

AN EXPERIMENTAL STUDY OF ARCHIMEDES SCREW PUMP EFFICIENCY

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Abstract— Archimedes screw pumps (ASPs) are an established low head pump technology that has been used for millennia to lift water. However, there is little literature available on the design of ASPs, and ASP theory is not well enough developed to enable full simulation of an ASP in efficient parametric models that would allow optimization studies. Complete datasets in which all important operating parameters are reported are also extremely rare in the literature. The experimental study reported here is an initial effort to provide additional useful ASP experimental data for research use. Experimental measurements are reported for a laboratory-scale ASP to characterize pumping efficiency as a function of lower and inlet basin water levels, as well as screw rotation speed. Comparisons are made to existing literature to assess the findings through the experiment. Pumping efficiency was sensitive to lower basin water levels, with efficiency declining once the inlet water level exceeded 80% of the screw inlet height. It was confirmed that ASPs should be operated with a lower basin level of 70 % to 80 % of screw inlet height for optimal efficiency. The study also identified an upper basin water level for maximum efficiency. The effect of upper basin water level on power was also examined.

Keywords- Archimedes screw; hydrodynamic screw; Archimedean screw; screw pump; efficiency

I. INTRODUCTION

The Archimedes screw pump (ASP) is a water lifting device that has been in use for more than two thousand years. Its name is attributed to Archimedes of Syracuse and his popularization of the device during the mid-third century BCE. There have been other reports of the device's use prior to Archimedes; it was purportedly implemented for irrigation in the Assyrian Empire in the 7th century BCE [1].

The Archimedes screw has been implemented for different purposes, including low-lying drainage systems, wastewater treatment, and irrigation. More recently, the screw has been used increasingly as a hydropower generator.

Archimedes screws are made by winding one or more helical surfaces (called "flights") around a central shaft (Fig. 1). Three

or four flights are usually used [2]. The screw is located within a cylindrical trough that is usually open at the top but can be completely closed. In a few cases, the trough is connected to the outer edge of the helical flights so that it rotates with the screw, but in most cases, the trough is fixed with a small gap between it and the outer edges of the flights so that the screw can rotate freely.

When used as a pump, the lower end of the inclined screw is partially immersed in water and rotated. As the screw rotates, water is trapped between successive sets of flights. These trapped volumes of water are referred to as "buckets" [3]. As the screw continues to rotate, buckets of water are translated upward along the screw and eventually empty from the upper (or outlet) end of the screw into an upper reservoir.

Despite its long historical use, there is relatively little guidance on ASP design. The Screw Pump Handbook [4] is a notable work in the field, providing information and a general design procedure for the design and installation of ASPs. The handbook draws heavily from an earlier Dutch-language work by Muysken [2]. The handbook's insights on screw pump design are largely based on heuristics and experience. Notably, neither Muysken nor Nagel provide explicit operating data [4].

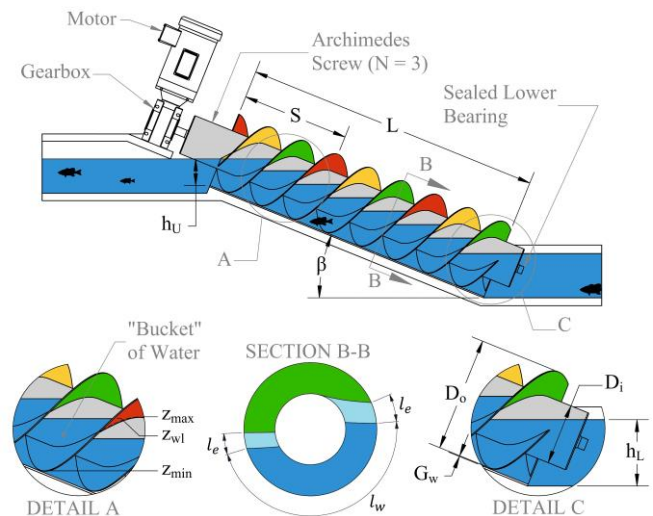


Figure 1. Archimedes screw geometry (adapted from [14]).

Literature on ASP theory is also relatively limited. Muysken's [2] foundational work is one of the early papers on the subject and includes information on recommended conditions for operating Archimedes screws that were subsequently expanded on by Nagel [4]. Rorres [3] proposed a mathematical optimization of a screw pump based on maximizing screw filling, assuming an idealized screw (i.e., with infinitely thin flights).

