ARCHIMEDES SCREWS FOR MICROHYDRO POWER GENERATION

Murray Lyons
University of Guelph
Guelph, Ontario, Canada

William David Lubitz
University of Guelph
Guelph, Ontario, Canada

ABSTRACT

Archimedes screw generators (ASGs) are beginning to be widely adopted at low head hydro sites in Europe, due to high efficiency (greater than 80% in some installations), competitive costs and low environmental impact. Compared to other microhydro generation technologies, ASGs have greatest potential at low head sites (less than about 5 m). The performance of an Archimedes screw used as a generator depends on parameters including screw inner and outer diameter, slope, screw pitch and number of flights, and inlet and outlet conditions, as well as site head and flow. Despite the long history of the Archimedes screw, there is very little on the dynamics of these devices when used for power generation in the English literature. Laboratory tests of small Archimedes screws (approximately 1 W mechanical power) have been conducted to support the design and validation of ASG design tools. This paper reports experimental results examining the relationship between torque, rotation speed and power. The laboratory screw maintained reasonable efficiency over wide ranges of operating conditions, although distinct efficiency peaks were found to occur. The cause of changes in power output caused by varying the water level at the outlet of the screw were attributed primarily to the corresponding variation in head, and dynamic limiting of screw rotation speed causing corresponding limits in volume flow through the screw. Test results were qualitatively consistent with data from a prototype ASG installed by Greenbug Energy in southern Ontario, Canada and recent data reported from European laboratory tests and commercial installations.

INTRODUCTION

Archimedes screw generators (ASGs) are beginning to be widely adopted at low head sites in Europe due to high efficiency, competitive costs, and low environmental impact. These same factors, as well as increasing policy support for distributed renewable energy generation, are expected to result in a significant market for ASGs in North America.

ASGs are a recent addition to the available range of microhydro generation technologies. Williamson, Stark, & Booker (2011) discuss the relative merits of microhydro technologies, and include a design approach for selecting an appropriate technology for a specific site. Compared to other generation technologies, ASGs have greatest potential at low head sites (less than about 5 m), and unlike conventional reaction or impulse turbines, have the potential for maintaining high efficiencies even as the head approaches zero (Williamson et al., 2011).

An Archimedes screw consists of an inner cylindrical shaft, around which one or more helical surfaces (flights) are wrapped orthogonal to the cylinder surface (Fig 1). The resulting geometry is very much like a conventional screw. The screw sits in (and in some cases has fixed to it) a cylindrical trough. This trough may be a tube that encircles the screw, or it may only extend around the lower half of the screw. When used as a pump, an Archimedes screw is rotated, which traps water between two consecutive flights. This body of water is called a ‘bucket’ and is raised along the trough as the screw turns. ASGs operate in reverse: water flows into the top of the screw, causing it to turn. As with pumping, the water is bounded by two consecutive flights in a ‘bucket’. The hydrostatic pressure this body of water exerts on the bucket surfaces causes the screw to turn, lowering the bucket in the process.

Available data show that ASGs are very efficient. A small ASG developed by Prof. Hiroshi Takimoto of Toyama Prefectural University (Japan) reportedly operates at 60% efficiency (Japan For Sustainability, 2008). Brada (1999) reported efficiencies on the order of 80% in an operational ASG in Germany. A recent survey of commercial ASG installations in Europe by Hawle...
and Pelikan (2012a) found a mean efficiency of 69%, with maximum efficiencies over 75% for this type of power system.

Unlike most microhydro technologies, fish and small debris can pass through an operating ASG without causing damage to the screw. Conversely, ASGs in general do not harm fish. Archimedes screw pumps are used in the aquaculture industry to move fish, and a California study of juvenile salmon found more than 98% survived passage through Archimedes screw pumps (Mcnabb, Liston, & Borthwick, 2003). Studies of an ASG on the River Dart (UK) found that almost all fish, including eels, trout and salmonoids, passed through the ASG unharmed, and that intake screening was not necessary (Kibel, 2008; Kibel, Pike and Coe, 2009). Laboratory tests found fish less than 1 kg were not injured by contact with the screw leading edge if the tip speed was less than 4.5 m/s (a speed greater than many operating ASGs): addition of a rubber leading edge further reduced injuries to larger fish at higher tip speeds (Kibel, Pike and Coe, 2009).

