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Adaptation and performance evaluation of low-head Archimedes screw-type turbine for power generation

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ABSTRACT

The study of Archimedes screw turbine as a micro-hydro power plant is being developed in this decade. Screw turbine has some advantages, namely no need draft tube, are fish-friendly, and can be operated in a low head (H<10 m). This research aims to adapt and evaluate the performance of the Archimedes screw turbine. Geometrical shapes are three blades, a screw angle of 30°, and a pitch of 2Ro. Water discharge 0.0664 m3/s, 0.0498 m3/s, and 0.0332 m^3/s and slope 10°, 20°, 30°, and 40° were considered as an independent parameter whereas rpm from the turbine screw shaft which was upgraded by pulley ratio, power, and voltage was considered as the dependent variable. From the result of the experimental data, the highest rotation of the screw turbine occurs at a flow rate of 0.0664 m^3/s, and the shaft slope 20^o was 95 rpm. The largest screw power occurs in the turbine shaft's slope (α) of 20^o in the amount of 136.2 watt at 0.0664 m^3/s. The highest generator voltage occurs at the discharge of 0.0664 m^3/s, and angle of inclination 20^o, which is 200V. The highest efficiency was 71% which occurs at 10° inclination and the discharge of 0.0664 m^3/s. The results of this study indicate that to obtain maximum voltage and power, flow conditions must be maintained at the highest water discharge conditions; even the efficiency obtained is not the maximum value.

Keywords: Archimedes; Efficiency; Flow Rate; Low Head; Performance; Power; Screw Turbine; Slope; Three Blade; Turbine Shaft; Voltage.

1. Introduction

Energy is everywhere and drives everything. It is the motive force within our bodies, propelling our vehicles, and lighting our world (Takeuchi, 2016). At present, one of the most important challenges facing the world is the production of sustainable energy for several reasons, including decreasing fossil fuels, increasing pollution, and increasing carbon dioxide emissions (Setiawan et al., 2021). Renewable energy uses energy sources that are continually replenished by nature the sun, the wind, water, the Earth's heat, and plants (Holt & Pengelly, 2008).

Approximately three billion people have no clean energy access (Kole et al., 2022). Among the renewable energy resources, energy from water in mini/micro hydropower has gained the highest attraction due to its environmentally friendly operation. Water energy is of great importance for a sustainable future because it is a clean, cheap, and environmentally friendly source of power generation (Date & Akbarzadeh, 2009). The largest share of energy consumption 87% in Ethiopia is dominated by traditional fuels (charcoal, fuel wood, dung cakes, and agricultural residues) which pose various health and environmental risks (Tiruye et al., 2021). Therefore, the study of energy source exploration, especially renewable energy, is important to develop in Ethiopia, which has a lot of river streams and irrigation channels. The river stream and irrigation channels are a potential source to build micro-hydro power-plant. Archimedes Screw was originally used for irrigation in the Nile delta and for pumping out ships (Boluk, 2024). In modern times, this screw can be applied in flood detention, and wastewater treatment facilities, and also use as a hydro turbine in electricity production (Zafirah Rosly et al., 2016). The screw turbine is one type of water turbine that was recently studied this decade. The advantages of screw turbines are low head operated (<10 m), easy maintenance, and fish-friendly (Syam et al., 2019), (Siswantara et al., 2019). The geometry of Archimedes

Irish Interdisciplinary Journal of Science & Research (IIJSR)
Volume 9, Issue 3, Pages 84-94, July-September 2025

Screw can be found by determining the external and internal parameters with the optimum pitch ratio depending on the number of blades and the radius ratio (R1/R0) equal to 0.54 (Maulana et al., 2019).

The efficiency of the screw turbine is influenced by the geometric shape and its flow losses. The analytical model of inlet flow in the screw turbine, by taking into account the leak flow in the gap between the screw and outer cylinder (casing), and also excessive water in the center of the pipe had been studied (Nuernbergk & Rorres, 2013). The experimental analysis conducted by (Kashyap et al., 2020) reveals that the screw angle ranges from 20^o to 25^o increasing the efficiency of the Archimedes Screw Turbine to around 90%.

