



Application of an Inline Pico-Hydro Turbine in Water Distribution System for Energy Generation

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ABSTRACT

The occurrence of water hammer in water supply systems usually damages the pipeline, unless suitable devices are used to regulate the excessive pressure head. However, this effect of water hammer can be utilized by installing appropriate turbines in water transmission pipeline. Hence, these study focuses on prototypes development of pico-hydro turbine for energy generation along a water distribution networks, which have the ability of converting the potential energy of the flowing water in pipes to an electrical power at the lower end of the inter connected pipes. To achieve this, the pico-turbine was designed and fabricated, and the generator was selected. Afterwards, the turbine was tested through measurements of water heads and flow rate as well as power estimation. It was found that at a maximum water head of 30cm, the turbine generated a power of 0.92 watts, with maximum value of current and voltage of 0.344mA and 2.66V respectively. It has an overall performance of 88%. Further investigation are required on increasing the capacity and integrating a rechargeable battery within the pico-turbine systems.

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INTRODUCTION

The term Pico-hydro comes from the word Pico which means very small and hydro refers to as water. Thus, Pico-hydro refers to as electrical energy that comes from the force of moving water which can used to power equipment. Also, it can generate a maximum electrical output from few hundreds watts up to five kilowatts (Zainuddin *et al.*, 2009). The amount of electricity generated depends on head and volume of falling water on the turbine (Ptolemaeus, 2014).

Hydro power system of "Pico" size benefits in terms of cost and simplicity from different approaches in the design, planning and installation than those which are applied

to large hydro power. On a global scale, a very substantial market exists for Pico hydro system (Cobb & Sharp, 2013).

The applications of large up to Pico Hydro systems have been well demonstrated by several authors. For example Pérez-Sánchez *et al.* (2017) have investigated the hydraulic energy production in drinking and irrigation water distributions from small to large hydropower systems, the types of machinery installed, economic and environmental implications were analyzed. However, their evaluation of hydropower system emphasized on existing review of literature.



Also, Kucukali (2011) carried out a case study of water supply distributions, in order to utilize the excess pressure that is usually dissipated using pressure reduction tank, to generate energy. To achieve this, the excess pressure was eliminated from the water distribution by installing a hydro-turbine, which then converted the excess energy of water into electricity.

Similarly, Soffia *et al.* (2010), studied energy generation using micro-hydro plants (MHPs) installed on water supply distributions in a region in Italy, which convert the potential energy of the drinking water through the pipes by utilizing a certain head into hydropower at a lower end of the region. They were able to successfully evaluate the potential and economic feasibility of the MHPs using standard methodologies such as GIS - Geographical Information System. However, it was recommended that a further assessment of the hydropower potential is required in other mountainous areas of different elevations. Singh *et al.* (2009), designed, fabricated and tested a five blade propeller turbine that gave 810 Watts output at 73.9% hydraulic efficiency while operating at 900 rpm under a head of 1.75 m and flow rate of 0.064 m³/s. Maher *et al.* (2003) carried a comparative study of pico hydro systems and solar photovoltaic systems in Kenya and established that the former was more cost effective on a per-household basis with a 15% lower cost per kWh.

Titus and Ayalur (2019) developed a hydro turbine that could be installed in an existing pipeline system to generate electricity. The turbine was designed in such a way that it could be installed in-line with the pipes. The turbine was installed at the outlet of an overhead tank, so that the energy from the flowing high-pressure water could be adequately utilized for power generation. An overhead tank with a head of 14 meter and a discharge of 9 liter per second and stores sewage treated water had a hydro turbine installed. They observed that with a flow of

8litres per second, maximum output of 212 watts were obtained from the turbine.

Similarly, Erinle *et al.* (2020) In their study developed a micro water turbine that could be used in an existing water distribution pipeline to produce electricity using water storage overhead reservoir tank as a source of water couple with generators. Their study revealed that the turbine produces a runner rotation range of 5 rpm to 100 rpm with an available torque of 3350 Nm. The water turbine could generate a power up to 35 kW. The turbine energy produced is clean and free of global warming tendencies.

The need for electric power supply in developing countries cannot be over emphasized. Most developing countries are associated with national power grid that are insufficient in terms of power production and not effectively distributed, therefore, there is urgent need for the development and design for alternate sources of power supply that can be locally harnessed (Erinle *et al.*, 2020).

