

## EFFECTS OF VARYING INCLINATION ANGLE ON ARCHIMEDES SCREW GENERATOR POWER PRODUCTION WITH CONSTANT HEAD

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**Abstract**—Archimedes screw generators are small-scale hydropower devices that are usually installed as diversion systems at sites with low head and moderate flow rates. Screw generators are usually designed empirically – they have been in use as pumps for millennia, and the same practical design principles are commonly implemented on generator schemes. For example, most Archimedes screws are installed at inclination angles at or about 25° - however, there is a lack of evidence to prove that this is best practice. This experiment tested three different screws, identical in all parameters except overall length so that the inclination angle could be varied while maintaining a constant head difference across the screw. Each of the screws were set in a test rig to measure power production. Since the head across the screws was the same, the screws were installed at varying inclination angles to meet this constraint. It was found that the longest screw (with the smallest inclination angle of 15°) performed the best, followed closely by the screw set at the common inclination angle of 25°. The shortest screw (at the steepest inclination angle of 33.8°) performed the poorest. Some suggestions are made with regards to the performance of the screws, and how to improve future power prediction models for Archimedes screw generators.

**Keywords**—Archimedes screw generator; computational fluid dynamics; microhydro generation; inclination angle; number of blades; efficiency; bucket fill height;

### I. INTRODUCTION

An Archimedes screw generator (ASG) is a small-scale hydropower device that is usually installed as a diversion (or run-of-river) system. ASGs have been implemented for hydroelectric energy conversion since the 1990s [1]. They have historically been used as pumping devices with evidence of use dating back as far as the 7th century BCE Assyrian Empire under the reign of King Sennacherib [2]. Due to its simple, robust design, the Archimedes screw has been used to pump a

variety of mediums including granular solids in agriculture and mixtures of liquids and solids in wastewater treatment.

The Archimedes screw is now widely accepted as an “eco-friendly” hydropower option – since it allows for sediment, debris, and even aquatic wildlife to pass through the screw unharmed when operating as a generator [3]–[5]. Additionally, as a run-of-river device, up- and downstream conditions in the waterway will be negligibly affected by the installation when compared to the impacts of conventional, impounded hydropower systems [6]. Altogether, this suggests that the device has limited impacts on riverine ecology.

The simple, robust design of the screw also lends itself to low costs of manufacturing and installation [7], [8], and maintenance [7]–[10] – especially when compared to other turbine options with similar operating ranges. Specifically, ASGs operate best under low head and moderate flow rates [11], and can reach efficiencies upwards of 80% in these ranges [12].

The construction of Archimedes screws is considered simple because it is made up of a set of helical blades that are welded around a central cylindrical tube. Screws are usually classified based on their geometries or design flows. The geometry of the screw is shown in Fig. 1.

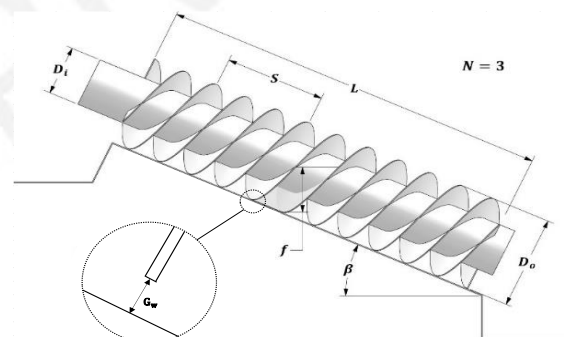


Figure 1. Archimedes screw geometric parameters

The screw rotates within a trough with a small gap between the trough and the blade tips – termed the gap width  $G_w$ . The screw has an inner and outer diameter ( $D_i$  and  $D_o$ , respectively), pitch  $S$ , number of blades  $N$ , and overall flighted length  $L$ . When operating as a generator, water fills in the space between a set of adjacent blades (termed a “bucket” [13]), and a torque due mostly to the static water pressure on the screw blades causes the screw to rotate. The screw can either have a fixed or variable rotational speed ( $\omega$ ) which, along with the available flow  $Q$  and head at the inlet and outlet of the screw, determines the fill height ratio ( $f$ ) of the buckets.