According to (Maulana et al., 2019) experimental studies indicate that to obtain maximum torque and power, flow conditions must be maintained at the highest water flow rate conditions, even though the efficiency obtained was not the maximum value. The Archimedes screw turbine was applied in the river. The prime mover force of the open channel is the weight of fluid due to gravity (Simmons & Lubitz, 2021). The kinetic and potential energy of water flow is changed into mechanical energy through the blade of the screw; finally, it turns a turbine shaft that produces electrical power by a generator via a transmission (Lee & San Lee, 2023). The specific weight of water on the blades causes the screw to rotate.

1.1. Study Objectives

The objectives of this study are:

(1) To adapt the low-head Archimedes screw turbine.

(2) To evaluate the performance of the screw turbine for power generation.

2. Materials and methods

2.1. Experimental site

The screw turbine was fabricated at Jimma Agricultural Engineering Research Center (JAERC), which is located in the South Western Zone of Oromia National Regional State, Ethiopia. The center lies at latitudes of 7°40'51.1"N and 36°50'41.4"E longitudes.

The site has an elevation of 1772 meters above sea level (masl) (Jifara et al., 2019). The experiment was conducted at Waro river, Ganji Abbayyi kebele, Dedo district, Jimma zone.

2.2. Materials

The raw materials used for the fabrication of Archimedes screw turbine were sheet metal 2 mm thickness, square pipe 30∗30∗3 mm, angle iron 30∗30∗3 mm, shaft 40 mm diameter, large pulley diameter 500 mm, and small pulley diameter 100 mm, bearing 204, belt A type 56, 2 kW Alternator, chain, sprocket, different size of bolt, and nut were used. Measuring tape, bubble level, tachometer, and calliper are instruments that were used while data was collected.

2.3. Methods

2.3.1. Experimental method

Irish Interdisciplinary Journal of Science & Research (IIJSR)
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Water discharge in meter cube per second and slope in degree was considered as an independent parameter whereas, RPM from the turbine screw shaft which is upgraded by pulley ratio, voltage, and power was considered as a dependent variables.

2.3.2. Working Principle

The Archimedes screw turbine was applied in the river, the prime mover force is the weight of the fluid (Abbas et al., 2024). The water flows into the top of the screw due to gravity. The hydrostatic pressure from the water on the screw surface causes it to turn, then the water is back into the river. Rotation of the screw shaft can generate electricity by connecting to a generator. Measurement data that were taken were generator voltage and turbine rotation (n) with a tachometer; the discharge was measured by using the floating method. The shaft's slope (α) of 10^o, 20^o, 30^o, and 40^o were taken for this experiment. In this experiment, the screw turbine consists of a cylindrical shaft onto which three helical blade (N = 3) is wrapped orthogonal to the shaft. The parameters of screw turbine dimensions are shown in table (1).

Figure 1. Model of three-bladed Archimedes Screw turbine

Table 1. Screw turbine nominal parameters

Parameter	Variable	Value
Slope	α	10^o, 20^o, 30^o, 40^o
Outer radius	R_0	200 mm
Inner radius	R_i	50 mm
Pitch	p	400mm
Number of screws	N	3
Gap	G	10 mm
Screw length	L	1000 mm
Flow rate	Q	0.0664 m^3/s, 0.0498 m^3/s,0.0332 m^3/s
Thread angle	β	30^o
Inflow velocity	V	(1, 1.5, 2) m/s

2.3.3. Performance calculations

2.3.3.1. Determination of power

The equation used in the data analysis was: The hydraulic power of the screw turbine (Saroinsong et al., 2016) which is shown as follows:

$P_{hyd} = \rho gQH\eta$ (1)

Where: ρ is water density (kg/m^3), g is gravitational (m/s^2), Q is the flow rate (m^3/s), η is overall efficiency 80%.

Discharge (Q) was calculated by the following formula:

$Q = A*V*0.83$ (2)

Where Q is the discharge in $m^3/_s$

V is the average flow velocity in m/s

A is the cross-section area in m^2 and 0.83 coefficient of friction

The torque provided by the screw is equal to:

$T_s = T_{motor} + T_{friction}$ (3)

Where T_s is the torque of screw N.m, T_m is the torque of motor N.m, and $T_{friction}$ is the torque induced by the friction in the bearing (Dellinger et al., 2016).

