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AN UPDATED MODEL FOR GAP LEAKAGE IN ARCHIMEDES SCREW GENERATORS

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Abstract—Archimedes screw generators are a small-scale, eco-friendly hydropower technology that are commonly implemented in diversion schemes. The technology has been in use for thousands of years for pumping fluids and granular solids and so its design is largely influenced by Archimedes screw pump manufacturers. There is little engineering design guidance in the literature discussing the optimal design of screw generators, and the existing models used in the literature to suggest the optimal design of screw generators are mostly developed and evaluated with laboratory-scale data. There was a need to evaluate and improve performance prediction models in the literature. This paper outlines a correction to the prediction of gap leakage loss outlined by Lubitz (2014). The correction presented in this paper was found to improve gap leakage predictions by an average of 10.7% when compared to accurate approximations gathered from a CFD simulation.

Keywords-hydropower; Archimedes screw generator; power loss; hydrodynamic screw; run-of-river; gap leakage; leakage loss;

I. INTRODUCTION

Archimedes screw generators (or ASGs) are a small scale, "eco-friendly" hydropower technology that are most often installed as run-of-river powerplants. They are less commonly referred to as "Hydrodynamic screws", or "Reverse Archimedean screws" in the literature.

ASGs consist of a helical array of blades wrapped around a central cylindrical tube (Fig. 1). The screw is commonly inclined, fixed between an upper and lower bearing, and enclosed in a concentric, open-topped trough. Volumes of water are trapped between the blades of the screw and trough – this is commonly termed a "bucket" [1].

The trough is usually fixed, and the screw rotates within it. In this orientation, there is a small, intentional gap left between the blade tips and trough to minimize friction and prevent wearing; however, this introduces a small area where leakage can occur. The flow rate between the blade-trough gap region is commonly called the "gap leakage rate". Gap leakage is a form of power loss in screw generators.

Archimedes screws are often described based on their geometry and operating parameters (Fig. 1). Its geometry is described by its outer diameter (D_o), inner diameter or tube diameter (D_i), flighted length (L), number of blades (N), inclination angle (β), screw pitch (S), and gap width (G_w). Operating parameters include the upper and lower water levels (h_U and h_L), flow rate (Q), rotation speed (ω), and bucket water level (z_{wl}) – though, the bucket water level is more commonly described by the dimensionless bucket fill height ratio (f). The bucket fill height ratio (f) is calculated as a function of the bucket water level (z_{wl}), and the minimum (z_{min}) and maximum (z_{max}) bucket water levels (cf. Fig. 1).

$$f = \frac{z_{wl} - z_{min}}{z_{max} - z_{min}} \quad (1)$$

Archimedes screws have been implemented for millennia as a pumping technology and have more recently found use as a hydropower technology. Screw generators have a design that is simpler and more robust than conventional hydro turbines. Their design allows for a lower cost of installation and maintenance when compared to conventional hydro turbines.

Archimedes screws are also "fish friendly". As a pump, Archimedes screws are often implemented as "fish elevators"

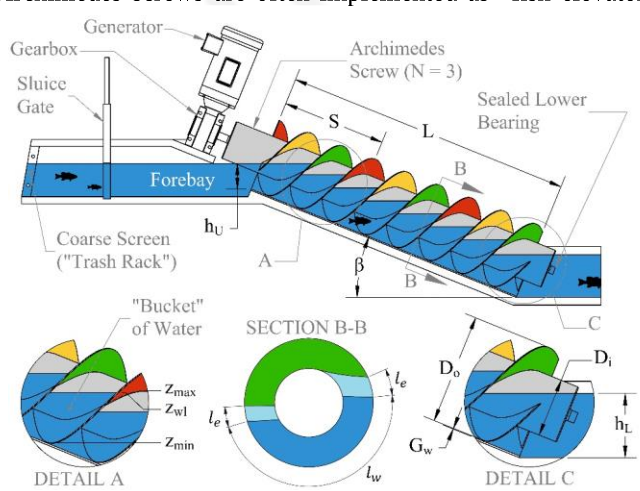


Figure 1. Archimedes screw generator layout and geometry. Detail A presents the parameters often used when quantifying fill levels of screw "buckets". Section B illustrates the parameters used in gap leakage modelling techniques. Detail C demonstrates the outlet water level and gap width in higher resolution.

to pump live fish and other aquatic fauna safely. The same mechanisms apply when operating as a generator; fish may safely enter, travel through, and exit the screw during normal operation [2], [3]. One study found safe passage may be dependent on species [4]. They found low mortality rates in eels, but much higher mortality rates for roach and bream (19% and 37%, respectively); however, the authors indicate it was not clear where trauma originated, and site-specific screw geometry was not available. In installations that have followed the United Kingdom's installation guidelines [5], mortality rates for eels, trout, and salmon were all found to be negligible [2], [3], [6]–[8] – indicating a properly sized screw installation is "fish friendly".

