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Effect of Penstock Area Reduction and Number of Turbine V-Blades on the Performance of a Simple Pico-Hydropower System

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ABSTRACT

The effects of penstock area reduction and number of turbine v-blades on the performance of a simplified Pico-hydro system which is currently undergoing development was investigated in this study. One and two stage area reductions from 3-2½ inches and then from 3-2½-2 inches were effected on the penstock, and turbine runners with 6 to 12 v-blades were tested for each configuration. The turbine and alternator shaft speeds as well as the depth of water in the overhead and underground reservoirs were monitored. The gross head, volumetric flow rates for each operation, fluid power and the head losses involved were computed. The results obtained indicated that the two stage area reduction of the penstock with the runners having 9 -10 blades produced the highest shaft rotational speeds as well as computed fluid power. The differences between the results for the two penstock configurations were however not statistically significant at 95% level while those between the different number blades were highly significant at the same level. This implies the existence of the possibility that further stages of reduction in the penstock area could improve the system performance while no advantage exists for system performance in its present state for number of blades lower than or beyond 9 to 10. This is useful for the further development of this simple decentralized and environmentally friendly system for end user implementation.

Keywords: Penstock area reduction, Number of v-blades, Turbine shaft speed, Alternator shaft speed, Pico hydro-power, decentralized and environmentally friendly

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INTRODUCTION

Several researchers have shown that the welfare of rural communities of a nation in relation to education, healthcare, increased productivity is enhanced by the provision of basic energy requirements [1]. Availability of energy is very crucial in the economic growth, progress, and development, as well as in poverty eradication and security of any nation. Uninterrupted energy supply is a vital issue for all countries today, especially in the under-developed nations [2 - 4]. The actualization of the United Nations' sustainable development goals (SDGs) is largely dependent on the availability of affordable, accessible, and environmentally friendly energy supply [5 - 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]. 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. Developing energy generation schemes which are cheaper and more reliable means of power for urban homes, communities and rural dwellers would help improve the standard of living and the economic state of the country [10].

According to [11], two very common ways of measuring energy access are metrics related to electricity, and those illustrating the level of dependence on solid or traditional fuels, such as biomass, for cooking. In these regards, nearly 17% of the global population live without electricity and about 38% without clean cooking facilities with the vast majority being in the Asia-Pacific region and in sub-Saharan Africa. However, the figures and trends differ greatly by region. In Africa, nearly 60% of people have no access to reliable electricity [12]. This translates to about 150 GW of installed power generating capacity for the entire continent, utilization of about 3% of the world's electricity (largely in South Africa) and as a result emits only about 1% of the world's carbon dioxide emissions. With an estimated supply of 45 GW of installed capacity, the entire sub-Saharan Africa (excluding South Africa) gets less than that of Turkey. The official electrification rate for sub-Saharan Africa is 32% [13 -14].

Great strides have been made in the industrialized Asian countries with regards to electrification. However, in other countries in the region, comparatively high percentages of national populations remain without access to modern energy. A few instances of this by approximate percentage of the population include India (19%), Bangladesh (39%), Pakistan (27%) and Indonesia (19%). Furthermore, more than 840 million people in India rely on firewood, dung cakes, charcoal or crop residue to meet their household cooking needs, along with an estimated 450 million people in China, 140 million in Bangladesh, 105 million in Pakistan and 98 million in Indonesia [15-16].

The Middle East and North Africa (MENA) region has an electrification rate of almost 92%, but in some individual countries, significant portions of the population still lack access to modern energy. About 54% of the population in Yemen do not have access to electricity with an estimated 8 million lacking access to non-solid fuel for cooking. Similarly, throughout Latin America and the Caribbean, where 95% of inhabitants have access to grid electricity, an estimated 22 million people concentrated largely in Argentina, Bolivia, Colombia, Guatemala, Haiti, Nicaragua and Peru are without access. Also, about 14% of inhabitants of the region do not have access to clean forms of cooking. Reports have indicated that in Haiti, 92% of the population use conventional cooking fuels and devices, while Honduras, Guatemala and Nicaragua have less than 50% access rates [14-16].