Moreover, from the foregoing discussion, in a water supply system, water hammer (excessive pressure head) has been always considered as one of the main problems that lead to pipeline failure. Numerous devices, like pressure relief valves or pressure reduction tank, are usually installed in the water systems to regulate the overhead. However, the dissipated energy can be utilized by installing appropriate mini, micro, or small turbines in the water transmission pipeline. In this regards, the idea and possibility of generating electricity by integrating micro-hydro plants into water distribution systems of interconnected pipes with flowing water becomes possible. The potential energy of the water flowing in pipes can be converted into electric power at the lower end of the pipes.

Thus, the main objective of the present study is to design and construct an inline turbine unit which can be rapidly and easily installed into a pipeline to provide energy for use on site to power various devices

located within close proximity of the turbine unit e.g. meters, sensors, sump pumps and lighting which can be applied in remote areas to produce a certain amount of power

Theoretical Background

The theoretical power (P_{th}) in kilowatts (KW) available from falling water can be calculated using established relationships of Arora (2001) as follows:

$$P_{TH} = \frac{wQH}{1000} \quad (1)$$

Where, w = Weight density of water in N/m^3 ,
 Q = flow through turbine (or quantity of water available for hydropower generation) in m^3/s ,
 and H = Head available in meters (m).

The actual or effective output depends upon the efficiency of the various part of the installation.

Since the turbine and the generator are directly coupled on common shaft the hydro-electrical power available will be expressed as follows:

$$P_{actual} = \frac{wQH}{1000} \times \eta_o \quad (2)$$

where overall efficiency is given as η_o .

MATERIALS AND METHODS

Materials

For an appropriate design and construction of the inline Pico hydro generation system the following under listed materials or tools were used in the fabrication process that include galvanized iron pipe, sheet of metal, water tank (a reservoir), electric wire, load (D.C bulb), dynamo (6V D.C generator), body filler, digital multi-meter, PVC ball valve and hose pipe. These have been illustrated in Figure 1.

Methods

The process followed in designing and constructing the Pico hydropower generating system is shown in Figure 2. The procedure includes design, construction work, selection of the turbine and generator, head measurement, water flow rate measurement and power estimation.



Figure 1: Materials and equipments used in the design and construction of the pico hydro system.

Turbine

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} \quad (5)$$

Where, N_s = Specific speed of turbine in revolutions per minute (rpm); N = Rated speed of turbine in revolution per minute; P = Turbine output in kW, and H = Rated head in m. Once the specific speed (N_s) is determined,

the chart given in Figure 3 may be used to determine the type of turbine (small, medium, or large size) that may be adopted for the particular design.

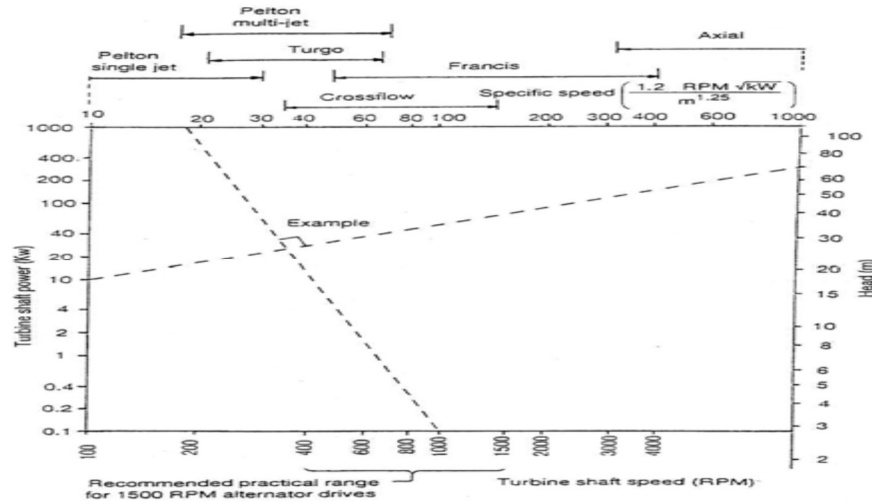


Figure 3: Monogram for selection of a turbine for a hydropower system.

Selection of Generator

For this design, a brush permanent magnet DC generator is preferred as the main function of the proposed Pico-hydro system is for energy storage (battery charging). This is because the permanent magnet DC generator has advantage over AC generator, due to the fact that DC generator is designed to provide high currents at minimum voltage requirement for the charging of battery and operation of direct current loads. Moreover, the DC generator is much cheaper and has smaller overall size, hence it is more efficient, with negligible loss in power to generate the magnetic field (Rajput, 2006).

