometrically to about 88GW by the year 2020. Considering the current installed capacity of less than 10GW, out of which less than 4GW is the actual reliable output, there is an acute energy deficit in the country. Now, thermal plants provide 61%, while hydropower generation is about 31% (Olivia, 2008). Although the overall potential of hydropower generation of Nigeria was estimated to be in excess of 11GW, less than 3GW has been harnessed (Zarma, 2006; Aliyu and Elegba, 1990). Utilizing the abundant hydro power resources could be a way of reducing the huge energy deficit Nigeria is currently facing.

The first hydropower supply station in Nigeria is at Kainji on the river Niger for which the installed capacity is 836MW with provisions for expansion to 1156 MW. A second hydropower station on the Niger is located at Jebba with an installed capacity of 540 MW. An estimate (Aliyu and Elegba, 1990) for rivers Kaduna, Benue and Cross River (at Shiroro, Makurdi and Ikom, respectively) put their total capacity at about 4,650 MW. Estimates for the rivers on the Mambila Plateau are put at 2,330MW. The foregoing assessment is for large hydro schemes which have predominantly been the class of schemes in use prior to the oil crisis of 1973. Since that time, however, many developed and developing countries have opted for small scale hydropower with appreciable savings made over the otherwise alternative of crude oil. It should be noted that hydropower plants that supply electrical energy between the range of 15kW to 15MW are mini-hydro while those supplying below 15kW are normally referred to as micro-hydro plants (Sambo and Taylor, 1990). Indeed, small scale (both micro and mini) hydropower systems possess so many advantages over large hydro systems, and these include ease of setting up, low maintenance requirement, less skilled operators required, and the problems of topography is minimal. In effect, small hydropower systems can be set up in all parts of the country so that the potential energy in the large network of rivers can be tapped and converted to electrical energy. In this way the nation's rural electrification projects can be greatly enhanced. Hydropower has been regarded as the ideal fuel for electricity generation because, unlike the non-renewable fuels used to generate electricity, it is almost free, there are no waste products, and hydropower does not pollute the water or the air. However, it is criticized because it does change the environment by affecting natural habitats and large hydropower schemes have been seen as a weapon of mass destruction in case of failure or attack during war (EIA, 2004).

Development of Micro hydropower from the overflow from UNILORIN Dam could be easily adapted for use in most rural areas because it has a flow (Q) and head (h) that most small rivers and streams in most rural areas can produce all-year-round. Small rivers and streams exist within many rural areas in Nigeria, and most of them maintain a minimum flow all year round (Aliyu and Elegba, 1990). These streams and rivers can be used to develop hydroelectric energy for rural agriculture. Studies by Aliyu and Elegba (1990) further confirmed the great potential of small hydropower to improve on the energy deficits experienced in rural households in Nigeria.

The objectives of this research were to assess the hydropower potential of the overflow from UNILORIN Dam, design, fabricate and test small hydro turbines for generation of electric power from the Dam overflow.

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

2. Materials and Method

2.1 Description of the Machine

The machine was made up of the turbine (cross flow or Pelton wheel), nozzle, chamber, alternator, pulley, bearing, shaft, adjuster, cover, frame. Figures 1 and 2 show the component parts of the Cross flow and Pelton wheel Turbines respectively.

