

# Outlet loss in Archimedes screw generators

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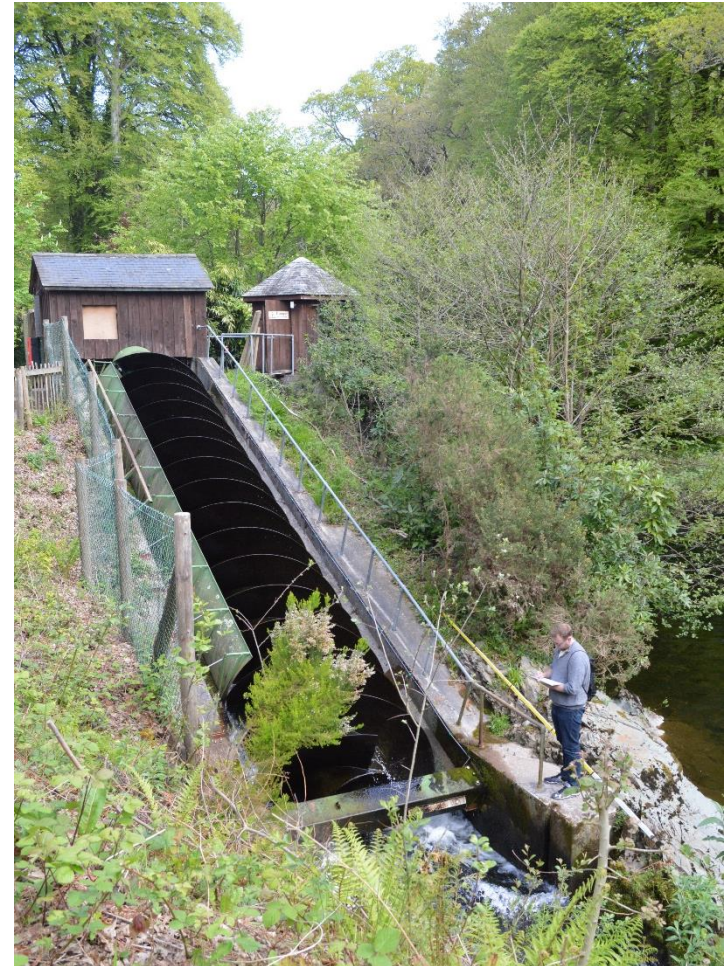
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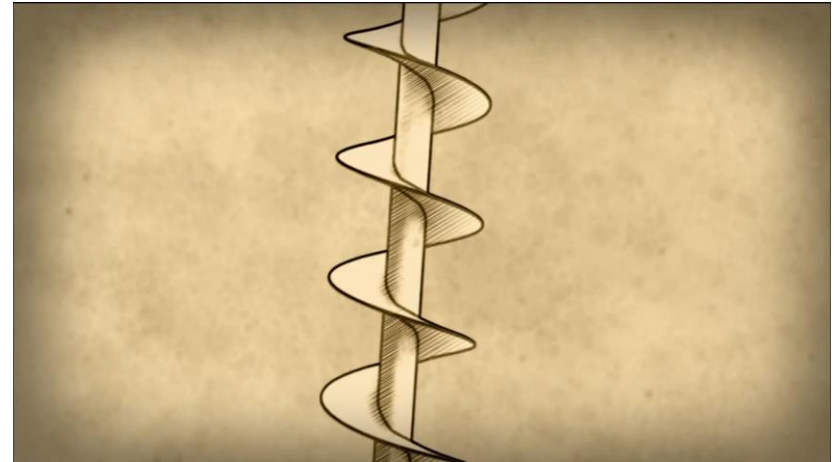
*Associate Professor*  
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University of Guelph  
Guelph, Canada

# Overview

1. Archimedes screws
2. Archimedes screw generators
3. Types of overflow leakage
4. Approach
5. Results
  - 5.1. CFD model evaluation
  - 5.2. Outlet losses
6. Conclusions



- Archimedes screws are an ancient pumping technology
- Named after Archimedes of Syracuse (~287-212 BCE)
- Evidence suggests it was used during reign of King Sennacherib (704-681 BCE) of the Neo-Assyrian Empire
- Trap water between blades as screw rotates due to an applied torque
- Water translates along axis of rotation



