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Original article

Modelling the energy extraction from low-velocity stream water by small scale Archimedes screw turbine

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ABSTRACT

In recent years, there has been a growth of interest in the development of micro-hydropower power generation, especially in the low head turbine. Low head turbine gained popularity due to its high efficiency, relatively low cost, ability to operate in low flow rate, and low environmental impact. In this aspect, the Archimedes Screw Turbine (AST) could be the primary key to electrifying the rural area in Sarawak, Malaysia, which is surrounded by rivers. This study starts with a conceptual design based on literature review findings. Eventually, the small-scale prototype is then being built and tested in the laboratory. The experiment is set up to simulate the actual Sarawak river velocity to determine the relationship between key performance variables such as the inclination angle of AST and water flow velocity. The findings revealed that the 45° angle of inclination was the optimum angle of AST within the water velocity of 1.0 m/s until 1.5 m/s. At this angle, the highest revolution per minute (RPM) generated by AST shaft was 179.8, and the highest torque recorded was 0.9Nm. The results were validated through statistical means. It was found that both angle of inclination and river water velocity are significant to RPM and torque generation ($p < 0.05$). Two statistical models were generated based on linear regression to explain the contribution of water velocity and angle of inclination as inputs to torque and RPM as outputs, with Pearson R^2 value of more than 60%. The maximum mechanical power generated is about 1.54 kW, with the maximum efficiency of 94.6%. The outcome of this study would be useful for designing a small-scale AST power generation system by utilising a low flow river (velocity < 1.5 m/s) as a power source. This study would contribute to the existing knowledge stock of small-scale AST, primarily to operate in low flow velocity rivers. For the future study, it is recommended for conducting a pilot study to test the actual performance of AST in the Sarawak river or rivers with similar flow characteristics.

1. Introduction

Hydropower is the energy harvester which is powered by the flowing of water. Back to 2000 years ago, the ancient Greeks used water as the main driving force to run wheels for agriculture production. Nevertheless, today, water is one of the most effective ways to generate electricity. In Norway, 98% of electricity comes from hydropower. On top of that, the world's largest hydropower plant, the Three Gorges Dam in China, produces 80 to 100 terawatt hours per year, enough to supply up to 80 million households (Chang et al., 2018). The existence of hydropower technology could contribute to power generation as a replacement for nonrenewable sources. Over the years, the utilisation of hydropower as an alternative power generation has attracted attentions of researchers (Behrouzi et al., 2016; Oliver Paish, 2002; Sangal et al., 2013). However, most of the study focuses on large-scale design due to the economy of scale and the output produced. On top of that, large-scale hydropower is known to cause environmental and social threats such as damaging wildlife habitat, prime farming lands that are the primary income source for native Sarawak people (Behrouzi et al., 2016). This creates the need for micro-hydro power which harnesses the power from the river without damaging wildlife habitats and disturbing prime farming lands, especially in Sarawak, Malaysia. In addition, most river conditions in Sarawak are generally classified as low head and low flow velocity (Shahidul

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et al., 2015). Micro-hydro systems are usually capable of generating an output of <100 kW and usually are used to supply electricity to small communities (Yoosefdoost and Lubitz, 2020). Micro-hydro has a much lesser impact on the environment than its large hydropower project counterparts because it does not require a reservoir and most of the design could harness kinetic energy directly from running streams or rivers (Abbasi and Abbasi, 2011). Often, low head micro-hydro projects end up being more expensive than large hydropower developments on a per megawatt basis (Schleicher et al., 2014). However, for rural development or powering a smaller community, micro-hydro seems like an excellent renewable energy solution, especially with Archimedes screw turbines (AST) (Lyons and Lubitz, 2013). ASTs are immensely advantageous over other turbines for sites with low flow (under 10 m^3/s) and low head (under 5 m) conditions (Lashofer et al., 2012). However, information related to AST is limited. In this aspect, this study aims to fill the gap by determining the optimum design characteristics of a small-scale AST which would be useful to operate under low flow velocity and low head. Eventually, the prototype would be useful for Sarawak rural development.

