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RESEARCH ARTICLE

Design of an Experimental Plug-Flow Helical Hydrokinetic Turbine for Power Generation in Kenya

[1]Clement N. Maiko
[2]Thomas F.N. Thoruwa
[3]J. Githiri

[1]Institute of Energy and Environmental Technology, Jomo Kenyatta University of Agriculture and Technology, Kenya
[2]Pwani University, Kenya, School of Pure and Applied Sciences
[3]Department of Physics, Jomo Kenyatta University of Agriculture and Technology, Kenya

Corresponding author:
Clement N. Maiko
clementxyzmaiko@gmail.com

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ABSTRACT

Micro-hydro power generation system is the most reliable form of clean source of sustainable renewable energy. It is an excellent method of harnessing renewable energy from untapped small rivers streams with low head especially in Kenya and other developing countries. In this study, an experimental micro-hydro a plug-flow helical hydro-kinetic turbine power generation system was mounted on a low head small river stream without storage reservoir in order to power the turbine. The water flowed straight through the turbine and discharged back into the river without causing environmental impact on the local ecosystem. The turbine described herein was designed and constructed using locally available materials with output of 50W operating at an average river flow of 1.2m/s. Much emphasis was placed on the selection of the aero foil and in particular NASA0018 was chosen as the best option. It was observed that the turbine self-started at 0.58m/s and generated 4.5W at 0.73m/s river flow speed with peak power coefficient of Cp =0.14 and a TSR=1.26. The cost of developing this project was about Ksh 22,000.00 or (USD220/=) with payback period of 5.7 years. It was concluded that a simple small hydro-kinetic turbine has potential to provide access to electrical power and water pumping for irrigation in marginalized areas of Kenya and other developing countries. Therefore an improvement of the turbine into economic viability is recommended for future advancement

Keywords- : *Hydrokinetic Turbine, Helical, Plug-flow, Low heads, Flow velocity, Performance.*

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INTRODUCTION

Electricity is a vital element for human development, yet 1.2 billion people have no access to it at all (IEA, 2010). In Kenya, most people live in rural areas, and only about 10% have access to electricity (Kamau *et al*, 2010). Kenya is highly dependent on hydropower for electricity generation (approximately 60%), but the unreliability of the water resource poses a problem (World Energy Council, 2013). Renewable energy sources are the world's fastest growing energy source (with an estimated annual growth rate of 15% by 2035) and will play a key role in meeting future energy demands (Gruenspecht, 2011). Hydropower is considered as the renewable energy source with the highest potential in this respect, both in industrialized and developing countries worldwide. The contribution of hydropower to decarbonizing the energy mix is twofold: the primary benefit is its clean, renewable electricity and also the benefit of being an enabler to greater contribution of other renewable on the grid. Other benefits from hydro include water supply, flood and drought control, irrigation. Literature review shows that available unexploited capacity of power from small hydro power systems in Kenya is substantially about 3000 MW according National Energy Policy Draft (MOE, 2013). Therefore, it is necessary to exploit these rivers with small heads using hydrokinetic helical turbine in order to bridge the gap between the ever growing demand and lack of enough power generation capacity in Kenya.

Literature review shows that, conventional hydropower stations require the use and construction of water storage dams which result to significant negative environmental impact reducing the water flow and affecting the wildlife habitat. This ecological impact may exceed the value of the generated electricity especially in small river streams. In order to harness power from small river streams in Kenya, a new approach has to be examined. One possible solution is to use low-head micro hydro installations, such as the Gorlov helical turbine [9]. In this research we developed a low head helical hydrokinetic water turbine coupled to a generator for power generation targeting rural areas with small river streams in Kenya. The turbine can also be utilized in urban areas especially in large sewer water pipelines for power generation. The turbine uses water currents on naturally flowing rivers for power generation [7]. Since water power is more predictable and can be gated and stored for later use, it is believed that hydrokinetic helical water turbine is the best method of extracting renewable energy compared to wind and solar. In this design of plug flow, the turbine was plugged into a stable metal frame structure and locked and once the gate is opened to some height the turbine starts to rotate until it attains the nominal speed at which power generation is realized. The orientation of helical hydrokinetic turbines can be either horizontal or vertical. In this design, we chose the vertical design due to its ability to admit the flow from any direction and also the costs related to generator installation and transmission of power are extremely reduced in this design.

1.1 Objectives

The goal of this research was to design a plug-in helical turbine for hydro electrical energy power generation. However, specific of the study were to:-

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a) Design and fabricate plug-in hydrokinetic turbine using locally available materials;
b) Test the performance and cost analysis of the fabricated turbine

2.0 METHODOLOGY

2.1 Selection of Helical Hydrokinetic Water Turbine

In this project, we chose helical turbine without energy storage because, it captures the kinetic energy of flowing water unlike the conventional turbines that rotate due to a fluid's high pressure head acting on the turbine's blades. Dams are constructed to produce a high-pressure head at the expense of a high potential energy. In particular Gorlov Helical Turbine design was chosen because its helical blade geometry allows the turbine's blades to always be at an optimal angle of attack to the incoming flow hence providing constant driving torque for the turbine and eliminating vibrations which are common in Darrieus turbines. Furthermore, the helical turbine has a maximum efficiency up to 35%, which is 42% more efficient than the typical marine turbine and 33% more efficient than the Darrieus turbine (Gorlov, 1998).

