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Design and Construction of a 5 kW Turbine for a Proposed Micro Hydroelectric Power Plant Installation at Awba Dam University of Ibadan

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Abstract: The designand construction of a 5 kW turbine for a proposed micro hydroelectric power plant installation at Awba Dam University of Ibadan was undertaken. Dam outflow rate and the average head of outflow were determined using a topographical survey of the dam and pertinent calculations. For selection of a suitable turbine from available options (Francis, Kaplan and Pelton), a selection matrix was used with compliance with turbine selection chart, affordability, ease of local constructionand long term cost effectiveness and suitability for expected working-speed range as the selection criteria. The various designed parts were constructed and assembled locally and the turbine was tested using both an elevated tap (a height of 4 m and a flow rate of about 0.00051 m^3 sec^{-1}) and a water tanker at a flow rate of about 0.00214 m^3 sec^{-1}. Results showed that Francis turbine was most suitable. Turbine inlet tip angle of 59°, turbine outlet tip angle of 47°, turbine runner outer diameter of 22 cm and inner diameter of 11 cm and a wicket angle of 22° were obtained. These values were used for constructing the turbine. Tests performed using the tap showed that the turbine worked at an average rotational speed of 110 rev min^{-1} while it worked at an average speed of 300 rev min^{-1} when it was tested using the water tanker. This showed that the turbine speed increased with increased water flow rate. A 5 kW Francis turbine for micro hydro installation at Awba dam has been designed and constructed. The turbine worked smoothly.

Key words: Dam, turbines, hydro, pumps, water tanker, outflow, Nigeria

INTRODUCTION

Turbine is a rotary engine that converts the energy of a moving stream of water, steam or gas into mechanical energy. The basic element in a turbine is a wheel or rotor with paddles, propellers, blades or buckets arranged on its circumference in such a way that the moving fluid exerts a tangential force that turns the wheel and imparts energy to it. This mechanical energy is then transferred through a drive shaft to operate a machine, compressor, electric generator or propeller. Turbines are classified as hydraulic or water turbines, steam turbines or gas turbines. Today, turbine-powered generators produce most of the world's electrical energy.

The oldest and simplest form of the hydraulic turbine was the waterwheel type, 1st used in ancient Greece and subsequently, adopted in most of the ancient and medieval Europe for grinding grains. It consisted of a vertical shaft with a set of radial vanes or paddles positioned in a swiftly flowing stream or millrace. Its power output was about 0.5 horse power. The horizontal-shaft waterwheel (that is a horizontal shaft connected to a vertical paddle wheel), 1st described by the Roman architect and engineer Marcus Vitruvius Pollio during the 1st century BC had the lower segment of the paddle wheel inserted into the stream, thus acting as a so called undershot waterwheel. Around the 2nd century AD, the more efficient overshot wheel had come into use in the hilly regions. Here, the water was poured on the paddles from aboveand additional energy was gained from the falling water. The maximum power of the water wheel which was constructed of wood, increased from about 3 horse power to about 40 kW in the middle ages. Wikipedia reported that the evolution from water wheels to modern turbines took about 100 years. Development occurred during the era of industrial revolution as a result of the application of scientific principles and methods. The extensive use of new materials and manufacturing methods developed at the time.

Smeaton John (1724-1792) as by Adeyanju (2009) was credited with the first important attempt to formulate a theoretical basis for water wheel design. Smeaton's theoretical calculations proved that the overshot wheel was more efficient; he reserached on and was able to improve the efficiency of the water wheel to 70%. The French military engineer Jean Victor Poncelet cited by Microsoft students however, devised an undershot wheel, the curved blades of which raised efficiency to

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Corresponding Author: T. Ajuwape, Department of Mechanical Engineering, University of Ibadan, Ibadan, Oyo, Nigeria nearly 70%. Jean-Victor Poncelet by Wikipedia, designed an inward-flow turbine around 1820 that used the same principles as that of Benoit Fourneyron outward flow turbine. Benoit Fourneyron went on to design and build wheels that achieved speeds of ≥60 revolutions $\min^{-1}$ (rpm) and provided up to about 40 kW for French iron works.

