



# Investigation of the Effect of Penstock Configuration on the Performance of a Simplified Pico-hydro System

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## Authors' contributions

This work was carried out in collaboration between all authors. Author AOE designed the study, wrote the protocol, wrote the first draft of the manuscript and managed literature searches. Authors JSI and EIK supervised logistics of the study and literature searches. All authors read and approved the final manuscript.

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## ABSTRACT

This paper presents an investigation of the effect of penstock configuration with regards to area reduction on the performance of a simplified Pico-hydro system currently undergoing development. The system explores the utilization of the head developed by pumping water into an overhead reservoir and releasing it through a vertically oriented penstock. The concept in this study was introduced in the system in order to extend the duration in which continuous recycling of the water can be sustained while minimizing head losses and achieving higher power output. Five different configurations were obtained by joining pipes of diameters 76.2 m and 50.8 m with respective lengths in ratios of 5:2, 4:3, 3:4, 2:5 and 1:6 over a total height of 6.8 m with the aid of area reducers. The rotational speed of the alternator shaft, water level in the two reservoirs, output voltage and duration of test were measured and the flow rate, losses and net head were computed. The configuration with the ratio of 5:2 produced the highest rotational speed and voltage of 1810.2 rpm and 223.65 V respectively. This suggests that the use of a penstock configuration with a larger diameter forming the greater part of the total head will favor better power generation while ensuring

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sustained continuous water recycling which is critical to the operation of this system. The results show good promise for future penstock configuration for this system as a stand-alone, small and clean power generation system.

*Keywords: Penstock configuration; area reduction; pico-hydro system; continuous water recycling; stand-alone; renewable energy.*

## 1. INTRODUCTION

Energy is a major player in the economy of any nation but it comes along with several adverse effects environmentally. Among the very many sources of energy, fossil sources seem to be the most used in nearly all countries which contributes immensely to the deterioration of environmental condition by depleting the ozone layer and therefore not sustainable. Interest is now being directed to renewable energy sources which are usually smaller, more efficient and confers full control and responsibility for its maintenance as well as security due to the end user. This becomes significant as a result of recent proliferation terrorism and regional instability in many nations [1,2].

Energy plays a vital role in the economic growth, progress, and development, as well as poverty eradication and security of a nation. Uninterrupted supply of energy is a vital issue for all countries today, and Nigeria as well as many developing nations are faced with this problem. The shortage of power supply in Nigeria has led to industries and households seeking for alternative means of supplying the required power for their various activities. Of the many alternatives available, the use of petroleum and other fossil fuel has emerged the most popular. The use of fossil fuels however, affects the environment adversely due to the evolution/emission of carbonaceous substances produced mainly by the use of petrol and diesel generators as a result of the highly unstable power supply. Consequently, researchers and various institutions are increasingly looking for other possible forms of power/energy supply systems as substitutes or supplements in order to combat the problem of shortage or unstable power supply resulting in outages and outright blackouts [2,3].

The nature of Nigeria's energy crisis can majorly be classified into three. Firstly, there are periodic recurrent severe shortages of petroleum products in the market, kerosene and diesel being the most prominent. Also, it has been confirmed that the highest consumption of

kerosene is by from Nigerians of poor and middle class status which forms the majority of the population. Again, the pressure exerted by the consumers of kerosene and diesel consumed mostly by low/middle and industrial sectors respectively on the government and the constraints on public financing of large-scale imports of these products, largely explains their more severe and persistent market shortages [4-6].

The second dimension of Nigeria's energy crisis is directed toward electricity blackouts and pervasive reliance on self-generated electricity. This development has occurred despite abundant energy resources in Nigeria. The electricity market, dominated by the state-owned Power Holding Company of Nigeria, has been incapable of providing minimum acceptable international standards of electricity service reliability, accessibility, and availability for the past three decades. The double-digit transmission and distribution losses are extremely large among the highest in the world. The system losses are five to six times higher than those in well-run power systems [4]. Hopefully, on-going restructuring of the sector could bring some relief.