2.1.1 Power requirements:

The following simple equations were used to estimate turbine power for free (kinetic) and constrained potential water flows as function of water velocity and water head (SI units used). The water power comes from energy contained in the flowing water [10] and is given as:

The rate of mass (m) flow $\frac{dm}{dt} = \rho_{water} * AV_a$ (1)

While the kinetic power per unit time is given as:

$$P_{water} = 0.5\frac{dm}{dt} V^2 = 0.5(\rho_{water} * AV) V^2 = 0.5\rho_{water} AV^3 \text{ (W)} \quad (2)$$

$$\frac{dm}{dt} = \rho_{water} * AV_0 \quad (3)$$

$$\text{Tangential Velocity}_{o} = \omega R \quad (4)$$

The kinetic power per unit of time:

$$P_{water} = \frac{1}{2}\frac{dm}{dt} V^2 = 0.5\, \rho_w\, AV^3 \quad (5)$$

The swept area of the turbine was calculated as:

$$A = 2H_{turbine}R_{turbine} \quad (6)$$

2.3 Design procedure for hydrokinetic turbine

Several design parameters were considered during the design including the number of blades, Tip Speed Ratio (TSR), solidity ratio, angle of inclination (pitch angle), swept area and angle of attack among others. Other parameters considered were blade profile, helical pitch, Aspect Ratio, Chord to Radius Ratio, Blade Wrap and Attachment design.

2.3.1 Experimental Turbine Blade Profile:

Literature review shows that NACA 0018 is the most common symmetric blade profile that is recommended in wind and marine turbine design. The NACA 0018 blade profile has an advantage in terms of turbine's lift and drag characteristics which offers a medium between the improved performance of thinner blades and the durability and manufacturability of a thicker blade. The blade profile is well known and experimental results been published by Sandia National laboratories. The good self-start capability of the helical turbine reduces the need for a special cambered blade design to increase self-start. Therefore, in this project, we used three bladed Gorlov turbine design since a single blade turbine lacks balance unless it has a counter mass which adds on cost and also on the basis of literature review (Gorlov, 1998 and Bachant and. Wosnik. 2011). The TSR of 1.5 was

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used due to its ability to attain better C_t results [7], and in this project design NACA0018, with a ducted water helical turbine was utilized.

The Gorlov design was adopted in which the distribution of blade cross sectional area was done using odd number around the circumference of the horizontal plane of the cylinder. This was achieved through the blade's positions being determined by a helix between the total numbers of blades, completes one revolution of the circumference of the turbine, such that at any one time as the turbine rotates there is a blade cross section located and acting relative to the fluid flow at each position around the horizontal circle.

2.3.2 Sizing of the Turbine

In this experimental project we targeted to generate an output power of 50W using an average assumed fluid flow velocity of 1.2m/s and from which the rotor diameter was derived.

From equation 2 above the following calculations were developed.

$50W=0.5x1000 \text{ x } A \text{ x}1.2^3\text{x } 0.2$

$$A = \frac{50}{0.5x1000x1.2^3x0.2} \quad \textbf{(7)}$$

Giving Swept area, A = 2HR=0.2894 m^2

2HR=HD

A=HD, Aspect ratio =H/D and is assumed to be 1.3

Therefore H=1.3D

$A=HD=1.3DxD=1.3D^2$

Therefore, $A=0.2894 =1.3D^2$

$$D = \sqrt{\frac{0.2894}{1.3}}$$

D=0.472m,

H=0.6133m

(H=1.3D =1.3x0.472).

It was found out that this helical turbine design has the self-starting capability at very low water velocities with minimum monitoring gadgets. Torque reduction in a helical turbine leads to increase in power production, reduced vibrations and less cyclic stresses on the blades.

2.1.3 Tip Speed Ratio, (λ) and Aerofoil choice

The choice of a suitable aerofoil section can significantly improve both the peak performance and the starting characteristics of hydrokinetic water turbine. In this project, a (National Advisory Committee on Aeronautics) NACA 0018, the airfoil of ducted water helical turbine, at Re 14000, Tip Speed Ratio 1.5 was utilized because it attains better C_T result compared to NACA0020 (Bachat and Wosnik, 2013). An experimental investigation helical-flow axis hydrokinetic turbine, found out that the tip speed ratio lead to an increase in performance that was achieved along with an increase in minimum TSR.

2.1.4 Solidity Ratio

Solidity ratio **σ** is a concept referring to the amount of solidness of a turbine. Also solidity ratio defines the strength of the turbine visa-vise the flow. In this project solid ratio is defined as the number of blades n multiplied by chord length C by the turbine blade circumferential sweep. According to NACA 0018 the chord length is taken as 270mm. The solidity ratio wad determined as

$$\sigma = nC/\pi D \quad \textbf{(8)}$$

$$\sigma=(0.27x3)/(\pi x0.472)=0.546,$$

this is the solidity for the turbine.