The fill height ratio is a dimensionless parameter that defines the amount at which a bucket is “full”. The full case, or  $f = 1$ , can be seen in Fig. 1 – the water level reaches the top of the inner cylinder without spilling over into the next bucket along that flight. Experience suggests that a screw can generate more energy with a small amount of overflow (i.e. if  $f > 1$ ). The fill height ratio is discussed in more detail in the literature [14].

The literature also contains a few models of ASG performance and power losses [15]–[19], as well as some data collected experimentally on laboratory-scale devices [20], [21] or through numerical simulation [22], [23]. However, there is a lack of evidence to definitively assure that the models are valid, particularly since the issue of scaling has not been rigorously addressed (i.e. most of the experimental evidence for ASG power production has been carried out at the laboratory-scale level, not on full-sized installations).

The University of Guelph’s Archimedes Screw Laboratory has an inventory of 16 unique laboratory-scale screws for experimentation. The screws vary in their diameter ratios, pitch, number of blades, and length. The laboratory setup allows for the flow rate, rotational speed, inlet and outlet water levels, and inclination angle to be adjusted.

Experience suggests that most installations have an inclination angle set around  $\beta = 25^\circ$  [12], but there is a lack of empirical evidence to back this claim. A recent study showed the effect of variable inclination angles on ASG performance [24]. In the study, a screw was installed in the University of Guelph’s laboratory and the inclination angle of the screw was varied, and the power production recorded. The experimental dataset was then extended with a computational fluid dynamic (CFD) simulation of the screw, which allowed the dataset to be extended to screw geometries beyond what was available in the laboratory. The head of the screw changed as the inclination angle of the screw changed in these experiments since the screw’s geometry remained constant (cf. Fig 2). This meant that the power production could not be directly compared between the different orientations (since the available power in the water changes with the head), but the efficiencies of the screw orientations could be compared.

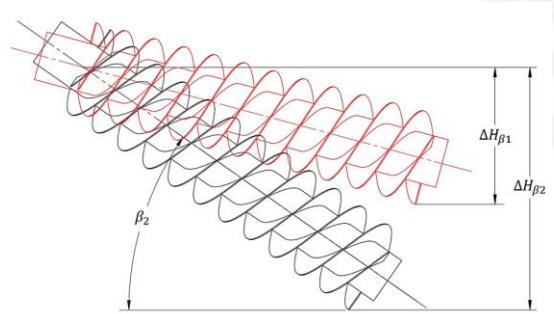


Figure 2. Head changes with inclination angle in these experiments, as the screw length and geometry are kept constant [24].

The objective of the study described in this paper was to compare the effect of inclination angle to power production and performance of an ASG, while varying inclination angle and keeping all other geometric parameters constant.

A couple hypotheses were made towards the goal of this paper. Firstly, as the inclination angle increases it is expected that the overflow and gap leakage losses will increase; however, as the rotational speed of the system increases they are expected to decrease at any inclination angle. For example, it is expected that a screw at the steepest inclination and slowest rotational speed will have the most leakage and overflow losses.

Secondly, as the inclination angle decreases, it is expected that the minor losses in the system will become more evident. The lower inclination angle lends itself to a longer screw – which has more surface area to exhibit frictional losses.

An experiment was carried out to gather performance data for laboratory-scale ASGs under a range of inclination angles and rotational speeds. The data was then analyzed and used to draw conclusions related to the hypotheses.

## II. EXPERIMENTAL METHODS

There is a set of three screws in the University of Guelph’s Archimedes Screw laboratory that have identical parameters except their flighted length – allowing them to be set at varying inclination angles that correspond to the same flow and head conditions at the screw’s inlet and outlet. For the purposes of this paper, the three screws will be called the “short screw”, “medium screw”, and “long screw”. They are shown drawn to scale in Fig. 3.