While there is significant scientific literature on the use of Archimedes screws as pumps (e.g. Rorres, 2000; Koetsier, & Blauwendraat, 2004, Nagel, 1968), there is still little English literature addressing engineering of Archimedes screws when used to extract energy from a flow, and much of what is available is case studies of installations. Most of the case studies are qualitative, however Brada (1999), Bard (2007) and (Hawle et al, 2012a) report sufficiently detailed performance data from operating ASGs to be useful for engineering modeling.

There is also little examination of the dynamics of ASGs in the literature. Muller and Senior (2009) are an exception, presenting an efficiency model of an Archimedes screw based on the difference in hydrostatic pressure across the screw surfaces. The model includes the effect of leakage between the gap between screw and trough. Muller and Senior (2009) concluded that the efficiency of a screw is theoretically independent of rotation speed. However, to achieve a compact equation for predicting efficiency, their model simplifies the screw geometry to such a degree that it is not useful as a practical design tool.

Nuenberkg and Rorres (2012) examined the inflow conditions to an ASG, and propose an analytical model which can be used to predict and design for optimal inflow conditions.

Hawle et al. (2012b) examined the effects of screw geometry on turbine efficiency, both in lab tests and via a survey of existing ASG sites across Europe. The survey found that plants on the order of 10 kW to 60 kW were most common, and that fixed speed generators are much less tolerant of large flow variations than variable-speed generators. Their lab tests also examined the use of a rotating trough in an effort to increase efficiency. They found that in most cases, a fixed-trough design is more efficient, and more tolerant to changing flow conditions.

There is insufficient English literature currently available on ASGs to guide designers seeking to optimize an ASG for specific site and flow conditions. It should be noted that there is a large body of non-English literature related to ASGs, with recent examples including Brada (1996), Aigner (2008), Schmalz (2010), and Lashofer et al. (2011). However, even this non-English literature does not answer all questions on ASGs. This paper focuses on experimental tests of a set of laboratory-scale prototype ASG turbines. This work is part of a larger research project seeking to develop engineering models of ASG turbines that can be used as practical engineering tools.

**EXPERIMENTAL SETUP**

Laboratory experiments allow measurement of ASG performance across a wide range of conditions and parameters, such as screw rotation speed, slope, and fill point, that are not easily obtained from field measurements of operating ASGs. Currently, only one research group has reported results of ASG laboratory studies in the English literature (Hawle et al., 2012a; Hawle et al., 2012b). Laboratory studies of ASGs were initiated at the University of Guelph to help fill this important gap in the literature.

A series of laboratory scale Archimedes screws were custom fabricated by Greenbug Energy Inc. The parameters of the lab screw reported in this paper is given in Table 1. The lab screw was tested in a custom built experimental apparatus capable of providing a range of controlled head and flow conditions (Fig. 2). During a test, the screw is suspended at each end on low friction bearings within a cylindrical trough. The trough is optically clear acrylic plastic to allow for future studies.
involving flow visualization. The nominal gap thickness between the screw and trough is 0.75 mm. This gap is necessary to prevent friction between the screw flights and the trough, but also allows for leakage losses. An upper reservoir supplies water to the screw. Water is supplied by an electric pump that operates continuously, and reservoir depth is controlled by an adjustable overflow weir.

Flow exiting the screw is collected in a lower reservoir (also with controllable depth) and then passes through a calibrated V notch flow meter before dropping back into a sump which supplies the pump that feeds the upper reservoir. Water depths within the upper and lower reservoirs were measured to the nearest millimeter using integrated sight tubes.

The power output of the screw was dissipated by an adjustable friction brake on the upper end of the rotation shaft. Torque was measured by a load cell (Omegadyne LCM703-25) affixed to an arm integrated into the brake assembly. Rotational velocity was measured using a custom Hall effect sensing circuit located in proximity to the path of rare earth magnets affixed to the ASG shaft.