The energy sources of earth are exhausting due to exploitation from centuries past. As a result, there is deliberate search for alternative resources to meet their increasing demand of energy. Broadly speaking, there are three sources of energy which are nuclear energy, renewable energy and fossil fuels. Renewable energy resources are cheaper, decentralized and more environmentally friendly for application in remote areas. It is generally defined as energy that comes from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy can replace conventional fuels in four distinct areas which are electricity generation, air and water heating/cooling, motor fuels, and rural (off-grid) energy services [17 - 19].

Based on REN21's 2014 report, renewables contributed 19 % to global energy consumption and 22 % to electricity generation in 2012 and 2013 respectively. This energy consumption is divided as 9% coming from traditional biomass, 4.2 % as heat energy (non-biomass), 3.8 % hydroelectricity and 2 % is electricity from wind, solar, geothermal, and biomass. Worldwide investments in renewable technologies amounted to more than US$214 billion in 2013, with countries like China and the United States heavily investing in wind, hydro, solar and biofuels [19]. Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits [20]. According to REN21, renewable energy provided about 19.2% of global final energy consumption in 2014 with growth in capacity and generation continuing in 2015. An estimated 147 GW of renewable power capacity was added in 2015 with renewable heat capacity increasing by around 38 gigawatts thermal (GWth). The report further added that biofuels production also grew despite tumbling global prices for all fossil fuels, ongoing fossil fuel subsidies and other challenges facing renewables, including the integration of rising shares of renewable generation, policy and political instability, regulatory barriers and fiscal constraints [11].

Of all the renewable sources of energy, water is the better choice because a small-scale hydropower is one of the most cost-effective and reliable energy technologies to be considered for providing clean electricity generation [21]. In the early 20th century, the term has been used almost exclusively in conjunction with the modern development of hydroelectric power. International institutions such as the World Bank view hydropower as a means for economic development without adding substantial amounts of carbon to the atmosphere, but in some cases dams cause significant social or environmental issues [22]. Hydro power is a renewable, economical, non - polluting and environmentally benign source of energy. Hydro power stations have inherent ability for instantaneous starting, stopping, load variations etc., and helps in improving reliability of power system [23]. Hydro stations are the best choice for meeting the peak demand. The generation cost is not only inflation free but reduces with time. Hydroelectric projects have long useful life extending over 50 years and help in conserving scarce fossil fuels. They also help in opening of avenues for development of remote and backward areas [24]. Hydropower throughout the world provides around 17% of electricity from the installed capacity as well as the ones under construction before 2013, making it by far the most important renewable energy for electrical power production. Also in 2015, an estimated 28 GW of new hydropower capacity was commissioned in 2015, with total global capacity reaching about 1,064 GW. The top countries for hydropower capacity remained China, Brazil, the United States, Canada, the Russian Federation, India and Norway, which together accounted for about 63% of global installed capacity at the end of 2015 [11].

There are many ways in which the boundless resources spread around can be used but it is paramount to device diverse means of utilizing hydro as an energy source because it is inexhaustible, environmental friendly, cheap and economical to maintain. Hydroelectricity eliminates the emission of flue gases, including pollutants such as sulphur dioxide, nitric oxide, carbon monoxide, dust, and mercury in the coal. Hydroelectricity also avoids the hazards of coal mining and the indirect health effects of coal emissions. Compared to nuclear power, hydroelectricity generates no nuclear waste, has none of the dangers associated with uranium mining, nor nuclear leaks. Unlike uranium, hydroelectricity is also a renewable energy source. Compared to wind farms, hydroelectricity power plants have a more predictable load factor. If the project has a storage reservoir, it can generate power when needed. Hydroelectric plants can be easily regulated to follow variations in power demand [25].

Hydroelectric power plants despite having many advantages over other energy sources, have potential environmental impacts that are negative. Since it depends on the hydrological cycle, hydropower is not a reliable source of energy. Also, global climate change will increase rainfall variability and unpredictability, making hydropower production more undependable. Increased flooding due to global warming also poses a major hazard to the safety of dams [26]. In addition, all reservoirs lose storage capacity to sedimentation which can in many cases seriously diminish the capacity of dams to generate power. Hydropower projects alter the habitats of aquatic organisms and affect them directly. Several millions of people have been forcibly evicted from their homes to make way for dams losing their land, livelihoods and access to natural resources and enduring irreparable harm to their cultures and communities [27]. Further, growing evidence suggests that reservoirs emit significant quantities of greenhouse gases especially in the lowland tropics [28]. Also, there is growing evidence that hydropower is often falsely promoted as cheap and reliable, are prone to cost overruns and often do not produce as much power as predicted [29]. The foregoing demerits are more directly applicable to large hydropower schemes. Future plans for new hydroelectric plants will need to consider that private capital may not favor hydropower, since they have long repayment periods and high returns. Furthermore, evidence that hydroelectric plants based on large dams are not environmentally neutral is growing and potential declining river flows due to climate change impacts may lead to low hydropower production, thereby impacting on the financial viability of such schemes [30].