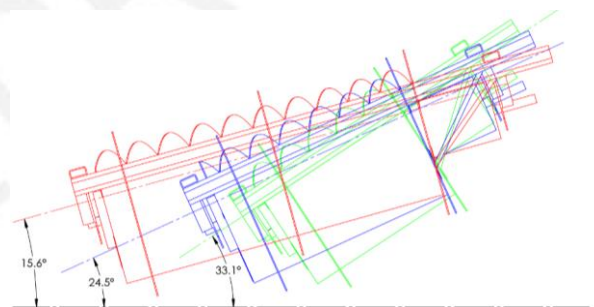


Figure 3. Angles of three screws with constant head. The short screw (green) has the steepest inclination angle, the long screw (red) has the shallowest inclination angle, and the medium screw (blue) has been set at an inclination angle of  $\beta = 24.5^\circ$  to match with previously collected data and the most common inclination angles of real-world ASG installations.

The dimensions of the three lab-screws are shown in Table 1. The inclination angle is found with respect to the flighted length of the screw and the constant head difference between the set of screws as demonstrated in Fig. 4.

The tests were started with the medium screw, since it was the closest representation to a typical “real-world” installation’s inclination angle. The screw was installed in the Archimedes screw test rig at the University of Guelph shown in Fig. 5. The system has settings to adjust rotational speed and the flow of water through the screw. The rotational speed of the screw is controlled with a variable frequency drive (VFD). The VFD controller allows the motor to turn at a specified frequency and will either apply a brake or accelerate the screw to maintain the set speed. A torque arm is attached to the VFD, and force is measured between the torque arm and the fixed frame of the setup. The water flows through a recirculating loop, and flow rate is controlled with a variable water pump in the lower basin. The system is also designed to utilize weirs to control the water level in the lower basin – allowing for the outlet water level and head difference in the system to be controlled.

Table 1. Experimental screw dimensions with corresponding inclination angles.

	Symbol	Short Screw	Medium Screw	Long Screw
Number of Blades	$N$	4	4	4
Inner Diameter (mm)	$D_i$	168	168	168
Outer Diameter (mm)	$D_o$	381	381	381
Pitch (mm)	$S$	381	381	381
Flighted Length (mm)	$L$	478	617	952
Inclination Angle (deg)	$\beta$	33.8	24.5	15.6

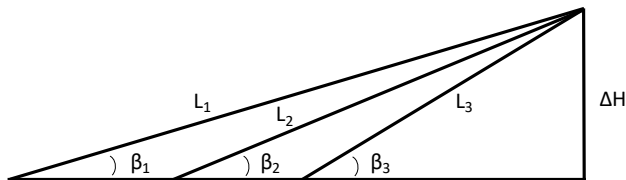


Figure 4. As flighted length of the screw changes, the inclination required to maintain a constant head  $\Delta H$  also changes.

The laboratory setup has sensors that measure the flow rate, torque, rotational speed, bucket fill height, and upper and lower basin water levels. The flow rate is measured with a propeller-type flow meter (Omega FTB-740) and verified with a Cipoletti weir on the inlet end of the system. Both the upper and lower basin have depth sensors (Keller Series 26 Y) in stilling wells that measure water level – these are verified with manual readings of the water level. The rotational speed of the screw is measured with an optical tachometer and verified with a separate handheld unit. Finally, the torque was sampled by mounting a load cell (Omega LC703-25) to a torque arm attached on the system’s VFD motor/generator.



Figure 5. Laboratory test setup.

The process for each experimental run was as follows. The screw and recirculation pump were set to a specified rotational speed and flow rate, respectively. Next, the system was given a few minutes to reach an equilibrium condition at the new settings. It was noted that the screw usually required less than a minute to reach equilibrium conditions after a change of settings. After equilibrium conditions were met, a data acquisition program was run to sample the sensors on the screw setup for one minute at a frequency of 1000 Hz – a frequency much higher than the Nyquist rate for the apparatus. The one-minute sample was then time-averaged to more accurately predict the system’s response to the given flow, rotational speed, and head difference. Next, the data from the sample run was reviewed to see if the flow rate, rotational speed, and outlet water level were within 1% of their target values - if it met the criteria, the data was accepted and recorded. The flow rate and rotational speed of the next run were then set, the screw was allowed to reach equilibrium at the new conditions, and the process was repeated.