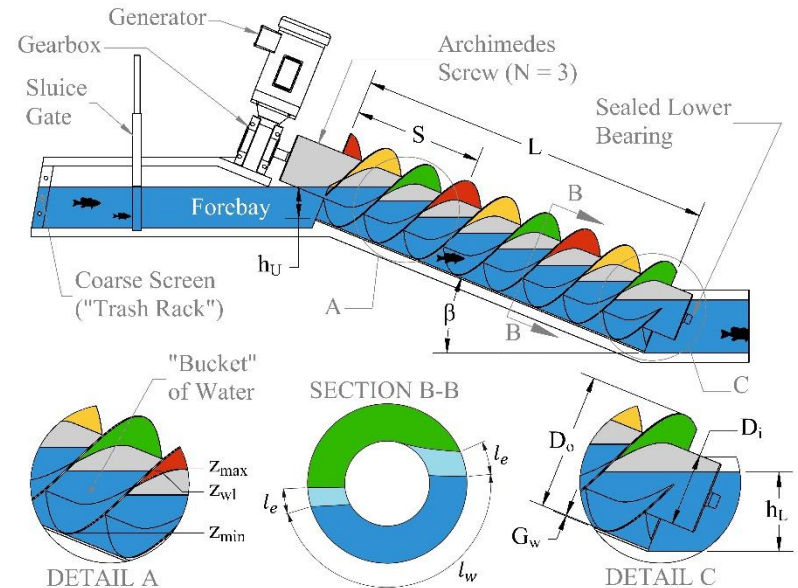
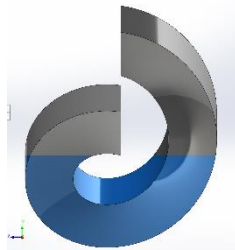
PBS (2014). *Secrets of the dead: Archimedes' screw and the Hanging Gardens of Babylon* [[https://www.youtube.com/watch?v=NhNEB\\_mWvBw&ab\\_channel=PBS](https://www.youtube.com/watch?v=NhNEB_mWvBw&ab_channel=PBS)].



Adriana Tub (2016). *Tornillo de arquimedes* [[https://www.youtube.com/watch?v=A\\_mZ6ekbJtw&ab\\_channel=AdrianaTub](https://www.youtube.com/watch?v=A_mZ6ekbJtw&ab_channel=AdrianaTub)].

# 2. Archimedes screw generators

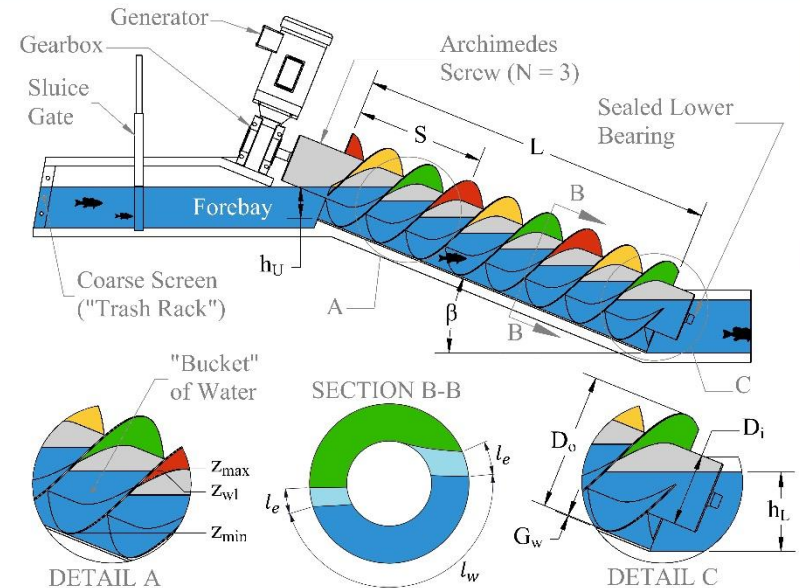
- Generators operate in reverse to convert mainly hydrostatic pressure into mechanical torque
- Inflow at top fills between blades
  - Termed a "bucket"