2.4 Helical Pitch Angle

Helical pitch angle for a vertical axis turbine refers to the pitch angle that the blade makes with a horizontal plane. This is the angle at

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which the turbine blades is inclined as measured from the horizontal circular discs and is given as:

$$\varphi = \tan^{-1}(nH/\pi D) \qquad (9)$$

Therefore, $\tan^{-1}(3x0.6133)/(\pi x0.472)$; gives blade pitch angle $\varphi = 51.1^{0}$

The engineering drawing for the experimental helical turbine is presented in Figure 1 while the turbine characteristics are presented in table 1.

Table 1: Summary of experimental the helical turbine characteristics.

ITEM	SYMBOL	VALUE
No. of blades	N	3
Blade profile	NACA 0018	NACA 0018
Chord length (m)	C	0.116
Turbine diameter (m)	D	0.472
Turbine height (m)	H	0.6133
Angle of inclination, (deg)	Φ	51.13
Solidity	Σ	0.23
Aspect Ratio	AR	1.30

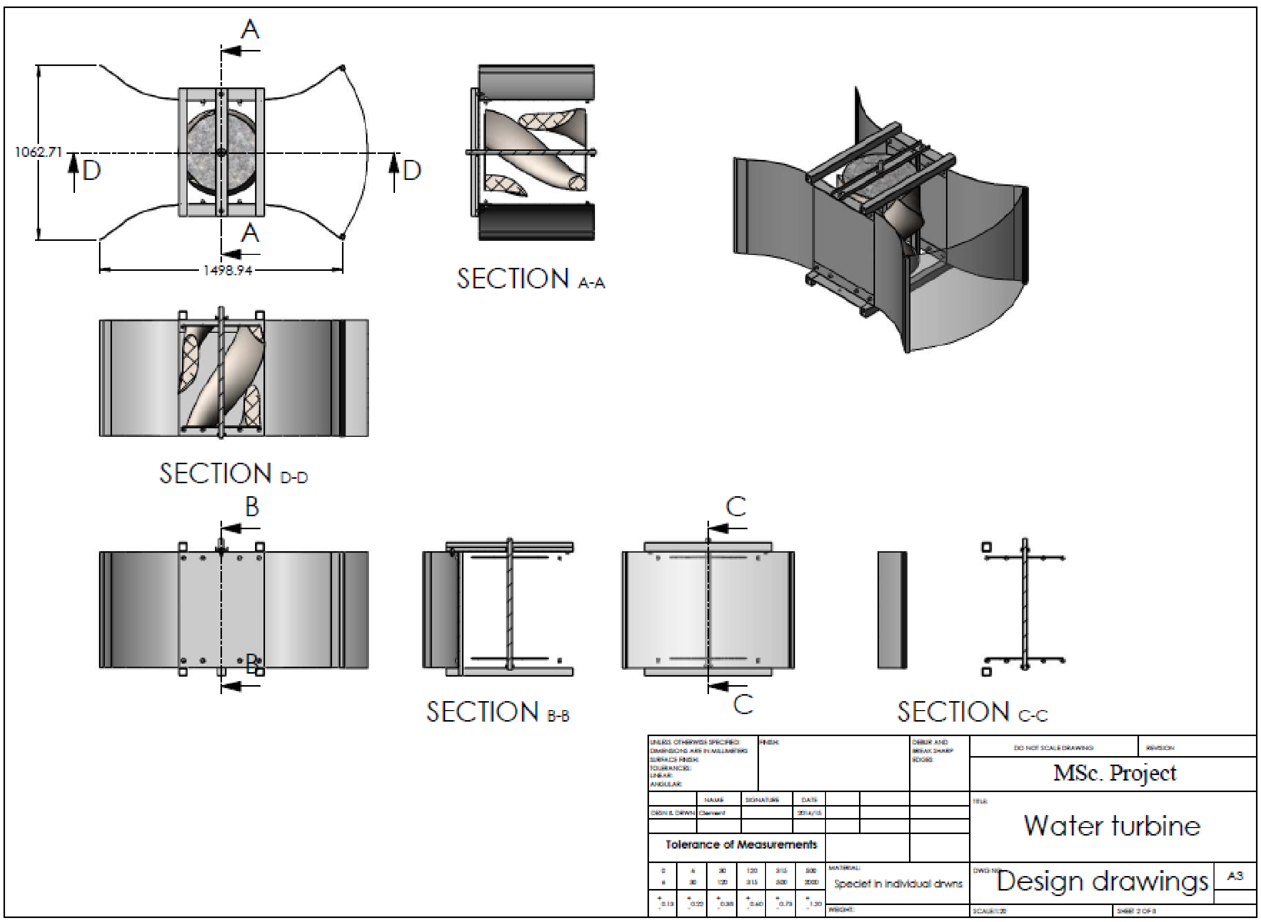

Figure 1: Assembly drawing for the turbine

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2.6 Design and construction of supporting rectangular framework

The supporting rectangular framework with dimensions 1m by 1m by 1m was designed and fabricated with 1 inch x 1 inch angle bars at the Jomo Kenyatta University Mechanical Engineering workshop facilities with help of workshop technicians as shown in Figure 2. The generator bearings and turbine guide bearing were centered to the true vertical position coupled to a 50 W generator.

