Experimental study of gap leakage in Archimedes screw pumps

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Abstract. Archimedes screws are an ancient pumping technology used for a variety of purposes including irrigation, land dewatering, water treatment. Archimedes screw pumps design guidelines are not well documented in the literature. Most design guidance for Archimedes screw pumps is based on empirical models and experimentation published before 1932. Current screw pump performance models do not accurately predict delivered flow rate for screws. Further, the available literature does not appear to document a phenomenon that impacts flow rate: the fill height gradient. Archimedes screw pumps are designed to rotate within a fixed trough; there is a small, intentional gap between the screw blades and the trough to mitigate wearing and friction. However, the gap introduces a leakage flow (termed "gap leakage"). As water is drawn up by the screw, it forms volumes of water between its blades (termed "buckets"). As the buckets translate up the screw, the gap leakage drains the buckets causing the volume of water, and therefore the water level, in the buckets to decrease as the buckets translate upwards towards the outlet. The fill height gradient is evident when viewing the screw since the first and last buckets have different water levels. It has been historically very difficult to measure the height and volume of water in each bucket due to the complex geometry of Archimedes screws. To address this, experiments were conducted on a small-scale Archimedes screw rotating within a clear, plastic trough which allowed the screw water levels to be viewed while pumping. The pumped water was dyed red to sharpen the contrast at the air-water interface. A camera recorded the screw during experiments. Recordings were processed to extract the fill height of the buckets during operation at various rotation speeds to quantify the fill height gradient and determine the gap leakage. The fill height gradient was greater when rotation speed was lower. The tested screw only delivered a positive flow rate when the rotation speed was greater than 8.46 rev/min. The data gathered in this novel experiment will be used to inform improvements to gap leakage modelling and screw pump performance modelling.

Keywords: Archimedes screw pump, water pumping, hydrodynamic screw, bucket fill height, gap leakage, flow visualization.

1 Introduction

An Archimedes screw is a device that has been used for pumping throughout a significant part of human history. The device resembles an auger, and more specifically, it commonly has three or four straight-profiled, helical blades that wrap along the length of a central, cylindrical tube. In central tube is roughly half the total diameter of the screw. In its most common implementation, an Archimedes screw is housed axially between bearings, and radially within a fixed trough (Fig. 1).

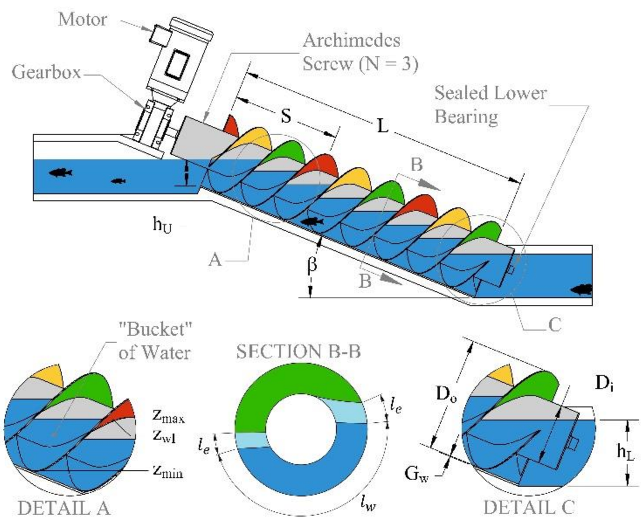

Fig. 1. Archimedes screw pump layout with common dimensions and variables.

Archimedes screws are often described by their outer diameter (D_o), inclination angle (*ß*), and number of blades (*N*) as well as a few design ratios. Common design ratios include the ratio between the central tube and outer diameter (D_i/D_o), the length to the pitch (*L/S*), and pitch to outer diameter (S/D_o).

As a pump, the screw is placed between a lower and upper basin or channel. The lower basin water level (h_L) is the main driver for the delivered flow rate of the screw, while the upper water level (h_U) is set to a height of zero in most schemes. The screw rotates in its fixed trough enclosing water at its lower end (inlet) to form what is called a "bucket" of water [1]. The lower water level is directly related to the height of water in the screw's buckets (z_{wl}). As the screw rotates, the buckets translate along the screw and exit at the upper end into a channel, basin, or reservoir.