Ultimately, Benoit Fourneyron in 1826 developed a high efficiency (80%) outward flow water turbine. Water was directed tangentially through the turbine runner causing it to spin. Despite its remarkable efficiency, the Fourneyron turbine had certain drawbacks as a result of the radial outward flow of water that passed through it.

Claude Burdin by Microsoft student, invented the term turbine, introduced as part of a theoretical discussion in which he stressed speed of rotation. Zuppinger and schwamkrug cited by Adeyanju (2009) also both used the principle of the water wheel to create the 1st turbine. They both pioneered the development of a waterspout or nozzle that directs a high velocity stream of water against blades set on a wheel; a colossal step away from the water wheel. Pelton cited by Microsoft students was responsible for the development of a type of turbine in which the water was piped from a high-level reservoir through a long duct or penstock to a nozzle where its energy was converted into the kinetic energy of a high-speed jet. The jet was then directed onto curved buckets which turn the flow by nearly 180° and extract the momentum of the impinging flow of water.

The turbine was named after its inventor. Crewdson (1920) by Adeyanju (2009) improved the efficiency of the already efficient pelton wheel. This improvement led to the development of the Turgo wheel which produced higher efficiency and simpler construction than either the pelton wheel or the water wheel. However, the impulse wheels have been upgraded in recent years by more complex and efficient reaction turbines.

According to Microsoft student, the increasing demand for hydroelectric power (2007) during the early 20th century led to the need for a turbine suitable for small water heads of 3-9 m (about 10-30 feet) that could be employed in many rivers where low dams could be built. Viktor Kaplan as by Microsoft student proposed a propeller (or Kaplan) turbine which basically acts like a ship's propeller in reverse. Kaplan later improved his turbine by allowing the blades to swivel about their axis. These variable pitch propellers improved efficiency by optimally matching the blade angle to the head or flow rate. Viktor Kaplan's research marked the advent of reaction turbines; unlike the water wheels and pelton turbine which are regarded as impulse turbines the Kaplan turbine is a reaction turbine. According to Energy bible reaction turbines are turbines in which the runners are fully immersed in water and are enclosed in a pressure casing. The runner blades are angled so that the pressure difference across them creates thrusts which cause the runner to rotate. Another type of reaction turbine that was developed around the same time as the Kaplan turbine is the Francis turbine Adeyanju (2009).

James B. Francis 1848 as by Wikipedia improved on jean Victor Poncelet's 1820 designs to create a turbine with 90% efficiency. He applied scientific principles and testing methods to produce a very efficient turbine design. More importantly, his mathematical and graphical calculation methods improved the state of the art of turbine design and engineering. His analytical methods allowed confident design of high efficiency turbines to exactly match a site's flow conditions.

Alexander *et al.* (2009a) described the design of four different specific speed micro-hydro propeller turbines operating at heads between 4-9 m and their application to a wider range of heads and outputs by scaling. Test machines were described and test results given; hydraulic efficiencies of >68% were achieved in all test models despite the fact that these turbines' blades were planar, further simplifying manufacture. Theoretical models showed how closely these flat blades could be made to approach the ideal blade shapes. Alexander *et al.* (2009b) provided drawings with key dimensions for each reference model along with the equations for scaling to sites ranging from 2-40 m of head.

Singh and Nestmann (2010) presented a detailed experimental investigation of the effects of exit blade geometry on the part load performance of low head axial flow propeller turbines. The experimental results presented explained the relationship between exit tip-angle, discharge through the turbine, shaft powerand efficiency. The study concluded that the effects of exit tip modification were significant.

Agnew turbine is a 45° axial flow Kaplan type micro hydro turbine which was designed to operate without guide vanes. The Agnew turbine was later improved to accommodate low head and limited flow potentials. Alexander *et al.* (2009a, b) described the design of and tested two different specific speed micro hydro turbines of the mixed-flow and radial-flow type, operating at heads between 6 and 12 m at small scale and up to heads of 50 m at larger scales. Hydraulic efficiencies of >70% were achieved in all test models despite the fact that the turbine blades were made from flat plate, specifically to simplify manufacture. Outline drawings were given with key dimensions for each reference model along with the equations for scaling to arbitrary sizes. Williams *et al.* (2000) presented a review of low head turbine technology for Pico hydro drawn from university research and information from manufacturers. The designs were assessed particularly in relation to their suitability for use in developing countries. Many had problems in terms of cost or reliability. The research concluded by describing the research being carried out to achieve a robust, low cost design of Pico propeller turbine suitable for local manufacture in developing countries.

