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Performance Evaluation of a Pump as Turbine in a Simplified Pico Hydropower System with Provision for Water Recycling

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The performance of a pump used as a turbine (PAT) in a simplified Pico hydropower system with the provision for recycling water to an overhead reservoir (OHR) 7.2 m high was investigated. A vertical PVC pipe of diameter 0.0762 m reduced into four replaceable nozzles of diameters 0.0635, 0.0508, 0.0381 and 0.0254 m was used as penstock. A 1.5 Hp surface pump was used to lift water from an underground reservoir to the OHR and the PAT was coupled to a generator by a pulley and belt drive. The volume of water discharged was monitored for each nozzle diameter till the OHR was empty, and the voltage developed and current flowing through the load measured. The flow rate, shaft power, and efficiency of the PAT for the no-load tests and then including the electrical power for the on-load tests were computed. The highest and lowest efficiency of the system (0.694

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and 0.497) corresponded to nozzle diameters of 0.0635 and 0.0254 m respectively, while the highest efficiencies for each nozzle diameter (0.684, 0.629, 0.550 and 0.497) were recorded for the highest respective flow rates for the no-load tests. For the on-load tests, the highest and lowest power developed (2.976 and 2.760 kW) were obtained for the largest and lowest nozzle diameters, with the highest power for each nozzle diameter corresponding to the highest respective flow rates. These results indicate the critical role played by the nozzle diameter in producing the torque required for power generation. This confirms the critical role of flow rate and available head for determining the site feasibility in conventional hydropower practice. Overall, the results show good potential for the system to be implemented as a clean, stand-alone, small power generation unit that will enhance end-user control.

Keywords: Flow rate; head; nozzle diameters; pico hydropower; pump as a turbine; water recycling.

1. INTRODUCTION

Electrical power plays an important role in the economic growth, advancement, development, and also poverty elimination and security of a country [1]. Steady supply of energy is a very important issue for all countries today, and Nigeria as well as several developing nations are faced with this challenge. The insufficient power supply in Nigeria has led many manufacturing industries in the search for accessible alternatives to use petroleum and other fossil fuel as the most common sources, affecting the environment negatively because of the emission of carbonaceous substance generated by the use of petrol and diesel generators as a result of extremely unsteady power supply [2-4].

Furthermore, 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. Up to 65% of Nigerians living in the remote areas still do not have access to electrical power and this has delayed the overall progress of rural communities. On the other hand, small hydropower system is one of the possible renewable energy systems that is appropriate and can be very important for remote area electrification in Nigeria because these areas have several rivers, streams and run-off waters with potentials for producing hydroelectric energy [5, 6].

Over the years, different kinds of technologies have being applied with the aim of meeting the electrical demand by the use of renewable sources in spite of hydrocarbon fuels [7]. However, in Nigeria energy supply has been epileptic in nature, causing the socio-economic status of the country to be downgraded [8]. Nigeria’s energy demand increases with an increase in population, but power supply has remained unreliable and insufficient with a country generation capacity of about 3500 MW as at 2011 [9]. According to Nnodim [10], power generation was 5,090 MW at some point which was one of the highest quanta of electricity ever witnessed on the national grid recently. According to IRENA [11], Nigeria’s net energy capacity utilization in 2019 shows that hydro/marine energy dominated with 46% followed by fossil and bioenergy with 26 and 23%, while solar was 17%. Also, the net capacity for non-renewable and renewable sources between 2015 and 2020 indicated that the non-renewables have dominated but have decreased to below 500 MW in 2020. Nigeria like other nations is feeling the adverse impact of adverse climate change that is partially attributed to the significant dependence on fossil fuel-fired power plants which is the main source of greenhouse gas emissions (GHG), coupled with activities of manufacturing industries, oil prospecting firms and deforestation and so on. The need therefore, continues to exist for the development of alternative sources of energy to tackle this problem [9,12].

Renewable energy has been known as the only option for addressing these problems [13]. Hydropower amongst other renewable sources offers a clean and sustainable source for rural power, provided there is water to power the turbines, causing little or no emissions to the ecosystem. The hydropower potential of Nigeria is very high, accounting for about 29% of the total electrical power supply with only around 19% is presently been developed [10]. According to ECREEE [14], the number of existing hydropower plants in Nigeria as at 2016 were 34 (< 1 MW), 23 (1-30 MW), 5 (30-100 MW) and 6 (>100 MW). Kainji and Jebba power plants are two of the hydro generation systems fed from the River Niger. The joint installed capacity of the two systems is 1330 MW, with Kainji producing 760 MW and Jebba 570 MW efficiently when the plants work at full capacity. Shiroro power station was commissioned in 1990, with an installed capacity of 600 MW, it presently runs at full volume, generating 2,100 GWh of electricity yearly. As Nigeria's latest hydroelectric system, Shiroro hosts Nigeria's SCADA-operated national control center. It is situated in the Shiroro Gorge on the Kaduna River, approximately 60 km from Minna, capital of Niger State, in close proximity to Abuja, Nigeria's Federal capital [13]. Nigeria's renewable energy capacity from 2014 to 2019 increased to around 8000 GWh with hydro/ marine energy dominating and reaching up to 98% in 2020 [11]. The Federal government have made some efforts to harness of this hydropower potential with about 40 MW expected to be evacuated from the Kashimbilla hydroelectric power station and work going on at Gurara falls.

However, hydroelectric power plants have potential adverse environmental impacts. 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. 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 affected 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. Further, growing evidence suggests that reservoirs emit significant quantities of greenhouse gases especially in the lowland tropics. 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. The foregoing demerits are more directly applicable to large hydropower schemes [15].