Head and Flow Rate Measurements

There are many methods of head measurement. However, the Pico hydropower system is expected to use domestic water supply, as such a water tank (bucket) was used with a storage capacity of 20 L and it was placed at a height of 0.4 m from the ground, and the net head available to the turbine was measured as 20 feet. Measurement of head was performed by measuring height between the top of the floor of the installed 20 L tank and the point where the water hits the pelton turbine blades. According to Arora (2001), Gross head (H_T) = net head (H) + head loss (h_L) where $H_T = H - h_L$

But, Rajput and Company Ltd. (2004) expresses head loss, $h_L = \frac{4FLV^2}{2gD}$

Where, F = the frictional factor.

$$F = 0.0055 \left[1 + \left(\frac{20000K}{D} + \frac{10^6}{Re} \right) \right]$$

where L = the length of the pipe (m), V = the velocity of the flowing water (m/s),
 g = the acceleration due the gravity (m/s^2) and d = the diameter of the pipe (i.e. the nozzles)
 Reynolds number is: $Re = \frac{vd}{\nu}$, $\nu = \frac{4Q}{\pi d^2}$ the diameter of the pipe is 3.4cm hence, velocity = 0.264m/s

$Re = 7747.9 \approx 7748$ taken the kinematic viscosity of water as 1.16×10^{-6} . Hence, it is a turbulent flow Frictional factor (F) was determined according to Marriott (2016),

$$F = [1 + (\frac{20000}{D} + \frac{10^6}{Re})^{1/3}]$$

$F = 0.035$ assuming the coefficient of pVC-pipe material (k) = 0.03m and $h_f = 0.0058m$

Since the length of the pipe considered = 39.7cm. Therefore, the effective/net head (H_m) is determine as $H_m = 0.444m$

Power Estimation

In general, the feasibility of the constructed Pico hydropower system was based on following potential input/output power equation according to Arora (2001).

$$P_{in} = H \times Q \times \rho g$$

$$P_{out} = H \times Q \times \rho g \times \eta$$

Where,

P_{in} = input power (Hydropower), P_{out} = output power (Generator output), H =Head (m), Q =Water flow rate (m^3/s), G = Acceleration due to gravity ($9.81 m/s^2$) and η = Efficiency. Input power was determined as $P_{input} = 1.05$ watts.

The power output is calculated using the voltage (V) and current (I) obtained from the digital meter when the water is flowing with the height of water equal to maximum height (I.e. 30cm). The current and voltage at a height of 30cm were determined to be 0.344 mA and 2.66 V respectively. Hence, $P_{output} = 0.92$ watts.

And the efficiency of the Pico hydropower was determined by taking the ratio of the power input to power output then multiply 100. Therefore, the efficiency of the Pico hydro turbine system is 88%.

DESIGN AND CONSTRUCTION WORK

Design of the blade (Pelton wheel)

The blade is constructed from a metallic sheet plate of approximately 1mm thickness. The blade was made to be a 4 cups turbine blade with each blade placed at right angle to each other. A plastic material was used as an additional component of the blade which serves as a bucket in order to widen the width of the blade and to help in accumulating a very large quantity of water that would easily facilitate the blade to derive the generator smoothly. A small round plastic wheel is also fixed (embedded) at the center of the blade which was held firmly using a body filler paste. The components used in the construction of the turbine are shown in figure 4 below.

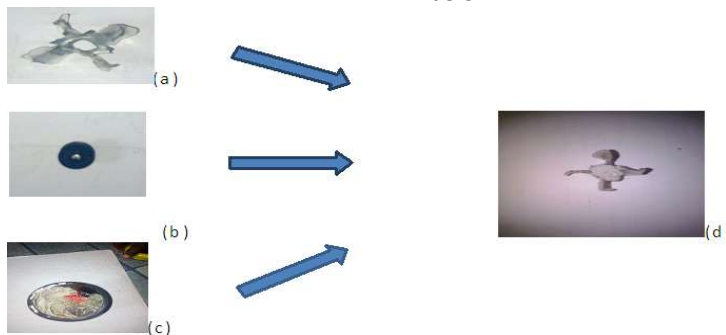


Figure 4: components used in the turbine construction

(a) Constructed blade without small narrow plastic (b) A narrow plastic wheel (c) Body filler (d) Constructed turbine blade

The various views of the constructed turbine blade (i.e. the front and the side view) in two dimensional (2D) are given in figure 5 below.

