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Effect of Blade Cross-Section on the Performance of a Simplified Pico-Hydro System

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ABSTRACT: *The effect of blade cross section on the performance of a simplified Pico hydro system was examined in this study as part of an on-going Pico hydropower system development. Blades with rectangular, trapezoidal, u, partial v, and full v cross-sections were fabricated for the turbine and the speed of rotation of the alternator shaft and the voltage developed were measured and computed in relation to optimum turbine performance using each of the specified blades. The results obtained indicated that the full v-shaped blade gave the best performance of the simplified system in terms of rotational speed and consequently voltage. The maximum values of the parameters obtained were 1678.95 rpm and 212.1 V. The partial v shape gave the lowest values of the parameters which were 1056.3 rpm and 129.2 V. Generally, the system performance for all the blade shapes indicated good promise for the implementation of the locally developed system for generation of clean, decentralized energy in line with current global trends. However, further development of the system will utilize the full V cross section in order to maximize the quantity of energy converted.*

Keywords**:** *Blade cross-section, clean energy, decentralized energy, output voltage, Pico hydro system, shaft rotational speed*

I. INTRODUCTION

There has been an enormous increase in the global demand for energy, and this has led to the generation of energy from resources that can be naturally replenished. Access to clean modern energy services is an enormous challenge facing the African continent because energy is fundamental for socioeconomic development and poverty eradication [1]. About 70% of Nigerian population does not have access to electricity hence, the increasing power crisis in the nation [2-5].

Energy plays the most vital role in the economic growth, progress, and development, as well as poverty eradication and security of any nation. Uninterrupted energy supply is a vital issue for all countries today. Future economic growth crucially depends on the long term availability of energy from sources that are affordable, accessible, and environmentally friendly [6-8]. It is noted that the standard of living of a given country can be directly related to the per capita energy consumption, as the per capita energy consumption is a measure of the per capita income as well as a measure of the prosperity of a nation [9].

The world energy crisis is largely due to the rapid population growth and the increase in the living standard of whole societies [10-12]. The energy crisis, which has engulfed Nigeria for almost two decades, has been enormous and has largely contributed to the incidence of poverty by paralyzing industrial and commercial activities during this period [13, 14]. Electricity as a very crucial aspect of life has to be available and distributed to both urban and rural areas of Nigeria and other developing countries. Electricity supply to urban and rural areas in Nigeria is grossly insufficient, unsteady and in some cases inexistent. This has adversely affected the economic and social landscapes of these locations. The need therefore, exists for the development of alternative sources energy to tackle this problem [15-20].

One of the major causes of power failure in Nigeria is that conventional power generation uses fossil fuels (coal, gas, and oil). These are non-renewable energy sources, and are being used up very rapidly. Fossil fuels take millions of years to form, and with heightened global demand they may be exhausted much sooner than later. The future of electrical power generation from fossil fuel combustion is threatened by escalating fuel prices and by adverse environmental consequences of large scale combustion of carbon-rich fuels. Combustion of these fuels unleashes intolerable amounts of carbon dioxide to the environment contributing to turning the Earth’s atmosphere to a greenhouse with the harmful effect of producing global warming [21, 22]

In respect to the current crisis and the insufficiency of the power sector, the need for more reliable and decentralized systems which are more economical and less hazardous to the environment arises, hence, the clamor for renewable energy systems. Renewable energy alternatives are an important part of our energy futures, and need to be promoted and enabled. But renewable energies can also negatively impact on the environment and people, therefore the need for impact assessment tools to be applied to such projects [23-30]. New renewables such as small hydro, modern biomass, wind, solar, geothermal, and bio-fuels account for about 3% of global final energy consumption and are growing rapidly, hence replacing conventional fuels [31-35].

Nigeria's economic history is coloured with various types of crises and fluctuations in important macroeconomic variables. These include crises in electricity generation and distribution, domestic and external debt crisis, balance of payments disequilibrium and fluctuations in key macroeconomic variables such as broad money supply, exchange rate, real (GDP) Gross domestic product growth rate etc. [36]. The focus of the government over the years has being that of direct investment on poverty alleviation without realizing that the state of energy supply in the country perpetually keeps Nigerians in penury and out of global touch [37-39].