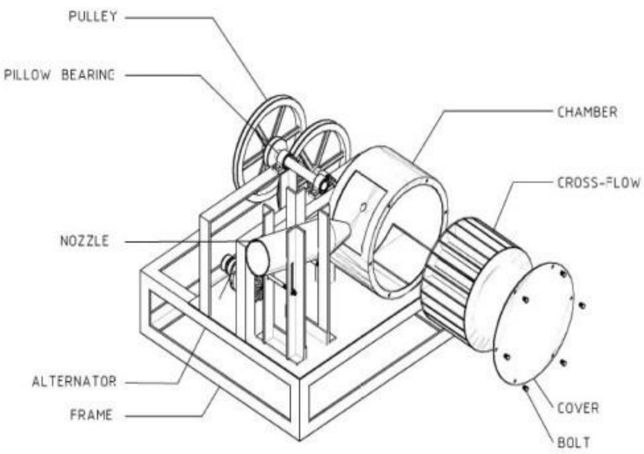


Figure 1: The Cross Flow Turbine

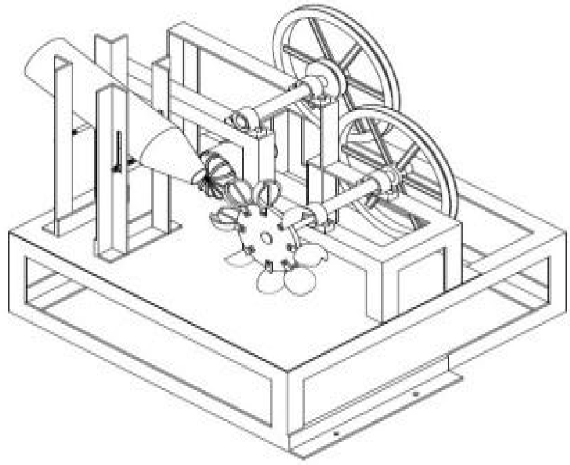


Figure 2: The Pelton Wheel Turbine

2.2. Design Criteria

Figure 3 shows the pictorial view of the University of Ilorin (UNILORIN) dam. The dam was commissioned in 2007 primarily for water supply. It is located on the Oyun River. The dam is a zoned earth-fill embankment with an ogee-shaped concrete spillway. The intake for water supply and the low lift pumping station are located on the wing wall. To decide on the hydropower potential of the dam, it is important to begin with an evaluation of the available water resource of the river. The energy potential of the scheme is directly proportional to the flow and head. To fairly select the most appropriate hydraulic equipment and estimate the dam's hydropower potential, the water resource analysis must take into consideration the water to meet the primary responsibility of the Dam. Considering this, only the water from the spill way was available for use.

Figure 3: Pictorial View of the Overflow from Unilorin Dam

2.2.1 Hydraulic Head (h)

In hydroelectric projects, calculations are based on the available hydraulic head which is a measurement of the difference in elevation between the water source and the turbine. According to a technical report on UNILORIN dam, the head was 4m.

2.2.2 Flow Rate (Q)

A portion of the overflow was channeled into a PVC pipe. To measure the amount of water available through the pipe, (known as the flow rate), the outlet valve attached to the end of the pipe was opened, and the amount that flowed out in 10 seconds was collected in a large bucket. Once the experimental time had elapsed, the content of the bucket was measured by pouring it into a measuring cup.

2.2.3 Available Hydro Power from the Channeled Overflow

The theoretically available hydropower from the overflow from Unilorin dam was calculated using Equation (1).

$$P = \frac{\rho g h Q \eta}{1000} \quad (1)$$

Where; P is Power in (kW), Q is Flowrate in (m3s-1), g is acceleration due to gravity which was taken as 9.8m/s2, ρ is density of water in (kg/m3) and η was the efficiency (since the power calculated is theoretical, it was taken as 100%)

2.2.4 Choice of Generator

Three main factors were used in choosing a generator for the project, namely cost, rate of rotation and available power. Specialty electric generators of the scale needed for this project, though available, are far too expensive to be considered and were rejected based on their price. The chosen generator (alternator) was a second hand 12v diesel engine alternator. No other information was available, but a survey of similar brands revealed that the alternators were rated 650W and run between 1000 and 1500 rpm. Since these parameters satisfy the factors considered for selection, and the test performance was satisfactory, it was selected for the project.

2.3. Design of the Hydropower Turbine (Pelton Wheel)

The design of the ideal Pelton Wheel was divided into three segments, namely calculation of ideal water jet width; calculation of the ideal diameter of the wheel and calculation of the dimensions of the runners. In the first two cases, the calculations were based on the initial characteristics, while the shape and dimensions of the runners were determined primarily by the calculated width of the water jet.

2.3.1 Ideal Width of the Water Jet

The width of the water jet used is an important factor that will help to establish the physical shape of the Pelton Wheel runners. The width of the water jet determines the flow speed of the fluid impacting the runners and is based on the available Hydraulic Head. The following calculations were used to design the water jet width.

*Note that all calculations and Assumptions used to generate the shape and dimensions of the Pelton Wheel were all based on those found in MHPG (1991) Series.