- Water translates down screw and trough and exits into outlet reservoir
- Mechanical torque converted to electrical power by a generator

# 2. Archimedes screw generators

- Archimedes screw generators (ASGs) usually have river-to-wire efficiencies of 75% (or greater in some cases)
- Power production is largely due to hydrostatic pressure in water (head drop)
- Power losses are largely due to both static and dynamic phenomenon
  - Friction loss
    - Hydraulic
    - Mechanical
  - Entrance losses
    - Inlet losses
    - **Outlet losses (focus of this study)**
  - Non-optimal lower water level
  - Leakage losses
    - Gap leakage
    - Overflow leakage



# 3. Types of overflow leakage

- Two forms of outlet losses are modelled in the literature:

## 1. Outlet expansion loss

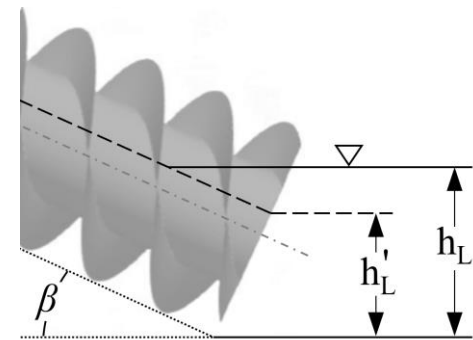
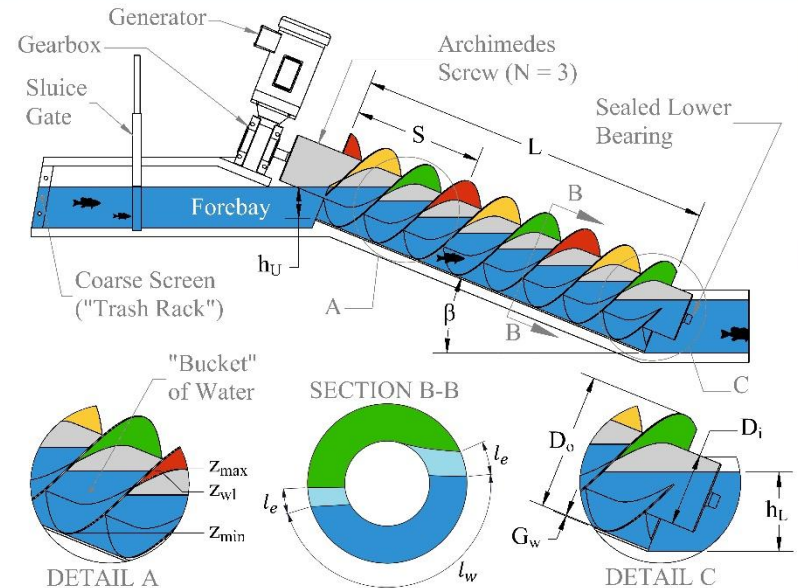
- Currently modelled using Borda-Carnot entrance relationships

$$P_{L_{oe}} = \rho Q \zeta_L \frac{v_t^2}{2}$$

## 2. Outlet submersion loss

- Currently modelled based on a comparison of the actual ( $h_L$ ) and optimal ( $h'_L$ ) outlet submersion level:

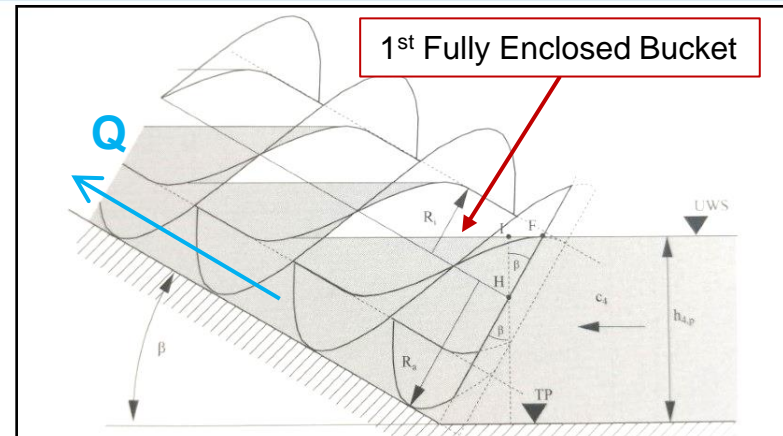
$$P_{L_{os}} = \begin{cases} \rho g Q \frac{(h_L - h'_L)^2}{h'_L}, & h_L < h'_L \\ 0, & h_L = h'_L \\ \rho g Q \frac{(h_L - h'_L)^2}{h_L}, & h_L > h'_L \end{cases}$$