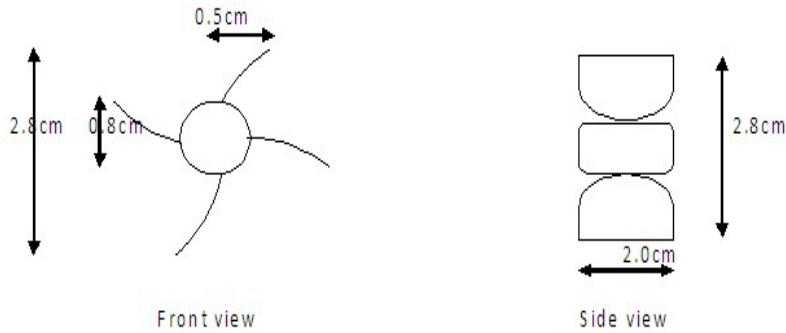


Figure 5: the front and side views of the Constructed turbine blade

The various dimension of the turbine blade from the fig. 5 above are;
 $B = 2.8\text{cm}$ $d = 0.8\text{cm}$ $L = 2.0\text{cm}$ $D = 2.8\text{cm}$ $T = 0.6\text{cm}$

Where, B = width of the pelton wheel, d = diameter of the jet (or the nozzle), T = tangential length of the bucket, D = mean diameter or pitch diameter of the pelton wheel, L = the width of the bucket, In the design aspect of the pelton wheel, the following points need to be considered according to (Rajput & Company Ltd., 2004).

i. The velocity of the jet:

The velocity of the jet is given by; $V_1 = C_v \sqrt{2gH}$
 Where, C_v = Coefficient of velocity (=0.98 or 0.99), H = Net head on turbine
 $V = 2.88\text{m/s}$

ii. The velocity of the wheel

The velocity of the wheel (u) is given by; $u = k_u \sqrt{2gH}$
 Where, k_u = speed ratio, it varies from 0.43 to 0.48
 $u = 1.26\text{m/s}$

iii. Angle of deflection of the jet

In this design the blade is considered to be plane i.e. having an angle deflection of 180° .

iv. Specific speed (N_s)

Rated speed of the generator (N) is given by; $N = \frac{60u}{\pi D}$ D = nozzle diameter
 $N = 3008\text{rpm}$

And the specific speed (N_s) is given by

$$N_s = \frac{N \sqrt{P_{out}}}{H^{5/4}}, \quad N_s = 178\text{rpm}$$

v. Jet ratio (m)



This is defined as the ratio of the pitch diameter (D) of the pelton wheel to the diameter of the jet (d). It is denoted by 'm' and is given as; $m = \frac{D}{d}$ (lies between 11 and 16 for maximum hydraulic efficiency)

Normally, the jet ratio is adopted as 12 in practice.

vi. Bucket dimension

Some of the main dimensions of the bucket of a pelton wheel are as follows:

$$\frac{B}{d} = 3 \text{ to } 4; \quad \frac{L}{d} = 2 \text{ to } 3; \quad \frac{D}{d} = 11 \text{ to } 16; \quad \frac{T}{d} = 0.8 \text{ to } 1.2$$

From the dimensions given above in fig. 5, the respective ratios are determined as follows in Table 1 below

Table 1: Computation of bucket dimension ratios to be considered in the design

S/No.	Ratio	Remark (comment)
1.	$\frac{L}{d} = \frac{2.8}{0.8} = 2.5$	This satisfies the condition because it lies between 2 to 3 (i.e. the limit).
2.	$\frac{B}{d} = \frac{2.8}{0.8} = 3.5$	This also satisfies the condition because it lies between 3 to 4 (i.e. the limit).
3.	$\frac{D}{d} = \frac{2.8}{0.8} = 3.5$	The ratio doesn't lie in between the 11 to 16, Hence some modifications are required.
4.	$\frac{T}{d} = \frac{0.6}{0.8} = 0.75$	It satisfies the condition, because it is approximately equal to 0.8. thus, lies between 0.8 to 1.2

Number of bucket (Z)

The number of buckets for a pelton wheel should be such that the jet is always completely intercepted by the bucket so that volumetric efficiency of the turbine is very close to unity (Rajput & Company Ltd., 2004). Number of buckets on a runner is given by, $Z = 15 + \frac{D}{2d} = 15 + 0.5 = 15.5$ m

Design of the Penstock

The penstock was constructed to have a combination of a galvanized iron pipe, hose pipe and a ball valve with a diameter of 3.4 cm, 3.2 cm and 2.5 cm respectively connected together to convey water from the reservoir tank to the blade. The

galvanized iron pipe was cutted into two pieces 8 cm and 9.5 cm length respectively, which serve as the inlet and outlet pipe to the blade. A hose pipe of 41.5 cm total length is also divided into 13.0 cm and 28.5 cm in order to fit the ball valve in between the two hose pipe to control the flow of water as it leaves the tank. A narrow pipe made from a relatively small thickness sheet of metals that gradually reduces in cross-sectional area was imbedded into the inlet pipe to converge the flowing water to hit the blade with a great pressure (Rajput & Company Ltd., 2004). The various material used in the construction of the penstock is shown in the figure 6 below.