Experimental data is also limited in the literature. Addison [5] presented the earliest-documented English-language experiments on Archimedes screw pump performance. The experimental work documented the performance (power and efficiency) of screw pumps with varying rotation speed, water level, discharge, and inclination angle. Though Addison's publication is the earliest known English-language document, there seem to be Dutch- and German-language experimental works referenced by Muysken [2] and Nagel [4] that pre-date them [6]–[9]; however, the authors were unable to acquire the texts.

More recently, Monserrat et al. [10] published an article investigating the cost-savings associated with variable inclination screw pumps. They measured the performance of a prototype screw pump and demonstrated the efficacy of a variable inclination system. Lyons et al. [11] presented a large experimental dataset gathered from laboratory-scale screw pumps ($D_o = 0.3$ m). The dataset was collected to facilitate further mathematical model development. As such, it measured screw pump performance while varying the lower water level, upper water level, and rotation speed of the screw. Though the data is readily available, more robust experimentation is required for further model development and evaluation.

While a fully developed theory is not available in the literature, there are practical guidelines. Nagel [4] recommends the ratio of inner diameter and outer diameter (D_i/D_o) be between 0.45 and 0.55 for most conditions and most actual screw pumps fall in this range. Rorres [3] found that the geometric optimum value of D_i/D_o is 0.54 for all practical numbers of flights (i.e. two to six).

Recommended inclination angles (β) vary in the literature. Muysken [2] states the installation angle of screw pumps can range from 26° to 40° , and that 30° , 35° , and 38° were the most typical angles in use.

Nagel [4] suggests the ideal operating inclination angle is $\beta = 30^\circ$, and the ideal pitch is around $S = D_o$. At lower angles ($\beta < 30^\circ$) Nagel (1968) suggests using a pitch of $S = 1.2D_o$ while for greater angles ($\beta > 30^\circ$) a pitch of $S = 0.8D_o$ is recommended (although it is not elaborated on why these values are suggested). Overall, there does not seem to be a consensus on the ideal inclination angle of an ASP.

Muysken [2] recommends the maximum rotation rate for a screw pump n_{max} as a function of the outer diameter is:

$$n_{max} = \frac{50}{\sqrt[3]{D_o^2}} \quad (1)$$

Note that this is a non-homogenous equation, which means that the units of D_o must be in meters, and the units of n_{max} will be in rev/min.

To allow the screw to rotate freely, there must be a small gap between the outer edge of the rotating screw, and the surface of the circular trough within which the screw rotates. The difference in free surface between consecutive buckets causes a difference in static pressure that drives the water through the gap, causing a steady gap leakage flow down through the screw, which in turn reduces screw efficiency. The width of this gap, in meters, is typically

$$G_w = 0.0045\sqrt{D_o} \quad (2)$$

where D_o is the screw diameter in meters (note that neither this or any of the equations that follow are dimensionally consistent, and must only be used with the specified units). Assuming this gap width, Nagel [4] also gives an empirical formula for approximating the gap leakage in Archimedes screw pumps. Leakage volume flow rate Q_L through the screw, in m^3/s , is

$$Q_L = 3.5G_wD_o^{1.5} \quad (3)$$

where G_w is the width of the gap between flight edge and trough in meters.

The loss of work caused by water leaking through the gap between the flights and the walls or leakage loss is given by Nagel [4] as another non-homogenous equation:

$$N_L = Q_L H / 75 \quad (4)$$

where N_L is the leakage power loss in horsepower, Q_L is the leakage flow in (m^3/s) and H is the effective useful delivery head in (m). Other more complex and versatile equations exist, including those presented by Nuernbergk and Rorres [12] and Lubitz [13].

The shaft power of the screw pump is

$$P_s = T\omega \quad (5)$$

where T torque is the torque (measured or predicted) and ω is rotation speed, typically in rad/s. The theoretical ideal power needed to pump the flow Q is

$$P_w = \rho g Q H \quad (6)$$

where ρ is the density of water (typically 1000 kg/m^3) and g is the gravitational constant 9.81 m/s^2 . Combining these two expressions gives a pumping efficiency

$$\eta = \frac{\rho g Q H}{T\omega} \quad (7)$$

which will approach 1.0 as the shaft power gets closer to the theoretical minimum power needed to lift the water in ideal circumstances.