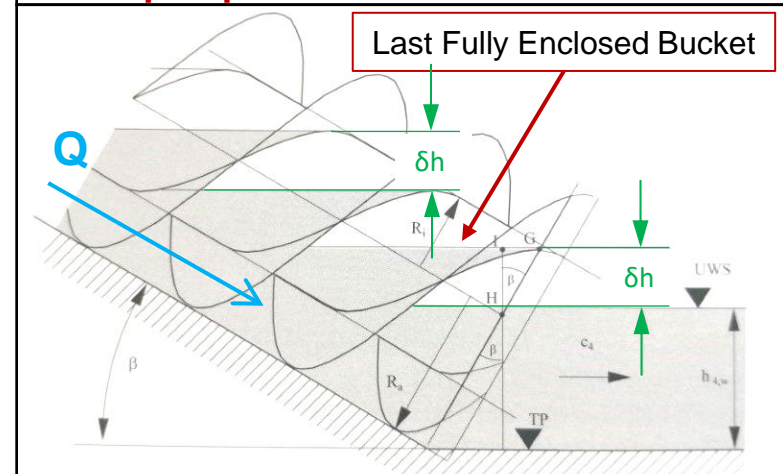
NOTE:  $\psi_L = \frac{h_L}{D_o \cos \beta}$

# 3. Types of overflow leakage

- Optimal outlet water level ( $h'_L$ )
  - In a screw **pump**, the optimal lower water level is the same level as the first fully enclosed bucket
  - In a screw **generator**, the optimal lower water level is the height of the last fully enclosed bucket minus the head drop across each bucket ( $\delta h$ )

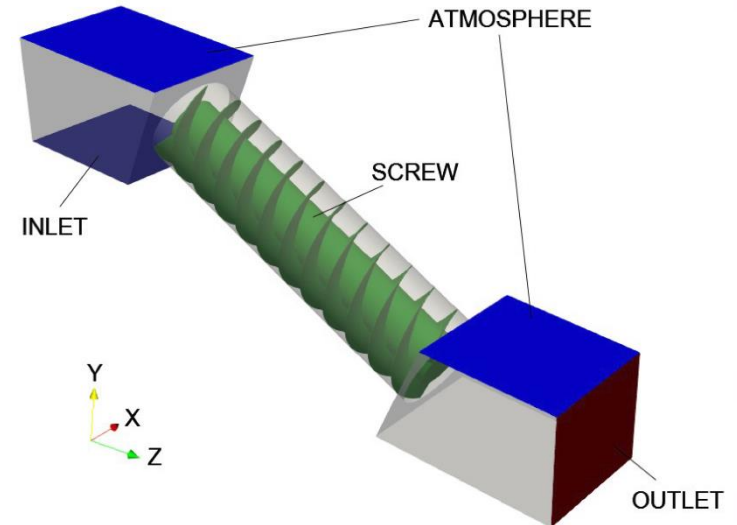


Optimal lower water level in an Archimedes screw **pump**



Optimal lower water level in an Archimedes screw **generator**

- It would be extremely difficult to accurately measure dynamic overflow
- We use computational fluid dynamics (CFD) to simulate an operating screw and measure overflow
  - **Software:** OpenFOAM 4.0, OpenFOAM foundation, 2016
  - **Meshing:** Dynamic mesh to simulate screw rotation
  - **Governing equations:** Reynolds-averaged Navier-Stokes (RANS) equation with the Volume of Fluid (VoF) method to account for two-phase flow (water and air)
  - **Turbulent closure:** Menter's Shear Stress Transport ( $k-\omega$  SST)