Small centrifugal pumps are suitable for use as hydraulic turbines and have the advantage of being mass produced in many countries throughout the world (Williams, 1996). Suitability of application of small centrifugal pumps as turbines are of two main types; firstly as a low-cost alternative to cross-flow turbines with an output of 5 kW or less; secondly for energy recovery in pipelines. These types of installation may be suitable for industrialized and developing countries. Rajput (1998) presented practical steps wise design of both the Pelton and the Francis turbine.

The Francis turbine: According to power electrical, Francis turbine (Fig. 1) is an inward flow reaction turbine that combines radial and axial flow concepts. Francis turbines are the most common water turbine in use today. Francis turbines typically contain runners which have water passages formed by curved vanes or blades. The runner blades, typically 9-19 in number cannot be adjusted. As the water passes through the runner and over the curved surfaces, it causes rotation of the runner. The rotational motion is transmitted by a shaft to a generator.

MATERIALS AND METHODS

Determination of head and flow: The average head of the dam was estimated using a prepared topographical survey of the dam (Appendix 1); it was estimated to be about 6 m while the outflow from the dam was estimated by calculation using the formula:

$$v=\sqrt{2gh}$$

Where:

v = The velocity of flow

g = The acceleration due to gravity and h the head

The estimated velocity was then multiplied by the size of the existing penstock to get the value of the volumetric flow rate of water out of the dam to be 0.244 m^3 sec^{-1}. However with a head of 6 m and expected power output of 5 kW the required flow rate is just 0.106 m^3 sec^{-1} out of the estimated 0.244 m^3 sec^{-1} and the use of 0.106 m^3 sec^{-1} of the total flow allows for flow fluctuations.

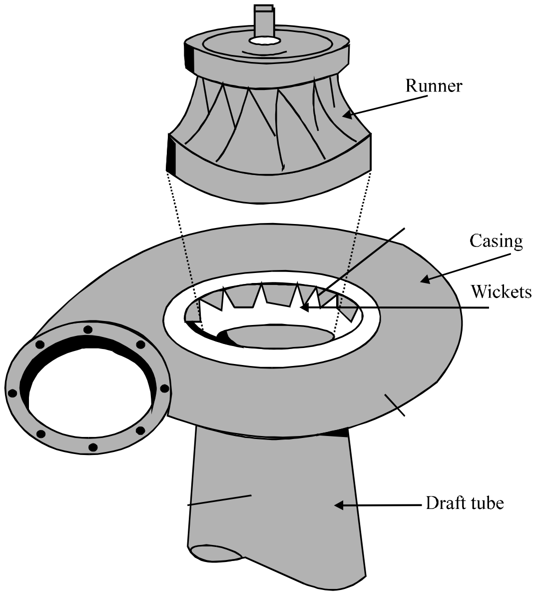


Fig. 1: Francis turbine

Turbine selection: The turbine selection exercise in this study employed the use of decision/selection matrix using: ease of local construction/manufacture, compliance with turbine selection chart, compliance with the rotational speed range and affordability as selection criteria to help give a holistic approach to the selection process (Table 1). Three turbine types: Pelton, Francis and Kaplan turbines were chosen for consideration.

- Score = Rating×Weight
- The desired running speed for the turbine is between 180 and 600 rev min^{-1}
- The turbine is expected to work under uniform loading condition

The use of the decision matrix, using the criteria stated above showed that the Francis turbine is the most suitable of the three of types of turbine considered for the power plant installation. The components of the Francis turbine that were constructed were runner, casing, wickets, draft tube, shaftand wicket control mechanism.