Screw generators operate with low heads (less than 6 m) and moderate flow rates (less than 15 m^3/s) [9], [10] at relatively high efficiencies; generally, they operate with 60 to 80% river-to-wire efficiencies [9], [11], but some screw generators operate at even higher efficiencies [12].

It is suggested that this large range of operating efficiency is mostly due to a lack of engineering and design guidance in the literature. Archimedes screws are an ancient pumping technology, but their design and design evaluation are not well documented in the literature. It is suggested that this is because most screw generator manufacturers have been designing screw pumps for hundreds of years, and have either developed proprietary optimization techniques, or continue to design-by-experience. As such, there is a need for design guidance and modelling techniques to be better documented in the literature.

To address this need, some performance prediction models have been published [13]–[17]. An accurate performance prediction model may be used to estimate the power production capabilities of any given screw geometry and operating regime. If accurate power production estimates can be made, optimization software may be implemented to iterate through a set of screw geometries and operating parameters at a proposed powerplant site to determine a site-specific optimum ASG design.

Current models in the literature seem to predict power production and power losses reasonably well; however, most models have been developed and evaluated against laboratory-scale experimental data, so they lack a robust validation against real-world scale powerplants. There are a couple gap leakage models in the literature, one presented by Nuernbergk and Rorres [18] and adapted from Muysken [19], which has the general form:

$$Q_l = C\,G_w\,R_o\left(1+\frac{G_w}{2R_o}\right)\sqrt{1+\left(\frac{S}{2\pi R_o}\right)^2} \cdot\left(\frac{2}{3}\alpha_3+\alpha_4+\frac{2}{3}\alpha_5\right)\sqrt{2gh_b} \qquad (2)$$

where the gap leakage (Q_l) is calculated as a function of a leakage coefficient (C), the gap width, the outer radius of the screw ($R_o = D_o / 2$), screw pitch, gravitational acceleration (g), the head difference between each bucket (h_b), and three angles that are used to describe the fill level of the screw (α_3, α_4, and α_5).

The other gap model in the literature was presented by Lubitz [20] and has the general form:

$$Q_l = CG_w\left(l_w+\frac{l_e}{1.5}\right)\sqrt{2gh_b} \qquad (3)$$

where the gap leakage is calculated as a function of a leakage coefficient, the gap width, the wetted perimeter (l_w) and extended wetted perimeter (l_e) of the screw blade, gravitational acceleration, and the head difference between each bucket. The wetted perimeter and extended wetted perimeter are shown labelled in Section B of Fig. 1. Interestingly, both models shown in Eqns. 2 and 3 are mathematically identical. Different coordinate systems were used during model development, which lead to the differences in the forms of the equations.

This study seeks to investigate the accuracy of current gap leakage prediction models [18], [20], [21], and will propose an update to gap leakage modelling techniques to improve the accuracy of predictions across all scale sized screw generators. This was achieved by conducting laboratory experiments, field measurement campaigns, and running computational fluid dynamic (CFD) simulations to gather reliable data from a wide range of scale sized ASGs.

II. Approach

CFD was used to simulate the operation of a wide range of scale-sized screw generators and develop a well-structured dataset for model development and evaluation. The CFD model was evaluated with data gathered through both laboratory experimentation and through field studies of four real-world ASG powerplants. The experiments, field studies, and CFD simulations were previously documented in the literature, so this section will provide a summary of each. Generally, the most valuable and useful data for quantifying screw performance and to aide in modelling would contain measurements of: upper and lower water level, rotation speed, flow rate, and torque. These were easy to measure in the laboratory and via CFD, but very difficult to gather from real-world screw generator powerplants.

A. *Laboratory Experimentation*

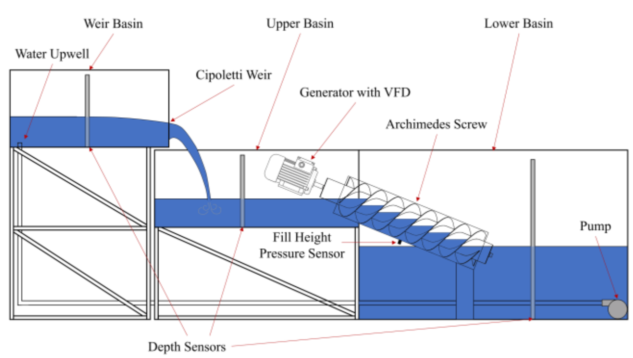


Figure 2. Diagram of the University of Guelph's Archimedes screw laboratory apparatus.