Hydropower is electricity generated using the energy of moving water. The energy generated is converted into mechanical or electrical energy. A typical hydro plant is a system with three parts which are the electric plant where the electricity is produced a dam that can be opened or closed to control water flow, and a reservoir where water can be stored. The water behind the dam flows through an intake and pushes against blades in a turbine, causing them to rotate. The turbine spins a generator to produce electricity. The amount of electricity that can be generated depends on how far the water drops and how much water moves through the system [40-42]. Hydropower is one of the most efficient renewable energy sources. It is particularly suited to small-scale applications typically being far cheaper per kWh of electricity produced than wind power or solar power [43-47]. A small or micro-hydroelectric power system can produce enough electricity for a home, farm, or ranch [48-50]. Hydropower is used primarily categorized include large (more than 100 MW, medium (15 – 100 MW), small (1 – 15 MW), mini (above 100 kW and below 1 MW), micro (from 5 kW – 100 kW) and Pico (from 300 W – 5 kW) hydropower [51].

Hydropower contributes one-fifth of the world's power generation. In fact, it provides the majority of supply in 55 countries. For several countries, hydropower is the only domestic energy resource. Its present role in electricity generation is therefore substantially greater than any other renewable technology, and the remaining potential, especially in the less developed countries, is vast [52]. While it is not a panacea, in that it is restricted to sites with available water and appropriate geomorphology, hydropower's flexibility and proven technology sets it apart from other renewable energy sources [53-55].

Large hydro power plants and other sources of energy generation are faced with so many crises which lead to the drop of energy generated. These crises arise from government policies, environmental issues, economic/financial issues and social issues, as well as variation in weather [55-65]. Also, the turbine blade can undergo erosion due to silt formation [66-68]. All these crises combine to make it difficult for the national grid to be distributed all the urban and mostly the rural areas.

Pico hydropower is a renewable local energy resource, which can be usefully harnessed for rural energy demands from small rivers at a specific height, where there is a gradient of a few meters and the flow rate is more than a few litres per second. Pico hydro system is used for hydroelectric power generation of under 5 kW. It can easily be controlled and maintained by homes, schools, farms and communities [69-76]. The instability and insufficiency of power supply from the national grid has given room for other sources of energy to compliment it. Pico hydro systems are smaller, more efficient and environmentally friendly, with various benefits such as reliability, simplicity, less maintenance and low operating expenses. The Pico hydro schemes have numerous social and environmental benefits [77-85].

Nigeria is facing extreme electricity shortage and this deficiency is multi-faceted with various causes. Hence, the need to come up with more reliable, economical, efficient, flexible and accessible energy system to the common Nigerian home arises. This has motivated this work. Presently a work is on-going in the Mechanical Engineering Department of Federal University of Agriculture, Makurdi on a simplified Pico hydropower system with an overhead tank serving as the source of water. It also has a reservoir for recycling the water to the overhead tank, a locally fabricated turbine, pump for recycling the water, tapered pipes to act as nozzles, PVC pressure pipes as penstocks and an alternator/generator. It uses the basic aspects of pumped hydropower systems in a very simple form [86-88]. The present development will explore all these while giving control to the user and as result minimize exposure to sabotage as well as bringing the benefits of hydropower to locations without natural water sources for conventional schemes. This present study focuses on an aspect of this work involving the investigation of the effect of different blade shapes on the performance of this Pico hydro system.

II. MATERIALS AND METHODS

Five turbine runners with blades or buckets of different cross-sections were fabricated. The cross-sections used were full v-shaped (A), u-shaped (B), rectangular (C), trapezoidal (D), and partial v-shaped (E). Mild steel was used due to some of the suitable mechanical properties which are: good weldability, machinability and in addition to the availability of the material at an affordable cost. Each runner comprised of a circular hub with six buckets (blades) welded around. The disc and buckets were fabricated from a 2 mm and 1.5 mm thickness mild steel sheet respectively.