Figure 2: Leveling and centering of the frame.

The rectangular framework was designed with a control gate to allow fluid flow, starting, stopping and controlling the turbine rotation. The frame was 1m by 1m by 1m and the side guides that also carry the control gate was made a little bit bigger to allow for more control of the fluid flow direction.

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Fitting the frame parts

Fitting the duct side plates

Inspecting the fit-up

Painting for corrosion protection

Figure 3: Duct cutting and fitting preparation

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2.7 Construction procedure for the turbine

The prototype turbine was constructed out of plywood and fibre-glass materials as shown in

Figure 4-6.. The wooden molds were professionally prepared and assembled as shown in Figure 7. Details of the manufacturing process are provided elsewhere in the thesis.

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Figure 4: Design transfer at the drawing table

Figure 5: Soft board preparation

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Figure 6: Complete soft board laminates ready for fibre-glass layering

Figure 7: Fabricated experimental system components

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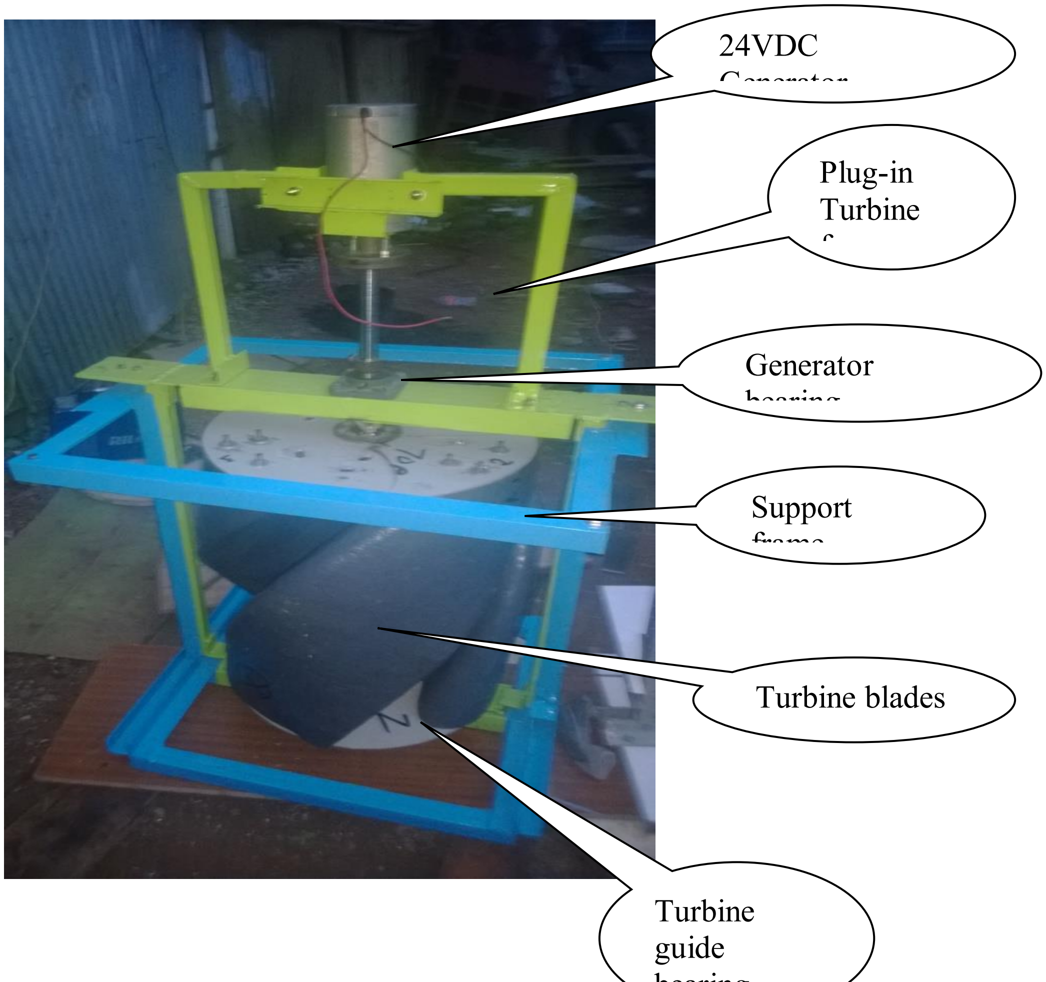

Figure 8: Assembled Helical Hydro turbine coupled to a 24V D

2.13 Test location.
The experimental helical turbine was tested on Ndarugu river near Jomo Kenyatta University of Agriculture and Technology (JKUAT) near the water pumping station in Juja as shown in Figure 9. The location was found acceptable in terms of fluid flow and security. A water flow meter model (state) was used to practically measure the flow of the river before starting the actual performance testing of the system