The bucket water level is quantified with the dimensionless bucket fill height ratio (*f*), which is calculated as:

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

where z_{min} is the minimum bucket water level and z_{max} is the maximum bucket water level before water overtops the central tube and flows into a successive bucket. This action is called overflow leakage (Q_o). Overflow leakage occurs when the bucket fill height is $f > 1$. When the bucket fill height ratio is at $f = 1$, the screw is full but not yet overflowing; this is often anecdotally considered to be the desired operating fill point.

Screw pumps experience another form of leakage through a small, intentional gap between the blade tips and the fixed trough. The gap is designed to mitigate wearing of the blade tips. Though it causes a loss in the form of a leakage flow rate, it prevents power loss due to friction. The gap width (G_w) is a main driver of gap leakage flow (Q_g). When the fill height ratio is $f < 1$, the screw is under-filled and not experiencing overflow leakage – it only experiences gap leakage (Q_g).

Like the bucket fill height, the upper and lower water levels are often described in dimensionless terms. The dimensionless upper (ψ_U) and lower submergence levels (ψ_L) are calculated as:

$$\psi_U = \frac{h_U}{D_o \cos\beta} \tag{2a}$$

$$\psi_L = \frac{h_L}{D_o \cos\beta} \tag{2b}$$

For optimal bucket filling, it is suggested that the lower water level be set to a height corresponding to the z_{max} level of the first fully-enclosed bucket (Fig. 2).

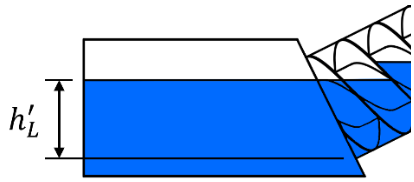

Fig. 2. Optimal lower water level shown with its dimensional variable h'_L.

This is called the optimal lower submergence (ψ'_L), and is usually represented non-dimensionally as:

$$\psi'_L = \frac{D_o + D_i}{2D_o} \tag{3}$$

Screw pumps can move a variety of effluent including liquids, granular solids and liquids with suspended solids or aquatic fauna [2]. Archimedes screw pumps (ASPs) are widely used in water [3] and wastewater treatment operations [4], drainage and land reclamation [5], and aquaculture farms [6, 7]. Due to their simple, robust design, screw pumps require a low frequency of maintenance which is advantageous for systems that are required to have consistent, reliable operation in rugged environments [8]. ASPs are ideal for pumping water contaminated with debris since other common pumping technologies, like centrifugal pumps, would be seriously damaged in such conditions. Additionally, screw pumps require less sophisticated control systems since they are able to run dry without issue, whereas centrifugal pumps would also be damaged if run dry [8].

Archimedes screws have been used in a variety of other applications including hydropower generation as an Archimedes screw generator [9] and Archimedes screw turbine [10], amphibious vehicles [11], injection moulding [12], and heart valve replacement [13].

Despite the many iterations and applications of Archimedes screw pumps, well-documented state-of-the-art design guidelines are not available in the literature. Screw pumps have been in use for millennia (since circa 700 BCE), and it seems they have mostly been designed by experience. Design guidelines [14, 15] in the published literature use modelling techniques that were developed in 1932 or before [16]. Current modelling techniques are largely heuristic and/or empirical and were developed based off experimentation conducted prior to 1932 [3, 17-19]. Likely due to the available technology, many assumptions were made to make modelling Archimedes screw pump performance possible.

Our research group has focused on improving performance modelling for Archimedes screw pumps holistically. While investigating ASP performance, a phenomenon was noticed while conducting experiments. Bucket fill height varied along the length of a screw during operation. The first bucket (at the low end of the screw) had the highest water level (specifically, $f = 1$), and the bucket fill height decreased along the length of the screw as it was transported to the outlet. The last bucket had the lowest fill height, and in-between buckets varied at what appeared to be a consistent gradient visually (Fig. 3). The phenomenon was termed the “bucket fill height gradient” by the authors. When the screw rotated at proportionally higher speeds, the fill height gradient was minimized, but not altogether removed.

Fig. 3. Fill height gradient as observed experimentally.

In ASPs, the bucket fill height drives the torque, friction loss, overflow leakage, and gap leakage. The existence of the fill height gradient complicates performance modelling since bucket water levels are not consistent along the length of the screw; meaning computations must be conducted for each individual bucket along the screw length to accurately predict performance (torque, power, etc.).

