Ram Pump, Fall 2016

Javier Paternáin Martínez, Christopher Galantino, Luna Oiwa

December 19, 2016

Abstract

The purpose of the Ram Pump team is to design and develop a properly functioning hydraulic ram pump, or hydram, for implementation in AguaClara plants. The hydram can be used to deliver water from below the facility back to the top for utilization in chemical stock tanks or to collect water at higher elevations for alternative uses. The team's goal for this semester is to find a practical method for measuring the pump's flow rate and efficiency, to determine the effects of adding distribution piping to the bottom of the apparatus, and implement methods to solve issues as they arise.

1 Introduction

The main function of a ram pump, also known as a hydraulic ram pump or hydram, is to take a portion of an incoming stream and, exploiting the properties of negative gauge pressure and momentum, deliver this water to a higher elevation. Such a method is perfect for implementation in AguaClara water treatment plants since the system is sustainable and can operate for long periods of time without constant maintenance. With water being pumped back to the top of the treatment facility, the plant can replenish its coagulant and chlorine tanks and provide the bathroom with water without manual labor.

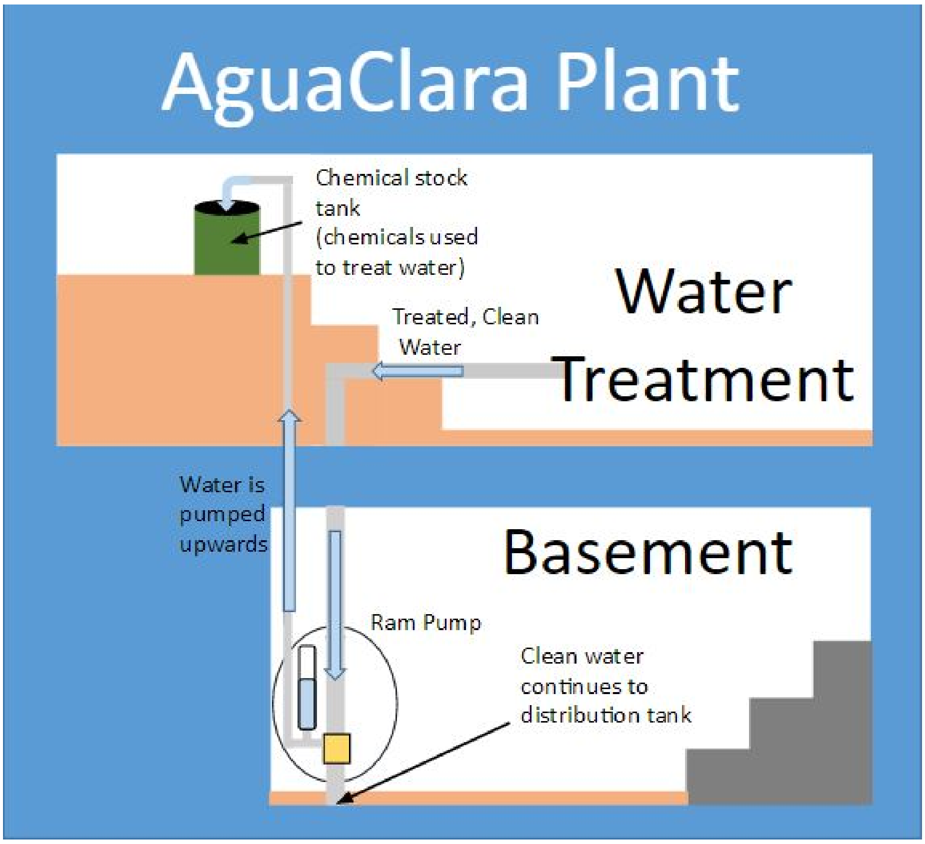


Figure 1: This image shows the overall concept behind the implementation of the ram pump design. Treated water flowing from the plant above reaches the pump below where it is then delivered back to the beginning of the treatment process. This allows coagulant and chlorine tanks to be replenished autonomously.

By perfecting the model and maximizing efficiency, the ram pump brings AguaClara one step closer to designing a completely self-contained, self-sufficient facility that will provide safe drinking water to thousands of people worldwide.

2 Literature Review

A hydraulic ram is a device that can pump water even in locations where electricity is not available. This device uses the energy of falling water to lift a lesser amount of water to a higher elevation, or hydraulic head, than the source. A benefit to the hydraulic ram is that it is relatively economical to purchase and install. Its simple structure makes it easy to build with detailed plans, and a properly installed pump will provide many trouble-free years of service with no additional costs to pumping. There are only two moving parts and thus there is little to wear out. The hydraulic ram is an attractive solution where the available water flow is at least seven times greater than the desired pumped water flow. For the pump to work, the water flowing through it must be free of trash and sand, the site for the hydram must be at least 0.5 m below the water source, and water must be pumped to an elevation higher than the source.

Recently, a team of Thai and German agricultural engineers worked to install a ram pump in Northern Thailand (Inthachot et al., 2015). Their investigation focused on making the pump both low-cost and efficient, goals similar to those of AguaClara. According to their report, they were able to pump water between 2.35 m and 5.65 m vertically, with water flowing into the pump at 7.55 liters per minute (126 mL/s). Their report, "Hydraulic Ram Pumps for Irrigation in Northern Thailand" was published in 2015 and attempts to relate hydraulic head and flow rate, by varying air pressure-chamber size. The air chamber is a small tank that temporarily stores the spurts of water pumped by the hydram and releases them at a lower pressure in order to push effluent during each pumping cycle while also ensuring the effluent has a more constant flow.

According to the report, after the air chamber reaches a certain volume, greater air chamber size will not affect pump efficiency or effluent flow rate. In the case of the Northern Thailand team, a 0.6 L air chamber did not function as well as a 2.3 L chamber, but a 2.3 L chamber functioned as well as a 3.6 liter one.