It is important to note that all of the tests in these experiments were carried out at outlet water levels of 60%, since previous testing has shown this to be the most optimal outlet condition for these screws [14], [21].

The medium length screw was run through a range of five flow rates (9, 9.5, 10, 10.5, and 11 L/s), and, at each of these flow rates, ten different rotational speeds (30 to 39 RPM) to find the setting that corresponded to the highest power production and efficiency. It was found that the most optimal flow rate for this screw was 10 L/s. Afterwards, the short and long screws were run through the same range of rotational speeds at the 10 L/s flow rate. The experiment was carried out this way to maintain the available power in the water. The flow rate corresponding to the most optimal power production in the medium screw was selected as the base case as a point of comparison (i.e. all the screws must be tested at the same flow rate and head difference, so the most optimal setting was chosen arbitrarily for the medium screw since it was most reflective of a real-world installation).

### III. RESULTS

As mentioned above, tests were first carried out on the medium screw to determine the optimal flow rate for the

experiment. The plot in Fig. 6 shows the efficiency of the screw with respect to rotational speed for each of the five flow rates tested. An uncertainty analysis was carried that found an average uncertainty for efficiency values based on measured data of about  $\delta\eta_{\text{avg}} \approx 0.054$  or 5.4%. The magnitude of the uncertainty is due to propagation of error in subsidiary measurements – as will be shown shortly.

In Fig. 6, the highest efficiencies occur along the curve for 10 L/s; the 10.5 L/s curve seems to have similar maximum efficiencies but tends to drop off faster at the lower rotational speeds. It is interesting to note that the maximum efficiency points seem to shift to different rotational speeds as the flow rate changes. As flow rate increases, the maximum efficiency occurs at higher rotational speeds. Since the data is so close together for all curves (noting that the Fig. 6 ordinate (“y-axis”) spans a range of less than 10% efficiency – the error bars also help to reinforce the closeness of the datapoints), the points near the highest efficiencies were run multiple times: multiple sets of one-minute time-averaged data were collected and averaged to verify that the points were not outliers and were representative of the performance of the screw under those conditions. It was determined that the medium screw performed best at a rotational speed of 36 RPM when experiencing a flow rate of 10 L/s.

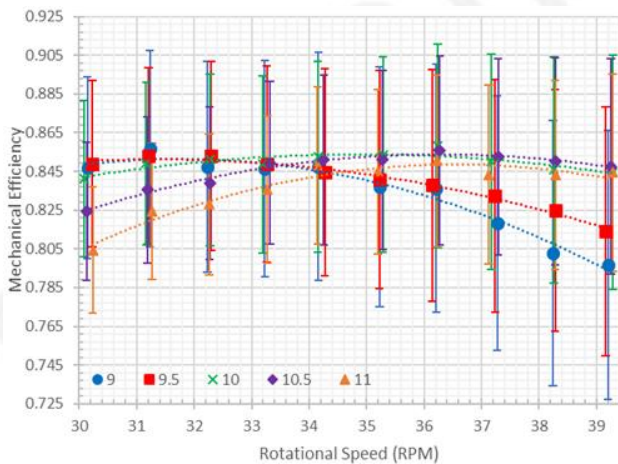


Figure 6. Mechanical efficiency of Screw 15, varying rotational speed from 30 to 39 RPM for 5 different flow rates (9, 9.5, 10, 10.5, 11 L/s). The plot has approximate trend lines superimposed to make it easier to visualize the data trends.