The existence of a noticeable fill height gradient made measuring gap leakage possible; something that has yet to be quantified experimentally in screw pumps. When the bucket fill height is $f \leq 1$, only the gap leakage flow rate contributes to a change in fill height. Therefore, under these conditions, if the fill height gradient was quantified, the gap leakage could be found as the change in volume of the buckets with respect to time. So, for a given rotation speed, the gap leakage of a bucket as it translates within an operating screw could be quantified.

It was hypothesized that the fill height gradient was largely impacted by rotation speed. Consider the case of a static bucket: water drains out of the bucket by leakage, and water height decreases with time until none remains. In an Archimedes screw, it is assumed that water leaks out of a bucket into the adjacent, lower bucket. Water then leaks out of that bucket into the next lower bucket. If this is true, the longer that a bucket is enclosed within a screw, the lower the water level will get, causing a larger fill height gradient. So, rotation speed should have a large impact on the fill height gradient. Screws with a lower rotation speed should have a larger fill height gradient since the buckets take longer to travel from inlet to outlet. Screw rotating at higher speeds house buckets for a shorter time duration, and thusly have a less drastic fill height gradient.

Modern technology (computers, computational methods, digital sensors, etc.) has made it possible to gather more robust performance data for Archimedes screw pumps, especially when compared to the foundational literature from 1932. Using modern numerical methods, the fill height gradient may be more accurately modelled to improve the accuracy of gap leakage prediction models and overall screw pump performance modelling. However, to do that, more data is required to inform model development. This paper documents experiments that were designed and conducted to optically measure the fill height gradient, and thus gap leakage variation, along the length of a small, laboratory-scale Archimedes screw pump with varying rotation speeds.

2 Methodology

This study sought to quantify gap leakage for each bucket along the length of an operating laboratory-scale Archimedes screw pump. It is very difficult to measure gap leakage directly in an operating ASP. To address this, an apparatus was designed and built with a transparent trough so that water levels could be visually observed during a pumping operation (Fig. 4).

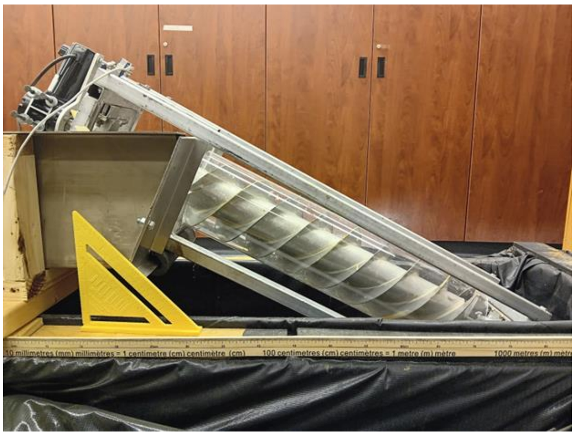

Fig. 4. Laboratory apparatus used for optical measurements.

Table 1 gives the dimensions of the tested Archimedes screw pump (cf. Fig. 4).

Table 1. Experimental Archimedes screw pump dimensions.

Dimension	Value
D_o	0.150 m
D_i	0.078 m
S	0.210 m
L	0.600 m
N	3
β	28.8°

The laboratory-scale screw was installed between an upper and lower basin. Water levels in the basins were controlled manually. For consistency with real-world screws, the upper water level was maintained at $h_U \leq 0$ (i.e., at or below the trough bottom at the outlet). The lower water level was set to its optimal level (cf. Eqn. 3) and was maintained by filling or draining the lower basin. Water levels were measured with manometers that were placed in stilling wells within the basins. A DC gear motor (7096, Bodine Electric Company) with a potentiometer was mounted to the top end of the screw via a moment arm to simultaneously control rotation speed and measure torque. Torque was measured with a load cell (LC703, Omega) that was placed between the moment arm and frame. The flow rate was measured manually by filling a large drum to a known volume and measuring the elapsed time of filling. Torque and rotation speed were multiplied to determine the power required to drive the screw and deliver the measured flow rate.

Bucket water levels were measured optically. A DSLR camera was used to record screw operation; videos were then post-processed with video annotation software Kinovea [20]. Kinovea is an open-source utility that is widely used in sport analysis to observe, annotate, and quantify athlete kinetics. The annotation utility can be used to trace an object's motion throughout a video and output the x- and y-position with timestamps to a spreadsheet. With some calibration, data was easily converted to x- and y-distance with respect to time.

