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SHAFT POWER OF A SIMPLE PICO HYDROPOWER SYSTEM AS A FUNCTION OF THE FLOW RATE AND NET HEAD PRODUCT

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ABSTRACT

The basic operational parameters of a simplified pico-hydropower system with provision for water recycling were investigated as part of an ongoing development. Five highly simplified locally fabricated turbines of runner diameters 0.45, 0.40, 0.35, 0.30 and 0.25 m were tested in conjunction with five pipes of diameters 0.0762, 0.0635, 0.0508, 0.0445 and 0.0381 m as penstocks and five simple nozzles of area ratios 1.0, 0.8, 0.6, 0.4 and 0.2 based on each penstock diameter. The effective vertical height from the outlet of the overhead reservoir to the plane of the turbine shaft was 6.95 m. A 1.11 kW electric pump was used to recycle the water downstream of the turbine back to the overhead reservoir. The mean maximum and minimum rotational speeds of the shaft of each turbine were measured for each penstock diameter and nozzle area ratio. The volume of water displaced was also measured. The measured data were used to compute shaft power, volumetric flow rate and flow rate/net head product for each operation. The shaft power was then plotted against the flow rate/net head product for each pair of turbine and penstock diameters to obtain expressions resembling the analytical expression for hydraulic power. The results obtained will be useful in the process of developing the system as a simple, environmentally friendly and decentralized small power generation system that could potentially contribute positively to the Nigerian energy mix.

Keywords:
Pico hydro, Shaft power, flow rate/net head product, turbine diameter, penstock diameter, decentralized, environmentally friendly

INTRODUCTION

Economic development largely hinges on access to energy but its development and application pose several issues bothering on the environment [1-5]. Attaining the SDGs as well as Nigeria's drive towards a better standard of living for its citizens will require a very robust role for energy. However, in many developing countries, the stark reality is that access to energy is very minimal as a result of a mix of several factors. There have been several rural electrification programmes which have not been able to achieve the noble goals they were aimed at since even the many urban areas are still battling with very low and intermittent energy supply [6-18]. In Nigeria, many of the functional energy supply systems have perpetually operated below installed capacity, and are frequently susceptible to limitations resulting from human and natural causes. Moreover, many of them are large and utilize energy resources that have some adverse effect on the environment [19-29]. Apart from the adverse effect on the environment, several of the energy resources in use especially the fossil ones are depleting so that sustainability is not guaranteed. Exploration and transportation of new deposits also compound the negative effects on the environment such as oil spillage while escalating friction in the host communities [30-31].

Globally, this has brought about growing interests in and clamour for the use of renewable energy sources. Researchers are focusing on smarter, hybrid, smaller and decentralised energy systems which utilize renewable sources and conventional ones more efficiently. Such systems give more control to the user thereby creating more sense of responsibility with regard to the maintenance and security of the system [32-41]. This is significant especially with the prevalent activities of saboteurs as a result of terrorism and/or insurgency. They alsohave the potential of mitigating attacks on the supply structures resulting from growing restiveness in host communities in developing countries like Nigeria partly due to economic imbalance and poverty, and usually unfavourable government policies. The need to maintain and protect the supply structure is also entirely eliminated [42-45].

Hydropower has numerous advantages over other renewable energy sources but the large schemes which are generally predominantly in use in Nigeria and other developing countries also pose a lot of environmental problems [46-56]. These include harm to aquatic animals and habitat, possibility of enhancement of disease to the neighbouring communities, as well as displacement of settlements. Large to small hydro which depend on flowing water sources are affected by the hydrological cycle (seasonal fluctuation) which translates to blackouts and significant power outages at some periods of the year. Also, debris and silt blockages of turbine passages often arise which also affect power supply. Developing a means of applying the advantages of hydropower while greatly minimising the operational and natural shortcomings will be a step in the right direction [57-59].