Pico hydroelectric power (PHP) systems provides up to 5 kW and it is the option that provides the least power output amongst the off-grid hydroelectric energy systems. Pico-hydro schemes have been successfully implemented in remote regions in the world [31]. Their common objective is to provide a cost effective and simplified alternative to supply electricity to areas that are relatively far from the electrical grid and unfavorable topography. The types of turbines and generators vary depending on the local conditions, budget, and equipment availability. These PHP units are found in markets and hardware stores and their capacity ranges from 0.2 kW to 3 kW. Pico hydro schemes are a cheaper and reliable means of power that have negligible environmental impact since large dams are not involved, and the schemes can be managed and maintained by a community [32]. Pico hydro systems like other decentralized systems are not prone to sabotage and terrorist attacks as individuals and communities take responsibility of safeguarding their own facilities [33 - 37].

In a Pico-hydro system, water is initially stored to generate a potential head, then this potential head is converted to kinetic head (through nozzle), this kinetic head is used to create mechanical power by hydro turbines. Hydro turbines are connected to the alternators for conversion of mechanical power to electrical energy of about 5 kW. While Pico hydro presents significant advantages including cost over other methods of electricity generation, its implementation also present several challenges including a heavy dependence on site specific conditions for scheme design [38 - 39].

Nigeria's economic history has been characterized by various types of crises and fluctuations in important macroeconomic variables such as electricity generation and distribution, domestic and external debt crisis, balance of payments disequilibrium and fluctuations in variables such as broad money supply, exchange rate, real GDP growth rate, etc. [40]. The focus of the government over the years has being direct investment on poverty alleviation without realizing that the grossly inadequate energy supply in the country perpetually keeps many Nigerians in penury and out of global touch. Hence, power demand management is useful for the purpose of economic stabilization in Nigeria as well as the need for policy makers to address supply issues, especially electricity supply, which is important to drive economic growth and development to the desired threshold. Access to electricity enables increased productivity and growth in revenues within the context of better delivery of social and business support services contribute to achieving higher social and economic benefits for communities and nations at large [41].

One of the major causes of power failure in Nigeria is that most conventional power generation systems utilize fossil fuels which are non-renewable and are being used up very rapidly [42]. Fossil fuels which take millions of years to form may be exhausted much sooner than later with heightened global demand. 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. Other causes of power failure include natural causes like weather fluctuation, dependence on large and centralised options, sabotage, resource control issues and so on [43 - 45]. There have been various rural electrification projects that were not able to attain their objectives. The reasons for this are not far-fetched but can all be traced to lack of or misplaced political will and the ever threatening issue of corruption.

The hydropower potential of Nigeria is very high and hydropower currently accounts for about 29% of the total electrical power supply. The first hydropower supply station in Nigeria is at Kainji on the River Niger where the installed capacity is 836 MW with provisions for expansion to 1156 MW. A second hydropower station on the Niger is at Jebba with an installed capacity of 540 MW. It has been estimated since the 1990s that for Rivers Kaduna, Benue and Cross River at Shiroro, Makurdi and Ikom, respectively the total capacity stands at about 4,650 MW. Only the Shiroro site has been exploited till date though along with the ones at Kainji and Jebba, the capacity is below the installed value. Estimates for the rivers on the Mambila Plateau are put at 2,330 MW. The overall hydropower resource potentially exploitable in Nigeria is in excess of 11,000 MW. 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. There have been concerted efforts to increase the power generation capacity in Nigeria by the current Government. However, there is no specific mention of Pico hydro systems in most of these efforts with concentration being on centralized and large systems [46 - 47].