The third aspect has to do with the increased restiveness as a result of regional resource control issues as well as the proliferation of terrorist activities especially in the North Eastern part of the country. The major energy production outfits being centralized and relatively large in nature are vulnerable to variously motivated sabotage arising from these activities apart from the inherent inefficiencies associated with such systems. Apart from these, the large energy systems have more adverse effects on the environment. Smaller and decentralized outfits could play a vital role in improving accessibility to power and are usually more environmentally benign [5,7-10].

Electricity is required for such basic developmental services as pipe borne water, health care, telecommunications, and quality education. The absence of reliable energy supply

has not only left the rural populace socially backward, but has also left their economic potentials untapped. Electricity as a very crucial aspect of life has to be available and distributed to both urban and rural areas of Nigeria. Unfortunately, electricity supply to urban and rural areas in Nigeria is grossly insufficient, unsteady and in many cases non-existent. This has adversely affected the economic and social landscapes of these locations [6,11–15]. The need therefore, exists for the development of alternative sources of energy to tackle this problem. The objective of this work is to investigate the effect of area reduction of penstocks of various lengths on a simple Pico hydropower system currently undergoing development at University of Agriculture, Makurdi. The ultimate aim of this work is to help individuals, communities and small scale industries in Nigeria to have access to a simple decentralized power system which is environmentally benign and directly under the control of the end user thereby reducing the vulnerability to sabotage.

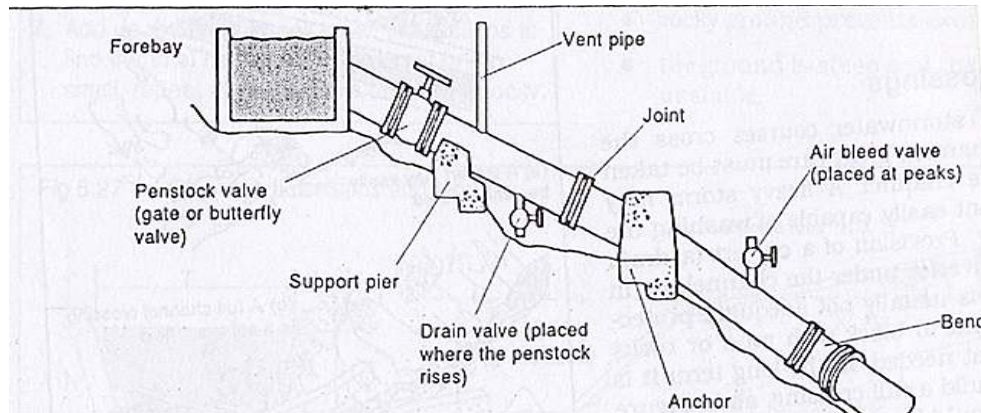
Many researches have been directed toward harnessing renewable energies and more efficient use of the existing options. Nigeria as a nation is blessed with abundant renewable energy resources such as hydroelectric, solar, wind, tidal and biomass. There is a need to harness these resources and chart a new energy future for Nigeria. Many indigenous researchers have looked into the various available renewable energy resources in Nigeria with a view to establishing their viability in the country. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable, accessible, sustainable and environmental friendly, thereby setting a standard that will be used to streamline the various renewable energy resources. Unfortunately, the energy policy for the nation is still a draft which does not even appear to address the real issues that can impact on access to energy by the populace in its present form [5,11,16–20].

Hydroelectricity is among the best sources of renewable energy and in a country like Nigeria bordered by the Atlantic Ocean and having several waterfalls, streams and rivers, it is a very viable option, especially Pico hydro. According to [18–21], the total hydroelectric power potential of the country has been estimated to be about 8,824 MW with an annual electricity generation

potential in excess of 36,000 GWh. This consists of 824 MW of small-scale hydropower technology. Presently, about 24% and 4% of both large and small hydropower potentials, respectively, in the country have been exploited.