II. OBJECTIVES

While there has been a lot of interest in Archimedes screw pumps over the years, there is still limited information in the literature on the effect of lower basin level on screw pump performance. Some data regarding the effects of lower basin level on screw efficiency was discussed by Muysken [2], but this is a small dataset from a single screw (the Oostmade Polder) at a varying rotation speed and a range of lower end fill levels.

Importantly, the data and discussions presented by Muysken [2] suggested similar results to more recent tests by Lyons et al. [11]. Mainly, that there is an optimal lower water level for the most efficient bucket filling and operation. Both Muysken and Lyons et al. found that high lower water levels resulted in increased impact losses and unnecessary friction losses, while low lower water levels resulted in low flow rates and reduced mechanical efficiency.

This study is an experimental investigation of the mechanical efficiency of a laboratory-scale Archimedes screw pump. The focus is on the effects of the lower basin level and rotation rate. The effect of the upper basin level is also examined. The study compares the experimental observations with existing guidelines on the optimal inlet end conditions and rotation speed for an Archimedes screw pump.

III. METHODS

Experiments were conducted during summer 2022 at the University of Guelph Archimedes screw testing facility, which has the ability to measure the performance of screws operating as either pumps or generators. In pumping mode, the screw is placed in the experimental setup so that the lower end is submerged in the lower basin and the upper end extends to the upper basin. The screw is rotated by a gearmotor controlled by a frequency inverter, which can maintain a wide range of selected screw rotation speeds regardless of the load. This causes the screw to pump water from the lower basin to the upper basin. An adjustable weir at the back of the upper basin allows for fine control over the water level in the upper basin. The water flows over the weir into a well and then through an inline flowmeter before returning to the lower basin.

The gear motor is supported by a rigid metal frame with a load cell connecting the motor to a fixed mounting point. The load cell measures the torque applied to the screw, and this information is used to calculate the mechanical torque needed to turn the screw. The rotation rate of the screw is measured by placing a magnet on the shaft, which trips a solid-state magnetic switch mounted on the fixed frame once per revolution. The flow rate is measured using a pulse-width signal from the flowmeter, and the upper and lower basin levels are recorded using Keller Valueline depth gauges and manually checked with graduated measures. All electrical signals are recorded using a data acquisition device (National Instruments) connected to a laptop.

The University of Guelph Archimedes Screw Laboratory has an inventory of 16 unique laboratory-scale Archimedes screws.



Figure 1. Test screw viewed from lower inlet basin.

In this experiment, tests were conducted on a single screw installed at an inclination of $\beta = 26^\circ$ from the horizontal (Fig. 1). Tests were conducted on a three-bladed screw ($N = 3$) with outer cylinder $D_o = 31.6$ cm, inner cylinder diameter $D_i = 16.8$ cm, pitch $S = 31.8$ cm and flighted length $L = 122$ cm.

The performance of the screw, measured as input power and flow rate, were measured for combinations of the three variables of upper water level h_U , lower water level h_L and screw rotation speed ω . Upper and lower water levels can also be represented non-dimensionally as

$$\psi_U = h_U/D_o \cos \beta. \quad (8)$$

$$\psi_L = h_L/D_o \cos \beta \quad (9)$$

Tests were conducted for all combinations of the values of these parameters shown in Table 1 that allowed steady state operation. The ranges of values in Table 1 were chosen to represent the reasonable span of values that might be possible in operation. Upper water levels above 0.6 resulted in significant water “overtopping” the screw outlet and flowing back down the screw: these levels are generally not feasible for practical pumping. Lower water levels span from a relatively low inlet level ($\psi_L = 0.2$) to complete submergence of the screw inlet ($\psi_U = 1.0$).

There were many combinations of the variables in Table 1 that resulted in no water being pumped (e.g., low lower water level and low rotation speed) or too much water being pumped (e.g. high rotation speeds and higher water levels). The experimental set up limited the maximum flow rate because the water return path was gravity driven flow through the connecting pipe that housed the flow meter.

TABLE I. VALUES OF TEST VARIABLES USED IN EXPERIMENTS.

ψ_U (-)	ψ_L (-)	ω (rev/min)
0	0.20	18
0.15	0.40	36.5
0.30	0.60	55
0.45	0.80	73.5
0.60	1.00	92

IV. RESULTS

Figure 3 displays the pumping efficiency at various rotation speeds in relation to lower basin levels. The upper basin level was kept at $\psi_U = 0$. The peak efficiency generally fell between ψ_L of 0.4 and 0.6. This range was consistent with past literature [2,4,10,13] which suggested that peak efficiency should occur at ψ_L values of about 0.6.