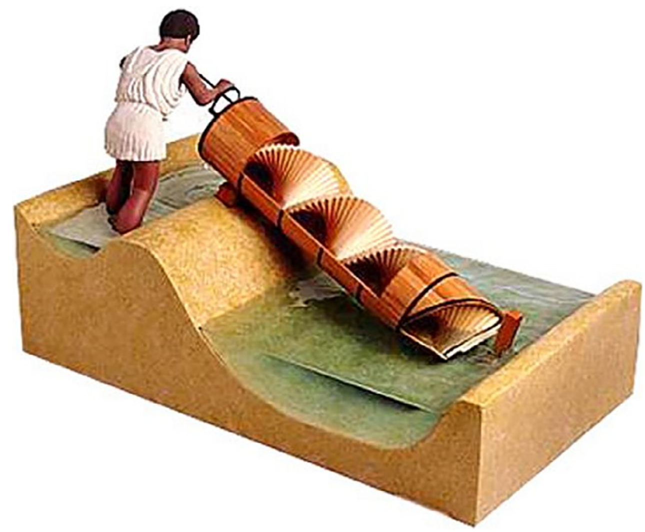

Fig. 1. Archimedes Screw as Pump in Ancient Times (AncientPages.com, 2018).

2. Literature review

2.1. Potential of micro hydro in Sarawak

Sarawak, being the largest state of Malaysia, is still suffers from electric poverty with more than 20% of the scattered rural communities doing not have access to national power grid (Julai and Buswig, 2020). Until now, most locals are still relying on small scale fossil fuel powered generators to run the basic appliances such as lighting and fans. There are few potential renewable energy resources options available which are micro-hydro (Gallego et al., 2020), solar (Shiun, 2016), biomass (Wu et al., 2017) and wind (Eltamaly, 2007; Saupi et al., 2018). The most potential renewable energy resource that is feasible to be implemented in Sarawak is micro-hydro due to Sarawak's geographical features and climate which has a lot of streams and rivers paired with high rainfall rate and high jungle reserves. The characteristics of most rivers in Sarawak are classified as low-pressure head of<10 m, and the average flow velocity of 1 to 2 m/s (Adzlan et al., 2013; Sa'adi et al., 2017; Saupi et al., 2018). A past study conducted by Raman and Houssein (2010) has revealed more than 22 potential sites in Sarawak that are feasible for micro-hydro power generation with the total power estimated about 5317.6 kW (Raman and Houssein, 2010).

2.2. Archimedes screw turbine

Archimedes has been accredited with the invention of a screw which lifts water for irrigation and drainage (287–212 BCE). It has been speculated that Archimedes acquired the knowledge from a trip to Egypt, where he had been studying (Waters and Aggidis, 2015). Since there is no recorded description of water lifting screws before his time, and Archimedes was already well established for his inventive, mechanical and mathematical abilities, hence the name, Archimedes Screw (Maulana et al., 2019), which is shown in Fig. 1.

In the basic knowledge of AST, the system consists of the transformation of energy in three stages from the kinetic energy of the flowing medium into the mechanical energy which is captured by the turbine and rotates the generator to produce electrical energy (Songin, 2017; Waters and Aggidis, 2015). The illustration is shown in Fig. 2. AST consists of several helical planes attached to a central cylindrical shaft in an enclosed inclined trough. A small gap exists between the trough and the screw, allowing the screw to rotate freely. ASTs rotate by allowing water to transverse the screw from high to low elevation. As water passes through the screw, a torque is created on the helical plane surface causing the screw to rotate. Attaching a generator allows this mechanical rotation to produce electricity (Lyons and Lubitz, 2013) (Fig. 3).

The actual performance of an AST depends on several parameters; rotational speed (Rohmer et al., 2016), angle of inclination (Erinofiardi et al., 2017), number of flights (Lyons and Lubitz, 2013), geometry and performance (Rorres, 2000), and gap (Lashofer et al., 2012), which are all related to each other (Maulana et al., 2019; Shahverdi et al., 2020). The selection of the optimum condition of these parameters is essential for the turbine to operate and generate electricity. Based on the literature review, several gaps have been found:

- Most of the studies related to hydropower focus on the energy conversion in the high head or high flow condition due to the higher output that could be generated.
- Most turbine studies focus on fabricating large-scale prototypes or high flow velocity and flow rate due to the economics of scale in power generation.
- Even though with the recent growth of interest in micro-hydro turbines, limited studies were found to generate power in the low head, low flow conditions that represent the most river conditions in Sarawak, Malaysia.

This study is designed to fill the gap to produce a small-scale turbine suitable to generate power even in low head, low flow conditions.