Micro and Pico-hydro is small compared to mini to large hydropower. Pico-hydro is categorized based on its capacity of producing electricity up to 5 kW. In Pico-hydro systems, water is initially stored to generate a potential head, which is then converted to kinetic head (through a nozzle). This kinetic head is used to create mechanical power by hydro turbines [22–24]. Hydro turbines are connected to the alternators for conversion of mechanical power to electrical energy of about 5 kW. A Pico hydro system has several components like the penstock, nozzle, water turbine, main inlet valve, runner and deflector [25–36]. However, large hydropower schemes are generally affected by seasonal fluctuations in water level [21–23]. To combat the problem of seasonal variation in water level as well as other issues with conventional hydropower systems, alternative methods, using pumped storage have been developed. Pumped storage involves storing water at a higher level and releasing it to generate power by turning a turbine at a lower level [24].

A major component of any small hydropower systems is the penstock. Figure 1 shows the components of a conventional penstock. Penstock pipes are basically closed conduit pipes that help to convey the water from the fore-bay tank to the turbine. The materials used in penstock are usually steel, HDPE (High Density Polythene) and increasingly PVC (Poly Vinyl Chloride). The velocity of water at the penstock is typically 3 m/s and is often located at a slope over 45 degrees [37–39]. Due to the risk of contraction and expansion of penstock pipes resulting from fluctuation in seasonal temperature, sliding type of expansion joints are placed between two consecutive pipe lengths. Anchor block, which is basically a mass of concrete fixed into the ground, is used to restrain the penstock from movement in undesirable directions. This study explored the potentials of using the energy of water stored in an overhead reservoir. The water is released through a vertically oriented penstock onto a locally fabricated turbine at the foot of the reservoir. The ideas of conventional penstocks were then applied.



**Figure 1. Components of a conventional penstock [40]**

According to [40–42], the important factors to be considered when selecting materials for penstock include design pressure, surface roughness, weight of the material, ease of transportation, method of jointing and cost of material. The features considered in selecting a penstock route include accessibility, soil condition, natural or man-made obstruction, gradient and above or below ground installation. A design layout is usually sketched for the proposed penstock which is helpful in identifying the number of elbows needed, determining where the penstock will be above or below the ground, and locating anchors and the thrust block and the like. The sketch will also be helpful in the estimating cost, additional equipment, and total material requirement and so on. Also, the sizing of a penstock depends on three factors which are:

- i. Energy (head) losses due to friction between the water flowing in the pipe and the inside pipe wall;
- ii. Pressure limitations of the pipe as a function of wall thickness; and
- iii. cost of the pipe and installation

For a given flow rate, as the pipe diameter decreases the velocity of the water must increase, and the corresponding energy loss increases. This occurs because friction is a function of velocity. On the other hand, a larger pipe diameter would mean a decrease in velocity and a corresponding decrease in friction (head loss). According to [40], constraints in deciding the diameter of pipes are the price and head loss. These constraints compromise minimum cost (smallest diameter) or minimum head loss (acceptable head loss). The major contributions to head loss ( $h_f$ ) are friction and turbulence.

Frictional loss is due to surface roughness and is given by Darcy's equation.

$$h_f = \frac{V^2 L f}{2gD} \quad (1)$$

where,  $V$  = flow velocity,  $L$  = penstock length,  $D$  = diameter,  $f$  = friction constant which can be obtained from the Moody chart.