The global challenge of the 21st century is how to develop sustainable energy and maintain the quality of life for a growing population with higher expectations for well-being [48, 49]. The utilization of energy generated from centralized sources is open to interruptions by natural factors such as weather fluctuations and man-made factors such as sabotage. Also, CO_2 in the atmosphere is increasing as a result of the burning of fossil fuels and over the last few decades, a decline in fossil fuels reserves has been observed world-wide. Fossil fuels are not being newly formed at any significant rate, and thus present stocks are ultimately finite. A need therefore exists for the development of alternative sources of power to tackle this problem. This study therefore focuses on the investigation of the effect of penstock configuration on the performance of a simplified Pico hydro system which is currently undergoing development [50 - 51]. Specifically, this work investigates the effects of area reduction within the last 1 m of penstock and the number of v-shaped blades on the performance of the system.

DESIGN, MATERIAL, PROCEDURE, TECHNIQUE OR METHODS

The materials and equipment used for the study are the same used by [50]. However, the outlet of the overhead tank was however modified to be directly underneath rather than the side as it was in the previous stages of this work. It was constructed using 1.5 mm thick mild sheet with a capacity of about 1.9 m^3. A square man hole was provided on the top with a cover to enable routine maintenance. A conical orifice which terminated with an internally threaded 3 inches’ connector was welded centrally to provide smooth exit for water from the tank. A 1½ inches internally threaded connector was used to provide water inlet from the underground reservoir lifted by the pump. The tank was body-filled, checked for leakages and painted to prevent corrosion of the surfaces due to exposure to water. Provision was made on the existing stanchion for the conical outlet of the tank to fit in.

The hub to blade ratio used by [50] and [52] was adopted since this study is a continuation of the on-going work. The runners had 6 to 12 v-blades with included angle of 60° welded appropriately around their circumferences. The disc and buckets were fabricated from a 2 mm and 1.5 mm thickness mild steel sheet respectively with a 20 mm diameter hole drilled centrally on it to accommodate the shaft. The assembled runners are shown in figure 1.

The penstock used comprised of nearly 6 m of 3 inches diameter pipe reduced within the last 1 m of its length to obtain two configurations. A 3 inches ball valve was provided very close to the conical water outlet while another ball valve (2½ inches) was located within the last 1 m of the penstock to enable easy control of flow. The first configuration had a two stage reduction from 3 to 2½ to 2 inches while the second one had a one stage reduction from 3 to 2½ inches. The two configurations are shown in figure 2. Figure 3 shows the whole set up for the study.

For each operation, the depths of water in the two reservoirs were measured using a calibrated dip stick and recorded. They were then used to compute the volume of water discharged and lifted. The upper gate valve was opened followed by the opening of the lower one to allow water to flow through the penstock and discharge into the underground reservoir through the turbine while the pump recycles the water. The operation was timed using a stop clock. The flow rate of the water was then computed using the volume of water discharged and the time taken.

The gross head was measured directly by summing the total length of the penstock to the initial depth of water in the overhead reservoir in metres for each operation. The minor and major losses were computed, and the net head obtained by subtracting the sum of the losses from the gross head. A DT-2268 Contact Type Digital Tachometer was used to measure the turbine and alternator shaft speeds in revolutions per minute (rpm). The hydraulic or fluid power for each operation was then computed using equation 1.

$$P_f = \tau\omega \tag{1}$$

Where $\tau =$ torque developed and $\omega =$ angular velocity.

The procedure was repeated for all the turbine runners before changing to the other penstock configuration and repeating the operation for each of the runners. The data obtained were plotted against each other and the shaft speeds as well as the computed fluid power were analysed for variance at 95% level of significance using two factors without replication.