In initial testing, the lower basin was filled with small, floating objects and suspended solids. It was difficult to post-process results with Kinovea due to the turbulent nature of the screw buckets. Objects moved in and out of camera focus due to secondary, turbulent flow patterns. So, water in the lower basin was dosed with groundwater tracing dye and the experiment was conducted again. The tracing dye made it much easier for Kinovea to trace the motion of the buckets' free surface water level during translation. Once optical analysis methods were developed, a full experiment procedure was conducted across a range of rotation speeds.

To run an experiment, the lower water level was set first. The screw was then set to a desired rotation speed. The lower water level drove the fill height of water within the screw, and as the screw filled, the lower water level decreased since water was held within the screw's volume and within the upper basin. The lower water level was then reset to its desired height. Changes to the lower water level, and the filling of the screw impacted the torque required to rotate the screw. Thus, the rotation speed controls were updated to reach the designed rotation speed. This process was continued until the system reached an equilibrium condition in which the net flow of water in and out of the screw was equal.

Once the equilibrium condition was reached, a recording was started on the DSLR camera. During the recording, torque was digitally sampled for one minute and the water levels were measured. Measurements were time-averaged over the one-minute sample time to better characterize screw performance.

Since the fill height gradient was heavily impacted by rotation speed, experiments were conducted at the 10 different rotation speeds in Table 2.

Table 2. Experiment speed (ω) and lower (ψ_L) and upper submergence (ψ_U) settings.

Run	ω (rev/min)	ψ_L (-)	ψ_U (-)
1	8.48	0.760	0
2	9	0.760	0
3	10	0.760	0
4	11	0.760	0
5	12	0.760	0
6	13	0.760	0
7	14	0.760	0
8	15	0.760	0
9	20	0.760	0
10	30	0.760	0

The screw was set at its optimal lower water level, which was determined to be at $\psi'_L = 0.76$ (76% submergence). One difficulty with the experiments was that the lower basin, unlike the trough, was completely opaque. The screw needed to be submerged to a level corresponding to the optimal lower water level. Because of this, the bottom third of the screw was out of range of the DSLR camera and therefore could not have its fill height measured optically with any accuracy. Additionally, the frame that joined the upper end of the screw to the upper basin was opaque. It prevented fill heigh measurements in the last 50 mm length of the trough near the outlet; this had less of an impact on results than the lower-end opacity.

The first rotation speed tested was 8.48 rev/min. At this speed, no flow of water was delivered to the upper basin. At rotation speeds immediately higher than this value, a small amount of flow was discharged to the upper basin. So, 8.48 rev/min was called the maximum no-flow speed. Experiments were conducted above the maximum no-flow speed by increments of 1 rev/min up to 15 rev/min. Additional experimental runs were conducted at 20 rev/min and 30 rev/min (cf. Table 2). The 20 and 30 rev/min runs were fast enough that it was difficult to reasonably capture the fill height gradient optically with the developed experimental methods. This was because flow in the buckets became highly turbulent, and the free surface became much more chaotic which caused difficulties tracing with Kinovea.

Due to the small-scale nature of the laboratory screw, the fill height gradient was noticeably different depending on which of the N=3 blades were measured. Buckets form between all three blade pairings; the path of a particular blade pairing along the length of a screw is called a “chute”. To eliminate the impact of the variations on experimental results, all three chutes were measured for fill height gradient. The measurements were then averaged to determine a characteristic fill height gradient for each rotation speed.

3 Results

The maximum no-flow rotation speed (8.48 rev/min) was the first experimental run that was post-processed. It was selected first because it only experience gap leakage flow (Q_g) and otherwise experience neither a delivered flow rate (Q) nor overflow leakage (Q_o). Due to apparatus design, it was difficult to optically measure screw buckets near the lower end of the screw, and the top approximately 50 mm of the screw due to opacity of the basin walls. However, the maximum no-flow rotation speed was known to have a first-bucket fill height of f = 1 and a last bucket fill height of f = 0 due to the lower and upper water level settings, respectively.