2.3.1.1 Absolute Velocity of the Water Jet (C1)

This was calculated using Equation (2). (kc ranges from 0.96 to 0.98) assuming worst case, 0.96 was used.

$$C_1 = k_c (2gh)^{1/2} \quad (2)$$

Where; C_1 is the Absolute velocity of the water jet and k_c is Nozzle Coefficient

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

2.3.1.2 Optimal Jet Diameter (d)

The Optimal Jet Diameter was calculated using Equation 3

$$d = \left(\frac{4q}{\pi c_1}\right)^{1/2} \tag{3}$$

2.3.1.3 The Ideal Diameter of the Pelton Wheel

The Ideal Diameter or Pitch Circle Diameter is the width of a circle calculated from the point of impact of the water jet. The water jet impacts the runners towards the back of the scoops, so the real diameter or Outside Diameter will be slightly larger. The Pitch Circle Diameter along with the width of the water jet will determine the speed of rotation and the torque on the wheel. The reason for this is that the jet width determines the speed at which the water strikes the wheel, while the larger the wheel, the larger the moment arm, but the slower its rotation. Based on the chosen generator and the expected load, the Pitch Circle Diameter will be designed to produce a minimum of 1500 rpms. (1: 5 belt transmission was used to obtain the needed 1500 rpm, thus, the required turbine speed was 300rpm).

2.3.1.4 Optimal Peripheral Velocity (U_1)

This was calculated using Equation (4) (k_u ranges from 0.45 to 0.49) assuming worst case, 0.45 was used.

$$U_1 = k_u(2gh)^{1/2} \tag{4}$$

Where k_u is the Coefficient after Impact

2.3.1.5 Pitch Circle Diameter (D)

The pitch circle diameter was calculated using Equation (5). no which is the rotational speed was taken to be 1500 rpm and Transmission Ratio: i which is the ratio of turbine to generator turns is taken to be 1:5).

$$D = \left(\frac{60U_1 \times i}{\pi n_0}\right) \tag{5}$$

2.3.1.6 The Physical Dimensions of the Runners

The dimensions of the runners were calculated based on the width of the water jet. The following formulas were used based on MHPG (1991) standards.

Bucket Width: b (mm): The Bucket width was calculated using Equation (6).

$$b = (3.2)d \tag{6}$$

Bucket Height: h (mm): The Bucket Height was calculated using Equation (7).

$$h = (2.7)d \tag{7}$$

Cavity Length: h1 (mm): The Cavity Length was calculated using Equation (8).

$$h_1 = (0.35)d \tag{8}$$

Length to Impact Point h2 (mm): The Length to impact Point was calculated from Equation (9).

$$h_2 = (1.5)d \tag{9}$$

Bucket Depth t (mm): The Bucket Depth was calculated from Equation (10).

$$t = (0.9)d \tag{10}$$

Cavity Width a (mm): The Cavity Width was calculated from Equation (11).

$$a = (1.2)d \tag{11}$$

Offset of Bucket k (mm): The Offset of Bucket was calculated from Equation (12).

$$k = (0.17)d \tag{12}$$

A typical bucket showing all the calculated geometries above is shown in Figure 4.

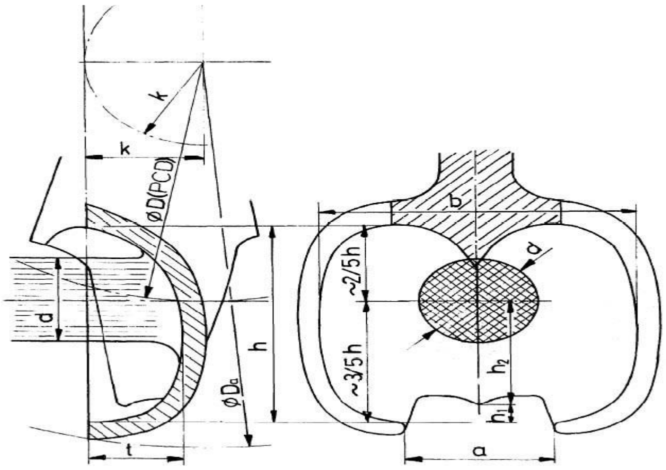


Figure 4: Ideal Dimensions of a Pelton Wheel.
Source: MHPG (1991) Series

2.4 Design of Cross Flow Turbine

2.4.1 Selection of the outside diameter (d_1)

According to Renewables First (2009), the size of the outside diameter of cross flow turbines is dependent on available hydraulic head and it normally ranges from 100mm to 500mm in 50mm or 100mm steps. For very high heads (above 10m), diameters below 200mm could be used while 300mm diameter is used for heads between 2m to 5m. Diameters between 400 to 500mm are used for very low head sites below 2.5m (Muhammad and Saeed, 2014). Therefore, the rotor diameter (d_1) is taken to be 300mm since the hydraulic head in this research was 4 meters.