The short and long screws were then run at 10 L/s for the same range of rotational speeds, the results of these tests are shown in Fig. 7. As the figure shows, the long screw (with the smallest inclination angle) proved to be the best performing screw – it generated the most power and was thusly the most efficient of the three inclination angles. The medium screw had similarly high efficiencies and the two trends seemed to converge as the rotational speed increased. The short screw (i.e. the steepest inclination angle) was the least efficient option but performed better at higher rotational speeds as it has less drop-off near the end of the curve.

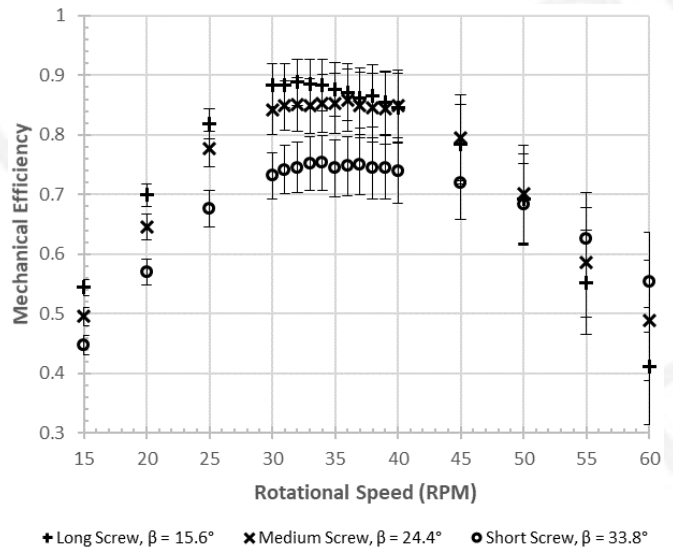


Figure 7. Mechanical efficiency of screw 14, 15, and 16 for varying rotational speeds.

Fig. 7 includes error bars calculated for each test run. The uncertainty in the mechanical efficiency was found by carrying out an uncertainty analysis given the accuracies of the equipment used in the experiment to calculate the power and efficiency of the screw. The power produced by the screw is a function of the torque and the rotational speed. Since the data was sampled at a frequency of 1000 Hz, and the rotational speed of the screw was less than 60 RPM, the uncertainty in the rotational speed measurements was neglected. The torque measurements were taken with a strain gauge that was shown to have an average error of  $\delta T = 0.22 \text{ N}\cdot\text{m}$  [14].

Efficiency is calculated by dividing the mechanical power produced by the screw by the power available in the flow (i.e.  $\eta = P / P_w$ , where  $P_w = \rho ghQ$ ). Two Keller Series 26 Y depth sensors were used to measure the head (h) each having an accuracy of 0.25 %FS. An Omega FTB-740 Inline Turbine Flow Meter was used to measure the flow rate, having an accuracy of 1 %FS. After carrying out uncertainty analysis it was shown that the average error in the efficiency measurements was about  $\delta\eta_{\text{avg}} \approx 0.054$  or 5.4%, as mentioned above.

The better performance of the long screw relative to the other two is likely due to the filling scenarios and the scale of the buckets. Past experience suggests that short screws will exhibit more gap leakage, more overflow leakage, will not contain as many buckets (since they are shorter), and that each bucket will have less volume due to the cylindrical and helical shape of the bucket geometry [25]. It was observed during testing that the short screw only has a fully formed bucket of water for a brief time before the water exits the screw. Since it is so short, there is only a very brief period where the height of the water in a bucket is fully independent of the upper or lower basin.

Interestingly, the long screw was predicted to underperform the medium screw – this was shown false in the experiments. While the power output of a short screw (at steep inclination) tends to be limited by geometric constraints, longer screws (at

shallow inclinations) will experience more minor losses and bearing losses [21], [25]. In this case, since the screws are all laboratory-scale, it may be that the minor losses and bearing losses will make up a much larger proportion of power loss than in a real-world installation. In any case, the long screw was able to fully form more buckets during power production and seemed to have less overflow than the medium screw. Power production is dominantly based on the static pressure distributions within the buckets. The fill heights within each of the three screws during their most efficient tests are shown in Fig. 8 to lend more insight into the performance curves found in Fig. 7. Since there are four blades for these screws (i.e.  $N = 4$ ) the curves of Fig. 8 have four separate peaks and valleys for each full rotation, and therefore a full rotation of all the screw blades is shown in Fig. 8.