Laboratory experiments were conducted in the University of Guelph's Archimedes screw laboratory. The laboratory houses more than 16 unique Archimedes screws and an apparatus that can simulate a wide range of conditions for both screw generators and screw pumps (Fig. 2).

The apparatus has a recirculating loop of three basins designed to simulate flow conditions for ASGs (cf. Fig. 2). Water was pumped from the lower basin to the most-upstream weir basin. The flow rate of water was controlled with a variable speed pump. Flow rate was measured within the piping between the lower basin and weir basin with an Omega FTB-740 inline turbine flow meter. Water upwelled in the weir basin through a perforated tube and spilled over two parallel and equal Cipoletti weirs to enter the upper basin. Cipoletti weir relationships were used to estimate the flow rate in the system, adding a layer of verification to the inline flow measurements. To complete the loop, water passed from the upper basin, through the Archimedes screw generator, and into the lower basin. Water levels in all basins were measured with depth sensors set in stilling wells. Water level was also manually measured to verify digital measurements.

Screw rotation speed was controlled with a variable frequency drive. Water entered the screw from the upper basin as the screw rotated to form a bucket. A pressure sensor was set along the screw trough to measure bucket fill height. Archimedes screws convert the pressure in each bucket into rotational mechanical energy about the screw's axis of rotation. So, to quantify screw performance, the rotation speed of the screw was measured with a magnetic tachometer. A handheld optical tachometer unit was used to manually verify the readings. The torque was measured with a torque arm and load cell assembly.

Regular photographs were taken to document test conditions and manual measurements, as well as observe free-surface phenomena. More details about the laboratory apparatus may be found in the literature [10], [21]–[25].

To run a test, the screw rotation speed and system flow rate was set. The system was allowed to reach an equilibrium condition. System equilibrium was reached when water levels in all basins were constant. Due to the interrelation between flow rate, rotation speed, and upper water level, water was sometimes added to or removed from the lower basin to maintain the same outlet conditions for each set of tests.

Once system equilibrium was reached, a datalogger program was run for 60-seconds. It recorded torque, speed, basin water levels, and bucket fill height. Data was then time-averaged across the 60-second period; this removed the effects of the natural oscillations that occurred as the buckets drained and filled. Data was gathered from three different sized laboratory screws to evaluate the CFD model (Table 1).

Table 1. Field data points for numerical simulation evaluation.

Screw Name	D_o (m)	D_i (m)	S (m)	L (m)	N (-)	β (°)	ω (rad/s)	Q (m^3/s)	P_{exp} (kW)
Waterford	1.390	0.762	1.390	4.538	3	22	4.26	0.462	7.386
Buckfast	2.500	1.220	2.500	10.562	4	26	3.01	2.095	92.88
Ruswarp	2.900	1.200	3.070	5.117	3	22	2.8	3.754	32.5
Ferrara	3.600	1.800	4.300	7.40	3	22	2.34	5.03	133.35

The data points in Table 1 were selected from a large database. Each point was selected since it corresponded to a fill height of f = 1, and the screws were operating under similar overall conditions. More details about each experiment my be found in the literature, specifically for Lab Screw A [22], Lab Screw 2 [21], and Lab Screw 15 [10].

B. *Field Experimentation*

As mentioned, it was very difficult to gather all necessary data to quantify screw performance. Some data were more readily available, such as: screw geometry, rotation speed, upper and lower water levels, and the on-grid electrical power production of the installations. It was much more difficult to gather the mechanical power of the screw and the flow rate through the system. So, there existed significant uncertainty in measurements of torque and flow rate in the field measurements.

Four screw generator installations of varying scale size were visited to gather performance data (Fig. 3). Flow rate and torque were measured in site-specific ways that have been documented in the literature, specifically for the screw in Waterford (Ontario), Canada [23], Buckfastleigh, UK [26], Ruswarp, UK [26], and Ferrara, Italy [27].