2.4.2 Other Dimensions

Most of the Construction Dimensions of the crossflow turbine can be established using the outside diameter (d_1) and the relationships are given by Muhammad and Saeed (2014).

a) Inner Diameter (d_2)

The Inner Diameter was calculated from Equation (13).

$$d_2 = 0.66d_1 \tag{13}$$

(b) The Radius of the blade (rb).

The radius of the blade was calculated from Equation (14).

$$r_b = 0.326\,X\frac{d_1}{2} \tag{14}$$

(c) The Spacing of the Blades (t) was calculated from Equation (16)

$$S_1 = K \times d_1 \text{ where } K = 0.09 \tag{15}$$

and $t = \frac{S_1}{\mathrm{Sin}\beta_1}$ where $\beta_1 = 30$

$$t = \frac{K\,X\,d_1}{\mathrm{Sin}\beta_1} \tag{16}$$

(d) Position of Blades.

The leading edge of the blade should be at 30 degrees to the tangent at the point of contact. The trailing edge of the blade is radial, i.e., all the trailing edges point directly to the center.

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

(e) Position of the Water Jet.

The water Jet angle to the blade should be 16 degrees with respect to the tangent at the point of contact.

A cross-section of a Cross Flow turbine showing all the calculated geometries above is shown in Figure 5.

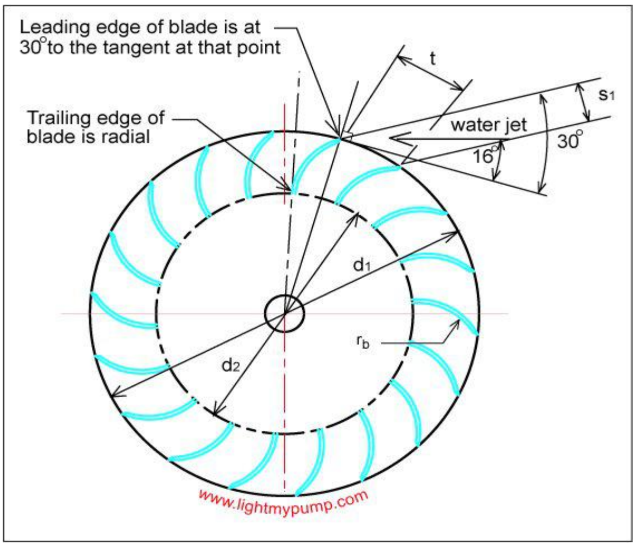


Figure 5: Critical geometry of the cross-flow turbine.

Source: www.lightmypump.com

2.5 Fabrication

The fabrication of the machine involved material selection, marking out, cutting, welding of components, sand casting of the Pelting wheel cups, assembling of component parts, finishing and painting. The materials used are Stainless steel pipes and plates (for parts in direct contact with water), galvanized steel pipes and plates (for frames and other parts) while Aluminum cast was used for molding the Pelton wheel cups because of ease of forming and its relative water resistance ability. All the important views of the hydro-generator were drawn with AUTOCAD 2019.

2.6 Testing of the Turbines

The turbines were tested by opening the control valve on the outlet pipe and left until the operation of the turbines become stable. The speed and the torque were measured using a tachometer which also doubles as a torque meter. The nob of the tachometer was placed at the punched center of the turbine and alternator shaft and the readings were recorded. The Tachometer used was a contact type manufactured by Fisons with model number TAF – 420 – K. The output voltage was measured using a Multimeter connected to the output terminals of the alternator. It was manufactured by Fison with model number DT9205M. Ten readings were taken each over a period of 30 minutes and the averages were found. The results were plotted on a graph using Microsoft Excel 2016 for a comparison between the two turbines

3. Results and Discussion

3.1 Design Results

Table 1 shows a summary of the hydraulic properties of the dam used and calculated geometry of the Pelton wheel while Table 2 shows a summary of the calculated geometry of the Cross Flow Geometry.

Table 1: Summary Table for Hydraulic properties of the dam and the Pelton Wheel Geometry.