Fig. 8 shows that the buckets of the medium and long screws have fully formed, with bucket fill height ratios above  $f = 1$ , indicating that some overflow leakage is occurring in these runs. Given that the error of the Omega PX309 pressure sensor was 2%, and, taking into account error in measuring offset, the error in the fill height measurements was found to be an average of  $\delta f_{\text{avg}} = 0.017$ .

The short screw seems to have fill heights much lower than a full bucket, which is further evidence that it does not have fully formed buckets along its length. It is interesting to note that the slope of the sawtooth (cf. Fig. 8) is proportional to the inclination angle of the installation. This means that the bucket will be filled closer to level as the length of the screw increases (i.e. the shallower incline corresponds to a larger bucket volume). It is also evident from Fig. 7, that the medium length screw experienced the most overflow leakage – partly leading to its lower-than-expected efficiency performance.

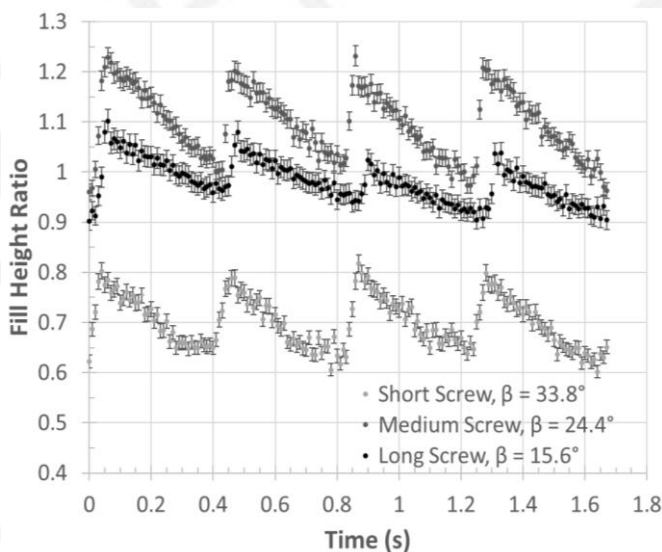


Figure 8. Fill height ratios for screws 14, 15, and 16 over one full screw rotation.

These experiments provided insight into the effects of inclination angle on power production in ASGs – they will serve to help further develop power loss modelling in screw generators.

#### IV. CONCLUSIONS

The experiment presented in this paper provides valuable insight into the effect of inclination angle on the performance of Archimedes screw generators. Experience has suggested that ASGs operate best at inclination angles around  $25^\circ$ , but the laboratory-scale data shows that this may not be true for all sizes of screws. Indeed, at this system scale the best performing screw had an inclination angle of  $\beta = 15.6^\circ$ .

The experimental observations provide support for some of the hypothesis made in this paper. For example, as the inclination angle increases the overflow losses and leakage losses are expected to increase. The experiments demonstrated that this is likely true, since there is much less power produced in this screw. As well, if volume flow rate is held constant, gap leakage and overflow leakage tend to decrease as rotational speed increases [21], and since the short screw performs best in higher rotational speeds, its likely because these effects are lessened in this range.

Another early hypothesis was that as the inclination angle decreased, it was expected that there would be an increase in minor losses in the system. This effect was not wholly evident in the data; however, it is very likely to be negligible in these laboratory-scale devices. In larger installations, a change in inclination angle can mean a screw that is meters longer, not centimeters (as seen in these experiments). Since the screws are all among a similar size and length at this laboratory-scale, it is suggested to continue to explore the relationship between inclination angle and power output in more detail on larger-scale installations or by means of CFD.

#### ACKNOWLEDGMENT

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