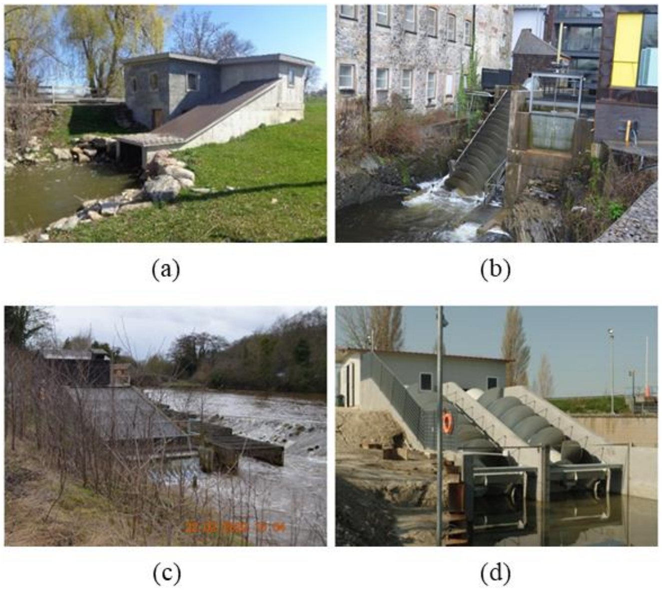


Figure 3. Archimedes screw generator powerplants in Waterford (Ontario), Canada (a), Buckfastleigh, United Kingdom (b), Ruswarp, United Kingdom (c), and Ferrara, Italy (d).

Generally, torque was estimated by assuming approximate efficiencies of each electrical and drivetrain component in the system, then back-calculating the mechanical shaft power [10]. The flow rate measurements for the screw in the UK were conducted by sampling a grid of velocity measurements along the inlet channel's cross-section, then integrating the results [26]. Four data points were selected from each powerplant to evaluate the CFD model (Table 2). More details about these measurements may be found in the literature.

Table 2. Laboratory data points for numerical simulation evaluation.

Screw Name	D_o (m)	D_i (m)	S (m)	L (m)	N (-)	β (°)	ω (rad/s)	Q (m^3/s)	P_{exp} (kW)
Lab Screw A	0.150	0.078	0.150	0.600	3	24.9	6.28	0.001	0.0021
Lab Screw 2	0.316	0.168	0.318	1.219	3	24.5	5.24	0.008	0.0299
Lab Screw 15	0.381	0.168	0.381	0.617	4	24.5	3.36	0.010	0.0224

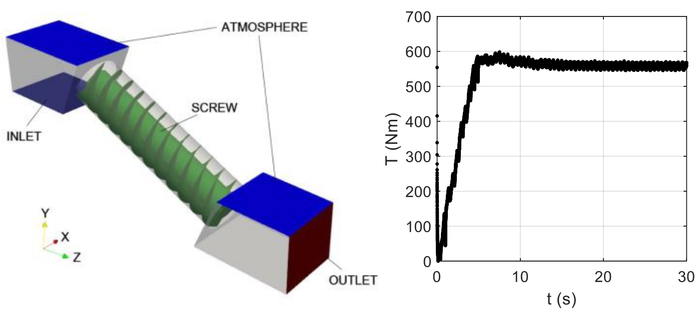
C. *Computational Fluid Dynamics Simulations*

A transient, two-phase, non-miscible, three-dimensional, dynamically meshed CFD model of an ASG was developed with OpenFOAM 4.0 (The OpenFOAM Foundation Ltd., London, United Kingdom). The model was developed to accurately approximate fluidic behavior during screw operation under a wide range of conditions and geometries. The simulation domain is shown in Fig. 4a.

Fluid motion was modelled using the Reynolds-averaged Navier-Stokes (RANS) equations with the Boussinesq eddy viscosity assumption. The volume of fluid (VoF) approach was used for free-surface modelling [28], [29], and Menter's Shear Stress Transport (k-ω SST) was used for turbulence closure [30]. This closure method was selected due to the relative importance of mesh size to model the gap region, and because it is very commonly implemented for hydro machinery applications [31].

An Euler scheme was used for time discretization with an adaptive timestep. The timestep was selected such that the Courant-Friedrichs-Lewy (CFL) number never surpassed unity, with typical timesteps on the order of 10^{-4} seconds. Gradient and Laplacian terms were discretized with the second order central scheme, and divergence terms were discretized with the second order upwind scheme.