- CFD models were simulated to convergence
  - Occurs at a quasi-steady state condition where torque oscillations are stable
- Simulations were carried out at the operating conditions of lab experiments and real-world data that we had collected



Archimedes Screw Laboratory  
University of Guelph



Waterford, Ontario



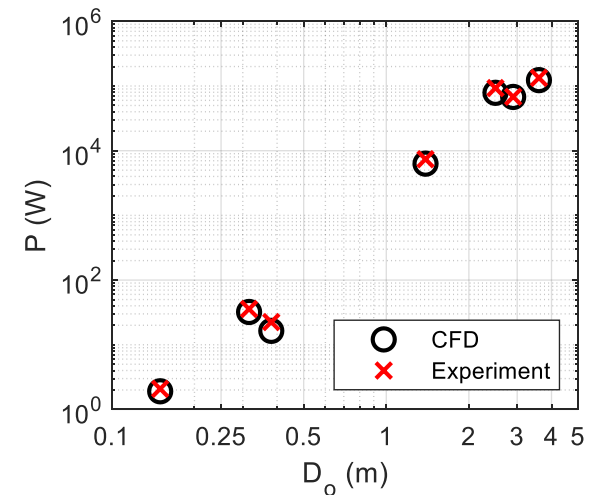
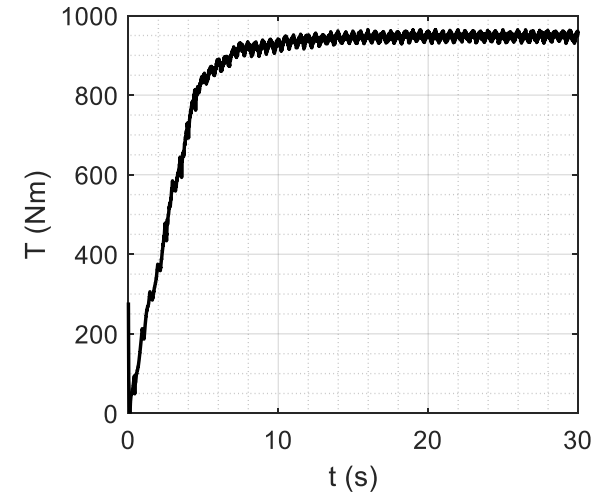
Buckfast, UK



Ruswarp, UK



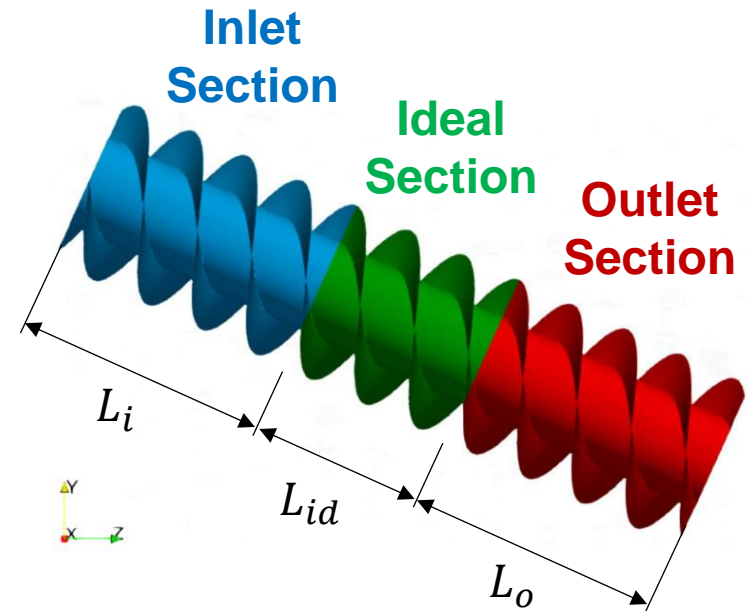
Ferrara, Italy



- CFD was then used to observe the effects of the lower water level on power production
- We ran 7 different scale-size screws, each at a range of outlet submersion levels
- The screw's boundaries were split into three sections to isolate inlet and outlet effects from power production