Generally, hydropower can be classified into Pico, micro and mini hydropower (small hydropower) or large hydropower depending on the power generated. In case of remote villages and high terrain region it has been proved that it is more suitable to use a pump coupled with induction motor as custom made turbines are expensive [16-18]. The pump is made to rotate in reverse by flowing water supplied to its discharge end through penstock and the induction motor is used as generator [19]. PATs have been used for several decades with power ratings of several megawatts. Standard pumps are now more and more used in MHP/PHP schemes (5 to 500 kW). For pumped storage systems, PATs are specifically used to operate in both modes; pumping water into an elevated storage lake overnight at low tariff electricity and during the day, generating peak demand electricity through the same machine operating in turbine mode [17].

The energy crisis in Nigeria have been aggravated by recent increases in the electrical power consumption tariff and uncertainty of fuel price in the country as well as the increased usage of electrical generators, causing health hazards and environmental pollution. These challenges can be overcome by utilizing alternative energy solutions in order to cushion these effects of the energy scenario. Among all the available renewable energy solutions, hydropower and particularly, Pico-hydropower is considered as the most promising source of energy [20,21]. However, it has been verified that seasonal fluctuations of water levels also affect the operation of the conventional Pico-hydro schemes [22,23]. Low water levels do not allow optimal operation while very high ones can sweep the units away. Developing a means of applying the advantages of hydropower while greatly minimizing the operational and natural shortcoming will be a step in the right direction. Hence, developing a Pico-hydro system that does not require naturally flowing water is attractive [24].

Some work has been done on the system with very promising results. However, a sustained power generation is yet to be achieved due to the imbalance between the discharge and replenishing of the overhead reservoir, and the water recycling sub-system still utilizes power from the mains. This work seeks to make a contribution to the development of the system by incorporating a pump-as-turbine in an attempt to address these specific problems. It evaluates the performance of a simplified Pico-hydropower system with a pump-as-turbine and with provision for water recycling as further effort in the development of a system that does not require conventional flowing water. The system will be beneficial to individuals, communities and small-scale industries in Nigeria by providing access to a simple decentralized power system which is environmentally benign and directly under the control of the end user [5,12,15,25]. Results have indicated good promise for this system as a small, clean and decentralized energy option especially where there is no naturally flowing water. Most remote villages and even some houses in the urban areas can take advantage of this. It could compliment power supply from national grid and due to the high initial cost of solar energy systems and the limited technical know-how, this option is attractive. This investigation will further strengthen the prospects of implementation of the system as an excellent alternative for electricity generation in remote areas and for small scale industries. The present study has become necessary in order to improve the balance between the discharge from the overhead reservoir and the replenishing of the water in it.

2. MATERIALS AND METHODS

The field work was carried out at Joseph Sarwuan Tarka University (formerly Federal University Agriculture), Makurdi. Fig. 1 shows the set-up of the system for the study consisting of an overhead reservoir mounted on a stanchion about 7.2 m high connected to the PAT through a vertical 0.0762 m diameter PVC pipe as a penstock reduced to a replaceable nozzle. Four replaceable nozzles were obtained by reducing the 0.0762 m diameter penstock to 0.0635, 0.0508, 0.381 and 0.0254 m as shown in Fig. 2. The outlet of the PAT discharges into an underground reservoir through a PVC pipe of the same diameter as the penstock. The overhead and underground reservoirs are of capacities of about 1.90 and 2.50 m^3 respectively. A surface pump of capacity 1.5 Hp with operating range 2 poles from 0.4 to 10.5 m^3/h powered from the mains was used to recycle water from the underground reservoir to the one overhead through a 0.0254 m PVC pipe.

A 20 Hp (240 V, 50 Hz) Lowar surface pump (RF: 038599) having a delivery up to 1800 m^3/h, head up to 160 m, and motor size of 1.5 kW, power supply from 0.25 kW up to 355 kW, and maximum operation of 16 bar centrifugal pump was used as a turbine. It has 0.032 m inlet and outlet diameters. The stainless steel impeller has curved vanes fitted into a shroud plate. The enclosed type impeller with total runner diameter of 0.30 m was immersed in water and made to rotate backward. The PAT was connected to a 3 kW generator via a v-belt arrangement with pulley ratio of 1:2 to meet the requirement for the alternator to generate power as shown in Fig. 3. The PAT was firmly secured on an angle iron base measuring 0.005 × 0.27 m. Leakages from the recycling pipe and the PAT itself were minimized by using appropriate mechanical seals. The system is started by opening a ball valve located before the inlet of the PAT.

The time taken for the pump to fill the overhead reservoir was measured several times and the mean value determined. Secondly, the flow rate from the overhead reservoir was determined using the bucket method for each of the four replaceable nozzle diameters. As part of the no-load test, visual observation of the flow through the penstock was carried out by opening the control valve with the nozzle removed. The typically turbulent flow observed is shown in Fig. 4. For both no-load (without generator) and on-load tests, the control valve was opened for a period and the required measurements made. This constitutes an operation for the study. The water levels in the two reservoirs were then measured using the calibrated dip stick. Two tachometers (DT-22358B Contact type digital and digital laser) were used to measure the rotational speeds of the PAT and alternator shafts. The digital laser tachometer has a range of 2.9 to 99,999 rpm, accuracy of ± 0.02% + 1 digit, resolution of 0.1 rpm at 2.5 ~ 999.9 rpm, measuring distance of 0.05 m ~ 0.5 m, sampling time 120 rpm and above within 0.5 second. For the contact type, the maximum, last and minimum values are delayed and can be recalled. It has a measurement range of 0.5 to 19999 rpm, accuracy of ± 0.05% + 1 digit, sampling time 1 second (6 rpm) and surface speed of 0.05 to 1999.9 m/min. Two multimeters (Mastech model MS2115A AC/DC clamp and Dg5274D digital) were used for measuring the electrical quantities. The water levels in the two reservoirs before and after each operation were measured with a calibrated dip stick and the duration also noted. Each procedure was carried out for nozzle diameters 0.0635, 0.0508, 0.0381 and 0.0254 m for a mean operation time of 20 seconds. The measured data were used to compute the Reynolds number, fluid flow velocity, flow rate, shaft power, fluid power and hydraulic efficiency. The power output was compared with the rating of the generators on the manufacturers' information.