Figures 4 and 5 further explore the efficiency as a function of the three primary dependent variables (ψ_U , ψ_L , ω), showing results for higher upper basin water levels of $\psi_U = 0.3$ (Fig. 3) and $\psi_U = 0.45$ (Fig. 5). While the overall pattern of all three cases in Figs. 3-5 remain similar, there is a noticeable shift in the apparent lower water level at which peak efficiency occurs. Notably, peak efficiency is slightly lower in the case where upper water level is at the bottom edge of the screw outlet ($\psi_U = 0$; Fig. 3). This is believed to be due to the screw lifting water within the screw to a somewhat higher level than required, and efficiency is lost as the pumped water “drops” into the upper basin.

Figure 6 shows the relationship between pumping flow and various basin levels and rotation speeds. The flow rate starts low and increases as the lower basin level rises. However, after reaching a peak, the flow rate starts to plateau or slightly decreases. There is a noticeable effect of rotation speed on flow rate, as increased flow rate can be seen with high rotation speeds, whereas flow rate increases at a slower rate at slow rotation speeds.

The practical goal with pumps is to be able to provide a useful flow rate. Figure 6 shows the flow rate produced by the pump at different lower water levels and rotation speeds, for the case of $\psi_U = 0$. It is apparent that the flow rate pumped increases with both rotation speed and lower basin level, although at high lower basin levels incremental increases in flow rate decrease as the pump approaches its capacity.

Figure 7 shows the efficiency of the pump for flow rates and lower basin levels, again holding the upper basin level constant at $\psi_U = 0$. Notably, the efficiency of the pump is relatively constant for different flow rates, and is more dependent on lower basin level. It is theorized, based on observations during the experiments, that at small lower basin levels, a greater portion of the water drawn into the pump flows back downstream to the lower basin as gap leakage flow (which will be proportionally greater at low screw fill levels associated with small lower basin levels).

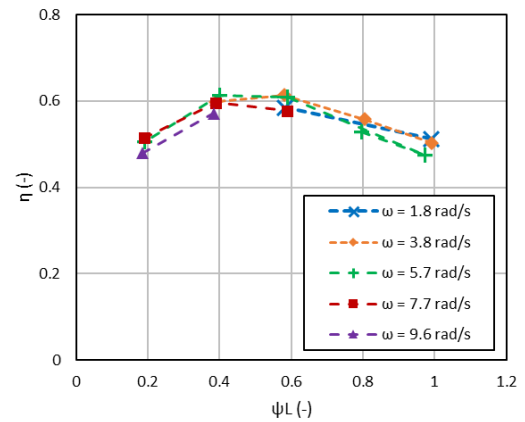


Figure 3. Pumping efficiency at $\psi_U = 0.00$ upper basin water level.

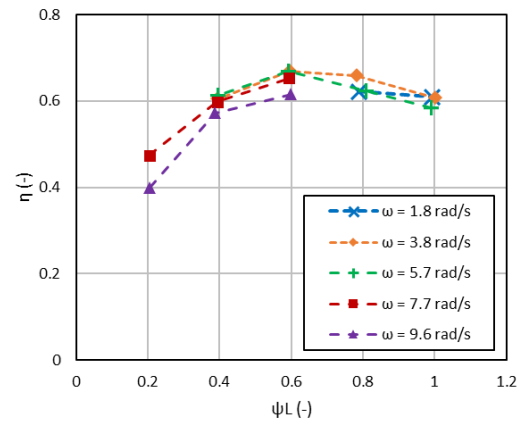


Figure 4. Pumping efficiency at $\psi_U = 0.30$ upper basin water level.

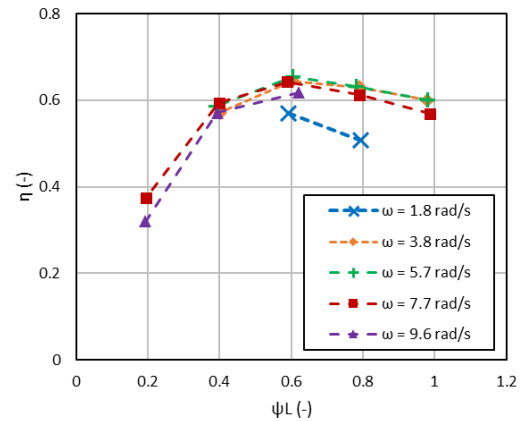


Figure 5. Pumping efficiency at $\psi_U = 0.45$ upper basin water level.