Another note on the optimal structure of a long-lasting hydraulic ram pump made by the Northern Thailand team was the potential benefit of a snifter valve, a small hole that permits the entrance of air bubbles into the air chamber. The only comment made on this subject was the inclusion of the valve; however, other works expand on this concept. Hofkes and Visscher (1986) explain in their compilation of papers on sustainable water supply and renewable energy that this valve is essential to a long-term functioning pump. They go on to state that as the pumped water fills the air chamber, the air within the enclosure is slowly dissolved. If this air pocket is not consistently restored, the air chamber will eventually fill with water and no longer operate correctly. The solution is a snifter valve, as mentioned above, which is attached to the pump chamber and serves to prevent this occurrence. Therefore, the team needs to look further into its potential use.

3 Previous Work

3.1 Ram Pump Setup

To simulate clean water flowing from a water treatment facility, the ram pump setup in the laboratory utilizes an electric sump pump. This sump pump carries water to a raised tank, and the water from this tank is free to move down the drive pipe, as is shown in Figure 2. When the water reaches the ram pump from the drive pipe, it undergoes the pumping process. It is important to note that the high elevation of the head tank relative to the ram pump is what allows the hydram to pump against gravity by creating an input of energy.

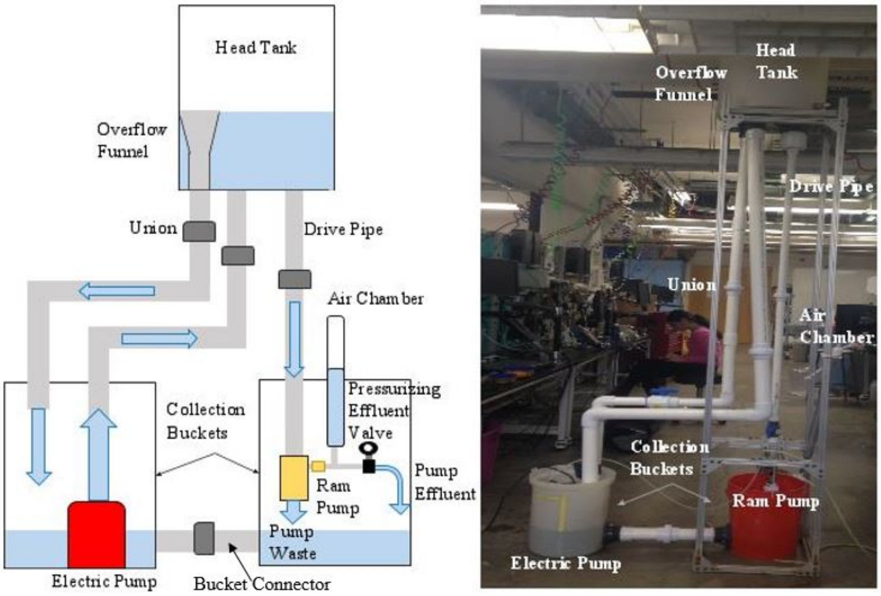


Figure 2: The electric sump pump delivers water to the head tank at the top of the system. From there, the water flows down the drive pipe and into the ram pump itself. While most of the water exits through the bottom as pump waste, a portion is pumped as effluent.

The ram pump functions as follows: when water rushes onto a plate within the pump, the downward pressure on the plate compresses the spring onto a constriction located under the plate. This briefly closes the opening of the constriction, and pushes water past the one-way stop valve and through the effluent pipe attached to the side of the main water channel.The combination of the pressure plate and constriction is known as the check valve.

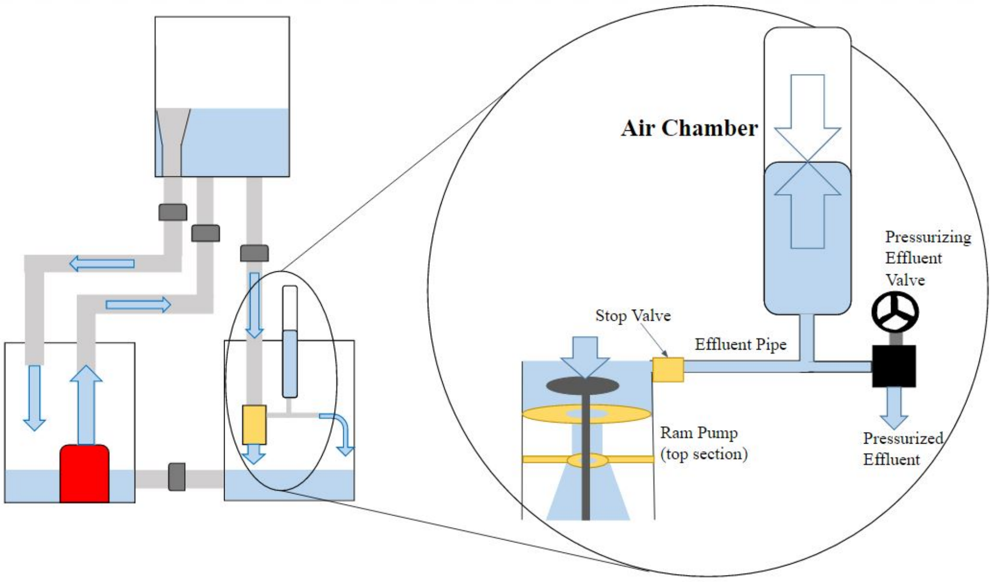


Figure 3: This schematic serves to help visualize the location of the ram pump's inner workings and their proximity to the air chamber and effluent valve. The effluent valve is located after the air chamber and is used to release pumped water. The stop valve is directly after the check valve and before the air chamber. It serves as a one-way path for pumped water in order to prevent back-flow.