The experimental flow rate, Q_e, was computed using equation 1. The flow velocity through the penstock for each operation was computed, assuming flow continuity using equation 2.

$$Q_e = \frac{Volume\ of\ water\ discharged\ (m^3)}{Time\ taken\ (s)} \quad (1)$$

$$V_n = \frac{V_p R_p^2}{R_n^2} \quad (2)$$

Where

V_n = velocity through the nozzle,
$V_p = {Q_e}/{\pi R_p^2}$ = flow velocity downstream of the overhead reservoir before the reduction,
$R_p = {0.0762}/{2}\ (m)$ = radius of the penstock corresponding to V_p, and
R_n = radius of the nozzle

The Reynolds number, R_e, for each flow was computed using equation 3, with the dynamic viscosity and density of water taken from a viscosity chart at 33º (average ambient temperature) as 0.7488 $N.s/m^3$ and 994.7 kg/m^3 respectively.

$$Re = \frac{\rho V D}{\mu} \quad (3)$$

Where

ρ = fluid density (kg/m^3),
V = flow velocity (m/s),
D = characteristic linear dimension (m), and
μ = internal fluid dynamic viscosity ($N.s/m^3$).

The rotational speeds of the alternator pulleys were double checked for adequacy to generate power using equation 4. This was however, based on the accuracy of the speed of the PAT pulley.

$$N_2 = \frac{D_1 N_1}{D_2} \quad (4)$$

Where

D_1, D_2 = pulley diameters of the PAT and alternator respectively, and
N_1, N_2 = the corresponding rotational speeds.

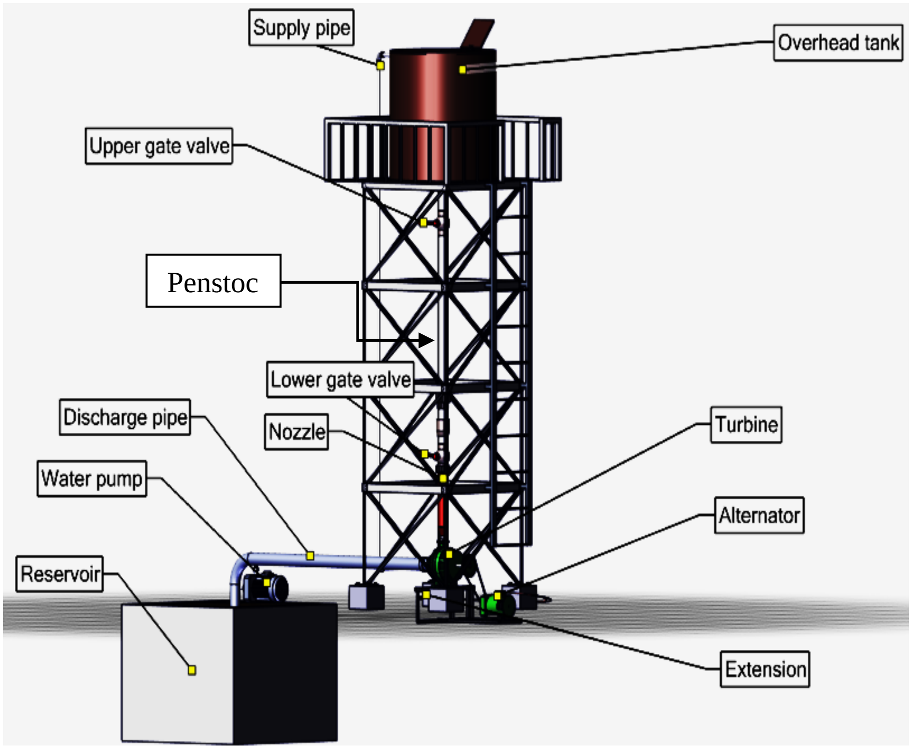


Fig. 1. Experimental set-up of simplified pico hydropower system

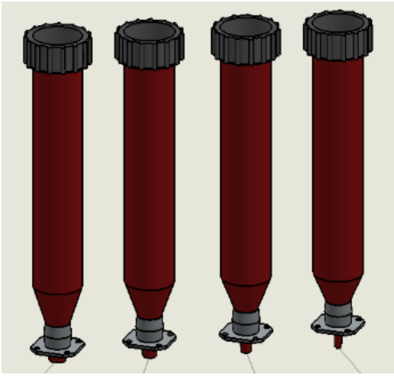
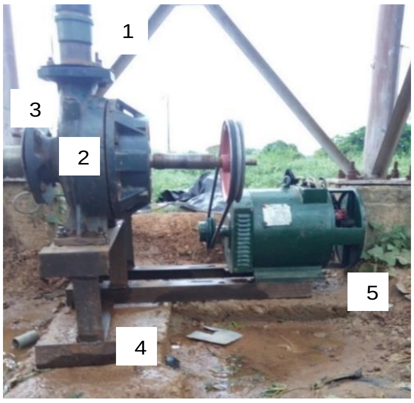


Fig. 2. The 4 replaceable nozzles used for the system



1. PAT Inlet
2. Pump as a Turbine (PAT)
3. PAT Discharge outlet
4. Welded foundation
5. 3kW Synchronous Generator

Fig. 3. The 3 kW AC synchronous generator linked to pump as turbine

Fig. 4. Turbulent nature of flow through the penstock

The efficiency of the PAT was computed using equation 5, with fluid or hydraulic power computed using equation 6.

$$\eta_t = \frac{P_b}{P_{hy}} \quad (5)$$

$$P_{hy} = \rho g H Q \quad (6)$$

Where

η_t = the efficiency of the PAT,
P_{hy} = Hydraulic power (kW), and
P_b = power output or shaft power (kW).