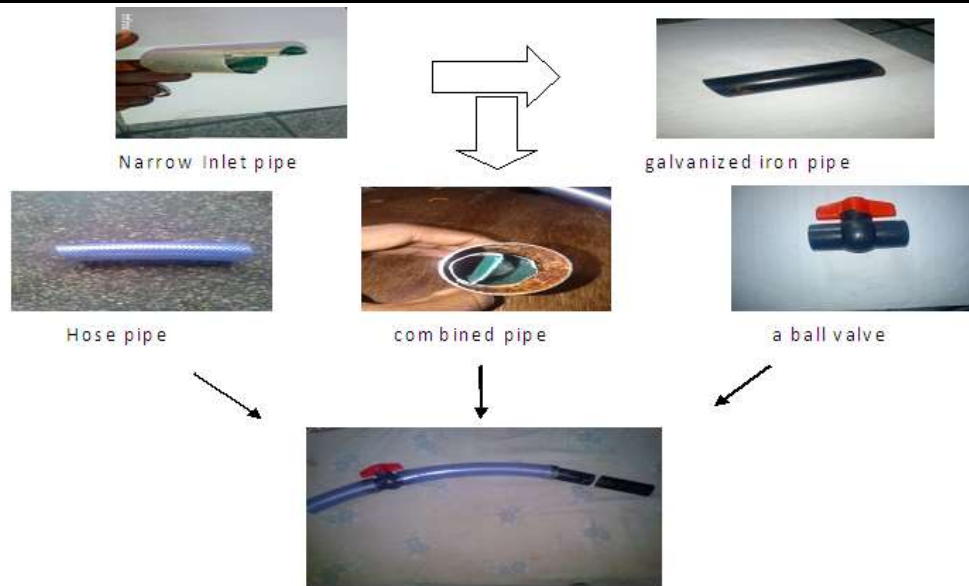


Figure 6: components of the penstock

Installation of the Generator

The outlet let pipe (galvanized iron) was drilled to have a hole of 0.2 cm in diameter on the mid axis of the pipe which is approximately 0.5 cm from the entrance region to the position of the turbine blade which serves as a provision for the installation of the generator. The hole is surrounded or enclosed by a welded

galvanized iron pipe of the same size as the outlet pipe, the generator was inserted into the hole while the blade was firmly connected to the generator inside the pipe. A body filler additive was also used to enhance the generator from being held firmly in its position (Rajput, 2006). The figure 7 below shows the positioning of the generator and the blade inside the pipe.



(a) Side view of the generator position



(b) plan view of the generator position

Figure 7: The side and plan view of the generator position

Assembling the Components of the System

The whole Pico hydropower system comprises of the water tank, the penstock,

the generator together with the blade and the load which are arranged in such a way that the water from the tank flows into the

penstock using the potential energy in the water due to the configuration (difference in height) to drive the turbine blade that led to the rotation of the shaft in a magnetic field

inside the generator to produce electric current. The figure 8 below shows the assemblage of the whole components of the Pico hydropower system.



(a) The right side (showing the calibration of water) (b) the left side showing the generator

Figure 8: The two various side of the whole assemblage of the system

RESULTS AND DISCUSSION

The results of series of experiments/observations carried out, quantitative analysis and the summary of the results obtained from the combined analysis at different conditions for various parameters accounted for generation of power by the Pico hydropower system. Hence, the relationship

between the various parameters (Current, Voltage, Diameter and RPM) at different condition is being produced. Table 2 below shows the values of Current, Voltage, Diameter and rpm obtained at 22 cm height of water. While Tables 3 – 4 show the variations of current and voltage due to changes in water height and / or discharge.

Table 2: Values of Current, Voltage, Diameter and rpm at 22cm water height.