3. Theoretical framework for design considerations

3.1. Rotational speed and mechanical power

Most of the ASTs designed in the European countries use Eq. (1) to determine the maximum rotation speed of AST before the turbine development process to determine the maximum rotational speed (n_{max}) with the external radius (Ro) of the screw (Lashofer et al., 2011). Eq. (1) is useful to set the limit of external radius for turbine design. However, it is only useful before AST starts to produce friction loss and centrifugal force due to excessive rotational speed which eventually affects the efficiency of the system. The maximum rotational speed, except for specific speed limits, is

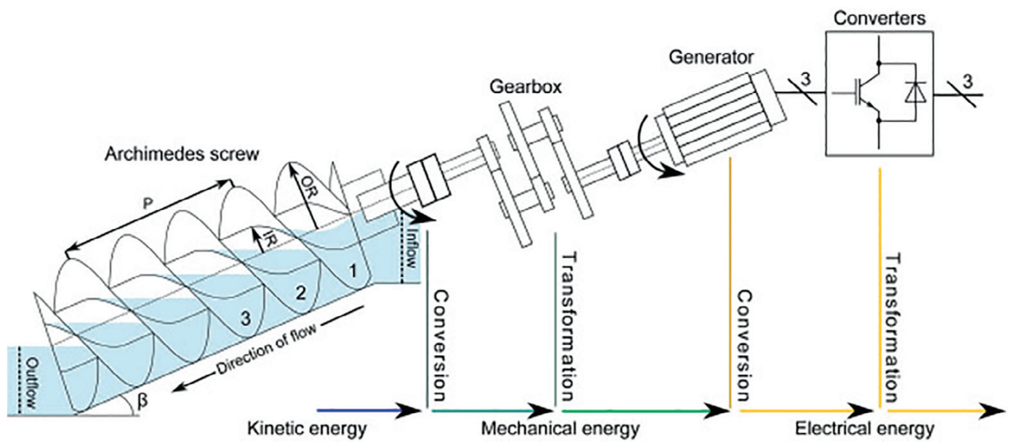

Fig. 2. Energy Conversion in AST (Rohmer et al., 2016).

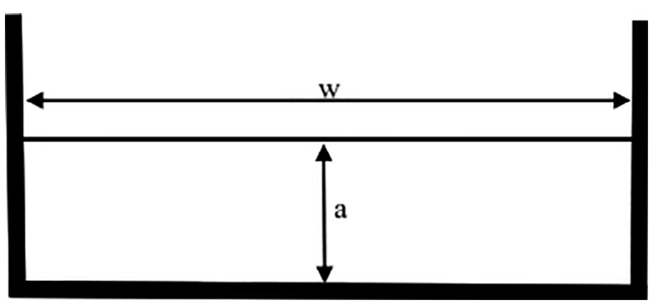

Fig. 3. Rectangle Open Channel Cross Section.

influenced by dynamic rotor restrictions and other technical limitations related to the stiffness of the construction.

$$n_{max} \le \frac{50}{(2Ro)^{\frac{2}{3}}}\left(min^{-1}\right) \quad (1)$$

Where, R_O = external radius of screw (m)

The total power, mechanical power, and efficiency of the water turbine can be determined by following equation (Erinofiardi et al., 2017):

$$TotalPower, P_w = pgQH \quad (2)$$

Where, p = density of water (kg/m^3)
g = gravitational acceleration, 9.81 m/s^2
Q = volume flow rate (m^3/s)
H = elevation of the system (m)

$$MechanicalPower, P_{mech} = T\omega \quad (3)$$

Where, T = torque generated (N/m)
ω = rotation of the turbine shaft (rad/s)

$$= \frac{Pmech}{Pw} \quad (4)$$

Where ρ is the density of water, g is the acceleration due to gravity, Q is the volumetric flow rate, h is the available head of water source, T is the torque at a corresponding angular speed ω.

3.2. Geometry and performance

The pitch ratio and the diameter ratio are the significant parameters of AST to be accounted for in the calculation. Previous studies indicate five components for the total discharge of the screw turbine, which are (Nuernbergk and Rorres, 2013; Rorres, 2000):

- Q_W: The flow that generates the torque.
- Q_G: The leakage flow between the screw and the trough.
- Q_O: The leakage flow when the screw is overfilled (f greater than 1).
- Q_F: The friction leakage flow formed by water that adheres to the flight.
- Q_P: The leakage flow if there is no guiding plate on one side of the trough.

The friction leakage Q_F can be neglected since it is comparatively small. The leakage flow QP can be eliminated with the use of a steel plate. The flow balance equation is shown in Eq. (5):

$$Q = Q_w + Q_G + Q_o \quad (5)$$

The total inflow Q is the total available flow at the inlet, and this can be the flow from an open delivery channel. Using Manning's equation, the total inflow can be correlated with the geometrical characteristics of the open inflow channel.

$$Q = \frac{A}{n_m} R^{\frac{2}{3}} Sf^{\frac{1}{2}} \quad (6)$$

$$A = aw \quad (7)$$

$$R = \frac{aw}{w + 2a} \quad (8)$$

Where, Q = total inflow (m^3 /s)
Sf = gradient because of friction losses
Nm = manning's friction coefficient
A = area (m^2)
a = height (m)
w = width (m)
R = hydraulic radius (m)