$C_{friction}(n) = 0.000171n+0.046065$ (4)

$T_m = 9.5488*\frac{P}{S}$ (5)

Where, P is generator power, the watt

S is generator speed, rpm

The power delivered by the screw was determined by:

$P_{screw} = T_{screw} + \omega_{screw}$ (6)

2.3.3.2. Determination of efficiency

The efficiency of the screw turbine was calculated as follows:

$\eta = \frac{P_s}{P_{hyd}}.100\%$ (7)

Figure 2. The photo was taken during collecting data

2.4. Testing Equipment

There are two variables in the testing of this screw turbine experiment, namely: independent variables such as discharge, and angle of inclination, and dependent variables which includes rotation, voltage, and power. Data collection carried out in this study includes two stages: field data collection, and calculations through computing devices. Determination of the flow rate in the field conditions was measured by the floating method**.** The tool is used to measure the turbine shaft rotation with a tachometer.

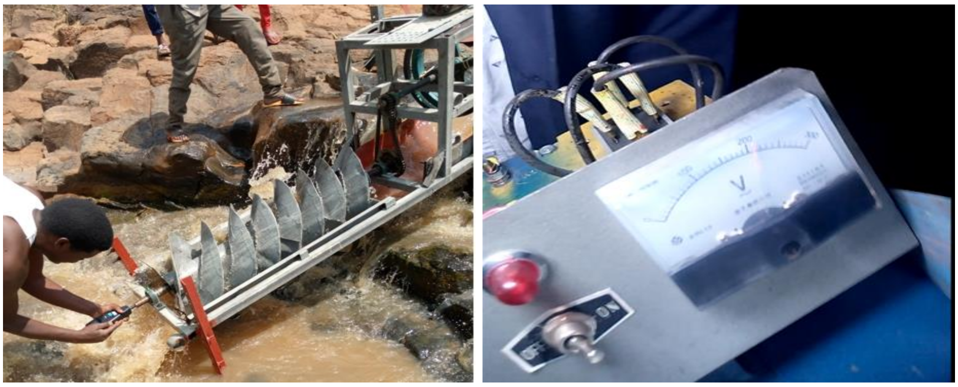

Figure 3. Measurement of the shaft rotation and voltage

Table 2. The four slopes (β) and three discharges that were used during the experiment, with the corresponding maximum values of hydropower, screw power, voltage, screw rotation, and efficiency

	Q(m^3/s)	H(m)	θ^0	RPM alternator	RPM screw turbine	P_{hyd} (W)	P_{screw} (W)	η	V (Volt)
Q1	0.0664	0.329	10	1340	85	171.4	121.8	71	150
	0.0664	0.64	20	1500	95	333.5	136.2	40.8	200
	0.0664	0.95	30	1200	76	495	108.9	22	120
	0.0664	1.22	40	940	60	635.7	86	13.5	70
Q2	0.0498	0.329	10	850	54	128.6	77.4	60	50
	0.0498	0.64	20	1080	68	250	97.5	39	110
	0.0498	0.95	30	1050	53	371.8	74.5	20	50
	0.0498	1.22	40	770	35	476.8	50.15	10.5	15
Q3	0.0332	0.329	10	725	30	85.7	32.9	51	15
	0.0332	0.64	20	900	42	116.75	44.4	36.8	35
	0.0332	0.95	30	790	25	247.5	35.8	14.5	10
	0.0332	1.22	40	460	13	317.87	17.79	6	5

The table (2) above shows the data collected and calculated during the experimental field test. The rotational speed of the screw turbine was upgraded by the pulley ratio, and hydropower, screw power, voltage, and efficiency were calculated to get the performance of the screw turbine.

2.5. Data analysis

The others software such as R software, Engineering Equation Solver (EES) and simple descriptive statistics were also used for data analysis according to its suitability.

