Experimental and theoretical examination of outlet power losses in Archimedes screw generators

BHA Annual Conference, 2018

Scott Simmons¹, Arianna Passamonti², Nicola Fergnani², Paolo Silva², and William Lubitz¹

¹ University of Guelph, College of Engineering and Physical Sciences
² Energy Department of Politecnico di Milano
Overview

1. Archimedes screw background
   1. Introduction
   2. Geometry
   3. Benefits

2. Current Models

3. Mechanisms of Power Loss

4. Conclusions and Future Works
Archimedes screw geometry

- Helical array of blades wrapped about a central cylindrical tube

- Defined by the following parameters
  - \( D_o \) = Outer Diameter
  - \( D_i \) = Inner Diameter
  - \( L \) = Flighted Length
  - \( S \) = Screw Pitch
  - \( N \) = Number of Blades
  - \( \beta \) = Inclination Angle
  - \( f \) = Fill Height Ratio
  - \( G_w \) = Gap Width
  - \( \Psi \) = Outlet Water Level (owl)
Archimedes screw generator (ASG)

- Distribution of hydrostatic pressure due to water in screw imparts net torque, turns the screw, which turns a generator
Since 1990’s the screw has found use generating hydropower

Three main benefits include:
1. Ecological Advantages
2. Low Cost of installation and maintenance
3. Operational Range

Williamson, Stark, and Booker (2011)
Current Models

- Current ASG models for power and performance:
  - Müller and Senior (2009)
    - “Simplified theory of Archimedean screws”
  - Nuernbergk (2012)
    - Wasserkraftschnecken
  - Lubitz, Lyons, and Simmons (2014)
    - “Performance Model of Archimedes Screw Hydro Turbines with Variable Fill Level”
  - Kozyn and Lubitz (2017)
    - “A Power Loss Model for Archimedes Screw Generators”

- The models are either theoretically based and require more robust experimental validation, or are developed on laboratory scale screws and do not yet include scaling effects

- This research focussed on further development of the loss models in ASGs
Sources of losses in Archimedes screws:
- Inlet and outlet flows
- Leakage
- Bearings
- Fluid friction
- Gearbox, generator
- Variable flows and head

We are working to understand and model these losses more accurately
16 unique lab-scale screws tested for varying flow rates, rotational speeds, and outlet fill heights

Dimensions of University of Guelph laboratory-scale Archimedes screws.