Turbine runner design and construction: For the design of the impeller; a software was developed in Microsoft access using the following parameters and equations which were obtained from Rajput (1998). With these, the diameter of runner at inlet, the tip angle of vane at inletand tip angle of vane at outlet were obtained.

Input parameters:

- Overall efficiency (η_0)
- Hydraulic efficiency (η_n)

Table 1: Turbine selection matrix

		Pelton turbine		Francis turbine		Kaplan and propeller turbine	
Criteria	Weight	Rating	Score	Rating	Score	Rating	Score
Compliance with turbine selection chart	0.4	5	2.0	10	4.0	5	2.0
Affordability	0.2	10	2.0	9	1.8	8	1.6
Ease of local construction	0.1	10	1.0	9	0.9	8	0.8
Suitability for expected working-speed range	0.1	10	1.0	10	1.0	6	0.6
Long term cost effectiveness	0.2	6	1.2	9	1.8	7	1.4
Total	1.0	-	7.2	-	9.5	-	6.4

- Ratio of width to diameter (n)
- Flow ratio (k_f)
- Head of water (H)
- Vane thickness factor (K_t)
- Shaft Power (P)
- Rotational speed of runner (N)
- Specific weight of water (w)
- Gravitational acceleration (g)

The output parameters:

- Diameter of runner at inlet (D_1)
- Tip angle of vane at inlet (θ)
- Tip angle of vane at outlet (Φ)
- Angle of absolute velocity at outlet (α)

Relevant equations:

$$Q = \frac{P}{\eta_o WH} \tag{1}$$

$$D_1 = \sqrt{\frac{Q}{K_f \sqrt{2gH}\, kt \prod n}} \tag{2}$$

$$V_{f1} = \frac{Q}{K_t \pi n D_1^2} \tag{3}$$

$$U_1 = \frac{\pi D_1 N}{60} \tag{4}$$

$$V_{w1} = \frac{\eta_n gH}{U_1} \tag{5}$$

$$\alpha = \tan^{-1}\frac{Vf_1}{V_{w1}} \tag{6}$$

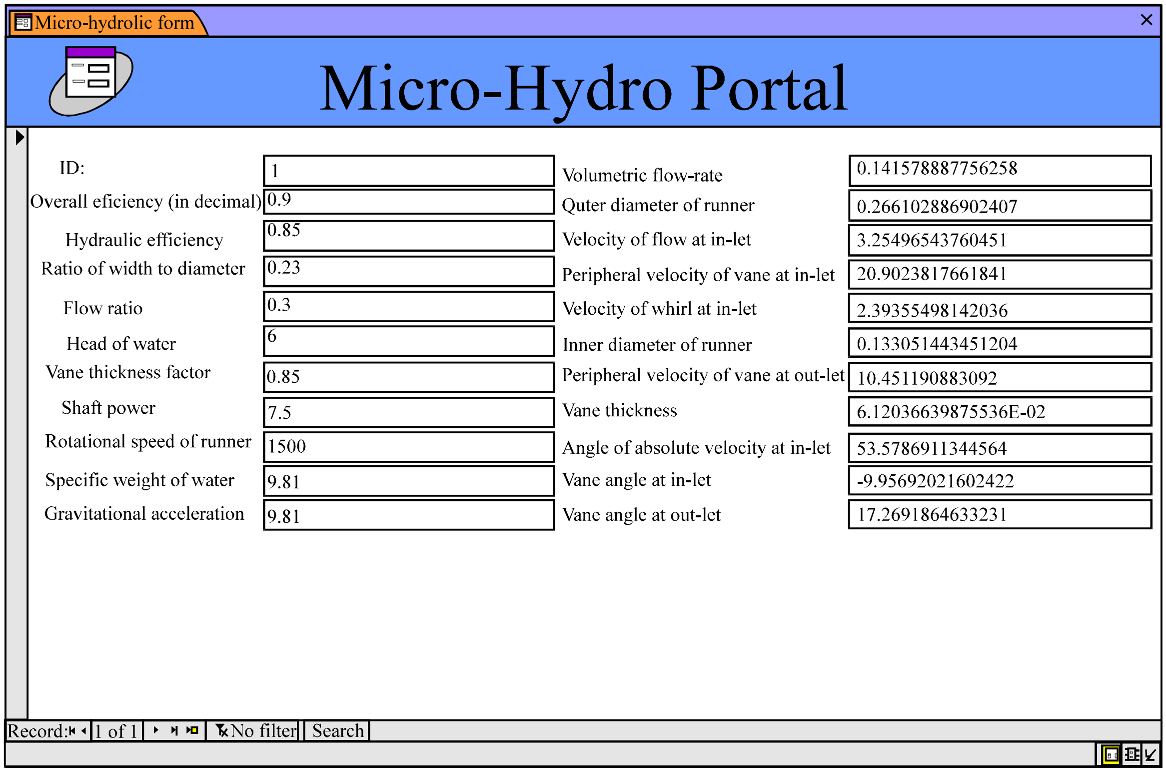
$$\theta = \tan^{-1}\frac{Vf_1}{V_{w1} - U_1} \tag{7}$$