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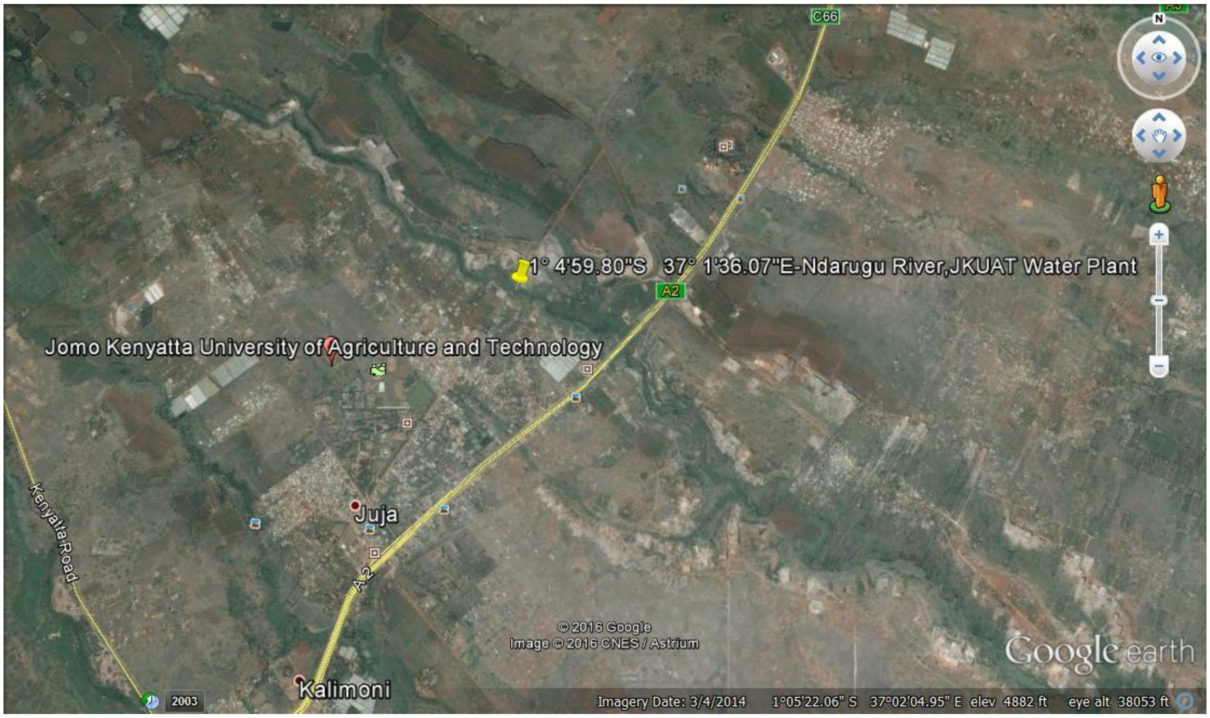

Figure 9: Map for second test site

Testing Plan

2.14 Test plan

The experimental helical hydrokinetic turbine was tested on river Ndarugo near the JKUAT water pump. Testing of the turbine was necessary to prove the turbine reliability and capability to produce power from the free flowing rivers utilizing the flow velocity. The reliability run test was undertaken for a period of 4 hours non-stop and the turbine was found to be mechanically sound and capable of withstanding all changes in flow. The control gate was found to be in good condition even after testing the starting and stopping of the unit. Starting of rotation was found to be at 50% gate opening and stopping was achieved at 30% opening due to momentum of the unit while running.

Reynolds number is a dimensionless value that describes the inertial to viscous force ratios and gives the degree of turbulence or laminar value of any given flow. For this report, Reynolds number was calculated based on the fluid velocity, kinematic viscosity of that fluid (water) and the chord length of the turbine blades.

$$\mathrm{Re} = \frac{Vc}{\nu} \qquad (10)$$

V-fluid velocity=0.723m/s as measured on the river

c-chord length=0.116m for this turbine

ν –fluid viscosity= (1.267E-6, at 10°C) m^2/s for water

Therefore the calculated Reynolds number is **Re=66,561.9** and is dimensionless.

Before starting the actual turbine testing, river flow measurement was done using a water flow meter, TASI-8740 model, from China. One of the Lab technicians accompanied the researcher and helped him to undertake the measurements. Several measurements were taken and averaged used as the river flow speed for power output measurements.

Rotational speed was measured using non-contact digital tachometers, TASI-8740 model, from China. The shaft was marked

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and a stroboscope was utilized for this measurements. For every one complete rotation of shaft, the red light from the stroboscope detected the different texture of a small tape on the shaft and this made the counts for the rotational speed. Electrical signals and output measurements were recorded at every step of the test to determine the real power output. Principally, testing this turbine –generator was undertaken in Ndarugo river and results recorded and tabulated. The experimental system was oriented to the true 90º perpendicular to the flow and slowly started opening the control gate till the unit started rotating. Data was accurately recorded and tabulated as presented in results section.