$$L_{id} = S \text{ (screw pitch)}$$

$$L_i = L_o$$



Screw Number	Scale	$D_i$ (m)	$D_o$ (m)	$D_h$ (m)	$L$ (m)	$S$ (m)	$N$ (-)	$\beta$ (°)	$G_w$ (m)	$n$ (-)	$\Omega$ (rev min <sup>-1</sup> )	$Q$ (m <sup>3</sup> s <sup>-1</sup> )
1	0.469	0.0789	0.148	0.0347	0.572	0.149	3	24.5	0.002	0.014	57.5	0.00115
2	1.00	0.168	0.316	0.0740	1.22	0.318	3	24.5	0.002	0.014	50.0	0.00827
3	2.13	0.359	0.675	0.158	2.60	0.678	3	24.5	0.004	0.014	44.8	0.0699
4	3.16	0.532	1.00	0.234	3.86	1.00	3	24.5	0.006	0.014	40.0	0.202
5	6.33	1.06	2.00	0.468	7.71	2.01	3	24.5	0.008	0.014	31.5	1.23
6	11.1	1.86	3.50	0.819	13.5	3.51	3	24.5	0.010	0.014	21.7	4.51
7	15.8	2.66	5.00	1.17	19.3	5.02	3	24.5	0.010	0.014	17.1	10.3

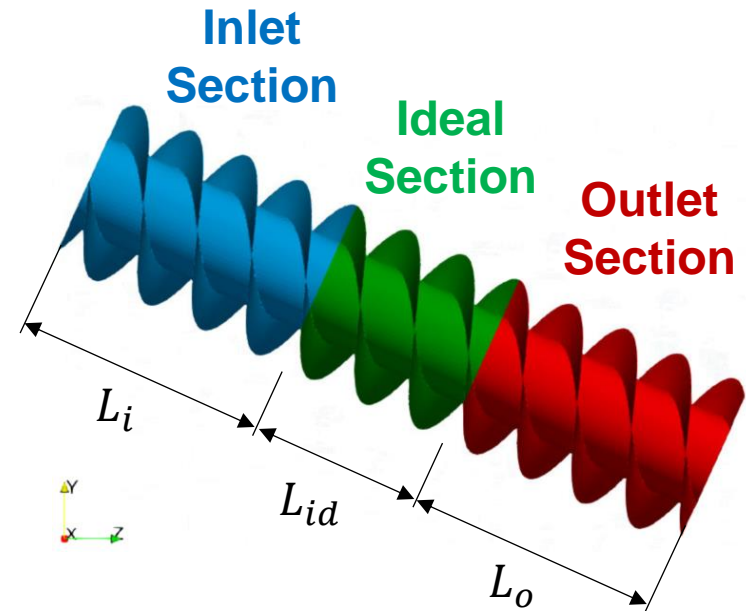
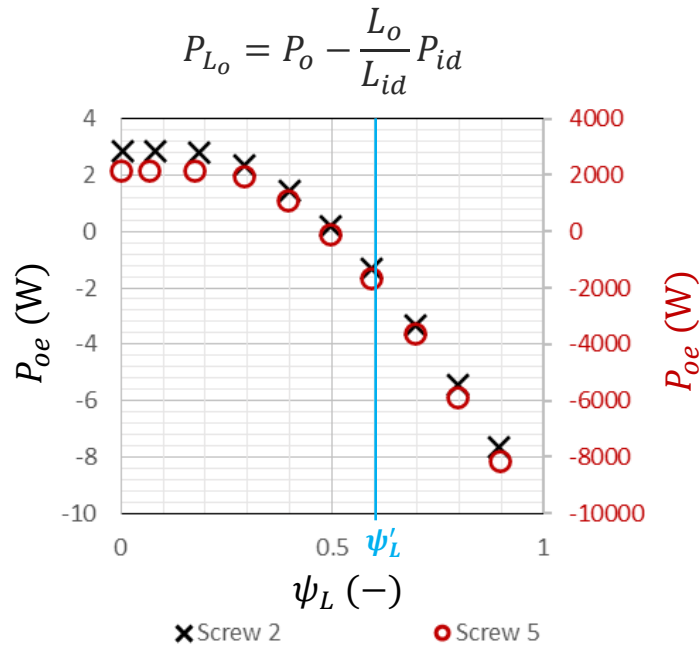
# 5. Results