The shaft or output power was computed using a derivation from first principles by Edeoja et al. [14] as shown in equation 7.

$$P_s = \frac{\pi \rho Q N D_T}{60} \quad (7)$$

Where D_T = PAT impeller diameter and using the density of water at 33ºC (994.7 kg/m^3) and g = 9.81 m/s^2.

The key parameters of the system along with the output power and the hydraulic efficiencies for the different nozzles were then analyzed for variance using a 2-factor ANOVA without replication at 0.05 significance level using Microsoft Excel 2013 software.

3. RESULTS AND DISCUSSION

It took a mean time of 651.57 s, about 10.85 minutes, for the pump to fill the overhead reservoir. From the visual inspection, the flow was largely turbulent, characterized by the irregular, chaotic movement of particles of the fluid. The Reynolds number computed for each operation was > 3500. Using the dynamic viscosity and density of water at temperature 33 ºC (mean average daytime temperature during the period of the study), the mean value of the Reynolds number was 51153.9.

The no-load tests were carried out to examine the performance of the system without the power generating sub-system. They provided useful insights and guides for the on-load tests. They involved the investigation of the various system parameters under no-load condition. Figs. 5 to 11 show the characteristics of the various system parameters these tests. The volume of water in the overhead reservoir was monitored during each period of operation of the system for each of the four-nozzle diameters used. Fig. 5 shows the variation of volume of water with number of operations for each nozzle diameter. The volume diminished most rapidly for the 0.0635 m diameter nozzle as indicated by the curves. Also, the curves for the 0.0254 and 0.0381 m nozzle diameter tended more towards linear variations thereby accounting for longer periods of operations than for the other 2 nozzles. As a result, the system is likely to operate for a longer period with smaller diameter nozzles. These observations are consistent with the basic fluid flow principles which provide for greater volume of flow through larger diameter channels [26-29]. The same observations were also made in earlier studies relating to this simplified Pico hydropower system [25,30].

The velocity of water through the nozzles were computed based on the continuity equation for flow in one direction and compared the flow of water through the parent size of the penstock (0.0762 m). This is shown in Fig. 6. Expectedly, the flow through the nozzles were multiples of that through the parent penstock diameter, with the 0.0254 m diameter nozzle reaching nearly 4 times higher. This is because the velocity of flow through a pipe is inversely proportional to its diameter since reducing the diameter converts the potential energy of the water to kinetic energy. This affirms the need for utilization of nozzles of appropriate sizes in order to increase the water velocity (production of a water jet) for operation in the system. This, however, must be carefully examined so that a beneficial trade-off can be established between the volume of water required and the velocity of water attained [4,7,31].

Fig. 7 shows the variation of flow rate through the various nozzle diameters. This figure shows that the 0.0508 and 0.0635 m nozzle diameters delivered higher volumes of water per unit time than the other 2 nozzle diameters as have been alluded to in the previous section. Theoretically, the system will develop more power with those nozzles so that such dimensions are desirable for the system operations [32]. However, within the context of the present study, the discharge through them took place over a shorter period of operation. This can be addressed by using a larger capacity reservoir, or by selecting a nozzle diameter in the range 0.0381 m $< \phi <$ 0.0508 m. This latter option will hopefully yield a better compromise between flow rate and period of operation as indicated by the gap between the 2 sets of curves in the figure. The former option appears less attractive because it will require a higher cost. This is a useful information for the implementation the system for end user applications [33,34].

Fig. 8 shows the variation of the PAT speed with number of operations. The largest diameter nozzle produced erratic responses in terms of speed of the PAT and sharper decrease after the initial value. For the 2 larger diameter nozzles, the values faded below those of the other nozzles 4th operation. The performance of the system with the 2 smaller diameter nozzles was steadier with the values of the PAT speed with the curves less steep compared to those for the 2 larger diameters. Overall, after the 5th operation, the 0.0254 m nozzle produced the higher values of PAT speed. Also, the 0.0381 m nozzle had the steadiest operation throughout with an almost perfect linear trend. The steadier operation was because of the smaller diameter jet which was able to interact more favourably with the impeller of the PAT. Also, the discharge of the water over a longer period of time meant that the flow rate decreased in a more controlled manner. A similar performance was also reported by Edeoja et al. [5] in an earlier study. The figures generally depicted a decreasing trend with number of operations as for the volume of water as well as the other system parameters.