S/N	PARAMETER	DIMENSION
1.	Hydraulic Head (Hn)	4.0m
2.	Flow Rate (q)	1.7 X 10-2 m3s-1
3.	Available Power	667 Watts
4.	Rotational Speed (rpm)	1500 rpm
5.	Absolute Velocity of Water Jet (c1)	8.50 m/s
6.	Optimal Jet Diameter (d)	51mm
7.	Optimal Peripheral Velocity	4.0m/s
8.	Pitch Circle Diameter (D)	0.26m
9.	Bucket Width (b)	163.2mm
10.	Bucket height (h)	137.7mm
11.	Cavity Length (h1)	17.5mm
12.	Length to Impact Point (h2)	76.5mm
13.	Bucket depth (t)	45.9mm
14.	Cavity Width (a)	61.2mm
15.	Offset of Bucket (k)	8.7mm

Table 2: Summary Table for the Cross Flow Geometry

S/N	PARAMETER	DIMENSION
1.	Rotor Diameter (d_1)	300mm
2.	Position of Water Jet	16 degrees
3.	Position of Blades	30 degrees
4.	Inner Diameter (d_2)	198mm
5.	Radius of Blade (r_b)	50mm
6.	Spacing of Blade (t)	28mm

3.2 Machine Fabrication

Figures 6 and 7 show the isometric view of the cross flow and Pelton wheel turbines respectively which reveals the position of the alternator, the pulley attached to the turbine and the intermediate pulley which was fabricated for speed increment. Figure 8 is the Exploded view of the Cross Flow Turbine which reveals the two Adjusters, the Nozzle inclined at an angle as well as the Turbine assembled in the casing. Figures 9 and 10 depict the orthographic views of the Cross Flow and Pelton Wheel Turbines respectively which show the front, plan and end views of the machines. Figures 11 and 12 show the pictorial views of the Pelton Wheel Turbine and the Cross Flow Turbine respectively. Table 3 is the Bill of Engineering Measurement and Evaluation (BEME) as at year 2014, which contains the quantity, description/specification and cost of component parts.

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

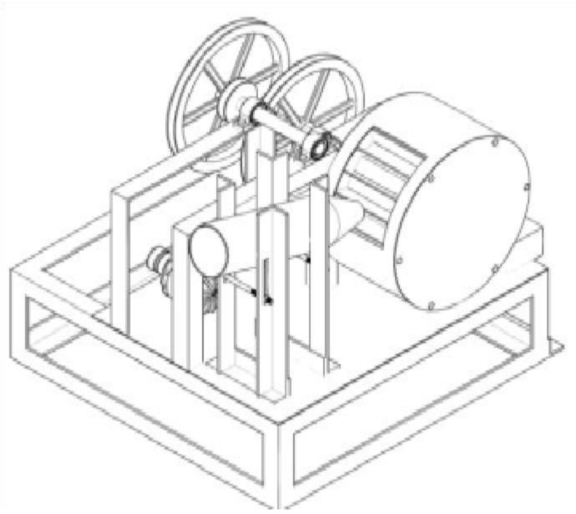


Figure 6: Isometric View of the Cross Flow Turbine.

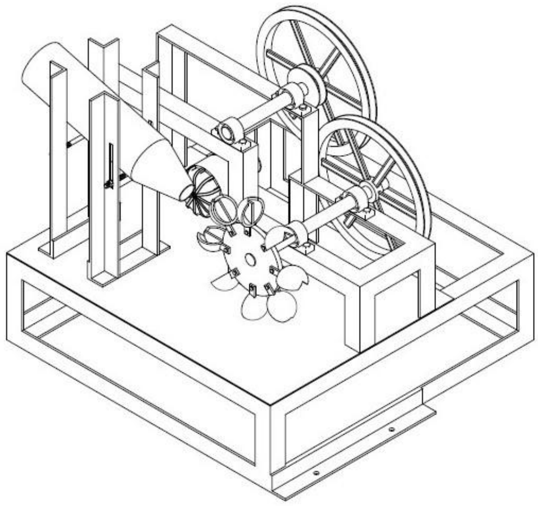
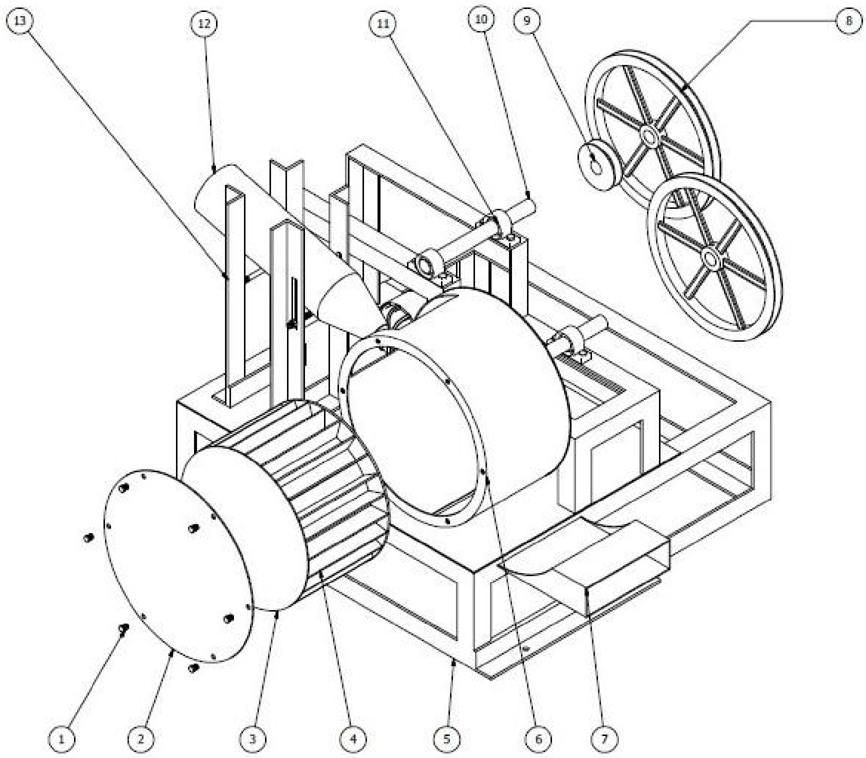