Fig. 1 The Assembled Runners with 6 to 12 V-Blades

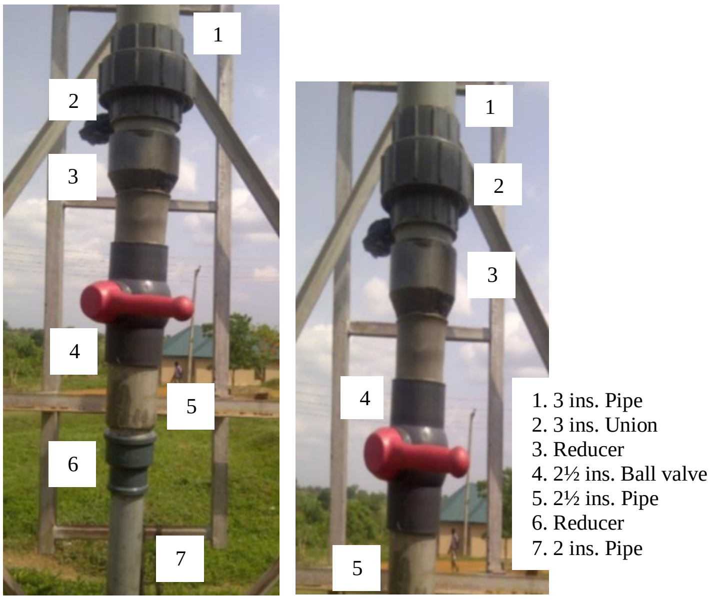

Fig. 2 The two Configurations of Penstocks (i) 3 to 2 inches and (ii) 3 to 2½ inches

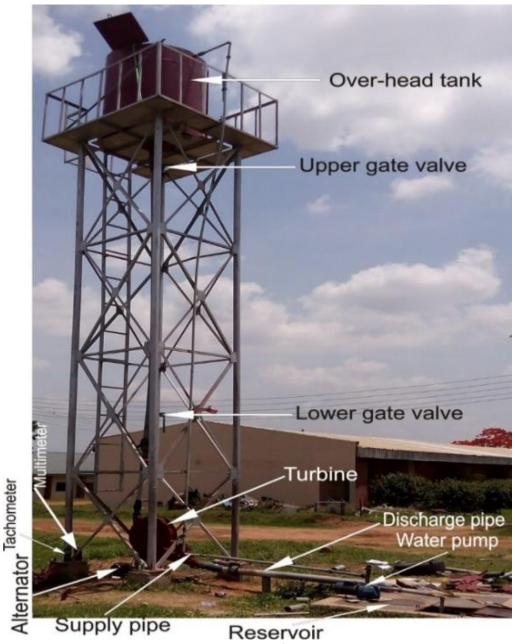

Fig. 3. The Setup for the Study

RESULTS AND DISCUSSION

Figures 4 and 5 both show that for each number of blades, the alternator shaft speed and hence the fluid power for the penstock configuration 1 was higher than those for configuration 2. This was because the configuration 1 created a stronger jet due to the further reduction of the area of the penstock which is required to produce the required torque. This is in line with conventional hydro turbine practice as well as the observations already made during the earlier aspects of this work [50, 51, 53 - 57]. The additional area reduction could have imposed more losses, but it is apparent that the flow acceleration in the water jet was adequate to compensate for this at least in a qualitative sense as observed from the results [58].

Table- 1 Summary of ANOVA for the Alternator Shaft Speed for the Two Penstock Configurations

Source of Variation	SS	df	MS	F	P-value	F_{crit}
Rows	87996.84	6	14666.14	2.828596	0.115671	4.283866
Columns	117248.1	1	117248.1	22.61314	0.003141	5.987378
Error	31109.73	6	5184.955			
Total	236354.7	13				

Table- 2 Summary of ANOVA for the Computed Fluid Power for the Two Penstock Configurations

Source of Variation	SS	df	MS	F	P-value	F_{crit}
Rows	70311.47	6	11718.58	2.739846	0.122701	4.283866
Columns	1063270	1	1063270	248.5965	4.13E-06	5.987378
Error	25662.56	6	4277.093			
Total	1159244	13				

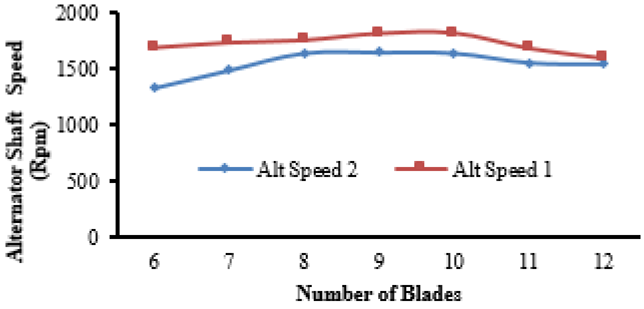

Fig. 4 Variation of Alternator Speed with Number of Blades for the Penstock Configurations used