To determine the volume per turn of the screw, Vu is the volume of water that flows into or out of the screw in one turn, which is the volume in length equal to one pitch, the following dimensionless parameters were introduced (Rorres, 2000).

$$Q_w = \frac{n_r}{60}.V_u \quad (9)$$

Where, Qi = flow generated the torque (Nm)

$$n_r = rotationalspeedofscrew(rpm)$$

$$V_u = volumeperturnofthescrew$$

Eq. (6) is useful to examine the geometry of the AST, whether it can accommodate the given flow of water. The estimated volume of water per rotation of the screw is possible to be calculated from the equation. However, it does not consider the leakage loss. Table 1 was developed to determine the optimal sizing for AST (Rorres, 2000). The sizing chart is used to determine the optimal geometric parameters shown in Eqs. (10), (11), (12) and (13) (Rohmer et al., 2016).

$$\rho = \frac{Di}{Do}(\text{diameterratio}) \tag{10}$$

$$\lambda = \frac{S\tan\beta}{\pi Do}(\text{pitchratio}) \tag{11}$$

$$\upsilon_u = \frac{V_u}{\pi S R_o{}^2}$$

$$(\text{volumeratio}) \tag{12}$$

$$\lambda\upsilon_u = \frac{V_u \tan\beta}{2\pi^2 Ro^2}$$

$$(\text{volumeperturnratio}) \tag{13}$$

Table 1
Optimal parameter for optimisation of archimedes screw turbine (Rorres, 2000).

Number of blades *N* (1)	Optimal radius ratio p* (2)	Optimal pitch ratio A* (3)	Optimal volume-per- turn ratio A*v(*N*, p*, A*) (4)	Optimal volume ratio v(*N*, p*, A*) (5)
1	0.5358	0.1285	0.0361	0.2811
2	0.5369	0.1863	0.0512	0.2747
3	0.5357	0.2217	0.0598	0.2697
4	0.5353	0.2456	0.0655	0.2667
5	0.5352	0.2630	0.0696	0.2647
6	0.5353	0.2763	0.0727	0.2631
7	0.5354	0.2869	0.0752	0.2619
8	0.5354	0.2957	0.0771	0.2609
9	0.5356	0.3029	0.0788	0.2601
10	0.5356	0.3092	0.0802	0.2592
11	0.5358	0.3145	0.0813	0.2586
12	0.5360	0.3193	0.0824	0.2580
13	0.5360	0.3234	0.0833	0.2574
14	0.5360	0.3270	0.0841	0.2571
15	0.5364	0.3303	0.0848	0.2567
16	0.5362	0.3333	0.0854	0.2562
17	0.5362	0.3364	0.0860	0.2556
18	0.5368	0.3380	0.0865	0.2559
19	0.5364	0.3404	0.0870	0.2555
20	0.5365	0.3426	0.0874	0.2551
21	0.5370	0.3440	0.0878	0.2553
22	0.5365	0.3465	0.0882	0.2544
23	0.5369	0.3481	0.0885	0.2543
24	0.5367	0.3500	0.0888	0.2538
25	0.5371	0.3507	0.0891	0.2542
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
∞	0.5394	0.3953	0.0977	0.2471

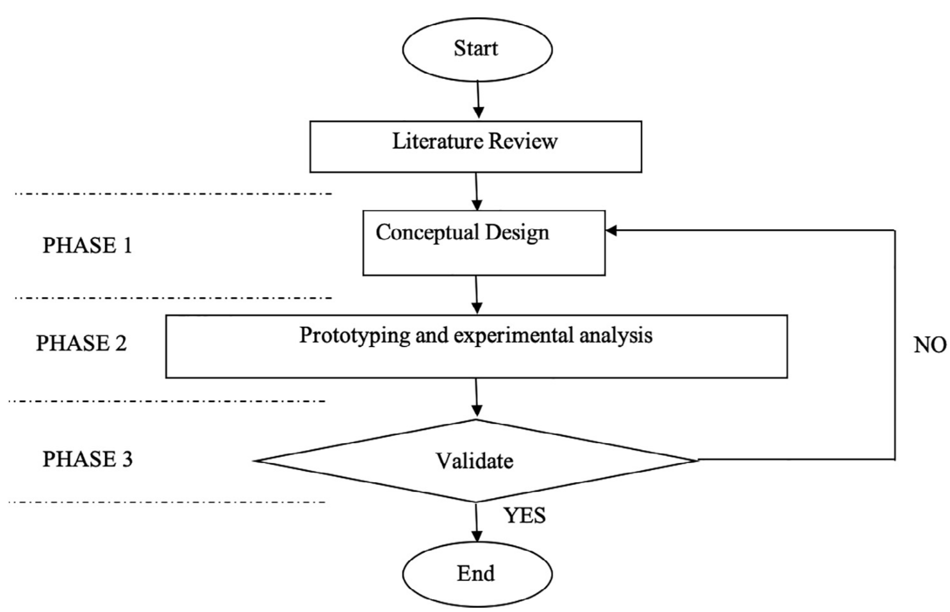

Fig. 4. Research Methodology.