Figure 10: The tests carried out during the months of May-July 2015 at Ndarugo River.

2.15 Data Collection Procedure.

Data was collected in a systematic way where by the after lowering the unit into river and anchoring it, the control gate was slowly opened using the graduated scale at intervals of 10% each and at 50% graduation that is equivalent to 50 cm deep the unit started rotating.

As the unit started rotation, the digital TASI-8740 model, was used to measure the rotational speed and records were taken. At the same time the TD9205A model, digital multimeter was used to measure voltage and current generated. Series of resistors 2.0, 2.5,3.0 capacity were used to allow the flow of current .The rpm, voltage and current were measured and presented in Table 5 in results and discussion section.

4.0 Results and Discussion

4.1 River flow speed

The flow speed of Ndarugu River was tested during May-July 2016 and the results were ranging from 0.530m /s to 0.723m /s and this is presented on table 4. This was adequate flow for testing the experimental helical hydro-generation system.

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Table 2: Ndarugu River Flow measurement

S/No.	Velocity(m/s)	Coordinates Southings	Coordinates Easting’s
1	0.530	$1^0$4’49.80S	$37^0$1’36.07E
2	0.610	$1^0$4’49.80S	$37^0$1’36.07E
3	0.700	$1^0$4’49.80S	$37^0$1’36.07E
4	0.680	$1^0$4’49.80S	$37^0$1’36.07E
5	0.612	$1^0$4’49.80S	$37^0$1’36.07E
6	0.720	$1^0$4’49.80S	$37^0$1’36.07E
7	0.660	$1^0$4’49.80S	$37^0$1’36.07E
8	0.701	$1^0$4’49.80S	$37^0$1’36.07E
9	0.642	$1^0$4’49.80S	$37^0$1’36.07E
10	0.723	$1^0$4’49.80S	$37^0$1’36.07E

4.2 Experimental helical hydro-turbine tests results

Results of experimental helical turbine are presented in table 3 as follows:

Table 3: Experimental helical turbine performance test results

Control Gate Opening (%)	Water velocity average (v)	Average rotational speed(rpm)	Voltage (V)
0	0.00	0.00	0.00
10	0.00	0.00	0.00
20	0.00	0.00	0.00
30	0.00	0.00	0.00
40	0.00	0.00	0.00
50	0.612	20.9	1.178
60	0.642	25.6	1.154
70	0.660	28.0	1.005
80	0.701	30.1	0.985
90	0.720	32.5	0.578
100	0.723	37.2	0.434

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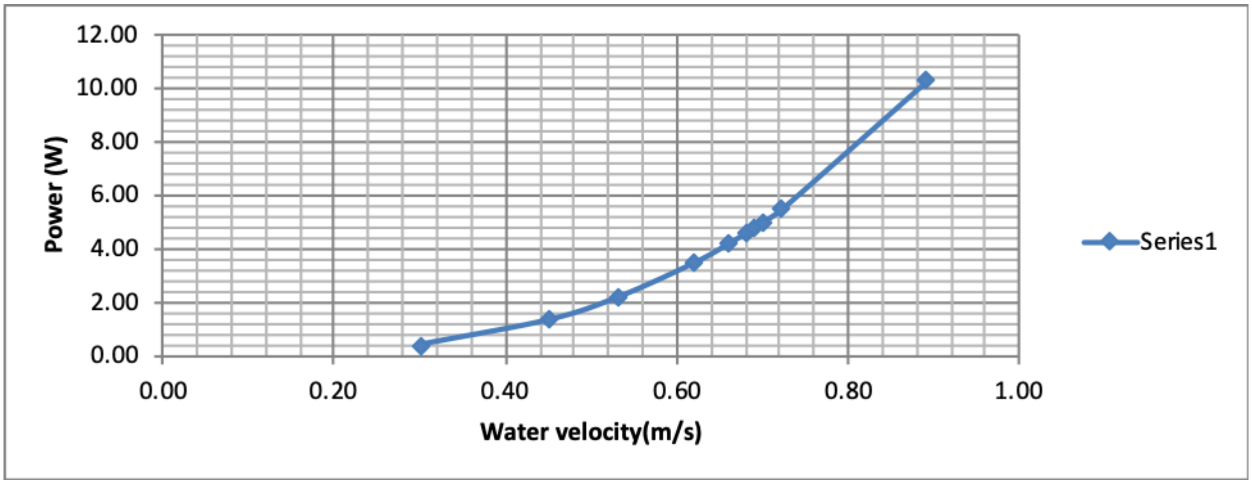

Figure 12 Generated Power as fuction of water velocity

In was observed that the experimental turbine started rotating when the water velocity reached 0.65m/s. This is a typical water flow velocity found on most small river streams in developing countries. The implication of this study is that the small helical hydro-generation systems have potential for power generation in small river streams including the irrigation schemes canals thereby generate much needed power for rural electrification applications in developing countries.