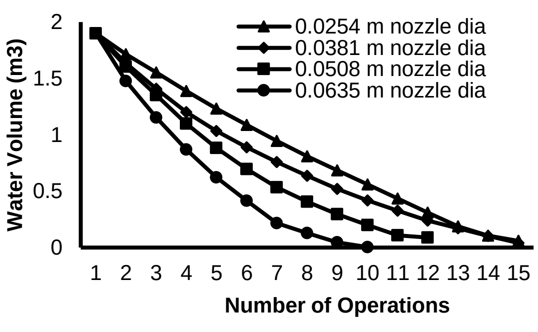


Fig. 5. Variation of water volume in the OHR with number of operations

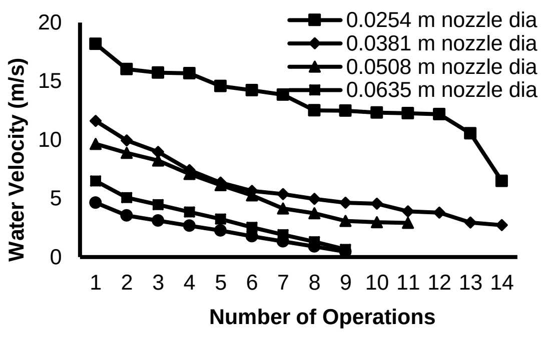


Fig. 6. Variation of water velocity with number of operations

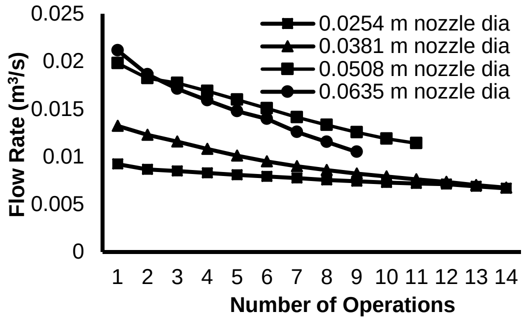


Fig. 7. Variation of flow rate with number of operation

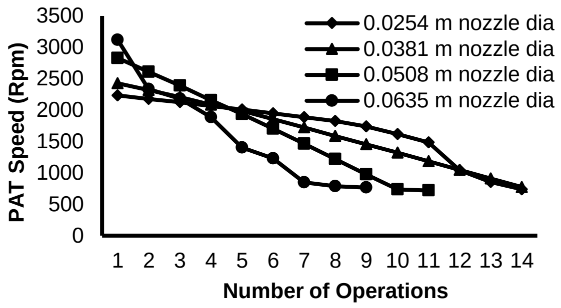


Fig. 8. Variation of PAT speed with number of operations

Figs. 9 and 10 show the variation of the computed shaft and fluid power of the system under no-load conditions for all the nozzle sizes. Fig. 9 shows that the shaft power was expectedly higher for the larger diameter nozzles in line with conventional hydropower practice in which higher values of flow rate translate to higher power developed [35-37]. However, the curve for the 0.0635 m diameter nozzle again indicated an erratic pattern. For the other 3 nozzle diameters, the performances were steadier as indicated by the smoothness of the respective curves. As earlier discussed, those nozzles produced steady flow rates which translated to such performances. Also, the figure shows that larger diameter nozzles potentially favour higher values of shaft power in agreement with earlier findings [38,39]. Fig. 10 shows the corresponding variations of the computed fluid power for the system. The respective values of the fluid power showed very similar trends compared to the computed shaft power values with the exception of those for the largest diameter nozzle. The trend of fluid power for this diameter of nozzle indicated more steadiness. Again, the values for the larger diameters were higher [4,40,41].

Fig. 11 shows the variation of the system efficiency with the number of operations for the no-load tests. Clearly the system had the highest efficiency with the largest diameter nozzle, though the erratic nature of the system performance with that nozzle was again evident from the figure. Again, the efficiency for the 3 smaller diameter nozzles also show smoother operation with more consistent values of efficiencies. The smoothest of them was the 0.0508 m diameter nozzle. On the whole, after the 3rd operation, the efficiencies for the 3 smaller diameter nozzles were higher than the values for the 0.0635 m diameter nozzle confirming the erratic nature of the flow through it. Also, for each of the nozzle diameters, the highest values of the computed efficiencies (0.694, 0.629, 0.550 and 0.497 respectively) corresponded to the highest values of flow rates. These efficiency values emphasize the need to strike a good balance between the advantage of larger diameter for higher flow rates and smaller diameter for better water jets with high kinetic energy [42-45].

For the no-load tests, the flow rate, PAT speed, shaft power and efficiency were analyzed for variance. The results indicated that the flow rate varied significantly from one operation to the other confirming the change in flow rate with the volume of water in the reservoir. The flow rate also varied less significantly from one nozzle to the other. Both observations are consistent with earlier assertions in the discussions, further affirming that the volume of water available affects the flow rate more dominantly than the nozzle diameter. In other words, for any given nozzle diameter, the volume of the water determines the flow rate [3,46,47]. The PAT speed varied significantly with nozzle diameters but the variation with change in water volume was not statistically significant. Again this strengthens the earlier observation that PAT speed depends more on the nozzle diameter than change in water volume because the nozzles supply the water to the turbine. The shaft power varied slightly significantly at 0.05 level both with the nozzle diameters and volume change. This further shows that both parameters jointly contribute to the value of shaft power developed. However, the efficiency of operation of the system depended more on the nozzle diameter in agreement with previous observations on the subject [48-51].

The on-load tests were a repeat of all the tests discussed in the previous section but this time with the alternator linked to the PAT using a belt drive as described earlier. The duration for these tests were longer due to the change in flow patterns brought about by the introduction of the generator. For the on-load tests, flow rate, PAT speed, generator shaft speed, voltage, current, flow rate-Head product and power developed were analyzed for variance. Figs. 12 to 18 show the variation of the system parameters for the on-load tests. Fig. 12 shows the variation of the volume of water in the overhead reservoir with number of operations for the on-load tests. The trends for the various nozzle diameters were quite similar to those obtained for the no-load tests but the number of operations were slightly more. Again the 2 larger diameter nozzles (0.0635 and 0.0508 m) had fewer operations or cycles than the smaller ones as indicated in the figure thereby affirming the point earlier made that larger diameter penstocks and nozzles will require the provision of larger reservoirs as far as a good balance vis a vis the cost can be struck [26,52-54].

Fig. 13 shows the variation of flow rate during the operations of the system the 4 nozzle diameters. The trends obtained were similar to those obtained for the no-load test. The 0.0635 m diameter nozzle had the highest discharge while the 0.0254 m diameter nozzle had the least. However, both of these nozzle diameters showed smoother operations (steady decrease) than the 0.0508 and 0.0381 m diameters through the 0.0635 m diameter nozzle has fewer operations or cycles. The results strengthen the fact established from the no-load tests that larger diameter nozzles will favour higher flow rates at the expense of shorter duration of operation than smaller diameters. The smaller ones however will enhance longer durations. A critical decision therefore is the shifting of a beneficial balance in selecting the appropriate nozzle diameter as well as the penstock diameter [55, 56]. For the on-load tests, the flow rate varied more significantly with volume than for the no-load tests while the variation was much less for the various nozzle diameters.