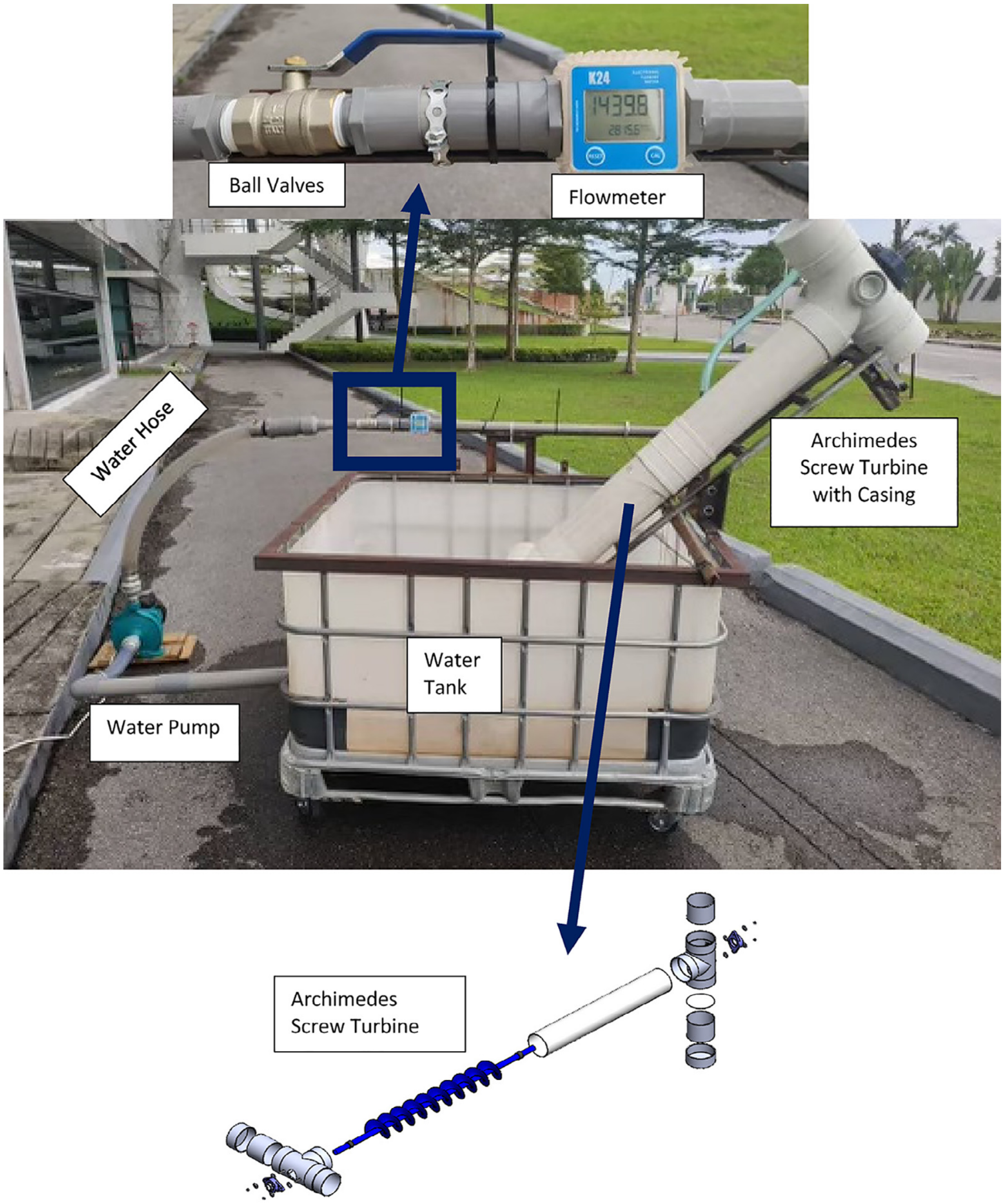

Fig. 5. Experiment Setup.