Simulations ran until convergence at a regularly oscillating equilibrium condition, called "quasi-steady state" [10]. Oscillations during the quasi-steady state condition were due to the draining and filling of the screw's buckets. The scale of oscillations increased as the total volume in the screw proportionally decreased. (i.e., shorter screws, steeper inclination angles, etc.). A convergence study was conducted on a mid-sized simulation (Fig. 4b, D_o = 1 m). In the figure, the quasi-steady state condition was reach at about 18 seconds. Simulations were designed so at least 10-seconds of quasi-steady state operation was captured; results were time-averaged to mitigate effects of the oscillations.



(a) (b)

Figure 4. CFD simulation boundaries (a) and convergence study (b) for a screw with the same proprtions as Lab Screw 2, but with D_0 = 1 m.

To evaluate simulation accuracy, seven simulations were designed to match the geometry and operating conditions of the three laboratory test points (cf. Table 1) and four points from the powerplant field measurements (cf. Table 2). The measurements and simulated results are compared in Fig. 5.

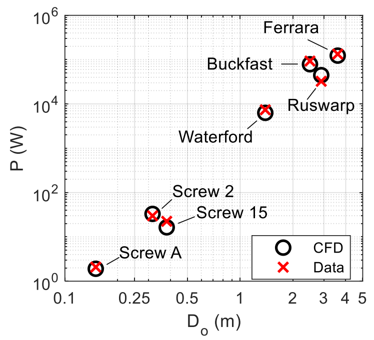


Figure 5. CFD model evaluated against experimental data.

The CFD model was model determined to be reasonably accurate when compared to the experimental data across the wide range of scale sizes. It was suggested that the model may be used to accurately approximate performance data for the operation of any realistic screw geometry and operating range.

For this study, five simulation sets were run that varied only one parameter, while keeping all the others equal. The five simulation sets were for speed (Ω = 10, 20, 40, 60, 80, 100, 150 and 200 RPM), fill height (f = 0.5 to 1.3 by increments of 0.1), inclination angle (β = 10 to 35 by increments of 5), number of blades (N = 3, 4, and 5), and a set to vary the simulation's scale size. In the scale size simulation, all parameter ratios were maintained; the outer diameter was varied while the screw maintained identical proportions.

The gap leakage rate of each simulation was then found and compared against predictions made with the Lubitz model [20]. Since each simulation set varied only one parameter, it was possible to isolate the effects each parameter had on gap leakage rate. This was very helpful during the model development stage since it was possible visualize the accuracy shortcomings in the Lubitz (2014) and made a targeted model correction possible.

III. Results and Evaluation

The results of each simulation set are shown in Fig. 6. To avoid redundancy, the figure shows the CFD results compared to model predictions made with both the Lubitz (2014) model and the proposed correction from this study.

It was observed that the Lubitz (2014) model had lower accuracy in a few cases. A correction to the Lubitz (2014) model will be proposed to address the inaccuracies. The Lubitz (2014) model (cf. Eq. 3) was derived from first principles and had a leakage constant (C) to improve prediction accuracy. The model correction proposed in this paper will empirically determine a more accurate leakage coefficient to improve gap leakage predictions based on the inaccuracies observed in the simulation results.

The most notable inaccuracies occurred with varying rotation speeds. The Lubitz (2014) model does not account for rotation speed; the model is based off the energy equation and is mainly driven by differences in static pressure between the buckets. The difference between the CFD results and the Lubitz (2014) model predictions in the rotation speed plot of Fig. 6 indicate that gap leakage is not solely driven by static