The construction procedure of the runners involved the generation of the hub which was a 240 mm diameter of a 2 mm metal sheet. A 20 mm diameter hole was then drilled centrally on the hub to accommodate the shaft. The blank sheets for the blades were then fabricated according to specifications by [89] before generating the respective cross-sections. Pieces of scrap sheet metals were trimmed to fit the respective ends of the blades and welded to them. The blades were then welded at 60 degrees intervals around the circumference of the hub. Fig. 1 shows the five runners used for the study. Fig. 2 shows the exploded view of the turbine used for the study.

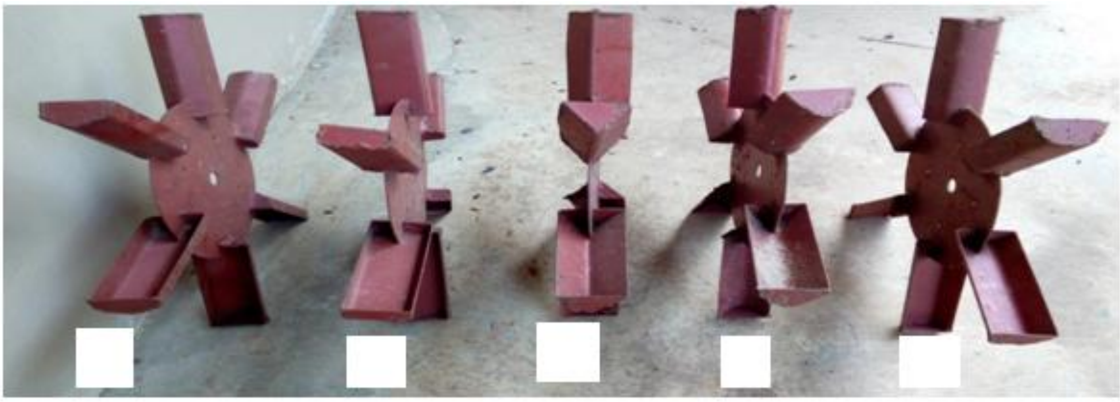

Fig. 1: Fabricated Runners with blades of different cross-sections: A- Full v-shaped, B - u-shaped, C - Rectangular, D - Trapezoidal and E - Partial v-shaped