<table>
<thead>
<tr>
<th>Screw</th>
<th>OD (cm)</th>
<th>ID (cm)</th>
<th>S (cm)</th>
<th>L (cm)</th>
<th>N</th>
<th>ID/OD</th>
<th>S/L</th>
<th>L/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>31.58</td>
<td>16.83</td>
<td>44.45</td>
<td>121.92</td>
<td>3</td>
<td>0.53</td>
<td>0.36</td>
<td>2.74</td>
</tr>
<tr>
<td>#2</td>
<td>31.62</td>
<td>16.83</td>
<td>31.75</td>
<td>121.92</td>
<td>3</td>
<td>0.53</td>
<td>0.26</td>
<td>3.84</td>
</tr>
<tr>
<td>#3</td>
<td>31.67</td>
<td>16.83</td>
<td>25.4</td>
<td>121.92</td>
<td>3</td>
<td>0.53</td>
<td>0.21</td>
<td>4.8</td>
</tr>
<tr>
<td>#4</td>
<td>31.69</td>
<td>12.7</td>
<td>31.75</td>
<td>121.92</td>
<td>5</td>
<td>0.4</td>
<td>0.26</td>
<td>3.84</td>
</tr>
<tr>
<td>#5</td>
<td>31.66</td>
<td>12.7</td>
<td>31.75</td>
<td>121.92</td>
<td>4</td>
<td>0.4</td>
<td>0.26</td>
<td>3.84</td>
</tr>
<tr>
<td>#6</td>
<td>31.62</td>
<td>12.7</td>
<td>31.75</td>
<td>121.92</td>
<td>3</td>
<td>0.4</td>
<td>0.26</td>
<td>3.84</td>
</tr>
<tr>
<td>#7</td>
<td>31.62</td>
<td>12.7</td>
<td>31.75</td>
<td>63.5</td>
<td>3</td>
<td>0.4</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>#8</td>
<td>31.57</td>
<td>12.7</td>
<td>31.75</td>
<td>40.64</td>
<td>3</td>
<td>0.4</td>
<td>0.78</td>
<td>1.28</td>
</tr>
<tr>
<td>#9</td>
<td>31.64</td>
<td>10.16</td>
<td>31.75</td>
<td>121.92</td>
<td>3</td>
<td>0.32</td>
<td>0.26</td>
<td>3.84</td>
</tr>
<tr>
<td>#10</td>
<td>31.61</td>
<td>10.16</td>
<td>44.77</td>
<td>52.07</td>
<td>4</td>
<td>0.32</td>
<td>0.86</td>
<td>1.16</td>
</tr>
<tr>
<td>#11</td>
<td>37.8</td>
<td>16.99</td>
<td>30.2</td>
<td>46.89</td>
<td>4</td>
<td>0.44</td>
<td>0.64</td>
<td>1.55</td>
</tr>
<tr>
<td>#12</td>
<td>37.69</td>
<td>16.89</td>
<td>30.4</td>
<td>61.39</td>
<td>4</td>
<td>0.44</td>
<td>0.5</td>
<td>2.02</td>
</tr>
<tr>
<td>#13</td>
<td>37.69</td>
<td>16.79</td>
<td>30.51</td>
<td>94.69</td>
<td>4</td>
<td>0.44</td>
<td>0.32</td>
<td>3.1</td>
</tr>
<tr>
<td>#14</td>
<td>38.2</td>
<td>16.99</td>
<td>38.3</td>
<td>46.61</td>
<td>4</td>
<td>0.44</td>
<td>0.82</td>
<td>1.22</td>
</tr>
<tr>
<td>#15</td>
<td>38.1</td>
<td>16.79</td>
<td>38.2</td>
<td>61.7</td>
<td>4</td>
<td>0.44</td>
<td>0.62</td>
<td>1.62</td>
</tr>
<tr>
<td>#16</td>
<td>38.61</td>
<td>16.89</td>
<td>38.3</td>
<td>94.89</td>
<td>4</td>
<td>0.44</td>
<td>0.4</td>
<td>2.48</td>
</tr>
</tbody>
</table>
- As Flighted **Length** (and available head) increases:
  - Power increases
  - Efficiency increases

- As Screw **Pitch** increases:
  - Power has a peak value
  - Efficiency has a peak value

<table>
<thead>
<tr>
<th>Screw</th>
<th>OD</th>
<th>ID</th>
<th>ID/OD</th>
<th>L</th>
<th>N</th>
<th>S</th>
<th>S/OD</th>
<th>Power</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>31.58</td>
<td>16.83</td>
<td>0.53</td>
<td>121.92</td>
<td>3</td>
<td>44.45</td>
<td>1.41</td>
<td>26.43 ± 1.36</td>
<td>66 ± 3.1</td>
</tr>
<tr>
<td>#2</td>
<td>31.62</td>
<td>16.83</td>
<td>0.53</td>
<td>121.92</td>
<td>3</td>
<td>31.75</td>
<td>1.00</td>
<td>27.98 ± 1.39</td>
<td>67 ± 3.1</td>
</tr>
<tr>
<td>#3</td>
<td>31.67</td>
<td>16.83</td>
<td>0.53</td>
<td>121.92</td>
<td>3</td>
<td>25.4</td>
<td>0.80</td>
<td>27.37 ± 1.34</td>
<td>63 ± 2.9</td>
</tr>
</tbody>
</table>
for a constant flow-rate?
Outlet Effects

- As **Outlet Fill Level** increases:
  - Power decreases
  - Efficiency is maximum at $\psi = 0.6$