The effect of lower basin submergence level (ψ_L) was compared to the screw pump’s mechanical power usage across a range of rotation speeds in Figure 8. As may be expected, a higher rotation speed resulted in a generally higher power usage. It is also notable that more power is required to pump with higher upper basin water levels, and that amount of power needed beings to increase markedly at the higher upper basin levels.

While the experiments were being conducted, it was observed that the water levels in the screw buckets varied along

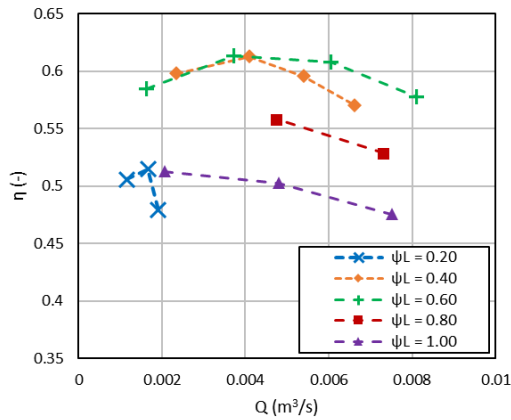


Figure 6. Pumped flow rates at $\psi_U = 0.00$ upper basin water level.

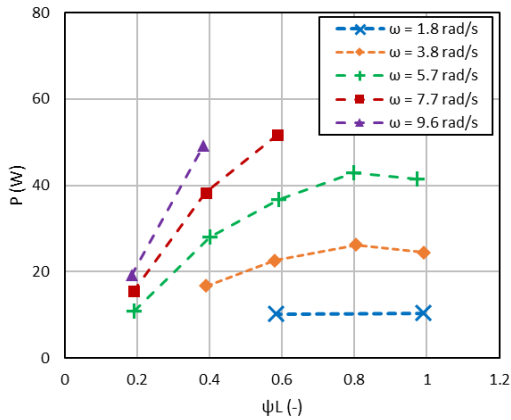


Figure 8. Pumping power at $\psi_U = 0.00$ upper basin water level.

the length of the screw. The variances were greater and more noticeable during low rotation speeds. Since mechanical power is a function of torque and rotation speed and torque is a function of the mechanical conversion of (mostly) hydrostatic pressure in the buckets, this suggests that the leakage between the buckets (i.e., gap leakage) varies along the length of the screw. In other words, the buckets slowly drain as they translate upwards, and the drainage is cumulative. If that is the case, a faster rotation speed would help to minimize drainage as the buckets would

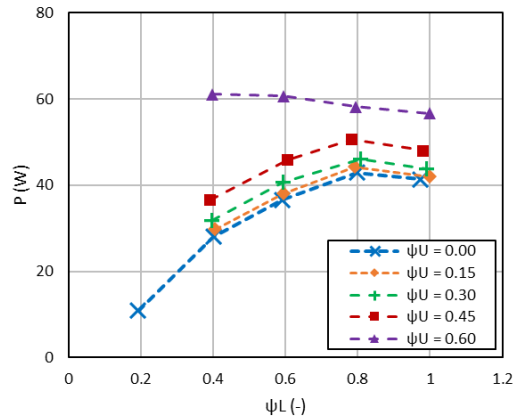


Figure 9. Pumping power at constant rotation speed $\omega = 5.7$ rad/s.

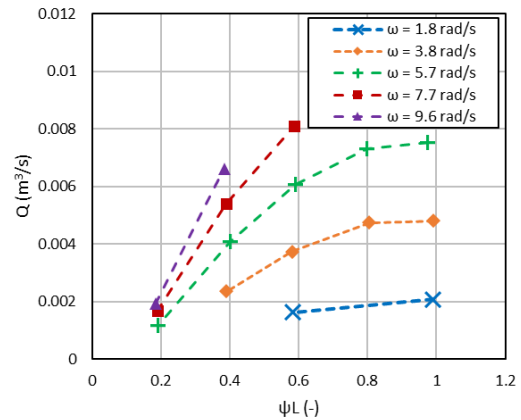


Figure 7. Pumping efficiency with $\psi_U = 0.00$ upper basin water level.

spend less time in transport within the trough. Thus, power usage may increase, but it may be more “useful” power since it transports a larger volumetric flow.