Head and flow data were recorded by visual observation of sight gauges and V notch depths. Rotational velocity and torque measurements were recorded using a National Instruments (NI USB-6009) DAQ. Reservoir levels, flow through the system, and braking force were set and allowed to settle to equilibrium before data was collected for a trial. Torque and rotational velocity were measured for one minute at 1000 Hz while reservoir levels and flow rate were observed and recorded.

### RESULTS

The mechanical power produced by an ASG is \( P = \omega T \), where \( \omega \) is the rotational speed of the turbine in rad/s and \( T \) is the torque in Nm. A typical test involved setting operating parameters (flow \( Q \), inclination angle \( S \), etc.) and varying braking load to produce a torque/speed curve. Fig 3 shows torque-speed curves for several different lower reservoir levels. Since power is the product of torque and rotation speed, each operating condition will have an optimal point on the torque-speed curve that maximizes power production.

![Figure 3. Rotational velocity versus torque, varying lower reservoir level](image)

The maximum power \( P_{\text{max}} \) available to a hydroelectric turbine is given by

\[
P_{\text{max}} = QH\rho g
\]

where \( Q \) is the flow rate, \( H \) is the head drop across the turbine, \( \rho \) is the water density, and \( g \) is the gravitational constant. The efficiency \( \eta \) of the ASG can be written as

\[
\eta = \frac{P_{\text{max}}}{P} = \frac{\omega T}{QH\rho g}
\]

During testing, a nominal flow rate of 0.785 l/s and head of 248 mm was used, giving a typical \( P_{\text{max}} \) of 1.9 W. In addition to a range of torque and speed combinations, tests were conducted under stalled (\( \omega = 0 \)) and free-wheeling (zero applied torque) conditions for each profile. At stall, it was possible to quantify the leakage losses through the test ASGs. On average, 30% of the overall flow (minimum 6%) through the ASG was estimated to be lost due to leakage. Typical efficiencies during the lab tests were on the order of 45%.

Maximizing the efficiency increases the power drawn from the water in all cases. This includes when the flow and/or head across the ASG changes.

### Table 1. Test Turbines

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lab ASG</th>
<th>Prototype ASG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter ( D ) (cm)</td>
<td>14.6</td>
<td>59.95</td>
</tr>
<tr>
<td>( P/D )</td>
<td>1.0</td>
<td>1.72</td>
</tr>
<tr>
<td>( d/D )</td>
<td>0.522</td>
<td>0.54</td>
</tr>
<tr>
<td>Length ( L ) (cm)</td>
<td>58.4</td>
<td>244.26</td>
</tr>
<tr>
<td>Number of flights ( N )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Slope ( ^\circ )</td>
<td>22.7</td>
<td>22</td>
</tr>
</tbody>
</table>
OUTLET WATER LEVEL

Most ASG installations are run-of-the-river, and varying water levels up- and downstream of the ASG can impact performance. Certain flow regimes in many smaller watercourses can increase water level downstream of an ASG, sometimes to the point where the lower end of the ASG is completely submerged (‘flooded’), decreasing effective head.

The effect of varying water depth relative to the ASG outlet was examined. A series of tests were conducted varying the depth in the lower reservoir while maintaining a constant depth in the upper reservoir. The lowest lower reservoir depth corresponded to a free surface just intersecting the lowest extent of the trough at the outlet, while the highest depth tested completely submerged the entire outlet of the cylindrical trough. It should be noted that the overall head across the ASG decreased as lower reservoir depth increased.

ASG performance was measured across a range of lower reservoir depths: torque-speed curves are shown in Fig 3. Fig. 4 shows the relationship between torque and power for varying outlet depths. As expected when the water depth rises (and overall head decreases), the maximum power output of the screw declines. It is also clear that the maximum power point occurs at different torques.

The same tests examined as a rotation speed-power curve (Figure 3. Power versus rotation speed at different lower reservoir depths) reveals that as the head increases, the rotational velocity where maximum power occurs varies very little. This suggests that, if the rotational velocity of the turbine is well selected for optimal conditions, the ASG will still perform well in decreased head conditions at a fixed rotational speed. Examining the efficiency as a function of rotational velocity for varying lower reservoir depths (Fig 7) confirms this.