Tap Diameter (mm)	Specific speed (rpm)	Voltage (V)	Current (mA)
$\frac{1}{4}$ of 34 = 8.5	178	1.9	256
$\frac{1}{2}$ of 34 = 17.0	150	1.6	230
$\frac{3}{4}$ of 34 = 25.5	120	1.2	208
$\frac{1}{1}$ of 34 = 34.0	82	0.7	160

Table 3: Values of Current and Voltage at different height of water

Height/Level of water (cm)	Current (mA)	Voltage (V)
30	0.344	2.66
22	0.256	1.90
20	0.234	1.73
18	0.220	1.62
16	0.205	1.33
14	0.196	1.19
12	0.182	0.98
10	0.145	0.74
08	0.125	0.63
06	0.089	0.57
04	0.067	0.28
02	0.000	0.00
00	0.000	0.00

Table 4: Values of current and voltage at variable heights of water and discharges

Discharge (L/s)	Height of water (cm)	Current (mA)	Voltage(V)
0.24	30	0.340	2.62
0.22	27	0.335	2.52
0.21	24	0.310	2.43
0.18	21	0.250	2.10
0.16	18	0.232	1.86
0.14	15	0.215	1.38
0.13	12	0.189	1.21
0.11	09	0.167	1.15
0.10	04	0.107	1.03

The figures represented in Figures 9 - 16 below shows the various graphs plotted that were obtained from the values of the results in Tables 2 - 4, respectively.