Turbulence losses are due to bends, entries, valves, and area reductions and so on. Head loss due to turbulence is given mathematically as

$$h_t = \sum K_i \frac{V_i^2}{2g} \quad (2)$$

where  $K$  = turbulence loss coefficient. According [43–45], the pipe diameter  $D$ , the volumetric flow  $Q$ , the pipe length  $L$ , and the coefficient of flow  $C$  all determine the amount of energy lost in the pipe due to friction in the Hazen-Williams equation.

$$H_L = KL \left( \frac{Q}{C^{1.852} D^{4.87}} \right) \quad (3)$$

This energy loss is called the head loss because this loss in energy may be viewed as if the system had lost some of its height. Pipe head loss is due only to friction in the pipe, head loss in fittings is due to friction and changes in pipe size at the pipe fittings, and total head loss is a sum of both these losses. Also, according to [46,47], the losses in a penstock can also be calculated using

$$h_f = \frac{6.87L}{D^{1.165}} \left( \frac{V}{C} \right)^{1.85} \quad (4)$$

where C = Hazen-Williams constant and for plastic pipe ranges from 135-140. Generally, for minor losses due to area reduction according to [47], equation 5 can be used.

$$h_c = K_c \left( \frac{V^2}{2g} \right); K_c = 0.42 \left( 1 - \frac{d^2}{D^2} \right) \quad (5)$$

where K= loss coefficient, which could be due to bend, fitting, contraction or expansion, or elbow, V= flow velocity, d = diameter of reduced pipe, D = diameter of large pipe, and g = acceleration due to gravity. A third empirical option is the Manning equation given as

$$h_f = \frac{10.29n^2Q^2}{D^{5.333}} \quad (6)$$

where n is the Manning coefficient [15].

The wall thickness of the penstock is also an important consideration and it depends majorly on the cost and the strength (withstanding pressure). The wall should be thick enough to withstand the maximum water pressure.

An analysis for the optimum penstock diameter considering cost and effect of slope was presented by [42] with the aim of achieving the condition that head loss  $h = H_g/3$ , where  $H_g$  is the gross head of the system and it is implied that the turbine head  $H = H_g/3$ . The optimum diameter is expressed as

$$D_{opt} = \left[ \frac{fQ^2}{2g \left( \frac{\pi^2}{4} \right) \left( \frac{h}{H_g} \right) S} \right]^{1/5} \quad (7)$$

Where f=friction factor determined by the surface roughness of the penstock,  $S = H_g/L$  = penstock slope, L= length of penstock and Q = optimum discharge.

## 2. MATERIALS AND METHODS

The materials and equipment used for the investigation are presented in Table 1.

Figure 2 shows the experimental rig for this study. It consists of a pump (1) which lifts water to the overhead reservoir (2). A gate valve is used to release the water through the penstock (3) at the end of which a jet is generated by means of a simple nozzle. The jet is directed to the blades of locally fabricated turbine (4) and the water exhaust into the underground reservoir (5) downstream of the turbine. A pulley is securely fitted to the turbine shaft. A v-belt transmits the rotary motion of the shaft to a smaller pulley (1:6) fitted to the alternator (6) shaft thereby generating electricity. A tachometer was used to measure the revolution (rpm) of the shaft of the generator and a multi-meter (7) was used to measure the voltage output of the generator. The process continues as long as the pump is powered and appropriate levels of water in the two reservoirs maintained. The above procedure was carried out for the five penstock configurations.