Small and pumped storage hydro have been attracting attention recently. Pico-hydro power provides a very good option. It suits the general characteristics of smarter, smaller, decentralised systems which can be utilized in locations where larger conventional systems cannot be optimally located. It is a very useful option in many Asian countries where the topography is not suitable for the uptake of conventional grid-connected energy systems. Pumped storage schemesare used for supplementing conventional power supply during peak periods. It involves storing excess water at a higher level which is then released when demand is higher than available power into a reservoir at a lower level.However, it has been verified that seasonal fluctuations of water levels also affect the operation of conventional Pico-hydro schemes. Low water levels do not allow optimal operation while very high ones can sweep the units away [60-69]. Hence, the development of a Pico-hydro system that does not require naturally flowing water becomes necessary.

There are many sites suitable for Pico-hydro development in Nigeria as in many other African countries, but deliberate focus has not been given to its development in all the policies been geared towards achieving solutions to the energy crisis [42, 60]. For instance, no direct mention is made of Pico-hydro systems in the current aggressive efforts of the Federal Government to strengthen and/or resuscitate and make more effective the hydropower sector in Nigeria [70-72].

This work is a study of a simplified Pico-hydro system that is a variant of the pumped hydro scheme which could be operated where there is no naturally flowing water by utilising an overhead water storage and having provision for water recycling. Such a system will eliminate several of the issues that conventional hydropower systems have contend with while retaining its substantial advantage as a system for power supply in the mould current renewable energy systems' best practices. It will be decentralised thereby conceding control to the user and reducing the risk of sabotage. The limitation imposed by seasonal variations of water levels on conventional Pico-hydro systems will be eliminated as well. It is an aspect of the ongoing development of a simple and environmentally benign pico-hydro system [73-80]. It seeks to explore the idea of estimating power output from the site parameters for a hydropower system. Conventionally, the power is a function of the product of the flow rate and the net head available [81-83]. This is shown in equation1. The density of water and acceleration due to gravity can be reasonably assumed to be constant for the analysis.

$$P_f = \rho g Q H_n \qquad (1)$$

where P_f = fluid power and QH_n = flow rate and net head product.

MATERIALS AND METHODS

The set up for this work is similar to the ones used in earlier aspects of this work [71, 77-79]. The same basic parameters of the system and their associated expressions were also applied to the present stage of the work.The rotational speed of the turbine shaft (N) was measured using the DT-2268 and DT-2858 Contact Type Digital Tachometer for each turbine runner diameter while varying the nozzle configuration and penstock diameter. The tachometers have a measurement range of 2.5 – 99,999 Rpm. The resolution is 1/1000 Rpm, accuracy ± 0.05% + 1 Rpm and photo detecting distance of 300 mm. They have memory capability of showing the last value, maximum value and minimum value, and a typical sampling time of 1 second.

The water levels in the two reservoirs were monitored simultaneously using calibrated dip sticks to obtain the volume of water discharged which was then used to compute the volumetric flow rates. The associated frictional losses were estimated using equation 2[84-86], 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 were estimated with the equation 3. Values of the loss coefficients, K, for pipe entry, gate valve and 90°elbow were obtained from [83] as 0.5, 0.25 and 0.9 respectively. For change in penstock dimensions, K values were obtained using equation 4[84, 87]. H_t values were then computed with only the valve, elbow and entry coefficients applied to the largest diameter penstock. The contraction coefficients were then successively added as the penstock sizes reduced. The net head available was then computed using equation 5.

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

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

where d = smaller inner diameter and D = the larger inner diameter.

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

where H = total height of the water surface above the plain of the turbine shaft and $H_L = H_f + H_t$. The flow rate and net head products were then computed.

The fluid power (P_f) available was computed using equation 6[85, 88]. The shaft power, P_s, was computed from first principles using equation 7.

$$P_f = \rho g Q H_n \qquad (6)$$

The shaft power, P_s, can be computed from first principles using the expression below.

$$P_s = \omega T \qquad (7)$$

where ω = the angular velocity and T = torque.