The results of the maximum no-flow rotation speed measurements are shown in Fig. 5. As mentioned, the fill height gradient was measured for all three screw blades and the average fill height gradient was found; it is shown overlaid on the plot. The plot shows the bucket fill height with respect to the dimensionless distance along the screw trough. The dimensionless distance along the screw trough is represented as the x-position along the length of the screw divided by the screw pitch S. In effect, it is the number of pitch lengths along the screw.

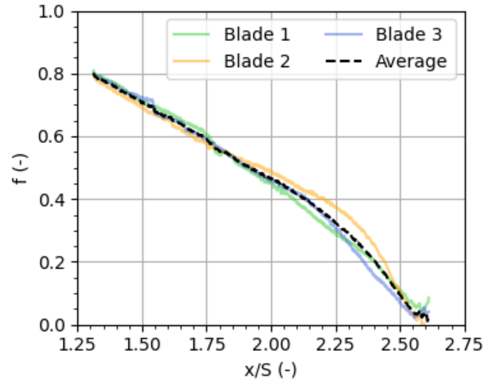

Fig. 5. Bucket fill height with respect to the dimensionless length along the screw for each blade, and the characteristic screw average of the 8.48 rev/min case.

It was observed that the bucket fill height noticeably varied along the length of the screw. At the end of the screw, the buckets approached a fill height of $f = 0$, so no flow of water was discharged to the outlet. Drainage seemed to be approximately linear in the main body of the screw. For all experimental runs, the buckets drained faster near the outlet. That effect was observed starting at approximately $x/S \approx 2.1$ in the maximum no-flow speed run (cf. Fig. 5). The exaggerated decrease in fill height near the outlet was likely due to the absence of back pressure caused by low upper water levels. For optimal efficiency, there exists a non-zero optimal upper water level for Archimedes screw pumps [21]. The upper water level helps provide a back pressure that is akin to the pressures experience by a central bucket of the screw due to the water heights in its immediately adjacent buckets. In essence, a screw set at its optimal upper water level will experience less premature draining of its final buckets near the outlet.

The results imply that gap leakage may effectively be linear in regions of the screw that are not directly impacted by the inlet or outlet. The full dimensionless length of the tested screw was $L/S = 2.857$. The bucket fill height results seemed to become non-linear at approximately one pitch length before the end of the screw (in the range of $x/S \approx 1.857$ to 2), which corresponds to this idea since the last pitch length would be affected by the screw outlet. However, it is very important to note that bucket fill height does not linearly relate to bucket volume, so the results had to be cast as bucket volume before the implication could be explored further.

The results in Fig. 5 were manipulated so they could be plotted as bucket volume (V_b) with respect to time elapsed during transport. In this form, it was possible to integrate the results and find the gap leakage with respect to time. A mathematical model [22] was used to convert the bucket fill height to a bucket volume based on screw geometry. The time-series data was manipulated so that $t = 0$ sec was when the bucket was first measured.

The bucket volume with respect to time for the maximum no-flow rotation speed is shown in Fig. 6. Note that time $t = 0$ sec corresponds to a dimensionless position along the screw of $x/S \approx 1.31$.

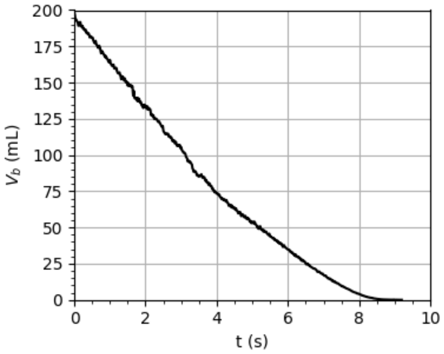

Fig. 6. Bucket volume (V_b) with respect to time optical measurements began for the 8.48 rev/min case.

It was observed that the change in volume with respect to time was approximately linear within the first half of experimental time; specifically, from t = 0 sec to $t \approx 4.2$ sec. Interestingly, a time of t = 4.2 sec corresponded to a dimensionless length along the screw of $x/S \approx 1.857$, which is one pitch-length before the screw outlet. Therefore, the results are consistent with the idea that gap leakage is approximately linear within the region of screw that is not directly impacted by the inlet or outlet.