3. Results and Discussion

The performance of the three-bladed Archimedes screw turbine was recognized through test data and data analyzed by using the equation above. The relationship of turbine rotation, hydraulic power, and screw power on characteristic length variable, and flow rate is shown in Table (2). From the measurement results obtained the highest water discharge Q_1 is 0.0664 m^3/s, the medium Q_2 is 0.0498 $m^{3/}s$, and the lowest water discharge Q_3 is 0.0332 m^3/s as shown in figure 4 below.

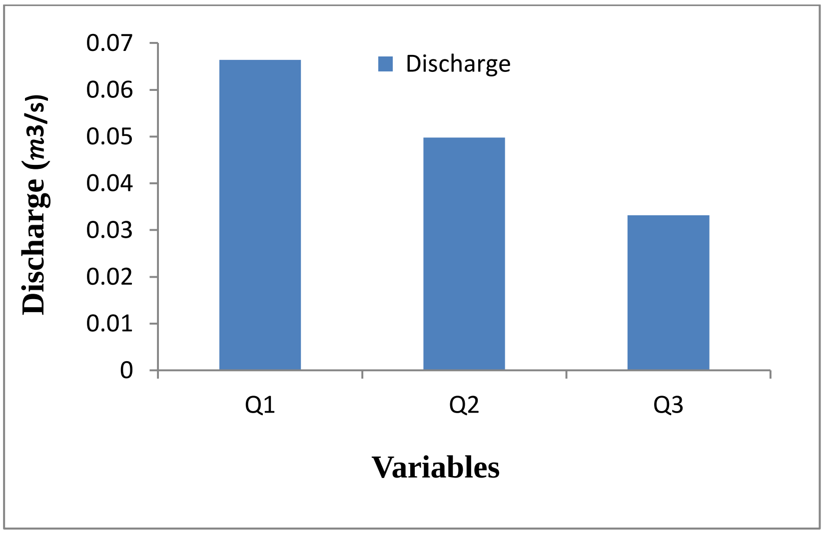

Figure 4. Water flow rate of the test results

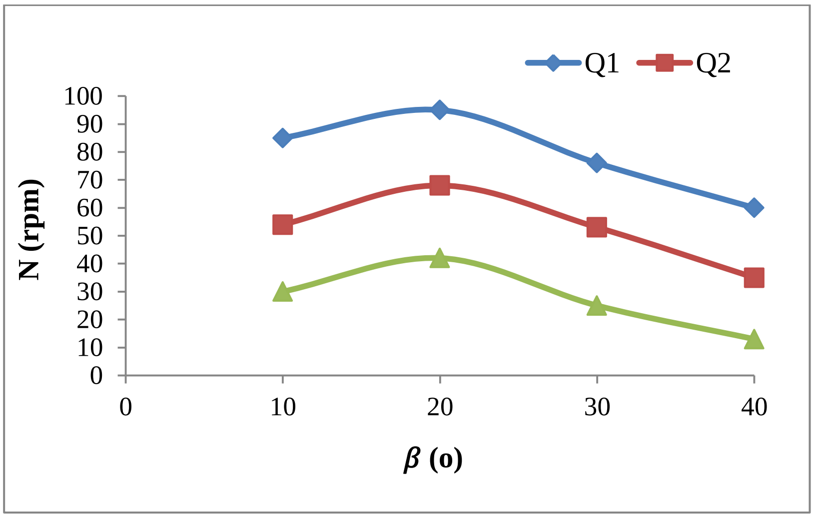

Figure 5. Inclination vs rotation of screw turbine with variations in flow rates

Figure 5 above shows the relationship between the inclination and rotation of the screw turbine in each shaft slope of 10°, 20°, 30°, and 40° in all variations in flow rate. Increasing slope affects to raise the rotational speed of the turbine. The graph shows that the highest screw rotation value occurs at 20° and at the flow rate of Q_1 with screw rotation that occurs in this condition was 95 rpm and followed by the flow rate of Q_2 with a screw rotation value of 68 rpm occurring at 20° and followed by the flow rate of Q_3 with a screw rotation value of 42 rpm occur at 20°. The revolution per minute of the screw turbine is increased up to the inclination of the turbine reaches 20° and then afterward starts to decline with the increase in tilt angle.