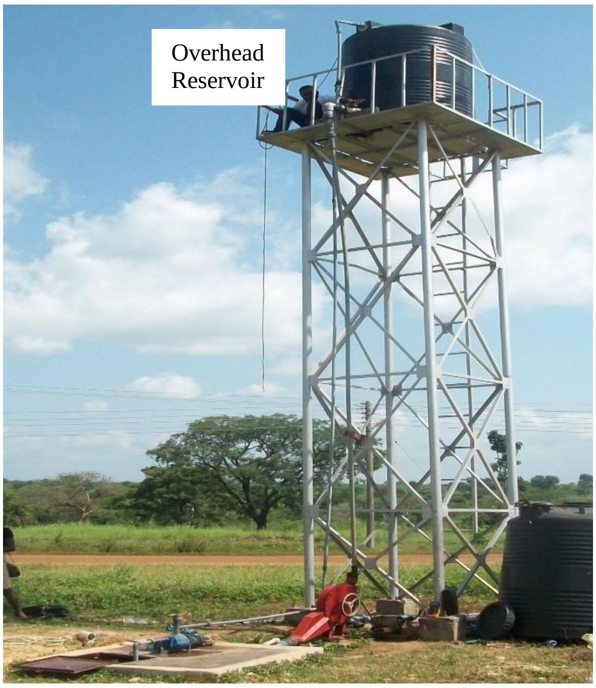


Fig. 1: The complete set up of the system used for the Study

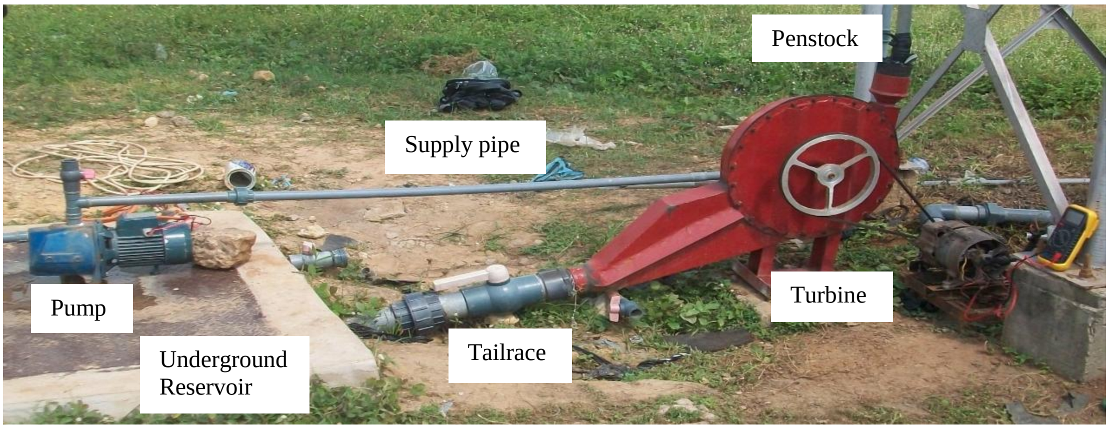
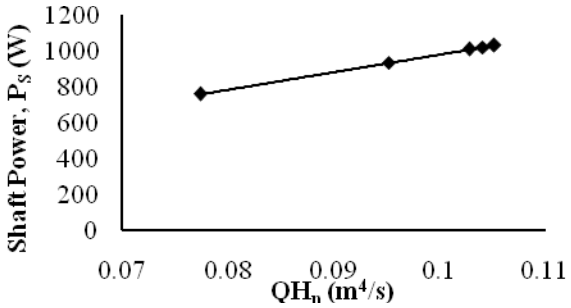