4.3 Performance indicators of the experimental system

Table 4: Helical generation System Tip Speed Ratio, Torque, Power coefficient, and power output

Gate Opening (%)	Av.RiverVelocity(m/s)	Power output (W)	Torque (Nm)	TSR	C_p
0		0	0	0	0
10		0	0	0	0
20		0	0	0	0
30		0	0	0	0
40		0	0	0	0
50	0.612	0.2988	7.88E+02	1.033	0.0174
60	0.642	0.4460	1.11E+03	1.077	0.0328
70	0.660	0.9396	1.52E+03	1.145	0.0478
80	0.701	1.4612	2.98E+03	1165	0.0659
90	0.720	1.8386	4.29E+03	1.273	0.09703
100	0.723	2.5384	4.72E+03	1.278	0.1424

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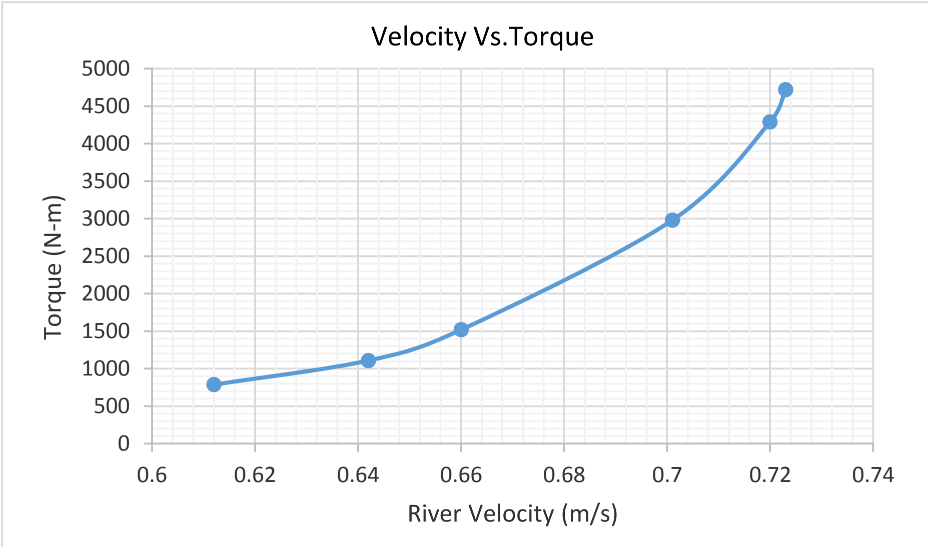