**Table 1. Materials and equipment used for the study**

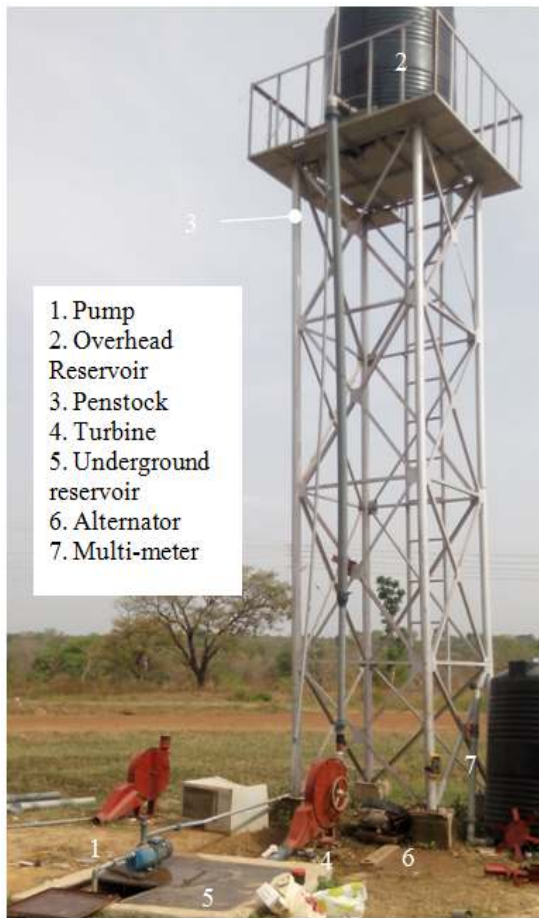
S/N	Description	Quantity	Size
1	Overhead Tank	1	2 m <sup>3</sup>
2	Underground Reservoir	1	2.367 m <sup>3</sup>
3	Gate Valve	1	
4	PVC Unions Coupler		
5	PVC Pressure Pipes as Penstocks	2 lengths	3 & 2 inches
6	PVC Pressure Pipe as Supply Line	2 lengths	1½ inches
7	Locally fabricated Turbine	1	
8	Simple tapered Nozzle	1	
9	Water Pump	1	1 hp
10	Alternator	1	2.5 kVA
11	V-belt	1	
12	Tachometer	1	
13	Multimeter	1	
14	Capacitor	1	
15	Stop Clock	1	
16	Measuring Tape	1	
17	Calibrated Dip Stick	1	
18	Aluminium pulley	1	300 mm dia.



PVC pipes of diameter 76.2 mm and 50.8 mm were selected for use as penstocks because the material is light, easy to transport, cheap, readily available in various sizes and possess better frictional characteristics compared to steel with friction loss correction factor ( $f_c$ ) of about 0.77 [38,39]. The penstock configurations were obtained by cutting the ratios of length of the pipes and joining them with appropriate reducers to obtain the approximate height of the outlet of the overhead reservoir to the plain of the turbine of 6.8 m. This was done for the respective ratios of 5:2, 4:3, 3:4, 2:5 and 1:6, with the larger diameter pipe mentioned first. The respective ratios were allocated the designations 1, 2, 3, 4 and 5. Figure 3 shows the appearance of one of the configurations in the region of the joint.

urations and the data used to compute the system flow rates. The gross head was measured directly as the sum of the height of the penstock and the initial depth of water in the overhead reservoir. The respective losses were computed using equations 5 and 6, and the results were used to obtain the net head. The net head and flow rate products were then computed.

1. 76.2 mm diameter pipe
2. Reducer
3. 50.8 mm diameter pipe



**Figure 2. Set up of the simple Pico hydro system**

The depths of water in the overhead and underground reservoirs before and after operations were measured for appropriate



**Figure 3. The joint of a penstock configuration**

### 3. RESULTS AND DISCUSSION

Table 2 shows the mean measured and computed parameters for the study. Figure 4 shows the system flow rates and head losses when the respective penstock configurations were used. It shows that the respective

configurations were able to produce flow rates within a very close range of  $3.0 - 4.3 \times 10^{-3} \text{ m}^3/\text{s}$ . The differences can be traced to the inclusion of a joint which tends to produce a polynomial trend for the output flow rates with transition in the lengths of the respective pipe diameters. However, the closeness of the respective flow rates can be largely explained by the provisions of flow continuity in spite of the area reduction introduced. In a general sense, this agrees with conventional penstock behaviour as maintained by [4,16,19]. This agreement which is only in the general sense is acceptable because the configuration and orientation of conventional penstocks differ from the ones for this study. Moreover, the likely existence of slight errors in monitoring the water level in the reservoirs cannot be ruled out although care was taken to minimize this.