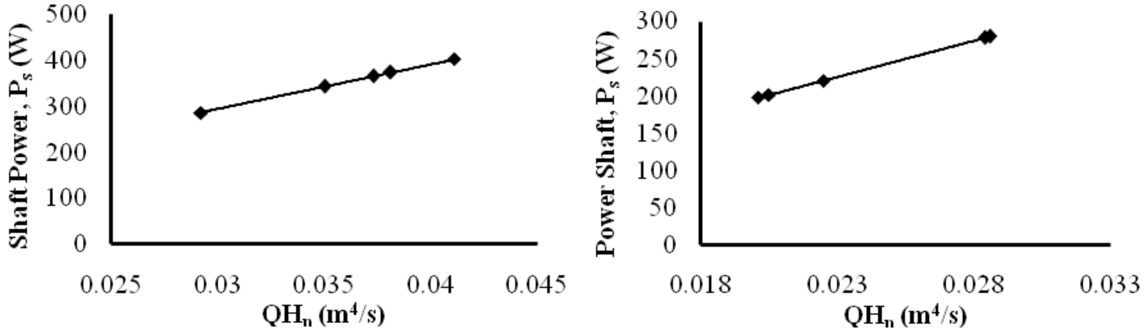
Fig. 2: Enlarged view of the 1.11 kW Pump, Turbine and Penstock

RESULTS AND DISCUSSION

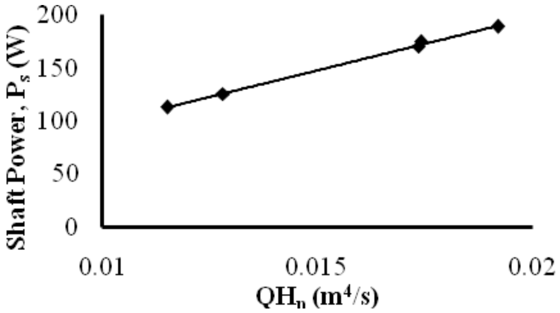
Figure 3shows representative plots used to develop empirical expression showing shaft power as a function of the flow rate and net head product for the turbine runner diameter of 0.45 m and the respective penstock diameters. The plots for the other runner diameters were similar to the ones shown in the figure. This attempt is informed by the fact that power output from a hydraulic turbine is obtained from the expression $P = \eta\rho g Q H_n$[67, 89-93]. Since $\eta\rho g$is constants for any specific site and turbine, it is convenient to manipulate the experimental data to obtain the product QH_n and relate it to the shaft power P_s. The resultant expressions can give an insight into the range of the power that could be generated by the simplified system.



(a) D_P = 0.0762 m (b) D_P = 0.0635 m



(c) D_P = 0.0508 m (d) D_P = 0.0445 m



(e) $D_P = 0.0381$ m

Fig. 3: Shaft Power as a function of Flow Rate/Net Head Product for Turbine Runner diameter of 0.45 m and the indicated Penstock of Diameters.

Table 1 shows the expressions obtained from Figs. 3 to 7 and for those of the other values of turbine runner diameters. As shown in the table, all the curves were similar with variations in the coefficients and indices. All the indices lie in the range $0.8 < n < 1.2$ which is quite reasonably acceptable because in the actual power equation, $n = 1.0$. The curves can all be approximated as linear trends though they are all power trends with very high R^2 values. The coefficients all compare well with the term $\eta\rho g = 9810\ kg/m^2s^2$ in the equation for the shaft power [94-103].There were however variations up to 34.7% less $(D_p = 0.0762\ m, D_T = 0.25\ m)$ and 7.31% more $(D_p = 0.0381\ m, D_T = 0.45\ m)$. These variations would have been partly as a result of the variations of the value of n from 1.0. The only glaring exception is the constant for the expression of $(D_p = 0.0381\ m, D_T = 0.40\ m)$. Since it is uniquely different from the others, it most likely could have resulted from some form of error or the other. The R^2 value for the curve is also clearly lower than those of the other plots.

These expressions based on experimental data which have been developed will be very useful for future modifications of the system. The equations can be utilized as base equations for further investigation relating to this work leading to eventual full implementation. They can be manipulated to include other system parameters such as the volume of the reservoir and the net head available or the penstock diameter in order to optimize performance of future stages of the system’s development or for specifications for particular users and/or sites.