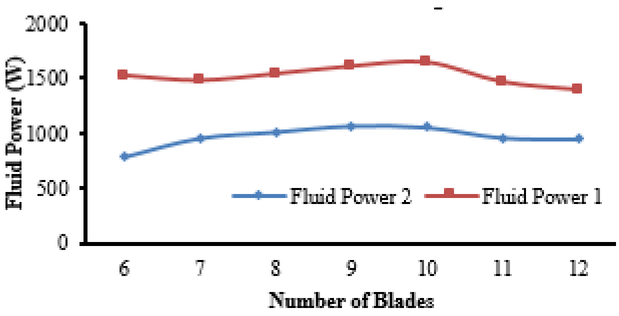

Fig. 5 Variation of Fluid Power with Number Blades for the Penstock Configurations used

Tables 1 and 2 show that the values of the alternator shaft speed and computed fluid power only statistically varied at 95 % level of significance as the number of blades varied. There was no statistical variance with the penstock configuration at the same level of significance and this could be directly because only two configurations were utilized since [50] showed that penstock configuration affects power generation as was observed earlier. However, it can be noted from the tables that the computed fluid power exhibited a stronger variance than the shaft speed. Also, both parameters generally increased with increasing number of blades, attained peak values for about 8 to 10 blades before declining in value. This suggests that the performance of this system is not enhanced by increasing the number of blades beyond these values or for given situations or sets of system parameters, there should exist a limiting number of blades [58]. This can be attributed to the fact that the circular distance between the blades is reduced thereby impeding the period of impact of the jet on the blades. It can also be opined that beyond this range of number of blades, the weight of the runner becomes a more significant factor in the process thereby affecting the shaft rotation adversely. This then means that though the trend of peaking and the declining may be established but the particular number of blades for this to occur may vary depending on the runner size. This can prove to be very useful in the future implementation of this system since the possibility of scaling the system depending on the particular power requirement has already been established by [51].

Figures 7 and 8 show the computed fluid power as a function of the alternator shaft speed (N_A) for the two penstock configurations. The general trend observed agrees with the basic fact that the power developed by an alternator among other factors depends primarily on the rotational speed of the shaft [59, 60]. For this study, the relationship established for the second configuration appears stronger than the case for the first one as shown by the higher R^2 value. This could be attributed to the possibility of the existence of more misalignment of the water jet on the runner blades for the first configuration arising from the use of more reducers. For both cases some slight misalignments resulting from the general system construction were present. The trend equations obtained which are shown below as equations 2 and 3 for configurations 1 and 2 respectively will be useful for further aspects of the study especially during actually installations for end user applications.

$$P_f = 0.3965 N_A^{1.1066} \tag{2}$$

$$P_f = 0.0737 N_A^{1.291} \tag{3}$$

In the equations, the indices of the alternator shaft speed (N_A) were lower than the usual analytically formulated expression. The index was 2 for the ideal case with the reduction possibly resulting from several factors including the fact that in conventional hydropower practice the water jet is not incident on the runner blades at nearly 90° as is the case with the system under development.

Figures 9 and 10 show the computed fluid power as a function of the flow rate and available net head product (QH_n). This is an attempt to generate expressions that resemble the analytical expression for obtaining the hydraulic power of a hydropower system which is given by $P = \eta\rho g Q H$. By expressing the fluid power as a function of the flow rate/net head product, the result obtained then resembles this equation with the coefficient representing the constant $\eta\rho g$, since for any given turbine, the efficiency, η, can be reasonably assumed to be constant and the density (ρ) and acceleration due to gravity (g) are constants at normal temperatures and for specific locations. The expressions formulated from this study both showed polynomial relationships of the second degree. However, the trend for the first configuration shown in figure 10 showed more resemblance to the power/flow rate relationships for conventional systems in literature. The relevance of this relationship derives from the fact that for any hydropower installation, the flow rate and available net head are primary operating factors that must be ascertained before other factors are considered [61 - 65]. Hence, the expressions for this system presented as equations 4 and 5 can be useful in taking decisions for further work or end user installations in the future.