The output inter-phase is as shown in Fig. 2. The design output from above was used to construct the runner. Structurally, there are two types of Francis turbine runners that are used in practice, the runner type A and runner type B (Fig. 3). The runner type A is the more commonly used of the two types of runners however for the ease of manufacturing the runner locally, the runner type B was selected for construction since, runner type B is similar to pump impellers which crafts men already manufacture locally with relative ease. Also, the number of runner vanes was taken to be twelve in number to make its local construction easier; a higher number of runner vanes would imply a tighter arrangement. The runner was casted using aluminum so as to make it as light in weight as possible.

Turbine casting: The turbine needed a casing which could sustain a flow rate of 0.106 m^3 sec^{-1} to house the turbine runner and wickets. A centrifugal hydraulic pump case was gotten which helped to eliminate the necessity of manufacturing the turbine casing locally which would have been a complex task. The casing had a water inlet of 8 cm and water outlet of 11 cm.

Three key adjustments were carried out on the casing. Firstly, the interior of the casing was converted from a tapered (Fig. 1) to a flat profile. The conversion was carried out using a steel plate (Fig. 1) which was machined to the appropriate dimensions and welded to the base of the casing. Secondly, the back of the casing was machined to create a grove to enable the control ring to sit properly at the back of the housing and act as a guide way for the control ring when it rotates. Thirdly, 17 holes were drilled around the circumference of the casing to make way for the studs of the wicket to pass through to the back of the housing where the studs would then be connected to the control ring by the control lever.

Turbine draft tube design and construction: The length of the draft tube was taken to be 3D and the angle taking to be 6° turbine outlet: Diameter (D) = 11 cm. Therefore, d = 3D tan6 = 3.5 cm and the total diameter of the draft tube exit is 18 cm. The draft tube (Fig. 4) was constructed using metal sheet which was cut into the appropriate dimensionsand wrapped to give a conical shape. A flat ring was welded to the end with the smaller diameter to make it possible to fasten the tube to the cover of the casing.



ID:	1	Volumetric flow-rate	0.141578887756258
Overall eficiency (in decimal)	0.9	Quter diameter of runner	0.266102886902407
Hydraulic efficiency	0.85	Velocity of flow at in-let	3.25496543760451
Ratio of width to diameter	0.23	Peripheral velocity of vane at in-let	20.9023817661841
Flow ratio	0.3	Velocity of whirl at in-let	2.39355498142036
Head of water	6	Inner diameter of runner	0.133051443451204
Vane thickness factor	0.85	Peripheral velocity of vane at out-let	10.451190883092
Shaft power	7.5	Vane thickness	6.12036639875536E-02
Rotational speed of runner	1500	Angle of absolute velocity at in-let	53.5786911344564
Specific weight of water	9.81	Vane angle at in-let	-9.95692021602422
Gravitational acceleration	9.81	Vane angle at out-let	17.2691864633231