Table 1: Empirical Shaft Power Models for the Turbines

Penstock Dia. (m)	Runner Dia. (m)	Empirical Model	Trend Type/R^2
0.0762	0.45	$P_s = 9825.5(QH_n)^{1.001}$	Power/1.0000
	0.40	$P_s = 9809.5(QH_n)^{1.001}$	Power/0.9998
	0.35	$P_s = 9805(QH_n)^{0.9998}$	Power/1.0000
	0.30	$P_s = 9859.2(QH_n)^{1.0021}$	Power/1.0000
	0.25	$P_s = 6410.5(QH_n)^{0.8151}$	Power/0.9960
0.0635	0.45	$P_s = 9353.4(QH_n)^{0.9843}$	Power/0.9990
	0.40	$P_s = 10496(QH_n)^{1.019}$	Power/0.9663
	0.35	$P_s = 9822.6(QH_n)^{1.0004}$	Power/1.0000
	0.30	$P_s = 9671.4(QH_n)^{0.9952}$	Power/1.0000
	0.25	$P_s = 9881.9(QH_n)^{1.003}$	Power/1.0000
0.0508	0.45	$P_s = 9791.6(QH_n)^{0.9997}$	Power/1.0000
	0.40	$P_s = 9785.2(QH_n)^{0.9994}$	Power/0.9999
	0.35	$P_s = 9494.5(QH_n)^{0.9902}$	Power/0.9999
	0.30	$P_s = 10010(QH_n)^{1.0052}$	Power/0.9960
	0.25	$P_s = 9833.1(QH_n)^{1.001}$	Power/1.0000
0.0445	0.45	$P_s = 9561.5(QH_n)^{0.9933}$	Power/1.0000
	0.40	$P_s = 9731.5(QH_n)^{0.998}$	Power/1.0000
	0.35	$P_s = 9918.6(QH_n)^{1.003}$	Power/1.0000
	0.30	$P_s = 9661.9(QH_n)^{0.996}$	Power/0.9999
	0.25	$P_s = 9736.1(QH_n)^{0.998}$	Power/0.9999
0.0381	0.45	$P_s = 10527(QH_n)^{1.016}$	Power/0.9986
	0.40	$P_s = 19988(QH_n)^{1.163}$	Power/0.9428
	0.35	$P_s = 10039(QH_n)^{1.004}$	Power/0.9998
	0.30	$P_s = 9588.6(QH_n)^{0.9945}$	Power/0.9999
	0.25	$P_s = 10125(QH_n)^{1.008}$	Power/0.9999

CONCLUSIONS

Expressions relating the shaft power of the system as functions of the flow rate and net head product were developed from empirical data. They can be very useful for estimation of the system parameters for further development to a status that will positively contribute towards ameliorating the effects of the energy crisis in Nigeria and other developing countries. Specifying the estimated power can give an idea of the flow rate and net head required. This can make the process of designing and installing a new system more convenient. Further development will however be necessary to realise this potential in full. Its parameters need to be properly manipulated to achieve a self-running status before it can become commercially viable.

The recommendations for this work are actually issues for immediate further phase(s) of this work. Based on the current findings and the original aspirations of this study, the following are recommended:

- The delivery pipe from the pump should be modified so as to cause the ratio of delivery to discharge from the reservoir to be more favourable for system performance (that is, to tend towards 1:1);
- The system should be tested with the overhead reservoir located above 7.0m to take advantage of greater head;
- The effect of multiple overhead reservoirs (or larger capacity ones) will also be investigated as part of the progressive development;
- Involvement by relevant agencies for funding will enhance the introduction of solar power for powering the recycling system in order to explore the hybridization option; and

- An economic comparative analysis of this system with a stand-alone solar power system and a fossil fuel powered system should also be undertaken.

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