Fig. 14 shows the variation of PAT speed with number of operations. The results indicated higher PAT speed values during the earlier operations for the 3 larger diameter nozzles while the smallest diameter nozzle produced higher values during the later operations. Also, this nozzle had a steadier discharge as indicated by the curve confirming the earlier point raised with regards to the discharge of water from it. This steady discharge aided more consistent interaction between the water jet and the impeller of the PAT. To achieve optimum PAT speed, a good compromise between cost and size of nozzle and/or penstock for the system has to be arrived at. This is because to prolong the duration of operation with the larger diameter nozzle (or penstock) the capacity of the overhead reservoir must be increased which could result in increased cost. On the other hand, choosing a smaller diameter nozzle prolongs the operational period at the expense of the PAT speed [4,50,57]. Furthermore, PAT with a larger diameter impeller could be selected along with the larger nozzle and overhead reservoir. The momentum of the rotating wheel could be beneficial for the speed of rotation especially as the volume of water in the reservoir becomes smaller [58]. The variation of the PAT speed was similar to that for the no-load tests, varying across the nozzle diameters and not with water volume change.

Fig. 15 shows that the variation of generator shaft speeds with number of operations is quite similar to those of the PAT speeds. This was expected as generator shaft speeds were multiples of the corresponding PAT speeds. This is because the belt drive was introduced to amplify the PAT speed in order to meet the minimum requirements specified for the operation of the 3 kVA generator used for the study. The belt drive was opted for because direct coupling of the generator to the PAT would have been detrimental for the operation of set up [19,24,33,36,59]. Expectedly, the generator shaft speed followed the same pattern because they were multiples of the PAT speed.

Figs. 16 and 17 show the variation of the voltage and current measured during the system operation. Fig. 16 shows that the generator was generally able to develop a voltage adequate for the operation of usually domestic appliances. For the earlier periods of the operations, a mean maximum voltage of 240 V was attained for all the nozzle diameters. This corresponds to the higher values of the generator shaft speed discussed in the previous section. Hence, the system can be adopted for general domestic applications [60-62]. However, contrary to the flow of the results before now, the 0.0508 and 0.0254 m diameter nozzles developed higher voltages during the 2nd half of the operations. The apparent aberration is with the 0.0508 m diameter nozzle because the performance of the 0.0254 m has been fairly consistent. The aberration could have stemmed from some slight cumulative errors in data capture. However, the location of the curves for the 0.0508 and 0.0381 m diameter nozzles between the 2 others has been very consistent both for the no-load and on-load tests. Fig. 17 shows that the measured current presented a better insight into the system's operation. This is indicated by the chemistry of all the values for all the nozzles, with the 2 smaller ones producing higher values for the later periods of the operations. The locations of the curves for the 0.0508 and 0.0254 m nozzles were more consistent with the line of discussion so far.