There are several important valves to take note of that will be referred to throughout the report's entirety. These valves are the check valve, stop valve, and effluent valve. The location of all three can be seen in Figure 4. The check valve consists of the pressure plate and constriction. It is what allows water to pass as pump waste, or be delivered through the stop valve as effluent produced by the pump.The stop valve serves as a one-way path for pumped water in order to prevent back-flow. The effluent valve is used to release pumped water.

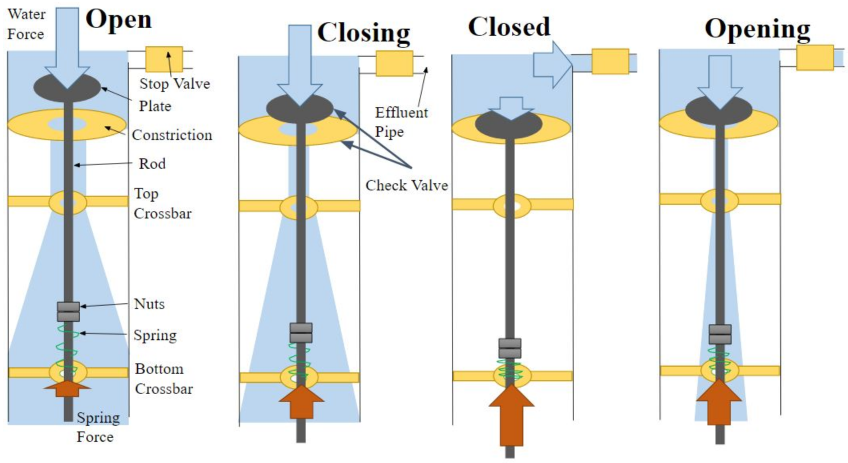


Figure 4: Water from the drive pipe above flows on and around the plate, applying a downward force. As this force persists, the spring-loaded plate covers the opening in the constriction, causing a buildup of pressure. This pressure pushes water through the one-way stop valve, located between the check valve and air chamber, and into effluent pipe. The spring then completes its oscillatory motion, allowing the check valve to reopen and repeat the process.

While most of the water exits through the check valve, the ram pump diverts some of the water received from the drive pipe through the one-way stop valve. From here, the water collects in the air chamber and proceeds towards the effluent valve, shown in Figure 5. The purpose of the air chamber is to assist in the pumping process and to allow for a steady stream of water to be supplied through the effluent valve whether the check valve is open or closed. In order to understand why this is, the behavior of a gas under pressure must be conceptualized.

Essentially, a constant mass of air resides within the air chamber, spread evenly throughout. When the pump goes through its cycles, the volume of air expands and contracts due to the ebb and flow of water. Initially, the gauge pressure is zero. However, when the check valve closes (Figure 5 left), pressurized water is forced into the air chamber and compresses the air inside. The check valve then opens again (Figure 5 right), allowing the temporary pressure gradient to push water back down. This addition of pressurized water acts as a cushion for intermittent bursts of water delivered by the ram pump, and increases the effluent flow rate.

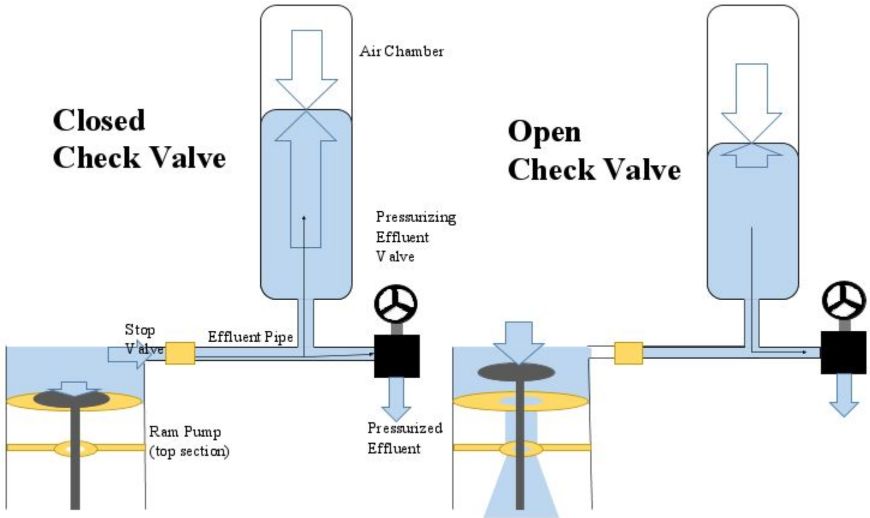


Figure 5: Starting at zero, the gauge pressure within the air chamber increases as the check valve closes due to pressurized water entering the partially-filled cavity. When the spring recoils and the check valve opens, the gas expands and pushes the water toward the effluent pipe and then to the effluent valve.

To obtain data necessary for the calculation of water flow rate, pressure sensors are attached to the pump, the air chamber, and the effluent valve (Figure 6). These pressure sensors are vital to understanding the behavior of the pump during experimentation. This is because the laboratory is a confined space in which pumping to high heads would require a higher ceiling. 200 kPa sensors attached to points of interest can transmit information to a computing software called ProCoDA. ProCoDA is a program that can convert electrical input into pressure readings which are displayed in centimeters of hydraulic head while also recording elapsed time in seconds. These are valuable units that are continuously monitored during the experiments of this report.