$\rho = \text{diameter ratio}$

$\text{Di} = \text{inner diameter (m)}$

$\text{Do} = \text{outer diameter (m)}$

$\text{Ro} = \text{outer radius of screw (m)}$

$\beta = \text{angle of inclination (rad)}$

$\text{S} = \text{pitch}$

3.3. *The gap between trough and screw*

The previous study indicates that the minimisation of the gap between the screw and its housing would significantly improve AST as it would lead to the minimisation of the leakage losses (Nagel et al., 1988). Therefore, Eq. (14) is significant to estimate the maximum gap of the screw and trough based on their (Do) outer diameter of the screw.

$$\text{SSP} = 0.0045\sqrt{\text{Do}} \tag{14}$$

Where, SSP = Maximum gap between screw and trough

4. Methodology

This study is divided into 3 phases, shown in Fig. 4. This study started with a literature review on the existing micro-hydro turbine related studies to determine the critical parameters affecting power generation performance. Upon determining the suitable concept, a conceptual model is then being developed in Phase 1. As for Phase 2, a prototype is then being fabricated based on the conceptual design developed in Phase 1. A series of experiments were carried out to determine the optimum working conditions of the prototype under low flow characteristics. In addition, the performance of the prototype is also being recorded and analysed.

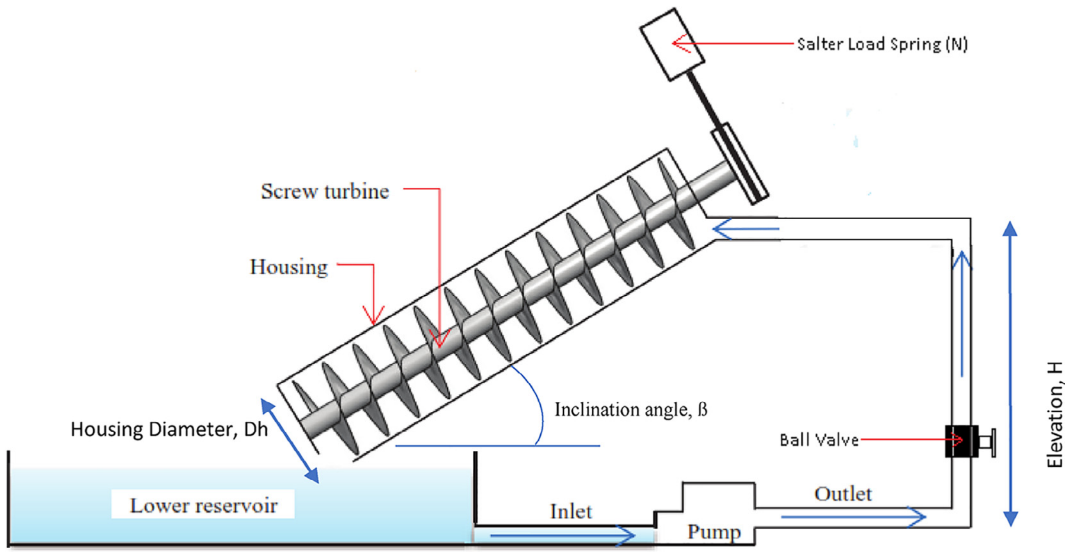

Fig. 6. Schematic Diagram of Experiment Setup.

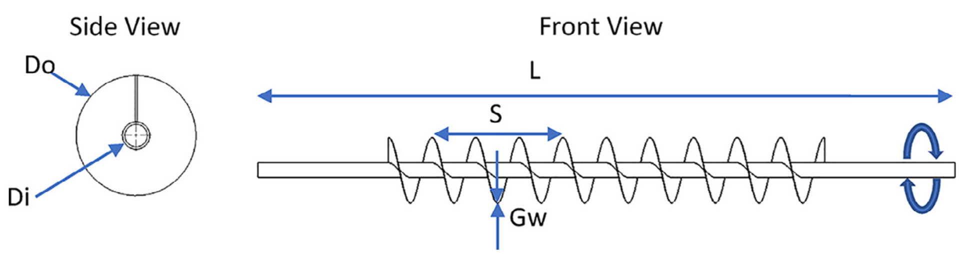

Fig. 7. Engineering Drawing of Prototype.

Table 2
Technical specification of prototype and experiment.

Parameter	Variable	Value
Slope	ß	30°,45°,60°,75°,90°
Outer Diameter	Do	120 mm
Inner Diameter	Di	60 mm
Pitch	S	150 mm
Number of Screws	N	1
Gap Width	Gw	5 mm
Screw Length	L	1560 mm
Housing Diameter	Dh	65 mm
Materials	–	Mild Steel Coated with Paint
Elevation	H	1 *m*
Pump Flow Rate	Q	20–100 LPM
Room Temperature (Celcius)	Temp	28 °C-35 °C
Humidity of Laboratory	Rh	60%-70%
Flow Velocity (m/s)	V	1.0 m/s −1.5 m/s

The findings were then being critically analysed and validated in Phase 3 with the aid of linear regression in IBM SPSS software.