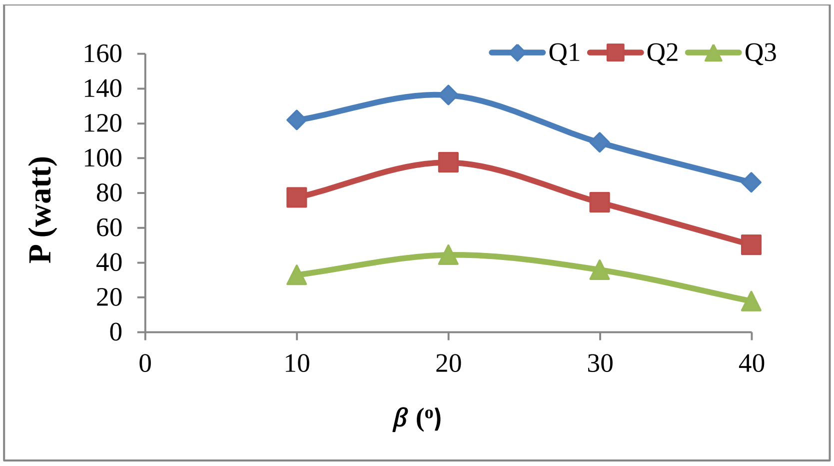

Figure 6. Inclination Vs output power of screw turbine with variations in flow rates

Figure 6 above shows the relationship between the angle of inclination and output power with variations in flow rates. The highest output power of the screw turbine was 136.2 watts with a discharge of Q1 and inclination of 20^o. For the discharge of Q_2 and inclination of 20^o, the output power reaches 97.5 watts. For the discharge of Q_3 and inclination of 20^o, the output power reaches 44.4 watts. It showed that the largest water discharge Q1 is the fastest screw rotation, therefore output power by the turbine becomes greater. The higher rotation will generally produce higher power, but the mass of water entering the turbine will also affect the momentum that occurs in the turbine blades.

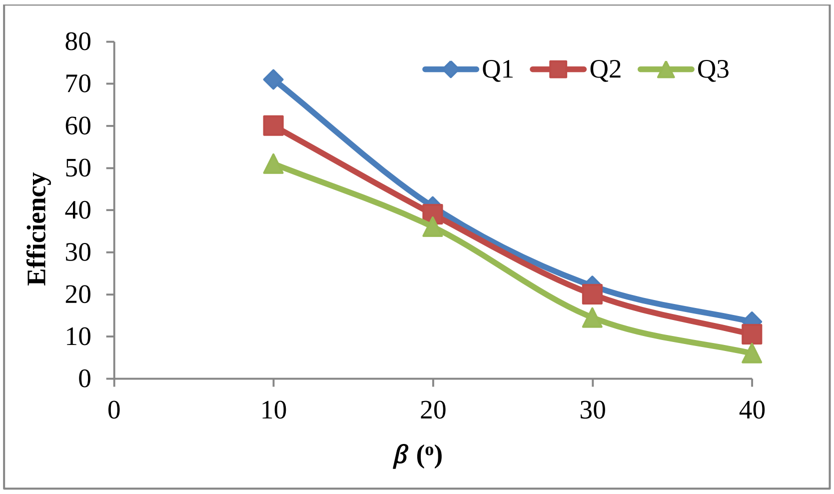

Figure 7. The effect of turbine discharge on turbine efficiency and turbine inclination

The performance of a three-bladed Archimedes screw turbine depends on its efficiency through equation (7). The figure 7 shows, the relationship between efficiency and inclination in each variation of flow rate. The highest efficiency was 71% which occurs at 10^o inclination and the discharge of Q_1. Followed by efficiency at the flow rate of Q_2, which is 60 %, and the lowest efficiency occurs at the flow rate of Q_3 is 51%. Turbines with high rotation do not necessarily have high efficiency (Rohmer et al., 2016). This trend has similarities with some of the previous studies conducted by (Saroinsong et al., 2016), (Erinofiardi et al., 2017). The result of this experiment shows the performance of the screw turbine will be maximized if the shaft slopes of 20^o and discharge of Q_1, which automatically become better in low head and rotation operation.