Figures 9 and 10 demonstrate the effect of lower submergence (ψ_L) on power usage (Fig. 9) and mechanical efficiency (Fig. 10) for varying levels of upper (or outlet) submergence level (ψ_U). The data shown in these plots has a constant rotation speed and the variations in lower water level are consistent, so the trendlines should all be consistent based on water availability. This logically suggests that any variation in power or efficiency between the trendlines was strictly due to the impact of the screw’s outlet condition (i.e., the variation in ψ_U).

The upper water level directly impacts the outlet of the screw as water discharges into an upper reservoir or basin. As the upper water level increases, there is a higher backpressure as the water exits to the upper basin. As such, there exists an optimum upper water level that will provide an appropriate back-pressure to prevent any premature emptying of the screw’s buckets. Based on the data in Figure 9 and 10, it is suggested that the optimal upper submergence level for the screw in these experiments was between $\psi_U = 0.3$ and $\psi_U = 0.45$ while operating at 5.7 rad/s, since those were the most efficient operating points (cf. Fig. 10).

There is a balance, however, in finding the most efficient upper water level. When the upper water level was too high, it

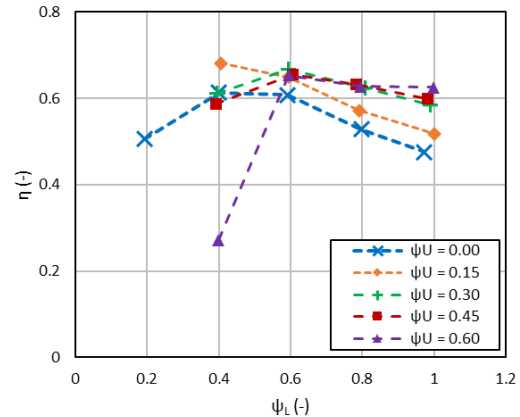


Figure 10. Pumping efficiency at constant rotation speed $\omega = 5.7$ rad/s.

caused a backflow through the screw that propagated downward through the screw via overflow leakage that overtopped the buckets. It was most evident at the point on Figure 10 with the screw operating at $\psi_U = 0.60$ and $\psi_L = 0.40$, requiring a power of $P = 61.1$ W (Figure 9) and an efficiency of $\eta = 0.272$ (Figure 10). So, for the most mechanically efficient operation, a screw pump should have a high enough upper water level to supply an appropriate backpressure that allows for optimal drainage, but not too high of a water level to cause flooding at the outlet that spills back through the screw via overflowing buckets.

In practice, the upper water level is usually set to $\psi_U = 0$ or less. This means that real-world screw pumps do not usually operate at an optimum mechanical efficiency. However, by draining into an under-filled upper basin/reservoir, other system components are not required at a pump house. Though the screw is doing more work than required, a backflow valve or gate system is not required to prevent backflow when the screw is not operating. So, the screw pump system may not be operating at an optimum mechanical efficiency point, but an economically or operationally efficient point.

V. CONCLUSIONS

The study presented here produced data on the effects of upper and lower basin water level and rotation rate on the efficiency, flow rate and power requirements of a laboratory Archimedes screw pump. This study expands on data available in the literature by examining multiple rotation rates and low fill levels. The figures presented in this paper here display relationships between different variables and outputs, and then multiple results are examined.

The experimental results showed that pumping efficiency was sensitive to lower basin water levels of $\psi_L \leq 0.8$, but that efficiency starts to decline as lower basin water level is increased above this level. This finding was consistent with the available literature that suggests screw pumps should be operated with a lower basin level of ψ_L of 0.7 to 0.8 for optimal efficiency. The effect of upper basin water level on efficiency is also worth noting. With increasing upper basin levels, the peak of efficiency shifts higher. The relationship between flow rate and lower basin water levels was also established. Pumped flow rate increases with increasing lower basin levels. However, at high lower basin levels of $\psi_L \geq 0.8$, the resulting flow rate begins more constant even if lower basin depth is further increased. The relationship between power and lower basin water level showed similar features. Upper basin levels are also important for efficient operation. Power for all upper basin water levels increase with lower basin water levels, but consistently drop off with $\psi_L \geq 0.8$.

While the trends observed in the data are well behaved, there is not enough data from the present experiments to model these trends as a function of screw geometry, which would be required in order to build a robust predictive model for picking an optimal combination of rotation rate and lower end fill for any given screw geometry. More data of a similar nature would need to be collected for various geometries and scales of screw pump. Future work should focus on increasing the resolution of the data collected, examining other screw geometries, and determining how to scale performance variables between screws of different sizes.

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