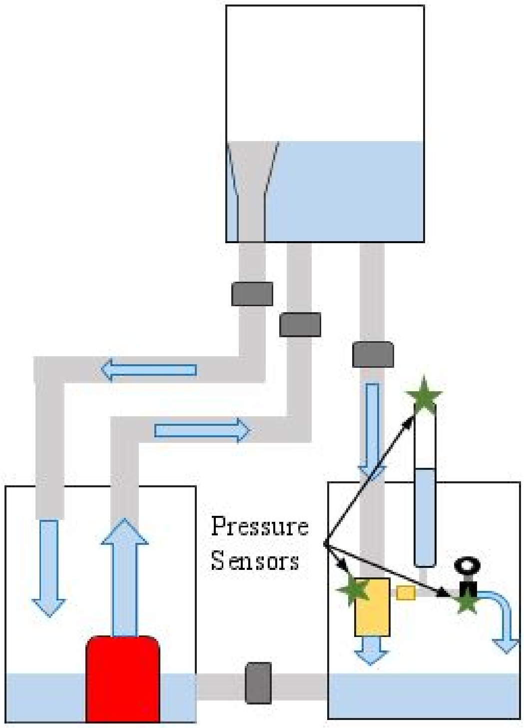
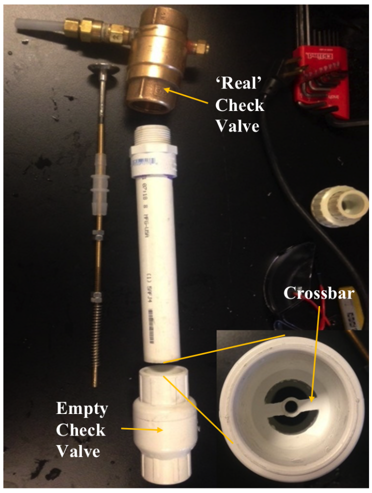


Figure 6: In order to obtain required data, pressure sensors attached to points of interest are connected to ProCoDA, a computing software that evaluates pressure readings. These values can then be monitored to understand how the ram pump behaves with respect to flow rate and efficiency.

3.2 Enclosed PVC Design

The Spring 2016 AguaClara team started with an unenclosed PVC ram pump prototype created by previous teams, and developed an enclosed PVC prototype. In this enclosed PVC design, an empty check valve was placed after the actual check valve in order to provide a surface on which the spring could compress while allowing the continuous passage of water past both valves (Figure 7a).

(a) This is the unenclosed PVC prototype of the ram pump.



(b) This is the enclosed PVC prototype of the ram pump. The pump contains two check valves: the "real" check valve is opened and closed to create water pressure spikes, allowing the pump to function. The "empty" check valve provides a surface on which the spring can compress while still allowing water to flow through it.

The Spring 2016 team worked to make the PVC ram pump prototype design stable, durable, and water-tight, so that the prototype could eventually be connected to distribution piping. Currently in AguaClara plants in Honduras, the ram pump is placed within a concrete collection box. Pump waste splashes into the box, then flows through a pipe connected to the bottom of the collection box. This creates air bubbles and occasionally causes the box to overflow, wasting clean water. Having the pump in-line with the distribution piping is advantageous because it allows the water to flow directly into the distribution tank and avoid these issues.

In addition to increasing stability, another objective was to make the ram pump easy to assemble and disassemble in order to facilitate testing, maintenance, and potential replacement of parts (Aggarwal and Guzman, 2016).

3.3 Enclosed Brass Design

Stability of the pump is vital to reducing both energy loss and wear resulting from unnecessary vibrations. The team replaced the PVC parts with brass without changing the design. They reasoned that the increased lifespan of the pump would decrease maintenance, and that this difference in operating expenses would make up for the higher initial cost of the metal parts (Figure 8).

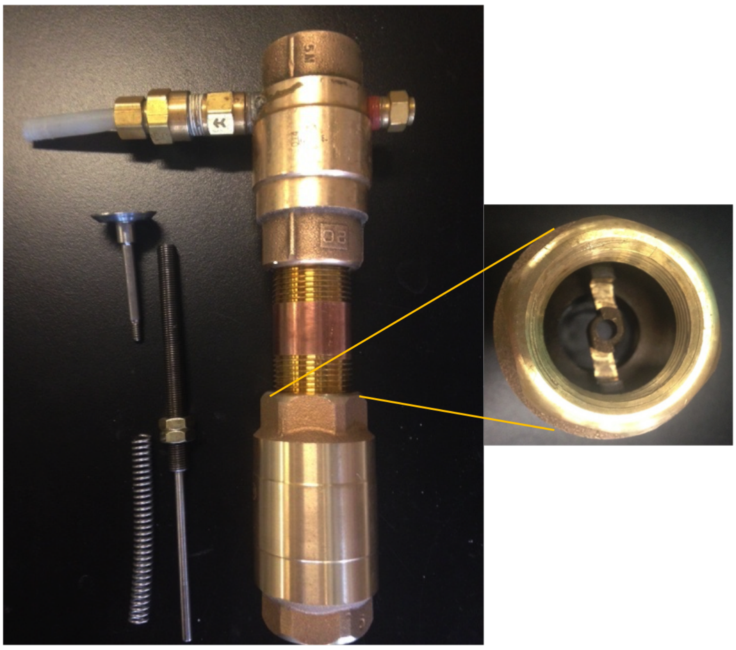


Figure 8: This is the brass prototype of the ram pump. Although PVC parts were upgraded to brass, the design of the pump is the same as that of the enclosed PVC prototype.

However, upon testing the enclosed brass design, the team found that the brass replacements made ram pump setup difficult. The problem lay in the fact that the brass nipple could not be screwed in the same amount each time the pump was reassembled. Since the location of the brass nipple determined the compression of the spring, accurate data could not be collected without a precise setup.

3.4 Enclosed Union Design

As a compromise, the team came up with the enclosed union design, in which a PVC union was added to connect the top and bottom halves of the ram pump. With this change, only a separation of the union would be necessary to adjust the spring. A metal union was not purchased due to the higher cost.