- Outlet loss is a function of:
  - **Borda-Carnot loss**
    - Pressure loss due to change in flow cross-section
  - **Interference-drag loss**
    - Dependent on Outlet Water Level, Flow Rate, and Rotational Speed
    - This loss utilizes the only empirically determined parameter in the model, the interference drag coefficient $C_d$
  - **Non-optimal Outlet Water Level loss**
    - Higher outlet water levels correspond to lower head values, and lower outlet water levels will see the water fall out of the last few buckets, thus a part of the available head is wasted
I would say "higher turbulence losses at discharge".
Nicola Fergnani, 30/10/2018
This was explored on both the laboratory scale screws and the large real world installations to develop a model that included scaling effects.
Outlet Effects - Fletcher’s Plant

Waterford, Ontario, Canada

Design electrical power: 7.2 kW
Design volume flow rate: 0.54 m³/s
Screw angle: 22°
Pitch: 1.4 m
Number of flights: 3
Inner diameter: 0.76 m
Outer diameter: 1.4 m
Length: 4.5 m
Design head: 1.7 m
Gap width: 0.0048 m

Mechanical Power v. Outlet Water Level

Efficiency v. Outlet Water Level Ratio

Measured
Simplified Model
Previous Model
New Model

3. Mechanisms of Power Loss

Simmons, Passamonti, Fergnani, Silva, and Lubitz
Outlet Effects - Ferrara Plant

Valpagliaro, Ferrara, Italy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design electrical power</td>
<td>121 kW</td>
</tr>
<tr>
<td>Design volume flow rate</td>
<td>5.5 m³/s</td>
</tr>
<tr>
<td>Screw angle</td>
<td>22°</td>
</tr>
<tr>
<td>Pitch</td>
<td>4.3 m</td>
</tr>
<tr>
<td>Number of flights</td>
<td>3</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>3.6 m</td>
</tr>
<tr>
<td>Length</td>
<td>7.4 m</td>
</tr>
<tr>
<td>Design head</td>
<td>3 m</td>
</tr>
<tr>
<td>Gap width</td>
<td>0.01 m</td>
</tr>
</tbody>
</table>

Mechanical Power v. Outlet Water Level

Efficiency v. Outlet Water Level Ratio

- Measured
- Simplified Model
- Previous Model
- New Model
Conclusions and Future Works

- Currently developing a more comprehensive model for gap and overflow leakage losses
  - Based on experimental data and full scale CFD simulations

- Investigating internal bucket dynamics using CFD and flow visualization techniques
  - Used to develop relationships for frictional loss and energy lost to water movement
Thank you!
Acknowledgements

- Natural Sciences and Engineering Research Council of Canada (NSERC)
  - NSERC Engage
  - NSERC Collaborative Research and Development (CRD)

- Greenbug Energy Inc. (Delhi, Ontario, Canada).
  - Tony Bouk and Brian Weber
Contacts

Scott Simmons
PhD Researcher, School of Engineering
University of Guelph
ssimmons@uoguelph.ca

William David Lubitz
Associate Professor, School of Engineering
University of Guelph
wlubitz@uoguelph.ca
+1-519-824-4120 x54387
https://www.uoguelph.ca/engineering/faculty/wlubitz

Greenbug Energy Inc.
Delhi, Ontario, Canada
info@greenbugenergy.com
+1-519-582-8563
www.greenbugenergy.com

Arianna Passamonti
Msc Energy Engineer, Department of Energy
Politecnico di Milano
ari.passa@yahoo.it

Nicola Fergnani
Engineer Researcher, Department of Energy
Politecnico di Milano
nicola.fergnani@polimi.it

Paolo Silva
Associate Professor, Department of Energy
Politecnico di Milano
paolo.silva@polimi.it

HydroSmart Srl
“Ferrara plant” - Ferrara, Italy
info@hydrosmart.it
www.hydrosmart.it
reference added
Nicola Fergnani, 30/10/2018