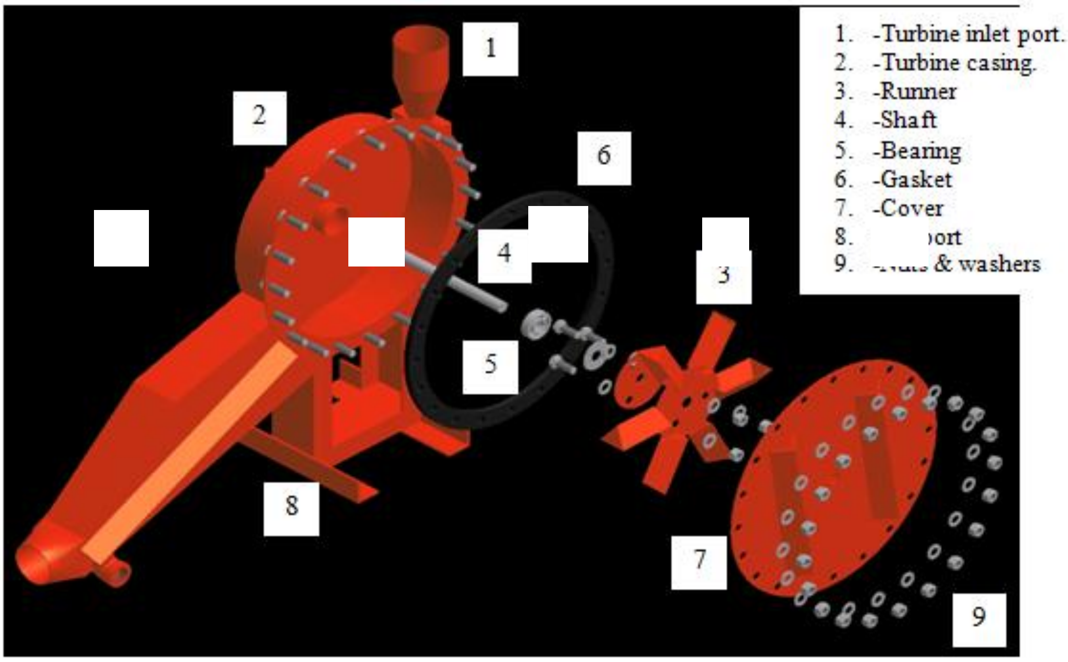

Fig. 2: Exploded view of the locally fabricated Turbine

The whole experimental setup shown in fig. 3 consists of 1Hp pump and one simplified turbine connected in a closed loop with the help of a combination of PVC piping as penstock to an 2000 l overhead tank and an underground reservoir of about 3000 l capacity. The suction pipe of the pump draws water from the underground reservoir to the overhead tank to create a head. The penstock configuration was taken from [89]. Water is released from the overhead tank by manually opening a gate valve at the top through the penstock and exits through a simply tapered pipe as nozzle. A pulley is mounted on the turbine and its rotation transmitted to a smaller pulley in a ratio of 6:1 on the shaft of a 2.5 kVA alternator by means of a v-belt drive in order to amplify the rotational speed to a magnitude capable of generating electricity.

A tachometer was used to measure the speeds of the turbine and alternator shafts in rpm. A multi-meter was used to measure voltage generated by the alternator. During the experiment the water levels in the two reservoirs before and after the every session of operation were continually monitored using a calibrated dip stick and the duration was also measured. Care was taken in align the turbine runner, turbine casing and the nozzle so as to ensure a good clearance between the runner, penstock and nozzle. The same procedure was carried out for each of the five runners fabricated.

The various flow rates (Q) for the different operations were computed using the (1):

$$Q = \frac{Volume\ of\ water\ displaced}{Time\ taken} \qquad (1)$$

The associated frictional losses can be estimated using the expression given by [90] for pipes of diameter greater than 5 cm and flow velocity below 3 m/s shown in (2), where L = length of penstock, D = diameter of penstock, C = Hazan-William Coefficient which lies between 135 – 140 for plastic pipes and V = flow velocity given by $V = {}^{4Q}/_{\pi D^2}$:

$$H_f = \frac{6.87L}{D^{1.165}}\left[\frac{V}{C}\right]^{1.85} \qquad (2)$$

The turbulence losses can be estimated with the expression given in (3):

$$H_t = \sum K_i \left[\frac{V^2}{2g}\right] (3)$$

Where K = loss coefficient associated with entry of flow into the penstock, valves, elbows, bends and penstock area reduction resulting from the use of reducers. For change in penstock dimensions, K values can be obtained using an expression given by [90] as shown in (4) where d = smaller inner diameter and D = the larger inner diameter:

$$K_c = 0.42\left[1 - \left(\frac{d}{D}\right)^2\right] \qquad (4)$$

The net head available can be computed using the expression given as (5):

$$H_n = H - H_L \qquad (5)$$

where$H$ = total height of the water surface above the plain of the turbine shaft and $H_L = H_f + H_t$.

The specific speed of the system was computed using (6):

$$n_q = \frac{N\sqrt{Q}}{H^{0.75}} \qquad (6)$$

where N is the speed in rpm, Q in m^3/s and H in metres.

Fig. 3: The simplified Pico hydro system

III. RESULTS AND DISCUSSION

Figs. 4 and 5 show the variation of the alternator shaft speed and the voltage developed with the blade cross-sectional shape respectively. It can be seen from fig. 4 that the turbine operated at a high mean speed of 1678.95 rpm when the runner with the full v-shaped blades was used. However, the speed decreases exponentially to a much lower speed when the runners with the partial v-shaped and trapezoidal shaped blades were used. The performance with the u-shaped blade was close to that of the full v-shaped. The streamline structure of the full v-shaped blade causes a reduction in the drag experienced by them.