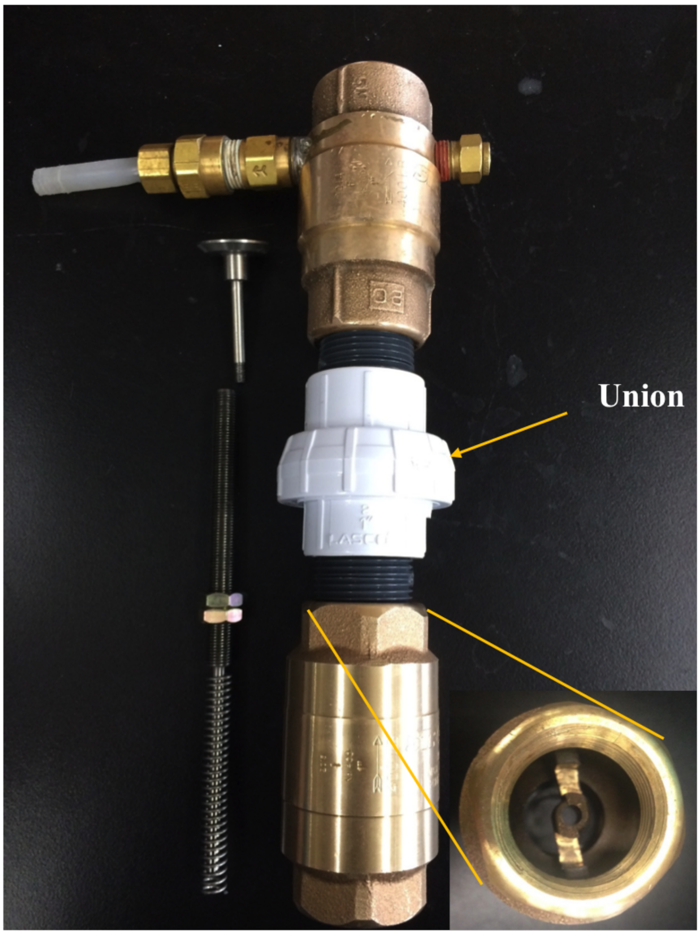


Figure 9: A collar was added to the enclosed union design to allow easy access to the pump's inner workings. This in turn allowed the team to conveniently and precisely adjust spring contraction.

The team then used Hooke's Law to calculate spring force knowing the spring's constant and the maximum spring compression. The spring constant was 1856 N/m (10.6 lbs/inch), and the spring force of the first and second tests were calculated to be 1164 N/m (6.65 lbs) and 1392 N/m (7.95 lbs) respectively (Aggarwal and Guzman, 2016). The force produced by the spring could be altered due to the relationship described by Hooke's formula: F = kx, where k is the spring constant and x is the distance of compression. By moving the nuts closer to the end of the threading, the resulting force is decreased and vice versa.

Subsequently, flow rates were determined, plotted against head, and compared with results from previous prototypes in which the spring was not exposed to water. Observing that the flow rates were nearly the same for given head values, it was concluded that exposing the spring to water did not affect the flow rate, which was encouraging.

3.5 Enclosed Union Design with Collar

The last major modification was the inclusion of a collar to allow for adjustment of plate-opening amplitude. Additionally, a long nut as part of the jam nut was placed within the enclosed union-collar design to restrict the spring and eliminate contact between the threads and spring. This reduces wear on the threads.

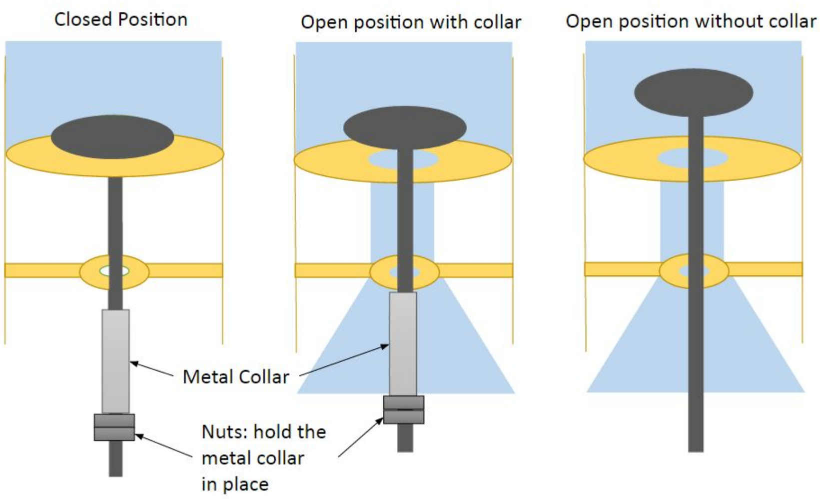


Figure 10: In order to stabilize the spring's movement and restrict the plate's amplitude, a metal collar was installed between the empty check valve and the nuts.

Tests run to determine the relationship between plate amplitude and flow rate revealed that pumping at low heads benefits most from small amplitudes, while pumping at high heads works best with plates of greater amplitude. In the scope of this project, this does not matter much since at 7 to 8 meters of head, the height to which most plants pump, there is little difference in the flow rate between large and small plate amplitudes. With input from Professor Weber-Shirk, the team hypothesized that this is because pumping to higher heads puts pressure on the opposite side of the stop valve and causes water to leak back through the stop valve when the check valve closes and the stop valve opens.

4 Methods

This semester, the ram pump team used the enclosed union design with a collar created by the Spring 2016 AguaClara team. The first goal was to develop an accurate and simple method to obtain a flow rate versus head curve for water pumped by this model. The hypothesis was that this data could be acquired by analyzing pressure differences within the air chamber. With the effluent valve closed, water passing the one-way stop valve would enter a closed system in which the volume of water in the chamber and the pressure within the chamber were directly proportional. The measured changes in pressure could be used to recalculate changes in water volume, and by extension, the flow rate.

To accomplish this, several tests were performed. When these tests were executed and the data was interpreted, an efficient and accurate method of calculating the flow rate produced by the pump was developed.