Figure 7: Isometric View of the Pelton Wheel Turbine.



PARTS LIST	
PART NUMBER	DESCRIPTION
1	BOLT
2	COVER
3	CROSS-FLOW
4	CROSS-FLOW BLADE
5	FRAME
6	CROSS-FLOW CHAMBER
7	WATER OUTLET
8	BIG PULLEY
9	SMALL PULLEY
10	SHAFT
11	PILLOW BEARING
12	NOZZLE
13	NOZZLE STAND

Figure 8: Exploded View of the Cross Flow Turbine.

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

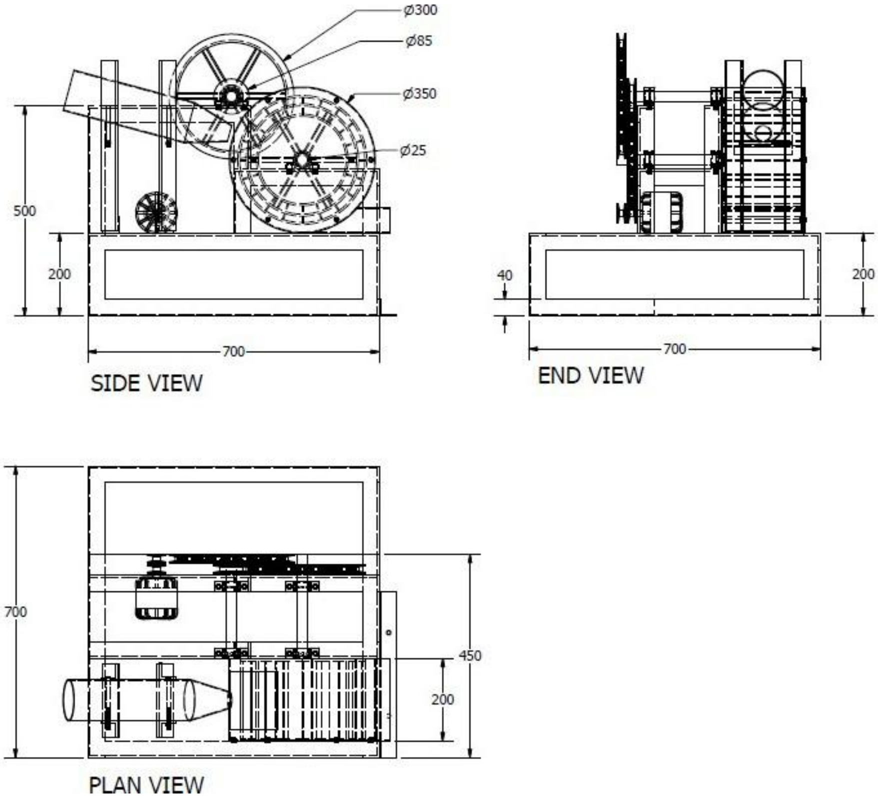


Figure 9: Orthographic View of the Cross Flow Turbine.