Figure.13 River velocity Vs Torque

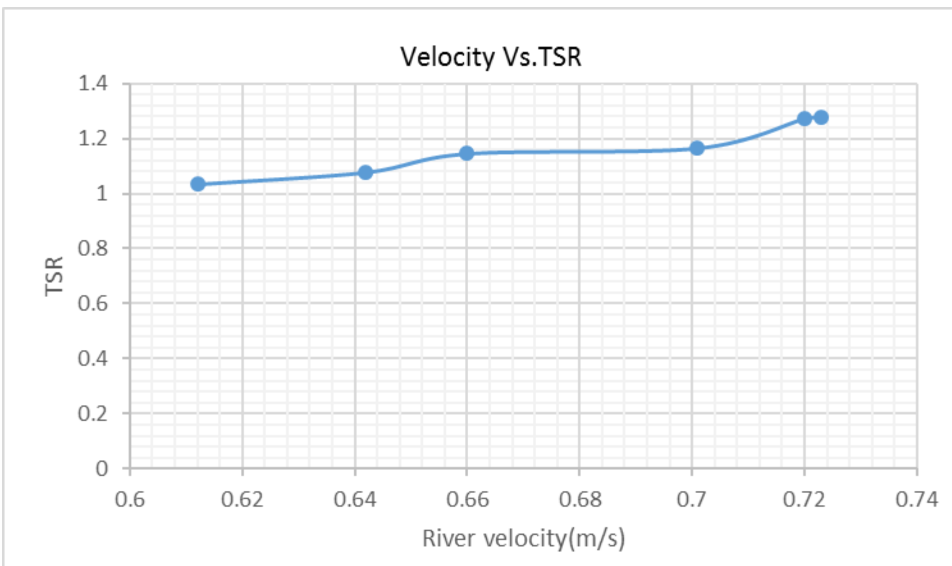

Figure.14 River velocity Vs Tip Speed Ratio

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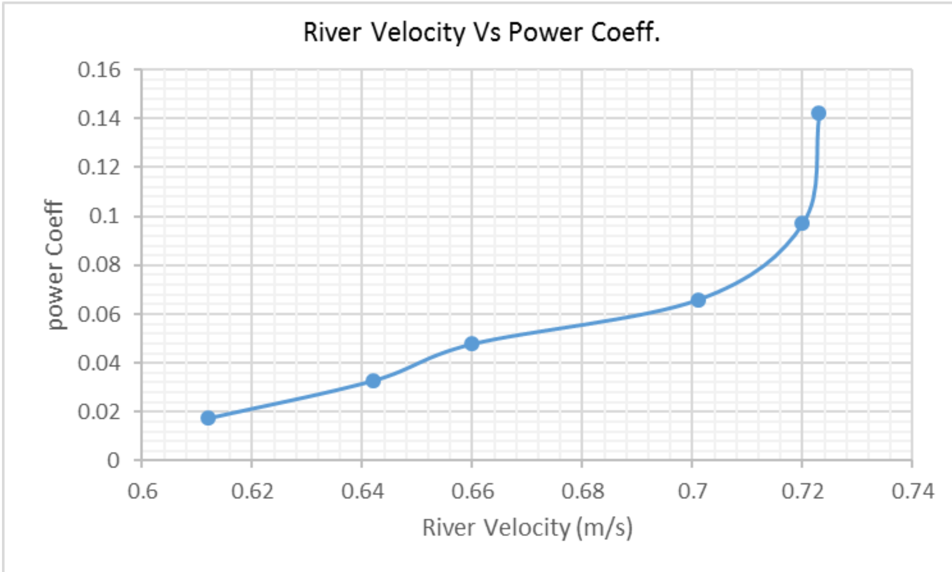

Figure.15 River velocity Vs Power Coefficient

Figures 13-15 as can be seen, the trend is similar, in that as the flow velocity increases so also is the other parameters, In conclusion the flow of the fluid is key to the success of this project outputs.

4.4 Economic Feasibility

In this study we carried out economic feasibility of the developed helical hydro-system using NPV criterion in its most basic form, the Levelised cost of energy as follows: **The NPV was calculated as**

$C_i.\ 1/((1+r)^n$ (11)

4.4.1 Investment Costs

The development of the current hydrokinetic turbine includes the blade costs, support frame costs, generator costs and the cost of constructing the prototype turbine in general. The total cost of this project was around Kshs 22000.00/= (equivalent of USD 220). The analysis of the same is as per table 10 herein.

Financial Economic Analysis	
Investment cost	
Capex (ksh)	21,150
Opex (ksh/y)	4200
Revenue (ksh/y)	8,000
Leverage (Equity)	30%
Years of Debt Payment	20
Interest Rate	6.0%
Inflation Rate	1.5%
Discounted Rate	12.0%
Tax Rate	30%
Depreciation period	10
Results of Financial Economic Analysis	

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IRR	48.48%
NPV	20950
ROE	330.18%

Table 5:NPV calculation

As can be seen from above table, the IRR is more than 12.5% and also the NPV is high thus this project is viable and profitable after three and half years.

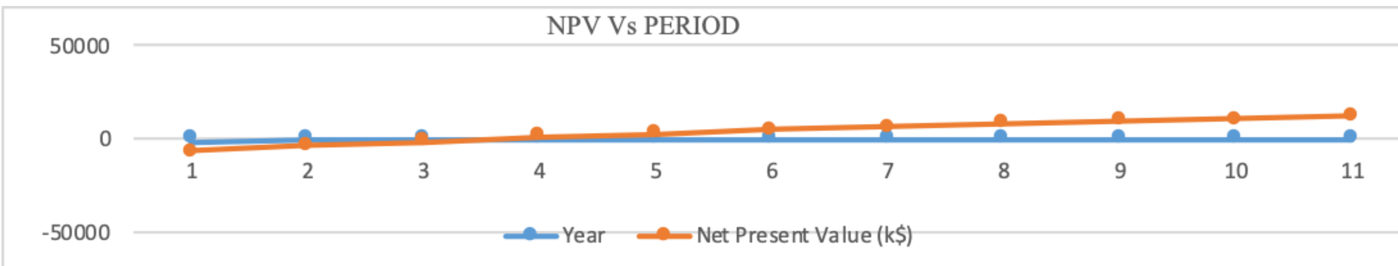

Figure.16 NPV Vs Period

4.3 Payback Period

Payback period is defined as a discounted rate and represents the number of years it takes before cumulative forecasted cash flow equal the initial investment. Its value is provided the year when the cumulative cash flow changes from negative to positive value. Using the 50W turbine generator at 1.2 m/s water flow, then the total assumed annual energy expected will be 437.5kWh/year. The revenue that can be realized if all conditions are met, is up to Ksh 8,000.00 per year and the O&M costs will be about ksh 4200.00 meaning that the net profit per year is about ksh 3700.00

Therefore the payback period (PBP) is calculated as,

PBP = (total investment cost / total revenues per year)

= 2100/3700 = 5.71years, (12)

5.0 Conclusions and recommendations

An experimental helical hydro turbine has been designed, fabricated and tested on small river stream in Kenya. The research has provided very important information with regard to local manufacturing of turbines for utilization of water currents especially in small river streams in Kenya. The results show that as the power output from the turbine increases with water velocity which also increases the tip speed ratio and thus proving that the turbine is able to extract available hydraulic power from the small river water flows. This project demonstrate a simple appropriate technology that can provide access to electrical power and water pumping for marginalized areas in Kenya and other developing countries.

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