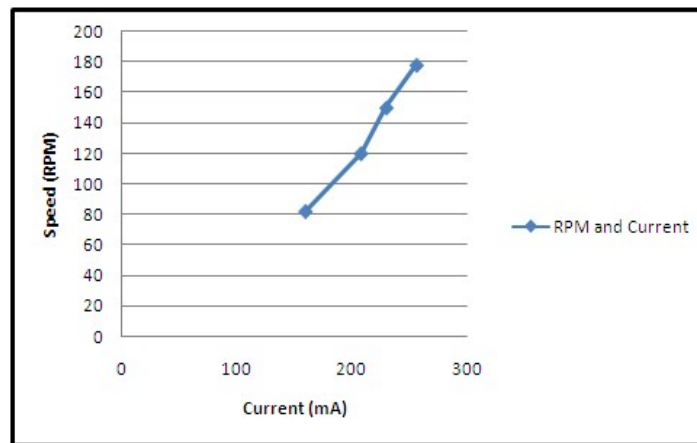


Figure 9: Graph between speed and Current

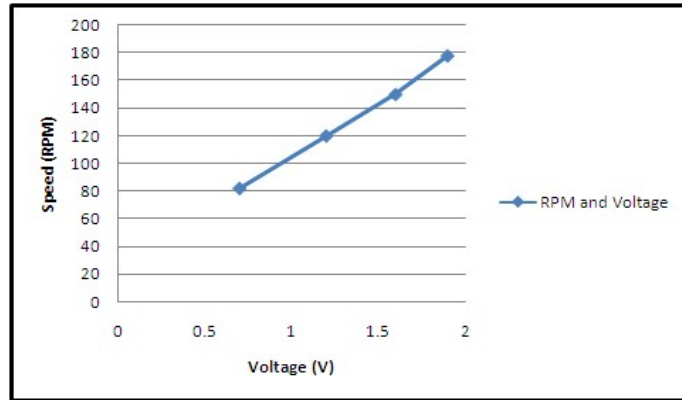


Figure 10: Graph between RPM and voltage

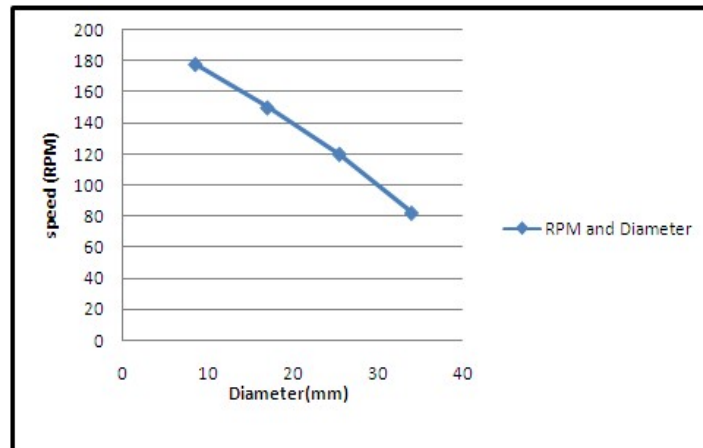


Figure 11: Graph between RPM and Diameter

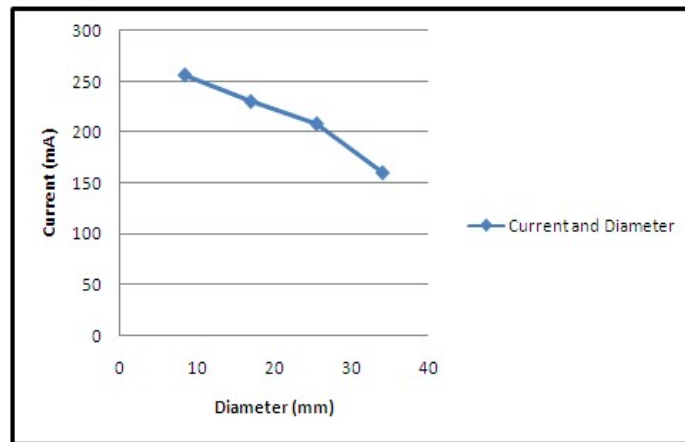


Figure 12: Current against Diameter

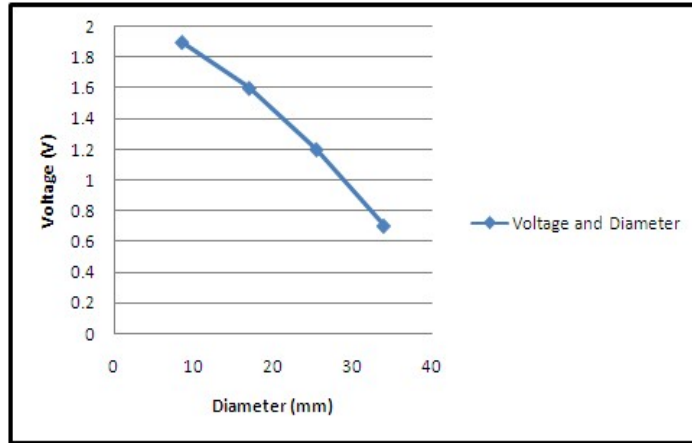


Figure 13: Voltage against Diameter

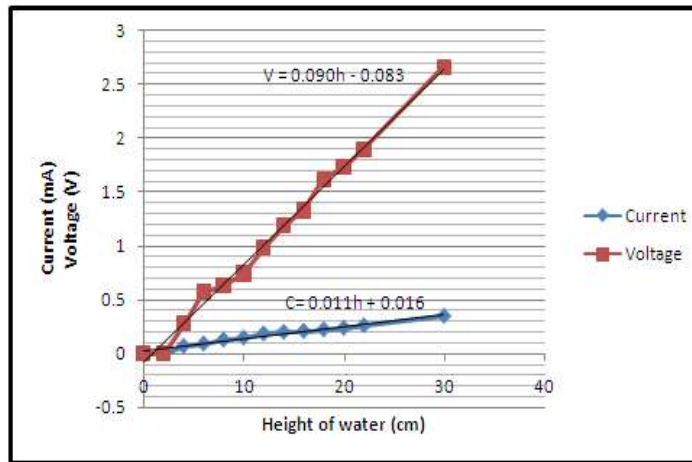


Figure 14: Height of water against Current and Voltage

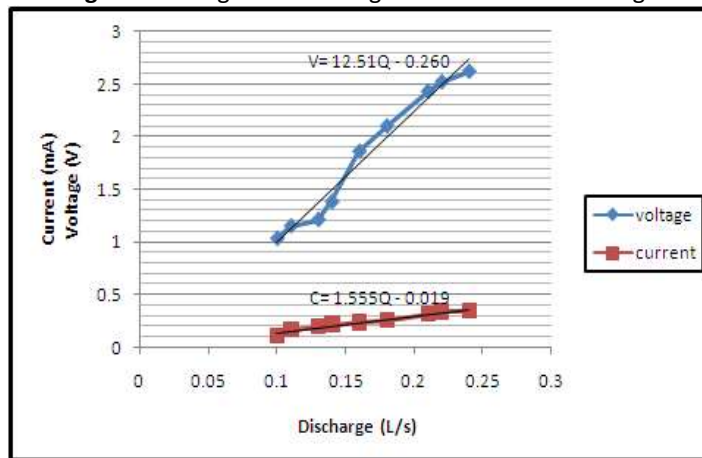


Figure 15: Discharge against Current and Voltage

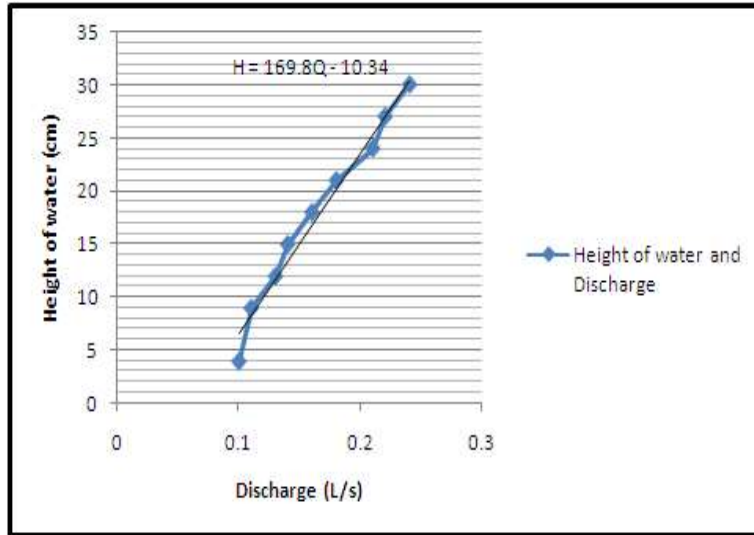


Figure 16: Height of water against Discharge

The graphs of the paired parameters plotted are: graph of speed against current, speed against voltage, speed against diameter, current against diameter and voltage against diameter. Thus, in each of the graphs, the nature of the adjoining plotted points on the graph merely indicates the kind of the relationship between the two parameters. The analysis of the parameters on the graphs are as follows:

From the graphs obtained in figure 9 and figure 12 above, it obviously seen that the current increases when the speed (rpm) increases and decreases when the diameter of the tap decreases respectively. From the graphs obtained in figure 10 and figure 13 above, it is shown that the voltage increases as the speed (rpm) increases and decreases when the diameter of the pipe increases respectively. From the graphs obtained in figure 9, figure 10 and figure 11, it is shown that the speed (rpm) increases when the current and voltage increases and decreases as the diameter of the tap increases respectively.

And

$$V = 0.090h - 0.083 \text{ --- (6)}$$

$$C = 0.011h + 0.016 \text{ --- (7)}$$

On the other hand, figure 14 shows the graph of Height of water against Current and Voltage, which linearly shows that the Current and Voltage values decreases as the level of water in the water tank decreases. Hence, both the graphs show a linear relationship. At some certain Height of water comes some values which shows limitation of generating power output i.e. the minimum and maximum values corresponding to the minimum and maximum Height of water. The corresponding values at minimum and maximum height of water are as follows:

At a maximum height of water equals 30 cm, the maximum current and voltage values are 0.344 mA and 2.66 V respectively. And at a minimum height of water equals 4 cm, the minimum current and voltage values are 0.067 mA and 0.28 V respectively.

The empirical equations generated for both current and voltage computations at any given height of water are;



Where V = Voltage (V), C = Current (mA) and H = Height of water (cm)

The graph plotted for Discharge of water through the nozzle against the values of current and voltage in Figure 15 shows that the values of current and voltage increases as

the discharge of water through the nozzle increases. The generated formulas for computation of current and voltage for various discharges is given as:

$$V = 12.51Q - 0.260 \text{ --- (8)}$$

And

$$C = 1.555Q - 0.019 \text{ --- (9)}$$

Where V = Voltage (V), C = current (mA) and Q = discharge (L/s)

And also from the graph of Height of water (m) against the Discharge of water through the nozzle obtained in figure 16: shows that the discharge of water decreases

as the height of water decreases. Hence, it shows a linear relationship.

The generated formula for the computation of discharge of water through the nozzle at a certain height of water is given as:

$$H = 169.8Q - 10.34 \text{ --- (10)}$$

CONCLUSION

The power generated by the Pico hydro system was obtained to be **0.92 Watts**. With the maximum values of current, voltage and RPM are **0.344 mA**, **2.66 V** and **200 rpm** respectively. The system has a very high performance with an efficiency of **88%**. From these results analysis it was observed that the current, voltage and speed (rpm) are inversely proportional to the diameter of the tap and directly proportional to the Head. Since the turbine and generator are manufacture locally, the selection of turbine and generator in terms of their type and size or capacity is also important in designing and constructing the Pico hydro system. Thus, wrong type and improper sizing of these components would cause the system to operate at undesirable performance. Further studies need to be conducted on integrating the Pico hydropower system with a rechargeable battery as an additional component to the system, so that, the excess power could be stored for loads and devices. Also, it can be used to power different types of load when power supply from the grid is insufficient.

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