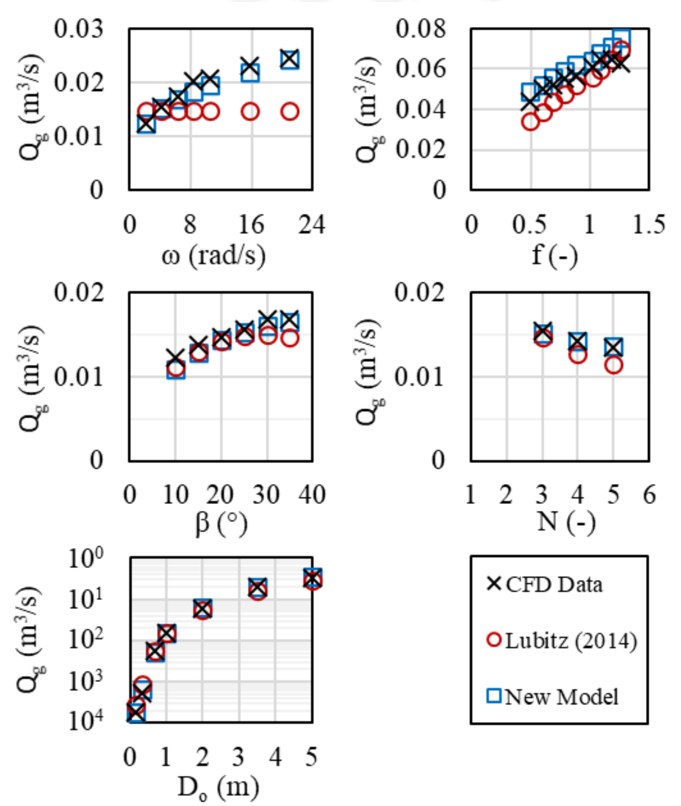


Figure 6. Results of CFD simulations compared to the Lubitz (2014) model and the new model with leakage coefficient correct proposed in this study. The results are presented across the five simulation sets (i.e., rotation speed, bucket fill height, inclination angle, number of blades, scale size).

pressure but has a dynamic dependency as well. So, the leakage coefficient correction must account for rotation speed.

The scale size (shown as a variation of outer diameter, D_o, in the Fig. 6 plot) seemed to proportionally impact the gap leakage as well; this was more difficult to visualize since the scale of the data was so large that a log-plot was implemented. Perhaps this inaccuracy was due to the observed changes to the Reynolds number as the scale size of the simulation changed. The largest screw simulation had the largest Reynolds number, suggesting that fluid motion in the gap region became more inertia-driven as scale-size increased.

Regarding the number of blades (N), the Lubitz (2014) model seemed to perform most accurately with the 3-bladed screw simulation. It was less accurate when compared to the 4- and 5-bladed screw simulations. As such, the number of blades was included in the corrected leakage factor.

The fill height (f) also impacted gap leakage predictions. The Lubitz (2014) model seemed to predict gap leakage reasonably well within a normal operating range of bucket fill height but was much less accurate in low or high fill heights. Fill height was thus accounted for in the correction factor.

Though inclination angle (β) did have an impact on model performance, its addition to the corrected leakage factor decreased the overall level of improvement. It is suggested that, though the inclination angle impacts gap leakage, it is itself influenced by other factors which have been included in the correction.

A dimensional analysis was conducted; it is suggested that the gap leakage coefficient is a function of the rotation speed, outer diameter, number of blades, and fill height. Regression analysis was conducted to determine the most appropriate fit between the non-dimensional term and the gap leakage coefficient. The resulting relationship is shown as Eq. 4.

$$C = 0.441 \cdot \left(\frac{\omega D_o N}{f}\right)^{0.285} \quad (4)$$

The corrected leakage coefficient was then applied to Eq. 3 to predict gap leakage. Gap leakage predictions made with the correction factor are shown in Fig. 6 under the label “New Model”. The new model improved model predictions by an average of 10.7% across the full range of simulated data shown in Fig. 6. The two gap leakage models were also compared to the simulations based on the field data (cf. Tables 1 and 2), the results are presented in Fig. 7. This allowed for a test against data that varied in all parameters simultaneously.

Aside from the smallest screw, which was coincidentally used to determine the original leakage coefficient presented in Lubitz (2014), the proposed correction showed performance improvements across all scales of simulations – with an average improvement of 14.3%.

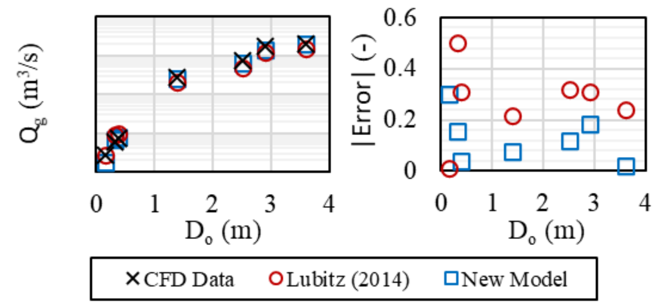


Figure 7. Comparison of the validation study dataset (Tables 1 and 2) and the gap leakage models. The absolute error of the Lubitz (2014) and new model with respect to the CFD data is also presented.

IV. Conclusion

A correction was applied to the leakage coefficient presented in the Lubitz (2014) gap flow model. Using the Lubitz (2014) model with the proposed leakage coefficient improved prediction accuracy by an average of 10.7% when compared to simulation data gathered using a CFD model. The CFD model was evaluated against laboratory experiments and field data and suggested to be an accurate approximation of Archimedes screw generator performance.

The improvements to gap leakage predictions provide a way to predict overall screw generator performance more accurately – something that is integral when developing an optimization model for screw generator design.

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