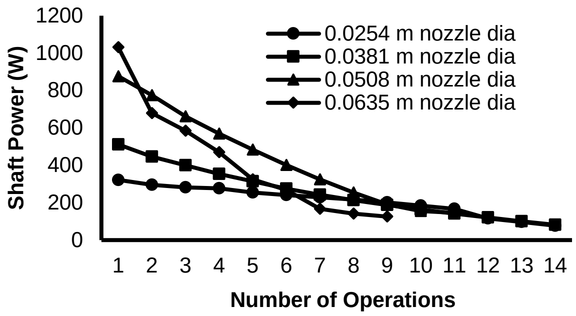


Fig. 9. Variation of shaft power with number of operations

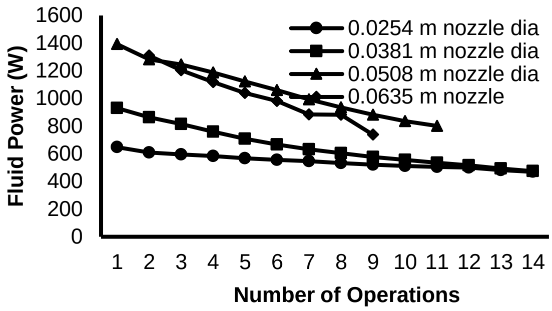


Fig. 10. Variation of fluid power with number of operations

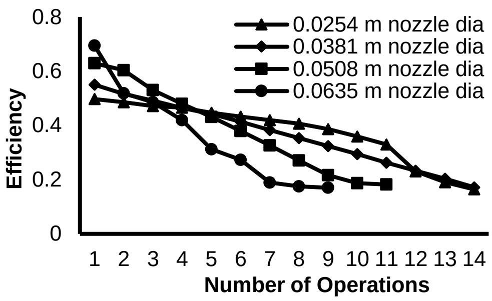


Fig. 11. Variation of system efficiency with number of operations

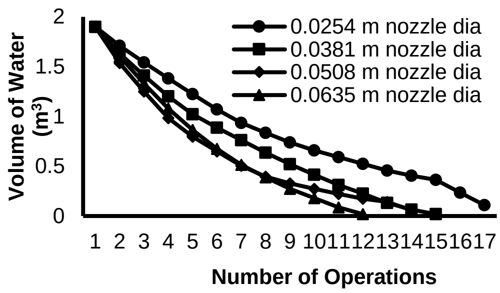


Fig. 12. Variation of volume of water with number of operations

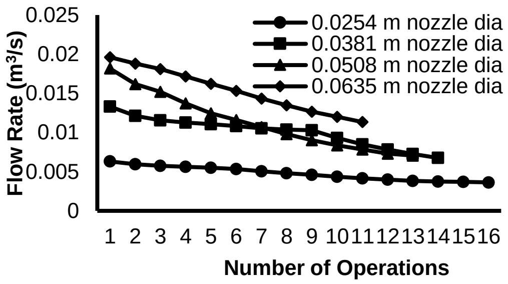


Fig. 13. Variation of flow rate with number of operations

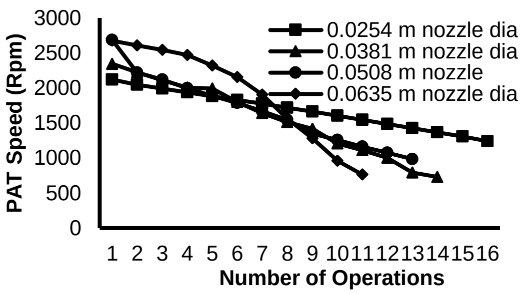


Fig. 14. Variation of PAT speed with number of operations

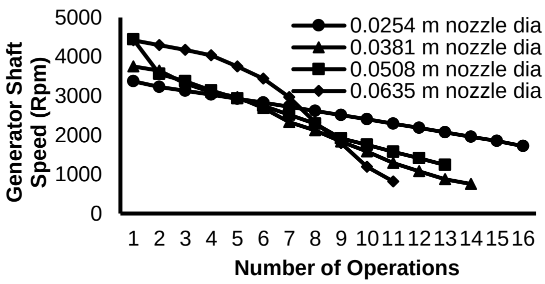


Fig. 15. Variation of generator shaft speed with number of operations

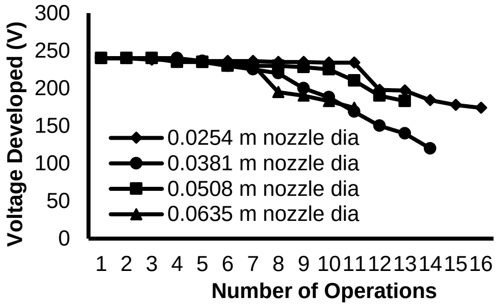


Fig. 16. Variation of voltage developed with number of operations

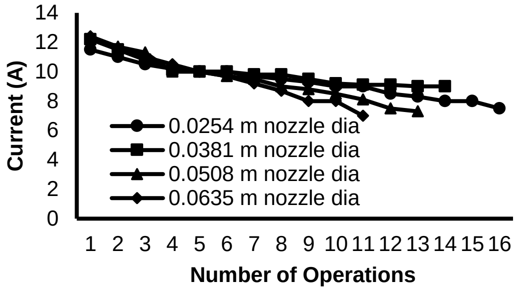


Fig. 17. Variation of current with number of operations

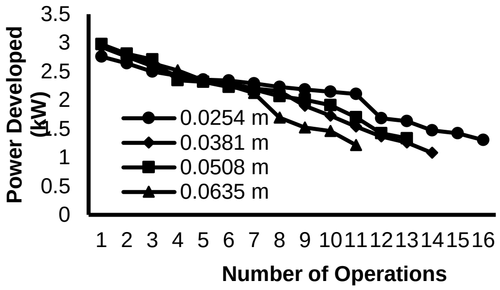


Fig. 18. Variation of the power developed with number of operations

Fig. 18 shows the variation of the power developed by the system during operation with the various nozzles. The figure indicates a clustering of the curves for the power developed between 2 and 3 kW for most part of the operations, with the larger nozzles dominating initially and the smaller ones taking over during the later stages. Also, the highest power developed for each nozzle diameter (2.976, 2.976, 2.928 and 2.760 kW respectively) corresponded to the highest values of the respective flow rates. This is generally consistent with the results discussed earlier [43,63]. On the whole, the system was able to develop on the average the power commensurate with the maximum rating of the generator used for the study, with minimal loses. This suggests that the power developed can be further extended if a larger capacity generator is employed [25].

The power consumed by 1.5 Hp surface pump used for recycling the water is approximately equal to 1.115 kW. The maximum and minimum power generated during the on-load tests for all the nozzle sizes were slightly above 2.9 kW and 2.7 kW respectively. The difference indicate a reasonable available balance after compensating for the power consumed by the pump. This confirms the suggestions made in previous studies on other aspects of this system that it suits a combination with other sources such as solar PV in hybrid arrangements [6,64,65].

The voltage developed was statistically significant for both nozzle diameters and volume change. This indicates that the two factors play a vital role in ensuring that the generator operates well in terms of producing the required voltage. The level of variations were similar suggesting fairly equal relevance of these parameters to the voltage developed. The current however, varied significantly only with the nozzle diameters, the change in water volume not showing any significant effect on the current flowing through the load. This indicates no direct contribution of the volume of water to the current flowing through the load. The electrical power varied more significantly with the nozzle diameters, affirming the critical role of the choice of nozzle size on the system performance [3,47]. The change in water volume also marginally contributed but the level of variation as indicated by the analysis was lower than the case for the nozzle diameters.

Figs. 19(a) to (d) show the variation of the voltage developed with the generator shaft speed for the different nozzle diameters. This is a usual characteristic of power generating systems. For all the nozzle diameters, the curves were quadratic with R^2 values greater than 0.85. They generally resemble curves obtained for generating units applied in hydropower deployment [66-70]. However, the curves for the 0.0508 m nozzle diameter had the least R^2 value.

This could be traced to the possible error in measurement alluded to earlier on. These curves can be utilized in selecting appropriate generators for specific implementation of this system.

Figs. 20(a) to (d) show the variation of the power developed with the flow rate-head product for the respective nozzle diameters. This relationship is useful for studying the performance of conventional hydropower systems since it shows the relationship between the power developed and the product of the 2 pre-dominant factors necessary for selecting sites (or setups) for hydropower implementation. The figures can be used to estimate the potential power that can be expected from a system with these set of equipment (PAT and generator) if the flow rate and the head (height of the overhead reservoir) can be specified [68,70].