Also, fig. 5 shows a similarity in trend to that of fig 4, and it can be seen that voltage also decreases with the loss in streamline shape of the blades with the best performance obtained when the full v-shaped blades was used. This is to be expected as it is well established that the voltage developed is directly proportional to the speed of rotation of the alternator shaft speed. Hence, the full v-shaped blades favor good performance in terms of speed and voltage developed.

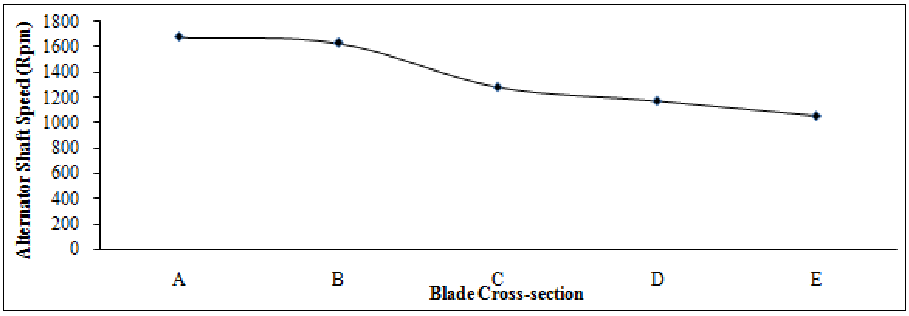

Fig. 4: Variation of Alternator shaft Speed with Blade Cross-section

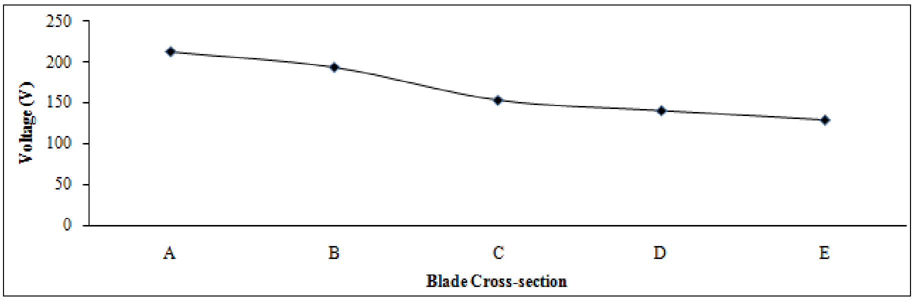

Fig. 5: Variation of Voltage with Blade Cross-section

The voltage when plotted against the speed of the turbine yields the trend shown in fig. 6 which shows that voltage increases with increase of the speed of the turbine runner. The plot expresses almost even increments in voltage but rapidly rises to a high voltage of 212 V at its peak. Further increase in speed of the turbine could give very high voltages all other factors being maintained and hence, increasing turbine performance. The partial v-shaped blades produced very low speed and voltage performance and this is probably due to the increased camber on its profile, as great blade camber produces great force variations, and less blade camber, just like the full V-shape produced less variations. It is also noted that the u-shaped blades though cambered but not as much as the partial v-shaped blades also gave an appreciable output. Equation 7 shows that the voltage-speed characteristic is polynomial of the third order and this generally indicates that the voltage increases with increasing speed of the alternator shaft:

$$V = 0.0000007N^3 - 0.0028N^2 + 3.7199N - 1504.9 \qquad (7)$$

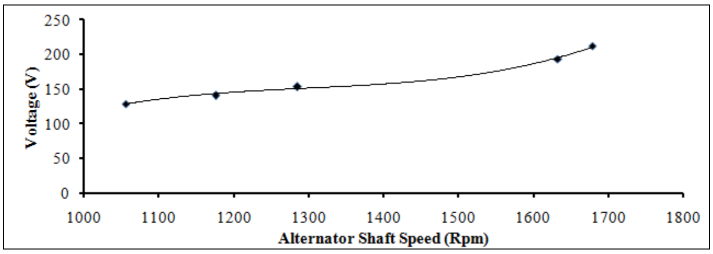

Fig. 6: Variation of Voltage with Alternator Shaft speed

Fig. 7 shows the variation of both the alternator shaft speed and voltage developed with the flow rate/net head product. This figure conveys an attempt to develop a relationship in the form of the equation for the hydraulic power of a hydropower system; that is $P = f(QH_n)$[90-92]. Since the power depends on the voltage developed and hence indirectly on the speed of the shaft, (8) and (9) obtained from fig. 7 both give some indications of the power generation of the system:

$$N = -0.00000008(QH_n)^3 + 0.0000005(QH_n)^2 - 743241(QH_n) + 4761.8 \qquad (8)$$
$$V = -1 \times 10^8(QH_n)^3 + 7 \times 10^6(QH_n)^2 - 108488(QH_n) + 681.51 \qquad (9)$$

The computed specific speed of the turbine was 23 calculated using(6) which therefore places it in the family of single jet Pelton turbines. This gives the work some level of credence because the basic turbine design adopted from [89] was that of a single jet Pelton wheel.

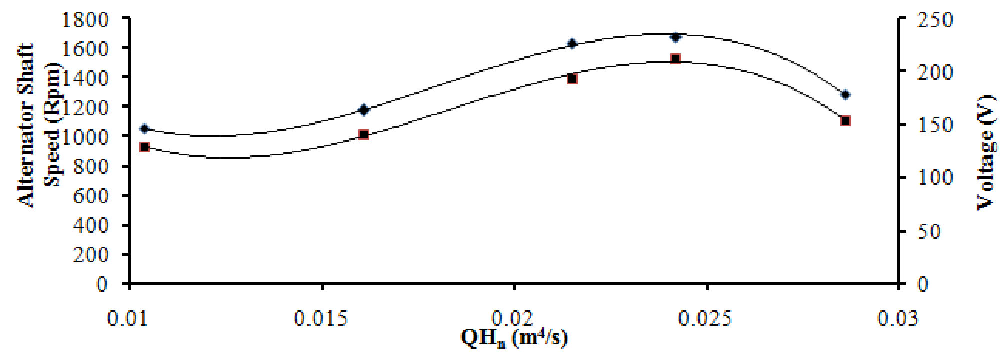

Fig. 7: Variation of Alternator Shaft Speed and Voltage with the Flow Rate/Net Head Product

Table 1 shows the analysis of variance performed on the alternator shaft speed and the voltage developed for the various blade cross-sections at 5% level of significance. The results show that the variation in the two parameters was statistically significant from one blade cross-section to the other. This establishes the conclusion that the blade cross-section affects the system performance and that hence, the selection of the blade cross-section is critical to optimum performance of the simplified Pico hydropower system currently being developed to eventually be implemented as a simple decentralized power generation system with all the attendant benefits for the end user [93, 94].

Table 1: ANOVA of Alternator Shaft Speed and Voltage Developed for the various Blade Cross-sections

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	195283.5	4	48820.88	1.663649	0.317004	6.388233
Columns	3601080	1	3601080	122.7126	0.000378	7.708647

Error	117382.6	4	29345.65			
Total	3913746	9				

IV. CONCLUSION

This study compared the effect of the various blade cross-sections on the performance of a simplified Pico hydro system undergoing development. The full v cross-section gave best performance in terms of the alternator shaft speed and the voltage developed.The main conclusion arrived are:

1. The maximum turbine speed and voltage for best blade profile was 1678.95 rpm and 212.1volts.
2. The computed specific speed of the turbine places it in the family of single jet Pelton turbines.

The results obtained in this work can further be improved and complemented with the following recommendations:

1. Improved quality of blade manufacture, as smooth surface finish as this also improves the performance of the turbine.
2. An adjustable nozzle diaphragm should be incorporated into the system to enable angle of attack to be varied.
3. An alternative source of power for the pump such as solar or wind should be incorporated for further experimentations.
4. Simple blade profiles can be used as complex blade shapes are difficult to manufacture locally.
5. Lighter metals such as aluminum should be used in fabricating the runners and blades as heavier meals like mild steel decrease turbine performance.

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