Nuernbergk and Rorres (2012) suggest that the point of maximum ASG efficiency corresponds to the maximum fill of the ASG’s ‘buckets’. This was verified in the course of these experiments. This point also corresponds roughly to the maximum non-stall torque. Fig. 4 shows that the maximum power output will occur roughly with the maximum non-stall torque; Figs. 6 and 7 show that this maximum power point corresponds to the maximum efficiency of the ASG.
While the lab test screws had lower efficiencies than commercial versions, this is likely due to the comparatively large leakage losses seen in the lab, due to the small scale of the tests screws.

Many commercial ASGs use constant-speed gearboxes and synchronous generators. This effectively limits the ASG to operating at a single rotational speed. Because ASG installations are typically run-of-the-river, the flow through the installation, and water levels up- and downstream of the ASG, may vary greatly over a typical year. It is important to examine the effects of partial-full operation, which is an area of continuing research in our lab.

**PROTOTYPE ASG**

In addition to laboratory tests, the performance of a prototype ASG installed on a small watercourse in southern Ontario (Canada) was examined. This ASG utilized an induction generator, and operated at an essentially constant rotational speed of 69.95 RPM when producing power. It was designed to operate with a volume flow rate of 70 l/s. Typical head was 0.85 m.

A Campbell Scientific CR1000 datalogger was used to measure air and water temperature, head, flow rate, generator electrical power output and rotation speed. It is important to note the difference in the power measurements: the laboratory experiments measured mechanical shaft power, while in this test the power measured was electrical power at the meter (which would be less than the shaft power due to generator and gearbox losses).

Fig. 8 shows the power and efficiency as a function of the flow through the turbine during a single testing day. Volume flow rate to the ASG was varied over the course of the test. This caused corresponding changes in the efficiency and power output of the ASG.

At lower flow rates, power output decreases at a roughly linear rate until there flow is insufficient to turn the ASG at its operating rotation speed. Similarly, the efficiency of the ASG decreases slowly down to 50% of design flow. Below 50%, the efficiency drops off rapidly. This implies that ASGs are relatively tolerant to large changes in flow.

**DISCUSSION**

Study of the impact of lower reservoir depth on ASG performance was initiated after the prototype ASG was observed to have a substantial drop in performance as water rose above the midpoint of the outlet in the lower reservoir.

The results in Fig. 7 show that peak efficiencies were relatively constant across the range of depths tested. This suggests that much of the impact on power output caused by changing lower reservoir depth is due to decreasing overall head. Flooding the lower end of the reservoir does reduce the range of rotation speeds that the screw can achieve, which has the effect of reducing volume flow rate. Effectively, as the lower reservoir level is increased, the efficiency of the screw remains high, however, the rotation speed is increasingly limited, which in turn limits the amount of water that passes through the screw. Fig. 6 illustrates this result: the maximum amount of power that can be extracted decreases markedly when the end of the screw is “flooded”: the screw is efficiently extracting energy from a flow that reduces markedly as the lower reservoir depth rises above the midpoint of the screw outlet.
CONCLUSIONS

Lab tests were performed to quantify the performance of ASGs under different operation conditions, notably changes in rotational velocity and lower reservoir depth. In addition, data was collected from a prototype ASG to examine the effects of changing flow rates. Both sets of data suggest that ASGs can be expected to operate efficiently across a range of head and flow conditions.

ASGs are relatively tolerant to changes in flow and varying water levels, maintaining reasonably high efficiency over relatively wide ranges of these parameters. This characteristic is an additional advantage for ASGs utilized in small-scale run-of-river applications. The operating volume flow rate range of the prototype ASG was limited because it must operate at a fixed rotation speed due to the use of an induction generator. One area of future research is to consider variable speed generators. These would allow the ASG to reduce rotation speed during low flow periods, resulting in increased bucket fill and torque, allowing continued operation.

Future research plans also include conducting flow visualization within the ASG’s buckets. The impact of varying other parameters, including the effects of inlet and outlet geometry, installed slope and pitch, will also be investigated. Based in part on the presented data and the ongoing research, a parametric model of an ASG is being developed, to allow numerically-based site specific optimization of ASG designs.

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REFERENCES