## 5.2. Outlet losses

- Effect of the outlet on power production (i.e. unrealized outlet loss):

$$L_{id} = S \text{ (screw pitch)}$$

$$L_i = L_o$$



Scaling:

$$\frac{P_{oe_{s2}}}{\rho g D_{o_{s2}} Q_{s2}} = \frac{P_{oe_{s5}}}{\rho g D_{o_{s5}} Q_{s5}}$$

$$\frac{P_{oe_{s5}}}{P_{oe_{s2}}} = \frac{\rho g D_{o_{s5}} Q_{s5}}{\rho g D_{o_{s2}} Q_{s2}} = 943.26$$

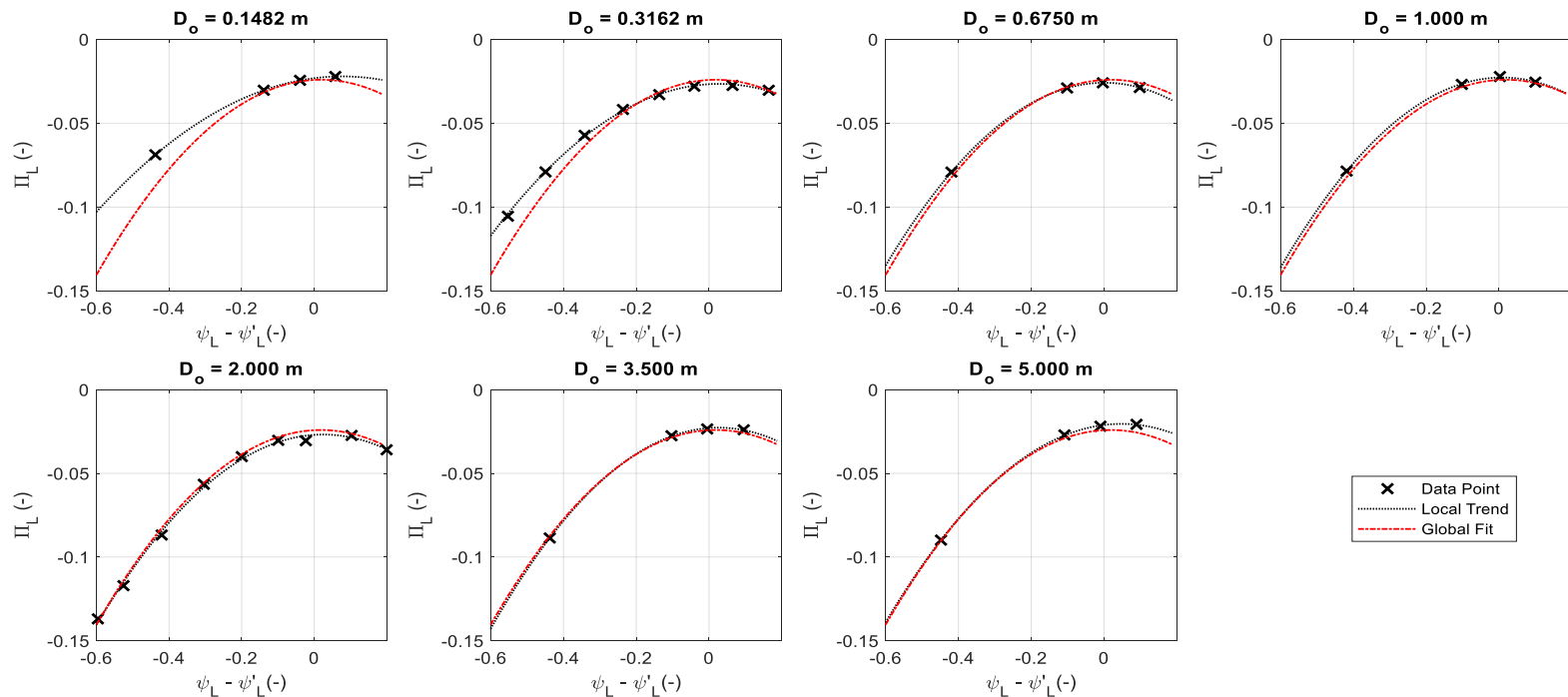
RECALL:  $\psi_L = \frac{h_L}{D_o \cos \beta}$