5. Experiment setup

The experiment setup is shown in Fig. 5. The schematic diagram to illustrate the working of the experiment setup is shown in Figs. 6 and 7. The main components are a 1000L water tank as a reservoir, 1.0hp water pump to transport water to simulate river flow, AST, the primary prototype of this study, and a ball valve to control the flow. The river flow velocity is controlled using ball valves from between 1.0 m/s and 1.5 m/s as classified as low flow similar to typical river flow conditions in Sarawak. The data collected are then analysed to study the effect of different AST inclination angles (30°, 45°, 60°, 75°, and 90°) and water velocity on the outputs [revolution per minute (RPM) of the shaft and torque generated]. The RPM of a rotating shaft is measured by using a digital noncontact tachometer. The tachometer has been calibrated by the original equipment manufacturer during the time of the experiment with 95% confidence level (coverage factor, k = 2). However, the accuracy of the tachometer is verified with a known known rotating motor which RPM can be controlled. A digital flow meter is being placed at the inlet to measure the flow velocity, while a ball valve is being used to regulate the flow velocity. Before the start of the experiment, a volumetric calibration (White, 2005) is performed on the digital flow meter to ensure accuracy within 95% confidence level. The experiment is being conducted in room temperature and partially filled water flowing through a pipe (30% – 60% filled). The technical specifications of the screw turbine and the experiments are shown in Table 1.

6. Research findings and analysis

The AST was being tested under various inclination angles and water velocities between 1.0 m/s and 1.5 m/s. The RPM generated was measured using a digital tachometer. The results to show the effect of AST angle inclination and water flow velocity on RPM generated are shown in Fig. 7. Overall, increasing the water flow velocity would increase the kinetic energy in the system, thus increasing the RPM generated by the shaft of AST. Generally, the RPM generated decreases with the increasing angle of inclination except for 45°, which exhibits the highest RPM generation

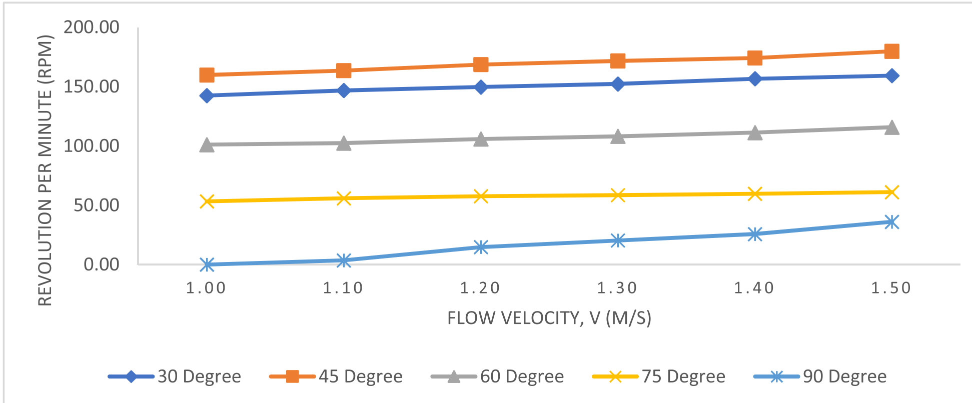

Fig. 8. RPM Generated by Various AST Inclination Angle and Flow Velocity.

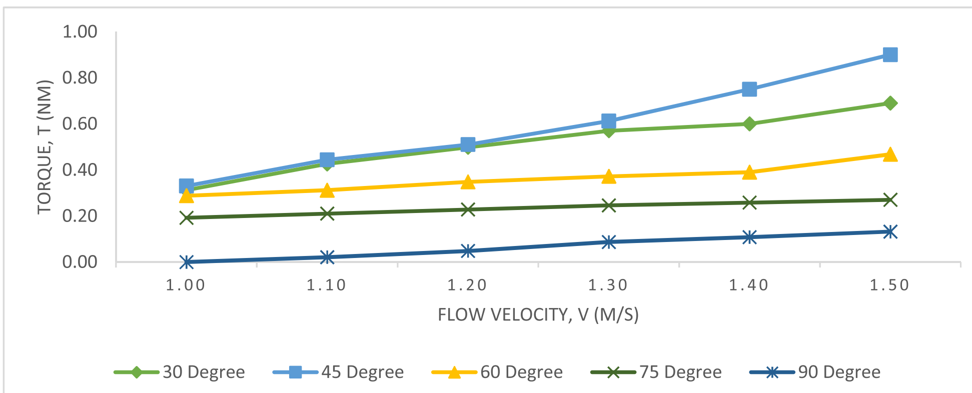

Fig. 9. Torque Generated by Various Angles of Inclination and Flow Velocity.

throughout the experiments. The findings are consistent with the results reported by Muller et al. and Dellinger et al., where both studies showed the trend of efficiency decreasing with increasing turbine inclination (Dellinger et al., 2018; Muller and Thompson, 2015). However, it was noteworthy to point out that other factors are involved, such as the number of blades, the gap of screws, turbine materials, and others. Findings also indicate that the maximum achievable RPM generated by the AST shaft is 179.8 at the angle of 45° with a flow velocity of 1.5 m/s (Table 2).