4.1 Cup and Timer Test

This test was used to obtain the effluent flow rate in a simple manner identical to that of the Spring 2016 Ram Pump team.

The effluent valve was opened completely to allow water to flow. A cup was used to collect the effluent while a timer was used to measure time elapsed during the filling process. After halting the flow of the effluent valve, the water collected was transferred to a graduated cylinder for an accurate volume reading. With data on time elapsed and volume of water, the flow rate was obtained through the following formula:

$$Q = \frac{Volume}{Time}$$

4.1.1 Results

The test was repeatedly conducted in order to get an accurate average of the flow discharge. After considering several trials (Figure 1), the flow rate was determined to be 23.99 mL/s.

Table 1: Cup and Timer Flow Discharges

Test	Volume	Time	Flow Discharge
1	720 ml	29.90 s	24.08 mL/s
2	718 ml	29.61 s	24.25 mL/s
3	732 ml	30.23 s	24.21 mL/s
4	362 ml	15.11 s	23.96 mL/s
5	362 ml	15.18 s	23.84 mL/s
6	360 ml	15.25 s	23.61 mL/s

4.1.2 Discussion

In this test, the system was held at atmospheric pressure as a result of holding the effluent valve completely open. However, this experiment is not an efficient way to acquire flow rates at varying heads. This is because it is highly prone to humans error and takes a lot of time to gain only a few data points. Therefore, a more effective method had to be implemented.

4.2 Threshold Test

The threshold test was utilized to obtain a graph relating flow rate and head. Previously installed pressure sensors were connected to ProCoDA in order to track the pressure in centimeters. The locations of these sensors are depicted in Figure 6.

The effluent valve was closed during the test, and water was introduced to the effluent pipe and air chamber. The function of the closed valve was to simulate in a laboratory setting the increase in pressure that comes with pumping water several meters vertically in a water treatment plant. Due to the increase in head, the water level in the air chamber rose and increased the pressure of the air compressed in the chamber. The smaller the volume occupied by air (due to the pumping of water), the higher the pressure exerted by the air; therefore, as more water was pumped, more pressure pushed back on the pump and the water in the effluent pipe by the air chamber. This explains why the water level in the chamber levels off after a certain amount of time (Figure 11).

The trials were run from the time at which the air chamber was empty to the time at which the water level stopped rising. With each trial, ProCoDA used the sensor on the air chamber to continuously record the pressure of the air throughout the test. The pressure in the empty air chamber was calibrated to atmospheric pressure. Thus, measuring the volume of the empty chamber to be 371.66 cubic centimeters, the change in volume of air within the chamber can be calculated by means of the ideal gas law:

$$P_1V_1 = P_2V_2$$

The negative change in air volume is equal to the change in volume of water. This change in volume of water between consecutive readings was divided by the time elapsed to calculate flow discharge.

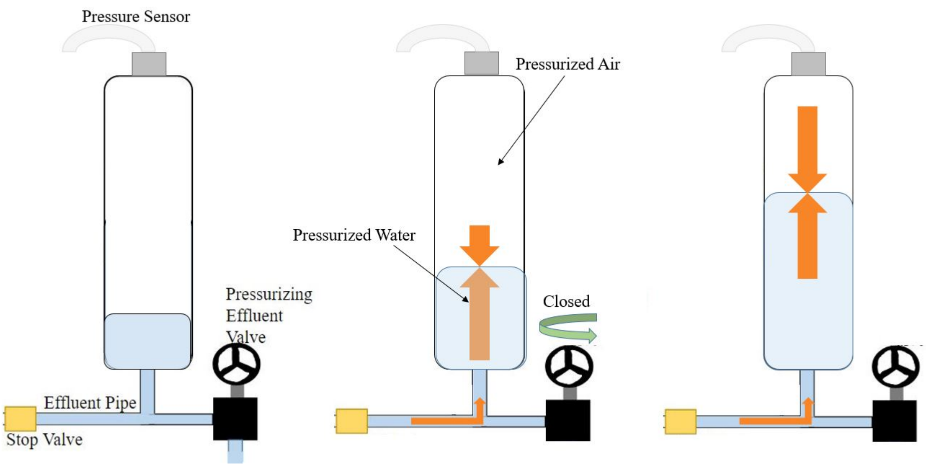


Figure 11: Once the effluent valve is closed, the pressurized water is forced exclusively into the air chamber. The more the water is pushed into the air chamber, the more pressurized the air within becomes. The pressure sensor at the top of the chamber relays pressure readings to ProCoDA, where the change in volume over time can be related to head.

In theory, the air pressure within the chamber continues to increase. However, the rate of air compaction slows over time because gas molecules tend to resist compression. Eventually, the air cannot be compressed anymore because the pressure of the air becomes equivalent to the pressure of the water being pumped. As a result, any water pumped after this equilibrium is reached is lost due to leakage in the stop valve. Therefore, each trial of the threshold test was ended when the water level in the air chamber stopped rising and the change in ProCoDA pressure readings reached a standstill. This process is depicted in Figure 12.