The results of the maximum no-flow rotation speed curve shown in Fig. 6 was then integrated to find the gap leakage with respect to time. To perform the integration, the data was divided into 20 equal segments and the following relationship was applied to each segment to determine an average gap leakage value over the duration of that segment.

$$Q_g = \frac{\Delta V_b}{\Delta t} \tag{4}$$

The results of this manipulation are shown in Fig. 7.

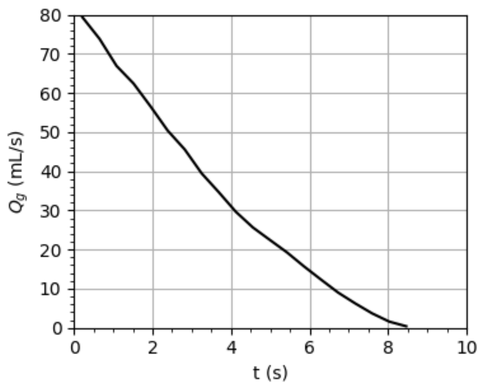

Fig. 7. Gap leakage with respect to time for the 8.48 rev/min case.

The results indicated that gap leakage varied relatively linearly in the first half of the optical measurement time, then asymptotically approached a leakage of zero near the outlet. This was consistent with what was observed during experimentation: the buckets visually drained much quicker near the screw outlet but maintained low levels right up to the outlet of the screw. The slowing of leakage flow rate in very low bucket volume cases may be due to the impact of wall shear and cohesion on the fluid in the bucket. When the volume of water was very low, the proportional impact of frictional effects was much higher, so the bucket drained proportionally slower.

While our research group has shown similar results with computational fluid dynamics (CFD) [23], these results represent the first time that gap leakage has been quantified in a real-world screw pump, and the results do reasonably correlate to those found using CFD.

Once the process for conversion from optimal fill height measurements to gap leakage with respect to time was developed, experimental results for the remaining rotation speed runs (cf. Table 2) were processed with the same method. Gap leakage with respect to time for all experimental runs are shown in Fig. 8. The figure uses a colour gradient from blue to red to indicate the experimental rotation speed, where dark blue is 8.48 rev/min (the maximum no-flow rotation speed) and the darkest red is 30 rev/min.

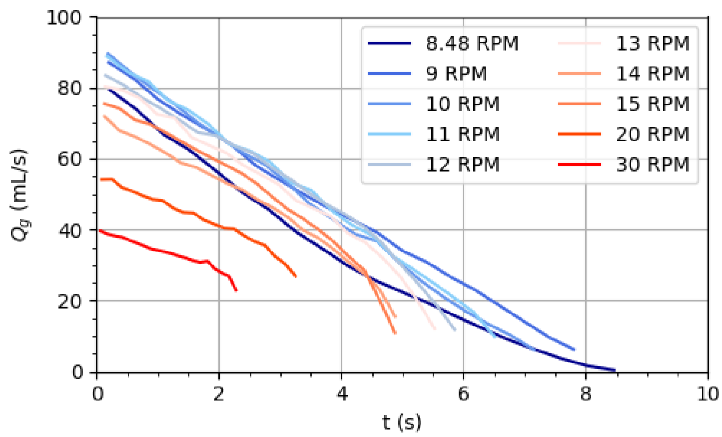

Fig. 8. Gap leakage for all experimental runs with respect to time

Though it was not always explicitly true, it generally appeared that lower speeds experienced higher rates of gap leakage. During low rotation speeds, buckets remained within the screw for a longer time period and thusly experience more drainage through gap leakage flow. The maximum no-flow rotation speed seemed to be the exception to this concept. That was likely since it started at time t = 0 sec with a lower fill height when compared to the other experimental runs since it had drained substantially by the point in which the optical measurements started (at $x/S \approx 1.31$).

The gap leakage trend seemed very well behaved for all experimental runs. Gap leakage generally varied with a curve that was approximately linear with respect to time. In all cases, the region corresponding to the last pitch length of the screw (1.857 ≤ x/S ≤ 2.857) experienced changes in leakage behavior that were not like the mid-screw leakage relationships. The last pitch length of the screw was highly impacted by the water level at the outlet (h_U); this screw segment was called the outlet region. As mentioned, the upper water level was set to zero for all the experimental runs since most real-world screws operate under such conditions. However, an upper water level of h_U = 0 m is known to be non-optimal with respect to mechanical efficiency. As expected, the outlet region buckets all drained prematurely due to the absence of back pressure in this region.