The torque generated by AST under various inclination angles and flow velocity were also recorded and shown in Fig. 8. Similar to the trend of RPM generated, the torque generated is also rises with the increasing water flow velocity. The trends also indicate that the decreasing angle of AST inclination would increase the torque generation but peaked at 45°. It was noteworthy that for AST inclination angle of 30° and 45°, both generate similar torque until the water flow velocity reaches 1.3 m/s and higher. The reason behind might be due to the overfilling phenomena which occur at an inclination angle of 30°. The overfilling phenomena are the flow of water through the screw exceeding the maximum volume of the bucket. The overflow is causing the power loss that does not aid in the rotation of the screw. Such phenomena are consistent with findings reported by Kathleen Songin (Songin, 2017) in which water begins to overflow over the screw central shaft and pours into the downstream bucket; the water surface is interrupted by falling water (Fig. 9.).

The optimum working conditions and performance of the prototype under the maximum flow of 1.5 m/s are recorded in Table 3. The maximum torque recorded in this study under the 45° angle of inclination and flow velocity of 1.5 m/s is 0.9Nm. The maximum mechanical power generated under the best working conditions in this study is 1.54 kW with 94.6% of mechanical efficiency. All findings signify that for a small-scale AST to work under low flow velocities up to 1.5 m/s, the angle of inclination must be designed to operate at 45°.

Table 3
Summary of prototype working conditions and performance.

Parameters	Variables	**Optimum/*Maximum Values
Angle	ß	45° **
Flow Velocity	V	1.5 m/s*
Torque	T	0.9Nm*
Rotation of Turbine	n_r	179.8RPM*
Mechanical Power	Pmech	1.54 kW*
Mechanical Efficiency	ηm	94.6%*

The outputs generated by statistical software are summarised in Table 4. There are two models generated which are shown in Eq. (15) for the model predicting RPM generated by AST (Model 1) and Eq. (16) for the model predicting torque generated by AST (model 2).

$$RPM(t) = 8770.AI^{-1.436}.WV^{2.261} \quad (15)$$

$$Torque(t) = 2466.AI^{-1.436}.WV^{2.261} \quad (16)$$

It was noteworthy that both models are statistically significant ($p < 0.05$) with a 95% confidence level under low flow low head condition. The Pearson R^2 value of both models was more than

Table 4
Model summary of regression.

Model	R	R Square	Sig.
1	0.775[a]	0.601	0.000[a,b]
2	0.823[a]	0.677	0.000[a,b]

[a] Predictors: (Constant), Log10 Water Velocity (WV), Log10 Angle of Inclination (AI).
[b] Model is significant ($p < 0.05$) with one-tailed test at 95% confidence level.

60%, which means the variables and results collected are significant to this study. Therefore, the outcome of this study would be useful for power generation with hydro energy under similar characteristics. Eventually, this study would contribute to the decarbonisation of the energy sector and rural development, especially in electrifying villages near the river stream with low head and low flow.

7. Conclusion and recommendation

In this study, there are two independent variables tested, which are the angle of inclination and water velocity with the dependent variables of RPM and torque produced by the AST prototype in the laboratory. Based on the results obtained, the best angle of inclination to produce the highest rotation per minute is at the angle of 45°, and its maximum RPM and torque generated were 179.8 and 0.9 N/m respectively with 1.5 m/s for the velocity of the water. The maximum mechanical power generated is about 1.54 kW with 94.6% efficiency. Findings also showed that the AST angle of inclination is negatively associated with both RPM and torque generated. This study has shown that the AST is significant in generating RPM and torque even under low flow. The limitation of this study is that the outcome of this study is only suitable to be implemented in river flow velocity, that is, between 1.0 m/s and 1.5 m/s. With higher flow velocities, the optimum operating characteristics such as inclination angle might varies. On the other hand, the results obtained from this study are purely experimental in laboratory. Therefore, testing with the similar setup in the actual river is highly recommended for future study. It is also recommended to design and develop an efficient power take-off system to couple with AST for harnessing the mechanical energy generated by the system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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