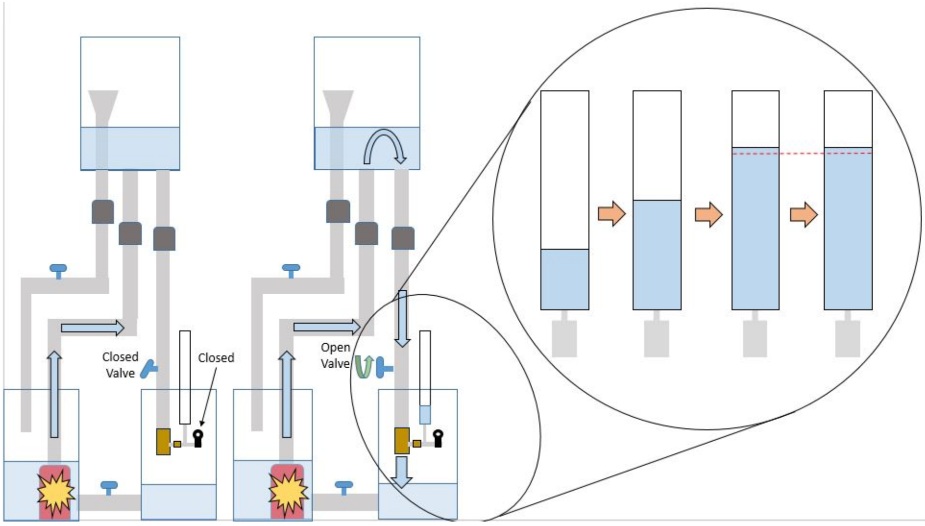


Figure 12: To begin the threshold test, the effluent valve is completely closed and the sump pump is turned on. Then, the drive pipe valve is opened, allowing water to move through the pump. As the test persists, the water level in the air chamber rises until the pressurized air restricts further inflow of water. Separately, pump waste falling through the ram pump is brought back to the sump bucket where it can be reintroduced to the head tank.

4.2.1 Results

The relationship between head and flow rate based on five threshold tests is represented by the following equation, which was found using a best-fit curve on Excel:

$$y = (1E-.07)x^6-(2E-.05)x^5+0.001x^4-0.0311x^3+0.497x^2-4.3x+19.88 \quad (1)$$

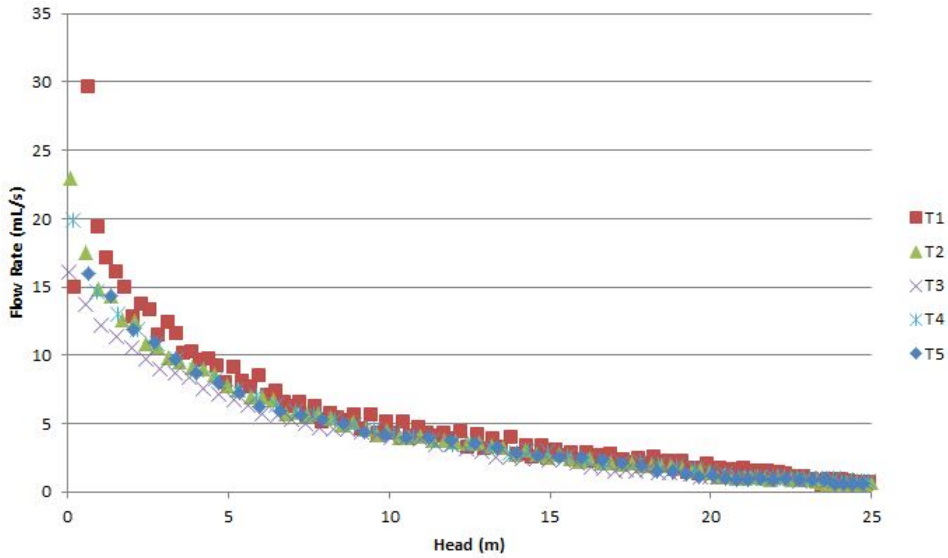


Figure 13: This graph depicts the decrease in flow rate as pressure in the air chamber is increased. Notice the smooth decline until the flow becomes minuscule. After performing the test five times, it is evident that this test is consistent in providing reasonable values for flow rate at varying heads.

4.2.2 Discussion

The graph relating flow rate and hydraulic head shows that as hydraulic head increased, flow rate decreased. The cup and timer method revealed a similar relationship, albeit with fewer data points. This shows that the flow rates obtained with the threshold test are reasonable, and furthermore that the threshold test gives a more complete set of data than the cup and timer method. Most importantly, the threshold test gives an entire, continuous performance curve for all values of head with only one test necessary. These flow rates can be used for later efficiency calculations. The fact that flow rate decreases as hydraulic head increases is described by the head form of the Bernoulli equation:

$$h = z + \frac{P}{\rho g} + \frac{v^2}{2g}$$

When water flows into the effluent pipe, the closed effluent valve forces the water to decrease its velocity. The drop in kinetic energy is equalized by an increase in potential energy. Since the volume of the water is fixed, equilibrium is achieved through an increase in pressure.

4.3 Efficiency Test

The goal of this test was to compare the energy in the water pumped by the ram pump with the energy of the water leaving the ram pump system. Energy is the product of flow rate and hydraulic head; therefore, the energy of the water pumped is the product of the effluent flow rate and the pressure of water against the pump. The quantity of water pumped is minuscule in comparison to the outflow of wasted water, and therefore the rate of water flowing from the drive pipe is very close to that of waste water exiting the system. With this approximation, the energy of the system can be equated to the product of the pump waste flow rate and the height of the head tank.

This can be described by the following equation:

$$P = \rho g Q h$$

Since the following method compares two different powers, ρ and g cancel out, allowing us to relate power directly to the product of Q and h. For the efficiency test, the sump pump was turned on and the ram pump was run with the effluent valve adjusted so that the water level in the air chamber and effluent were constant. This was to establish air pressure within the chamber as the independent variable.