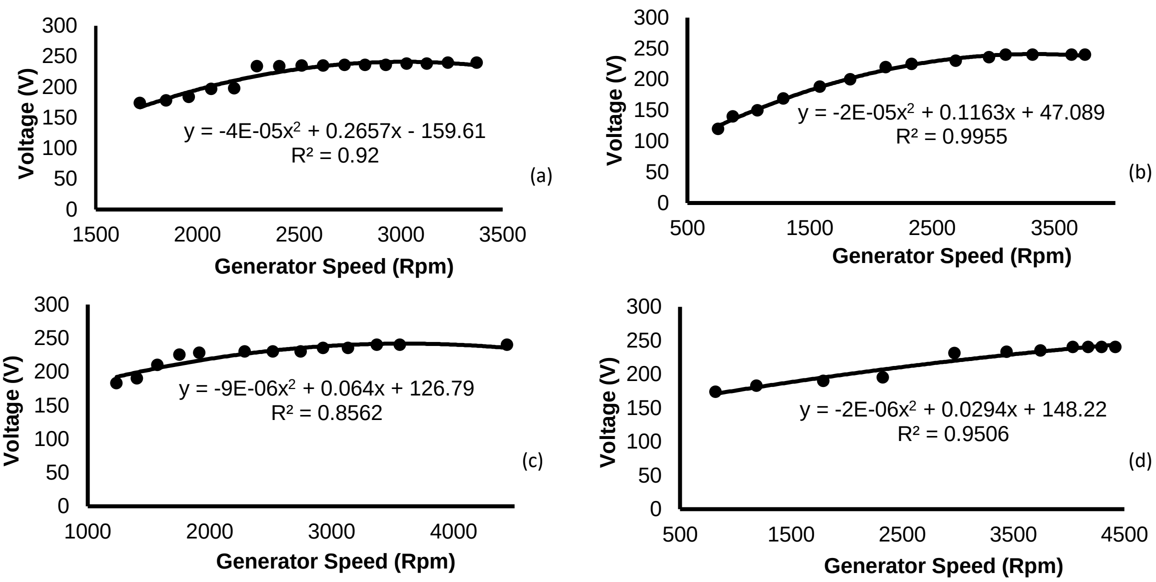


Fig. 19. Variation of Voltage developed with the generator speed for the (a) 0.0254 m, (b) 0.0381 m, (c) 0.0508 m and 0.0635 m diameter nozzles

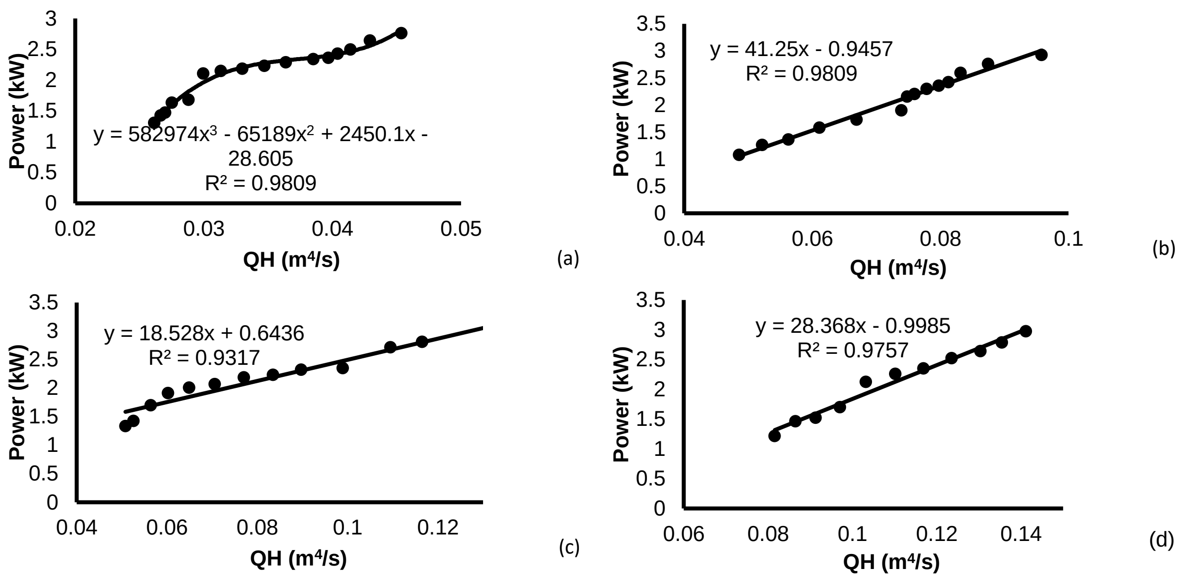


Fig. 20. Variation of power developed with the flow rate – head product for the (a) 0.0254 m, (b) 0.0381 m, (c) 0.0508 m and (d) 0.0635 m diameter nozzles

The figures indicate that for 0.0254 m nozzle, the curve was a polynomial while those for the other 3 nozzles were linear. All of the curves had very high R^2 values ($R^2 > 0.9$), indicating very strong relationships. They will be quite useful for further development of the system either in terms of increased height, capacity of the overhead reservoir or larger diameter nozzles. The flow rate-head product varied significantly with both nozzle diameters and change in water volume, though like with the flow rate, it varied more significantly with water volume. This was however expected as the flow rate showed a similar variation as mentioned earlier in this section.

4. CONCLUSION AND RECOMMENDATIONS

A pump-as-turbine (PAT) was successfully implemented in a simplified Pico hydropower system with provision for water recycling in line with a recommendation from previous studies on the system using locally fabricated turbine options. The system performance further strengthens the flexibility of the system for utilization as a simple clean energy option. The maximum power produced by the system ($\cong 2.9\ kW$) which was limited by the generator used is an indication of the promising potentials of the system for end-user implementation. The power output can be upgraded by using a larger capacity generator, directly causing an increase in cost. This is a decision that must be arrived at in selecting as appropriate pump for implementation of the system. However, apart from using a higher capacity pump, other approaches that can improve the power generation status include hybridization and/or utilization of a higher elevation of or multiple overhead reservoirs and/or PATs.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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