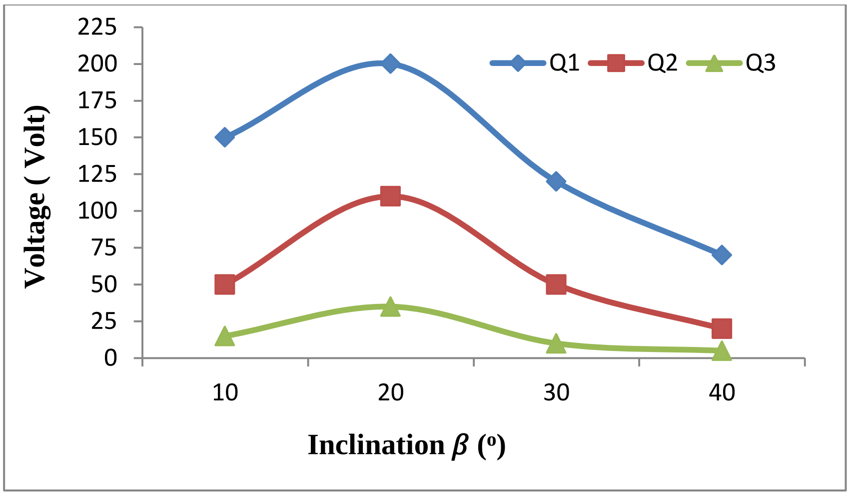

Figure 8. The effect of discharge toward voltage and turbine inclination

In figure 8, a graphical form of the measurement results for generator voltage versus angle of inclination with variations in flow rates. From figure 8 above, the graph shows that the highest generator voltage occurs at the discharge of Q_1, an angle of inclination 20^o, which is 200V, followed by generator voltage occurs at the discharge of Q_2, an angle of inclination 20^o, which is 110V, and the lowest generator voltage occurs at the discharge of Q_3, and angle of inclination 20^o, which is 35V.

According to (Indarto, and Bustomi 2021) study on characteristic analysis of Archimedes' screw turbine with variations in water discharge show that an increase in water flow will cause an increased voltage.

The experimental analysis conducted by (Kashyap et al., 2020) reveals that the screw angle ranges from 20^o to 25^o increasing the efficiency turbine. Generally, an increase in generator voltage is due to the increase in water discharge and rotation.

4. Conclusions and Recommendation

4.1. Conclusions

The turbine model used in this study was Archimedes' three-blade screw turbine. The independent parameters in the experiment are water discharge of 0.0664 m^3/s, 0.0498 m^3/s, and 0.0332 m^3/s. while the parameters that change are the angle of the Archimedes screw turbine (10^o, 20^o, 30^o, and 40^o). According to the experimental results, the optimal output was obtained at an angle of the turbine screw shaft of 20^o, among other things: voltage of 200 volts, generator rotation at 1500 rpm, power of 136.2 watts, and efficiency of 71%. Since the Archimedes screw turbine was conducted and evaluated for power generation, for future work the following ideas were suggested:

1) Better to evaluate for irrigation purposes to substitute fuel water pumps.
2) Better to use for modern irrigation canals as a dual function.
3) Different governments and NGOs should work on it to reduce the energy security in the country.
4) It is suggested to give awareness about this technology, especially for rural communities.
5) Since it is simple and portable, it could be suggested for demonstration.

4.2. Recommendations

Based on the obtained results and conclusions the following recommendations were made:

1) The fabricated and evaluated Archimedes screw turbine will be recommended at an angle of inclination of 20° and a discharge of 0.0664 m^3/s.

2) Hence, the Archimedes screw turbine did not need a draft tube, was fish-friendly, and could be operated with a low head. Therefore, it is better to use it for small-scale electricity generation purposes.

3) It is preferable to produce more different sizes of Archimedes screw turbines in order to further optimize the use of different heads and discharge water capacity.

Declarations

Source of Funding

This study did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare that they have no competing interests related to this study.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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