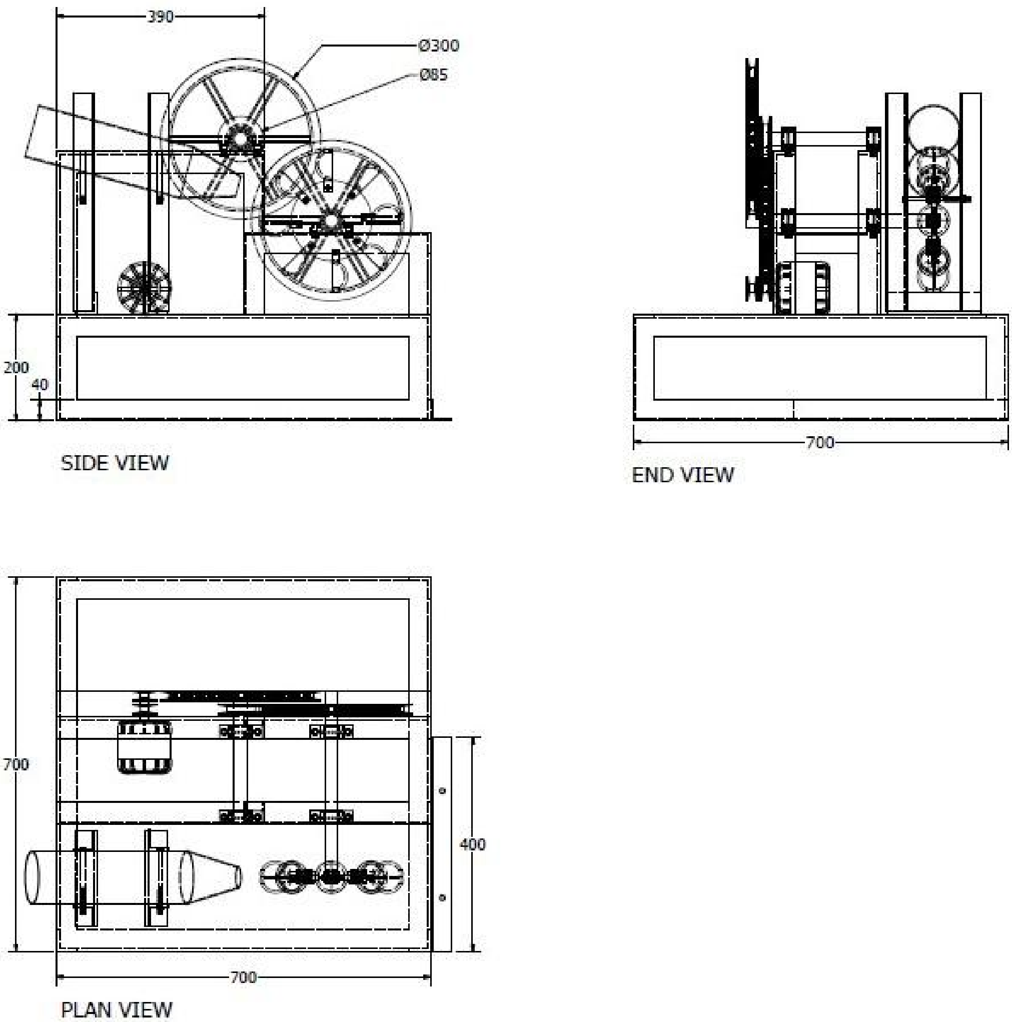


Figure 10: Orthographic View of the Pelton Wheel Turbine.

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

Figure 11: Pictorial View of the Pelton Wheel Turbine

Figure 12: Pictorial View of the Cross Flow Turbine

Table 3: Bill of Engineering Measurement and Evaluation (BEME) (2014)

S/N	Item	Description/Specification	Quantity	Unit Price ₦	Amount ₦
1.	Pulley	300mm	2	4000	8000
2.	Pulley	50mm	1	2000	2000
3.	Flat Bearing	25mm Self Aligning	4	1000	4000
4.	Shaft	25mm	2	800	1600
5.	Belts	C - Type	3	300	900
6.	Angle Iron	2 by 2 (Mild Steel)	1.5	4000	6000
7.	Mild Steel Plate	(2 by 4) 4mm gauge length	1	1000	1000
8.	Flange	150mm	2	1500	3000
9.	Pelton Wheel Cup Pattern		1	8000	8000
10	Pelton Wheel Cup		16	1000	16,000
11	Stainless Steel Plate	(4 by 4) 2mm gauge length	1	12,000	12,000
12	Cross Flow Turbine		1	6000	6000
13	Nozzle	100mm by 50mm	1	2000	2000
14	Electrode	Stainless	24	100	2400
15	Electrode	Mild Steel	4 dozens	100	400
16	Transportation				5000
17	Workmanship				30,000
				Total	108,300
18	Plumbing Work				30,300
				Sub Total	138,600
	Over Head @ 10%				13,860
				Grand Total	152,460