Fig. 2: Output interface of the Francis turbine design program

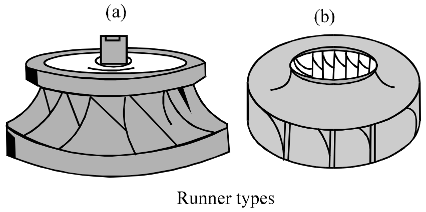


Fig. 3: Turbine runner types

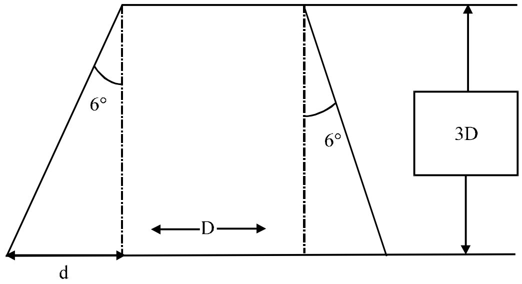


Fig. 4: Draft tube profile

Turbine wickets design and construction: The wickets/adjustable vane of the Francis turbine were designed as part of the runner, the wicket angle is given by the angle of absolute velocity at inlet (α). The wickets also were casted using aluminum. The number of wickets was taken to be seventeen for ease of construction and assembly.

The wicket control mechanism: The manual wicket control mechanism is made up of the control ring and the control lever. The wicket have studs which are inserted into the hole that have been drilled into the casing, these studs protrude out of the back of the casing and are clipped by one end of the control lever while the other end of the lever is attached to the control ring such that when the ring is rotated the lever moves with it and also turns the studs of the wickets which in effect closes and opens the wickets.

The wicket control ring: The control ring (Fig. 5) was constructed by machining a purchased steel ring into a finished ring of 29 cm outer diameter, 28 cm inner diameter with a thickness of about 2 cm.

The wicket control lever: The control lever (Fig. 5) which serves as the connecting link between the control ring and the wickets are seventeen in number; one for each wicket. The levers were casted using aluminum and its surfaces were then finished by filing. The levers are about 4 cm in length and about 0.5 cm thick.

The turbine casing cover: The turbine casing cover was made using 6 layers of 5 mm transparent plastic sheets which was 1st glued together and then machined to the appropriate dimensions.

Turbine bearing and shaft: A 35 mm stainless steel shaft was purchased and machined into appropriate diameters for use in the turbine. A bearing with suitable dimensions was also purchased for use in the turbine.

Turbine assembling: After the construction of the different parts of the turbine had being completed, the various parts of the turbine were coupled as follows: The bearing was 1st placed on the shaft, the shaft was then inserted into the turbine casing from the back of the casing with the bearing on the shaft sitting firmly in a bearing seat which had been machined into the turbine casing, thus holding the shaft firmly in place. The turbine runner was then attached to the shaft from the front side of the turbine casing with the aid of threads which had been tapped into both the runners and the shaft and a lock nut. The next step was to place the wicket into turbine casing with the studs at the base of the wicket protruding through hole that had been prepared in the casing to the back of the casing after which the casing was then flipped and the stud of the wicket were then attached to the wicket control ring with the aid of the wicket control lever. Finally, the turbine casing cover was fastened to the front of the turbine casingand the draft tube screwed to it.

Turbine tests: The turbine tests were carried out using an elevated tap with an elevation of about 4 m and a water tanker because the proposed point of installation of the turbine had not been excavated. Attached compact disk for a video detail of the tests. The rotational speed of the turbine was measured using hand held Tachometer.

RESULTS AND DISCUSSION

The outcome of the construction is as follows: The finished turbine runner is shown in Fig. 6. The housing and the conversion plate for the housing are shown in Fig. 7 while the back view of the casing with the control ring is shown in Fig. 8. The finished housing cover and draft tube are shown in Fig. 9 and 10. The finished wicket is shown in Fig. 11 and 12.

The finished wicket control lever and control ring are shown in Fig. 13 and 14, respectively. A front view of the turbine assembly without the casing cover is shown in Fig. 15 while Fig. 16 shows the back view of the assembly. The turbine was tested using an elevated tap and a water tanker as the source of pressurized water, respectively. Figure 6-18 present various views of the finished parts of the turbine and also the turbine assembly.