Based on the results, as rotation speed increased the proportional rate of gap leakage in the outlet region increased. Conversely, in low-speed cases, the outlet region experienced a proportional decrease in gap leakage flow rate. The inflection point for this relationship (changing from a proportional decrease to increase in gap leakage rate) seemed to occur at 10 rev/min.

When performing experiments along the range of rotation speeds, it was observed that fill height was higher than f = 1 in the high rotation speed runs. Since the lower water level was set to its optimal submergence, the first bucket should have filled to a level of f = 1. The higher-than-expected fill heights indicate that two different phenomena may be occurring. The higher bucket fill heights may be caused by friction effects. The bottom of the screw rotated towards the camera that was used for optical measurements. So, friction on the screw blades may have pulled the volume of water in the buckets towards the side of the screw with the camera. The camera side of the screw was called the “front side” of the screw buckets. If this were true, the back of the screw that was not in view of the camera would have a correspondingly lower bucket fill height.

The second phenomenon that might cause bucket fill height to be higher-than-expected may be occurring at the screw inlet. As the blades closed on the free surface and formed the first bucket, they may have performed a scooping action that caused an additional surge of water to enter the buckets. Due to higher speeds, it is possible that the blades scooped up more water than would correspond to a fill height of f = 1. A surge at the inlet would also cause an impulse and a sloshing effect to propagate through the screw. The sloshing phenomenon was observed experimentally [21], in the field, and in computational fluid dynamic simulations [23]. It is possible that the first bucket had over-filled and translated along the screw before the water in the bucket sloshed back and began to overflow back to the lower basin. By the time the bucket sloshed back to the front side of the screw (the side that experiences overflow), it may have started to overflow into a partially- or fully-formed bucket. In this case, the screw would continue to form buckets higher than f = 1 and translate up the trough with higher-than-expected fill heights. Gap leakage and overflow leakage would continue to contribute to the development of a fill height gradient, which was ultimately observed. It is possible that adding a camera to the back-side of the screw could better characterize bucket fill levels since the front- and back-side of the screw bucket could be optically measured.

4 Conclusion

Novel experiments were performed to optically measure the fill height gradient of an operating, laboratory-scale Archimedes screw pump. It was found that a fill height gradient existed within the screw such that the lower buckets (near screw inlet) had higher water levels that upper bucket (near screw outlet). The fill height gradient was directly impacted by changes in rotation speed, with lower rotation speeds experiencing more drastic fill height gradients and higher speeds exhibiting more moderate fill height gradients.

The fill height gradients were post-processed to yield bucket volume and gap leakage with respect to the time elapsed during translation of the buckets within the screw. Gap leakage was generally impacted by rotation speed such that higher rotation speeds held buckets within their domain for a shorter duration and therefore experienced less leakage flow. The maximum rotation speed that delivered Q = 0 mL/s at the outlet was found to be 8.48 rev/min. This was called the maximum no-flow speed. The maximum no-flow speed only experienced gap leakage flow rate during operation, it did not deliver a flow rate nor experience overflow leakage. So, it is a great case to explore the impacts of gap leakage on screw pump performance.

It was found that the high-speed experimental cases experienced higher-than-expected bucket fill heights. It was suggested that the high fill heights may have been due to frictional effects or due to a surging caused during bucket filling at the screw inlet. Either effect (or both) may contribute to the higher-than-expected bucket fill heights. Regardless, an additional camera in view of the back side of the screw buckets would help address this issue in future experimentation. The current camera had a view of the front-side of the screw bucket. The authors recently used a similar process, an ongoing computational fluid dynamic study of ASPs. Measurements of the back- and front-sides of the screw buckets would help to quantify the bucket fill height variations and determine the cause of the higher-than-expected fill levels.

Altogether, this study presented novel data to the literature that will be very helpful for future performance prediction model development. The study also demonstrated that video analysis software, like Kinovea, has potential as a tool in applied hydraulics research. The software yielded reasonable results without the added expenses and complexities of a Particle Image Velocimetry (PIV) system. Additionally, the conventional Archimedes screw pump has a geometry that would be difficult to set up with a PIV system.

The bucket fill height gradient phenomenon has never been quantified experimentally before, so this data is an integral addition to the literature. The results of this study will be used to evaluate and improve gap leakage prediction models.

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