3.3. Machine Testing and Performance

For the Cross Flow turbine, a maximum turbine speed of 538.4 rpm and turbine torque of 46.2 kNm was achieved in off load condition, while at on-load condition, a maximum turbine speed of 392 rpm, turbine torque of 36.5 kNm, alternator speed of 1768.6m rpm. Similarly, a maximum turbine speed of 330.1 rpm and turbine torque of 39.1 kNm was achieved in off-load condition, while at on-load condition, a maximum Turbine Speed of 197.7 rpm, turbine torque of 25 kNm, alternator speed of 879.24 rpm.

Generally, for all the measured outputs, the Pelton Wheel Turbine recorded higher values than the Cross Flow Turbine as shown in Figure 13. This is in contrast to the findings of Dunavent and Erwin, (1998); Gass, (1998); Staubli, et. al., (2001); Atthanayake, (2009) which concluded that pelton wheel is not efficient at low heads and also, Robert and Robert, (2002); Donners, et. al., (2002) reported that the most efficient turbine for low head is the crossflow turbine. This could be due to some design modifications in the pelton wheel used, such as the cup size, cup shape, groove inclusion and number of cups amidst others. To corroborate this assumption, Tilahun et.al. 2017 reported that Changing the length, depth, angular position (Jet bucket interaction), and number of the buckets while keeping all other parameters constant could improve maximum efficiency and reduce production cost.

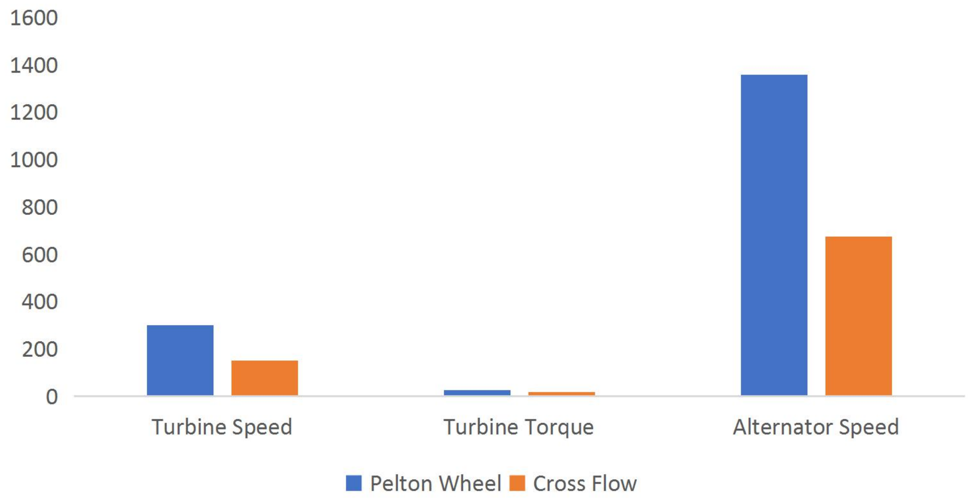


Figure 13: Comparing the Mean Output from the Two Turbines
* Turbine Speed (rpm) Turbine Torque (Nm) Alternator Speed (rpm)

4. Conclusion

Two turbines were designed, constructed and evaluated. The turbines were designed for use at the UNILORIN dam which has a net head of 4m, flow of $0.017m^3$ and a theoretical hydro energy of 668W. The two turbines were tested, and the result showed that the Pelton wheel turbine gave the highest alternator speed of 1768.6rpm which exceeded the required 1500rpm needed for optimally running the alternator. This improved performance of the Pelton wheel could be due to some design modifications in the Pelton wheel used, such as the cup size, cup shape, groove inclusion and number of cups amidst others. The rotary motion generated also has sufficient torque that could make it adaptable for powering small farm machines like threshers, winnower, press, etc. Since, the overflow from the dam was sufficient for powering the turbines, other flowing streams and rivers with similar head and flow rate could as well be able to power the developed turbines.

Corresponding author's e-mail address: oyebodeoyetayo@yahoo.com

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