The trend of the head loss also in Figure 4 however, shows more clearly the effect of the respective lengths of the pipes in the respective penstock configurations. The trend shows some resemblance to the head loss characteristics reported by various researchers on conventional

penstocks [4,28,30,34,37-39]. Configuration 1 expectedly has the least head loss obviously because most of its length is made up of the larger diameter pipe. The head loss progressively increased with decreasing length of the 76.2 mm diameter pipe on a general note. This agrees with the behaviour of penstock diameters according to [42-45]. This strongly suggests that it is possible to combine a large diameter with a smaller one in order to minimize losses while ensuring that the continuous system circulation period is enhanced without increasing the budget by using other options such as a larger pump or larger diameter return pipes to the overhead reservoir.

Figure 5 shows the voltages developed and the alternator shaft speeds recorded when each of the penstock configurations was used. It shows that configuration 1 enhanced the highest shaft speed and hence output voltage. This arises from the fact discussed already that the configuration had the least head loss. This means that the system could potentially develop appreciable power when this penstock configuration is used.

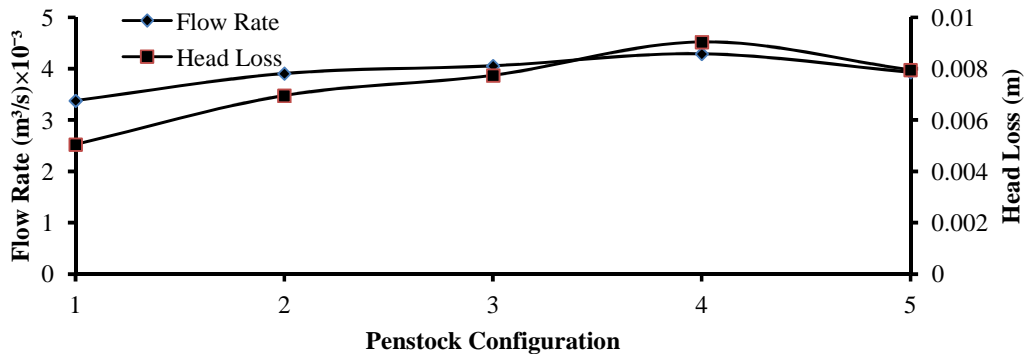


Figure 4. Flow rates and head losses of the penstock configurations

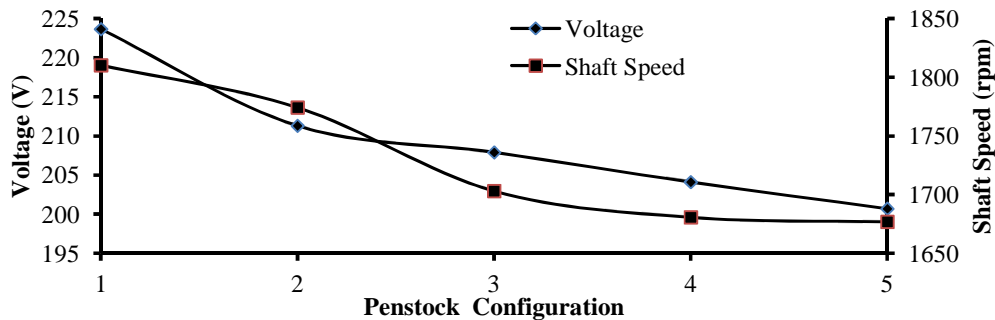


Figure 5. Voltage developed and shaft speed for the penstock configurations

**Table 2. Mean measured and computed parameters for the study**

Penstock configuration	Speed (Rpm)	Flow Rate x $10^{-3}$ ( $m^3/s$ )	Voltage (V)	Net head (m)	$QH_{net}$ ( $m^4/s$ )	Head loss ( $H_f + H_t$ ) (m)
1	1810.2	3.378	223.65	8.02	0.0271	0.00505
2	1774.2	3.906	211.3	7.783	0.0304	0.00695
3	1703.1	4.056	207.9	7.802	0.0316	0.00774
4	1680.7	4.290	204.1	7.881	0.0338	0.00904
5	1676.8	3.932	200.7	7.835	0.0308	0.00795

This however remains to be verified during further phases of the study during which the results of the investigations of the several aspects will be jointly implemented.