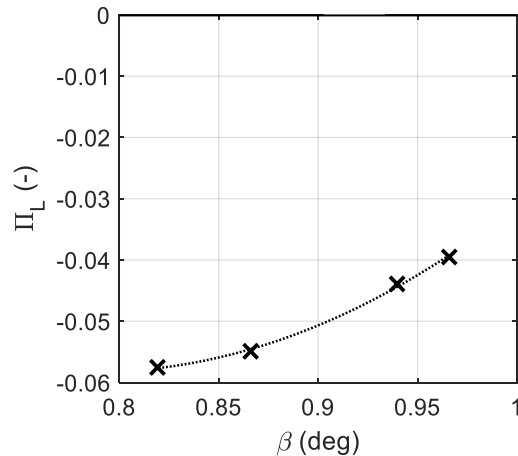
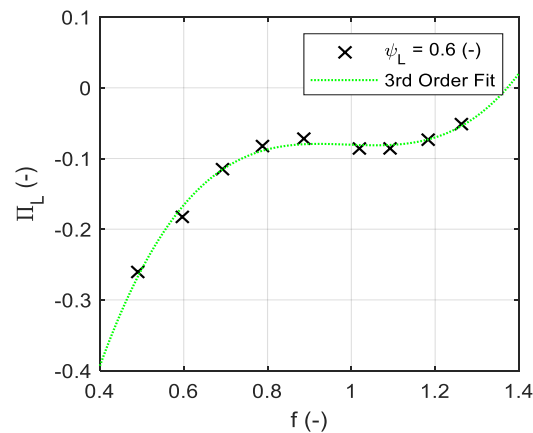
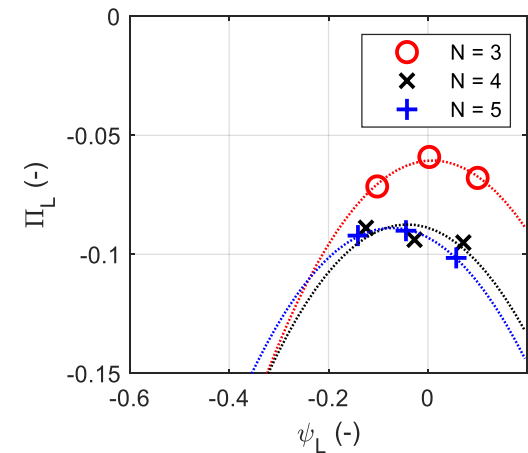
- Unrealized outlet power loss:

$$P_{L_o} = P_o - \frac{L_o}{L_{id}} P_{id}$$

- Dimensionless unrealized outlet power loss:

$$\Pi_{L_o} = \frac{P_{L_o}}{\rho g D_o Q}$$



Effect of  
Inclination AngleEffect of  
Bucket Fill HeightEffect of  
Number of Blades

- ASG powerplants may be designed with optimization software to produce power most effectively
  - Optimization software requires accurate performance predicting algorithms
- Outlet power loss is not accurately included in any current performance prediction models of the literature
- Modelling outlet loss is underway at the University of Guelph
- Its addition to optimization software will help improve plant design
  - Optimizing screw placement within the civil works to best produce power for return on investment



# Overview

Thank you for your time!

# Acknowledgements

- Tony Bouk and Brian Weber at Greenbug Energy Inc. (Canada)
- David Mann and Adrian Clayton of Mann Power Consulting Ltd. (UK)
- Chris Elliot of On Stream Energy Ltd. (UK)
- David DeChambeau of Southeast Power Engineering Ltd. (UK)
- Mike Ford of Esk Energy (Yorkshire) Ltd. (UK)
- Mohamed A. Samaha of RIT Dubai (UAE)
- Nicola Fergnani of HydroSmart Srl (Italy)
- Natural Sciences and Engineering Research Council of Canada (NSERC)  
Collaborative Research and Development (CRD)