Figure 6-18 show the finished runner, turbine casing, casing cover, draft tube, wickets, wicket control lever, wicket control ring, turbine assemblyand turbine tests. The coupled turbine was tested using a water tap with an elevation of about 4 m and a water tanker, respectively because the proposed site of installation of the turbine has not been excavated and the necessary pipe network put in place. There was also the non-availability of a test rig. During test, using the elevated tap at a height of

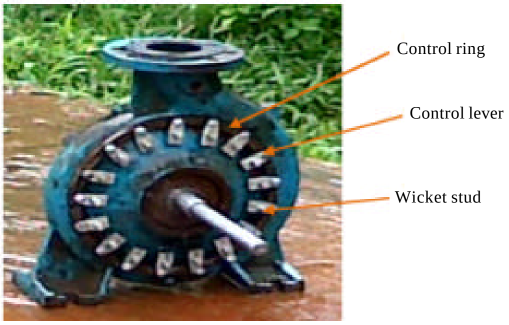


Fig. 5: Wicket control mechanism

Fig. 6: The finished runner

Fig. 7: The turbine housing/casing and conversion plates

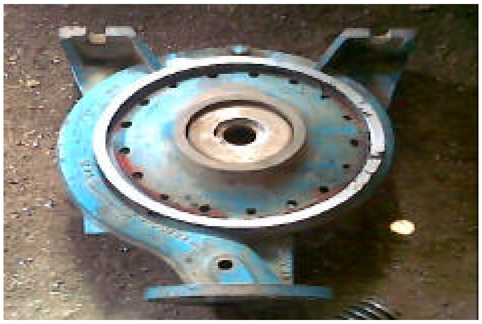


Fig. 8: Back view of the turbine housing

Fig. 9: Turbine housing cover

Fig. 10: The Finished draft tube

Fig. 11: Top view of finished wickets

Fig. 12: Side view of finished wickets

Fig. 13: The control lever

Fig. 14: The control ring

Fig. 15: Front view of turbine assembly without the casing cover

4 m and a flow rate of about 0.00051 m^3 sec^{-1}, the turbine worked at a rotational speed of 110 rev min^{-1} while it worked at an average rotational speed of 300 rev min^{-1} when it was tested using the water tanker at a flow

Fig. 16: Back view of turbine assembly

Fig. 17: Turbine test using elevated tap without the casing cover

Fig. 18: Turbine test using water tanker

rate of about 0.00214 m^3 sec^{-1}. However due to the tests constraints, the actual efficiency of the Turbine could not really be determined.

CONCLUSION

The selection, design, construction and testing of a 5 kW turbine for a micro hydroelectric power plant installation at Awba dam University of Ibadan, Ibadan were undertaken. The turbine was tested using an elevated tap and a water tanker because the proposed site of installation had not been excavated and the lack of a standard test rig. Both tests showed that the turbine would achieve its purpose. However, the angular speed and the efficiency of the turbine under the different tests could not be determined due to the lack of standard equipment and test rig.

REFERENCES

Adeyanju, A.A., 2009. Technical feasibility of a micro hydro installation. J. Eng. Applied Sci., 4: 324-334.

Alexander, K.V., E.P. Giddens and A.M. Fuller, 2009a. Axial-flow turbines for low head microhydro systems. Renewable Energy, 34: 35-47.

Alexander, K.V., E.P. Giddens and A.M. Fuller, 2009b. Radial-and mixed-flow turbines for low head microhydro systems. Renewable Energy, 34: 1885-1894.

Rajput, R.K., 1998. Fluid Mechanics and Hydraulic Machines Part-2. 3rd Edn., S. Chand and Co. Ltd., New Delhi.

Singh, P. and F. Nestmann, 2010. Exit blade geometry and part-load performance of small axial flow propeller turbines: An experimental investigation. Exp. Thermal Fluid Sci., 34: 798-811.

Williams, A.A., 1996. Pumps as turbines for low cost micro hydro power. Renewable Energy, 9: 1227-1233.

Williams, A.A., D.R. Upadhyay, G.M. Demetriades and N.P.A. Smith, 2000. Low head pico hydropower: A review of available turbine technology. Proceedings of the 6th World Renewable Energy Congress, Brighton, UK., July 1-7, Pergamon, Amsterdam, pp: 1475-1480.