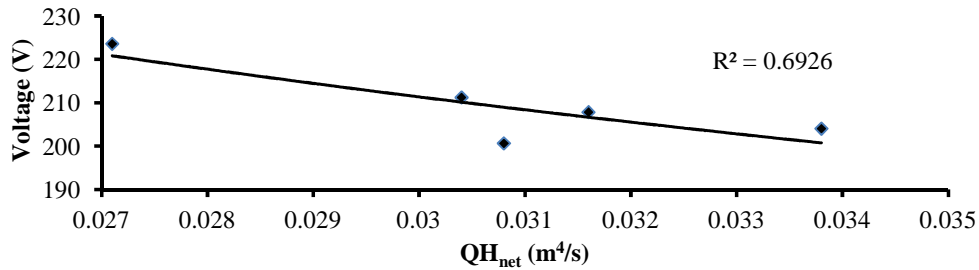
Figure 6 shows an attempt to predict the theoretical power that the system can generate when using penstocks of the configuration studied. The expression for the power generated for a hydropower system contains the product of the net head and the flow rate and electrical power depends on the voltage [38,39,44,45]. Hence, an expression linking these three parameters of the system could give an indication of the power that can be generated. Equation 8 shows the expression generated from the data obtained from this study relating the voltage developed to the net head and flow rate product.

This gives an idea of the voltage component of the possible power that can be generated. It shows that the smaller the value of  $QH_{net}$  the higher the voltage. Remembering that this pair of data corresponds to configuration 1 penstock strengthens the fact that it is a more efficient option since an efficiency term appears in the right hand side of the actual expression.

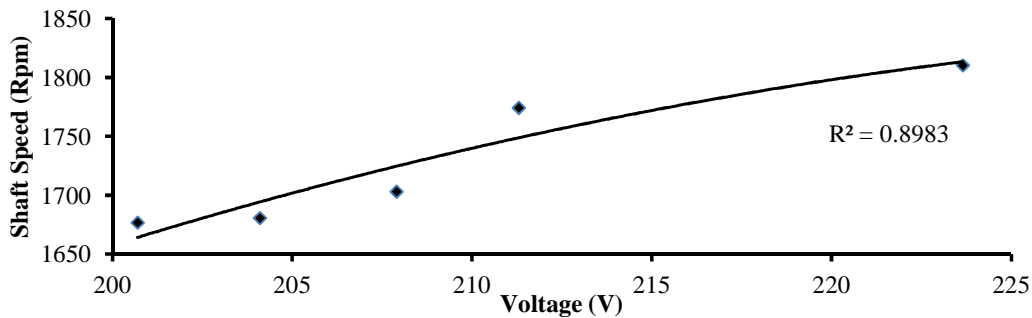
Figure 7 shows the variation of the alternator shaft speed with voltage with agrees with conventional hydropower systems behaviour. Again the figure confirms the better performance of the system when the penstock with the larger diameter pipe being longer was used. The expression relating them developed from the data obtained indicates a polynomial relationship given by equation 9.

$$V = 46.527QH_{net}^{0.432} \tag{8}$$

$$N = -0.1198V^2 + 57.322V - 5015.4 \tag{9}$$



**Figure 6. Flow rate and net head product for the penstock configurations**



**Figure 7. Variation of the alternator shaft speed with voltage**



#### 4. CONCLUSION AND RECOMMENDATION

This work presents a simple investigation for determining an appropriate penstock configuration for a simple Pico hydro system that is undergoing development. The experimental values obtained show that

1. The penstock configuration 1 produced the maximum shaft revolution (1810.2 rpm) corresponding to the highest voltage (223.65 V) for the study.
2. Head losses in the penstocks were lower for configurations having longer lengths of larger diameter.

However, the results obtained represent only one aspect of the series of preliminary tests outline for the development of this system. Along with the results of the tests on other aspects of the system, a more robust implementation will be undertaken as the system is developed towards the main objective of actual small and clean power generation for the end user targets.

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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