$$P_f = 7\times10^7 (QH_n)^2 - 4\times10^6 (QH_n) + 49690 \tag{4}$$

$$P_f = 7\times10^7 (QH_n)^2 - 4\times10^6 (QH_n) + 49690 \tag{5}$$

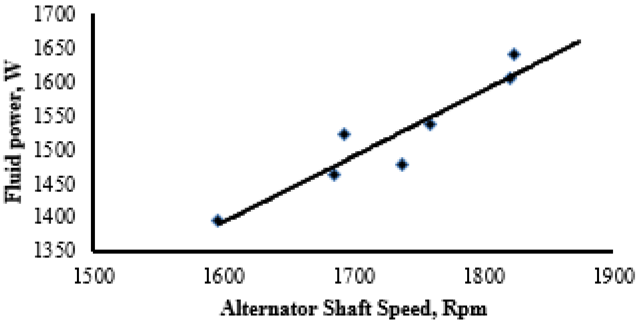

Fig. 7 Fluid power as a function of Alternator Shaft Speed for Penstock Configuration 1

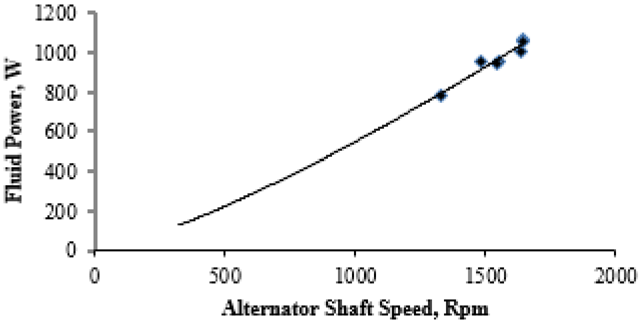

Fig. 8 Fluid power as a function of Alternator Shaft Speed for Penstock Configuration 2

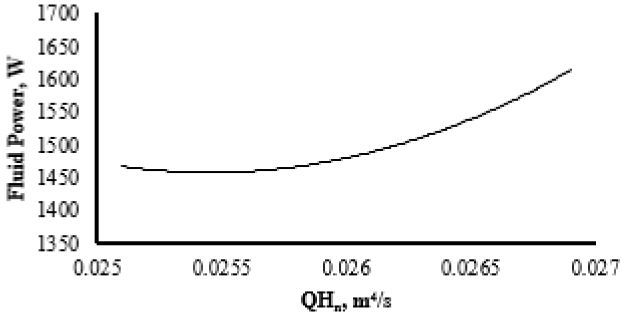

Fig. 9 Variation of Fluid Power with the Volumetric Flow Rate/Net Head Product for Penstock Configuration 1

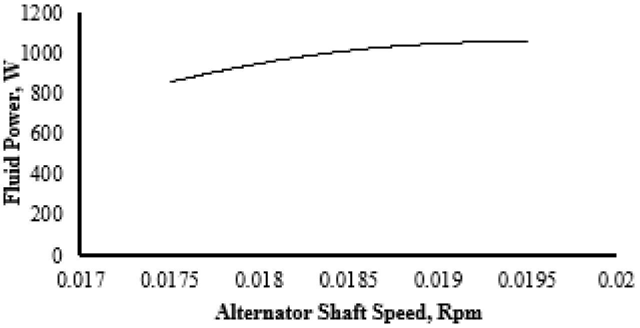

Fig. 10 Variation of Fluid Power with the Volumetric Flow Rate/Net Head Product for Penstock Configuration 2

CONCLUSION

The influence of the number of blades of the turbine runner as well as area reduction within the last 1 m of penstock on the performance of a simplified Pico hydro system under going development has been investigated. The following conclusions were drawn based on the results obtained in terms of the alternator shaft speed and computed fluid power:

- The penstock with the two stage area reduction produced higher values of the shaft speed and as a result computed fluid power.
- Turbine runners with 8 to 10 blades produced the maximum values of the parameters tested which reduced for larger blade numbers indicating the existence of a limiting number of blades for the system in its present form.
- A larger number of blades may be required to obtain maximum performance for a larger diameter runner though the trend will likely be maintained.
- From the findings of this investigation the following aspects for further investigation will be undertaken:
- Larger diameter runners will be used to check the influence of more blades.
- Larger hub diameters will be used in order to investigate smaller blades.
- Better construction planning will have ensured to reduce misalignment of the water jet from the turbine blades.
- An adjustable nozzle diaphragm will be incorporated into the system to enable the angle of attack to be varied.

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