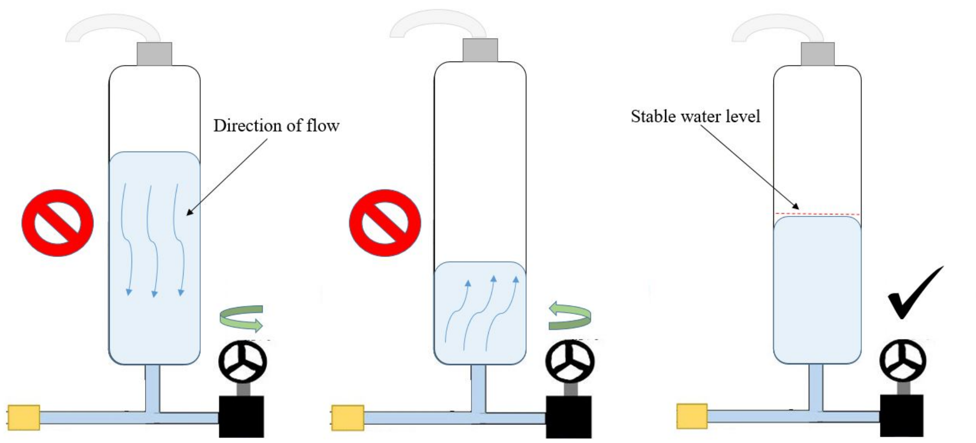


Figure 14: For the efficiency test to be conducted, the water level in the air chamber had to be constant. This was achieved by running the ram pump normally and adjusting the effluent valve accordingly.

Before the experiment, the bucket-connector valve (see Figure 15) was closed. The head tank was filled, the sump pump used to fill the head tank was subsequently turned off, and the drive pipe, previously closed, was opened to let the ram pump run. Each trial was completed when the head tank was empty. As water rose in the waste-collection bucket, the added water increased the pressure in the bucket-connector pipe. This change in pressure was tracked by a sensor placed on the top of the bucket-connector pipe, and converted by ProCoDA to centimeters of head. Because the pressure sensor used was located at the top of the pipe connecting the buckets, it was crucial that the water in the waste collection bucket was at a level above the opening to the bucket-connector pipe throughout the experiment. Should the water level have dropped below the sensor at any point in the efficiency test, the sensor would not have accurately detected changes in pressure exerted by increasing water levels.

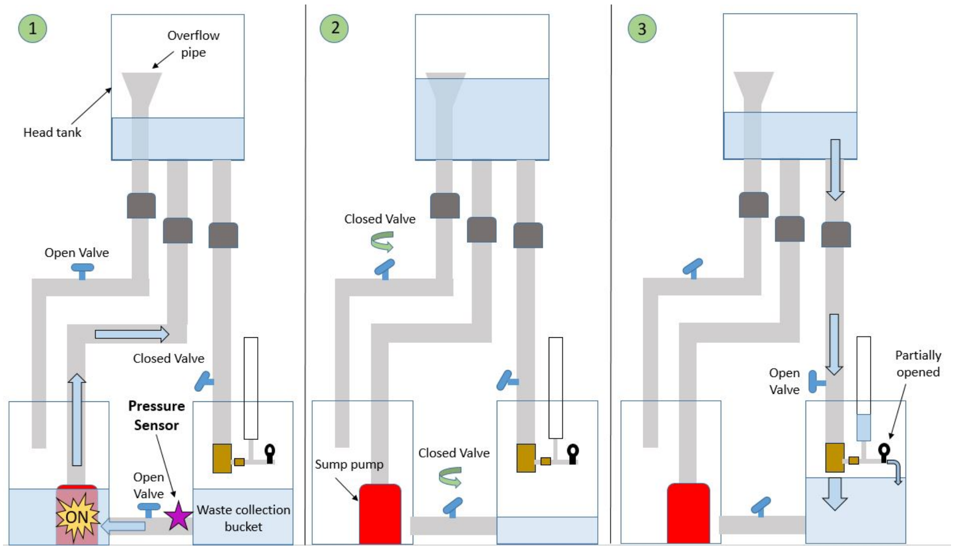


Figure 15: The efficiency test is a three step process that ultimately helps determine the flow rate of the pump waste that has not been pumped by the hydram. This flow rate can then be used to calculate the energy out of the waste valve and, in turn, find the efficiency performed by the pump. First, all the water is pumped to the head tank above. To prevent water from flowing back down to the sump pump, the valve on the overflow pipe is shut. The bucket connector valve is shut as well. It is important that the water level in the rightmost bucket does not fall below the bucket connector's opening in order to obtain an accurate pressure reading. To begin the test, the drive pipe valve is opened and water flows freely through the ram pump.

The pressure sensor at the bucket-connector valve was used to measure the change in water level within the waste-collection bucket. Due to the high amount of "noise" produced by the ram pump, a more sensitive pressure sensor of 7 kPa had to be used instead of the 200 kPa used for the other sensors. This pressure reading, displayed in centimeters, was multiplied by the horizontal cross-sectional area of the bucket to obtain the change in volume of water in the bucket at any given time within the test. Taking the slope of this volume over time gave an average pump waste flow rate for water being pumped to a constant hydraulic head. The average flow rate was then multiplied by the height (220 cm) of the head tank to compute the energy of the system. Similarly, the flow rates obtained in the threshold test were multiplied with the instantaneous heads as was recorded by the air chamber pressure sensor. The energies obtained from the threshold test and the energy of the entire system together gave the efficiency of the system at each point in time. The efficiency can be calculated with the following equation, in which $(Qh)_1$ is the energy of the pumped water and $(Qh)_2$ is the energy of the pump waste:

$$Efficiency = \frac{(Qh)_1}{(Qh)_2} \times 100 \tag{2}$$

4.3.1 Results

After the test was run five times, the average energy of the system obtained from the waste discharge was 49,679.44 mL·cm/sec. Comparing this energy to the effluent energy obtained from the flow rates in Figure 13, a consistent relationship between efficiency and head was derived (Figure 16). The efficiency increases and reaches a maximum between 10 and 15 meters before exponentially decreasing. The efficiency at any head, x, can be described by the following polynomial, which was found using a best-fit line on Excel:

$$y = (-4E-.08)x^6 + (5E-.06)x^5 - (3E-4)x^4 + (7.6E-3)x^3 - (1.4E-1)x^2 + 1.3x + 0.4 \tag{3}$$

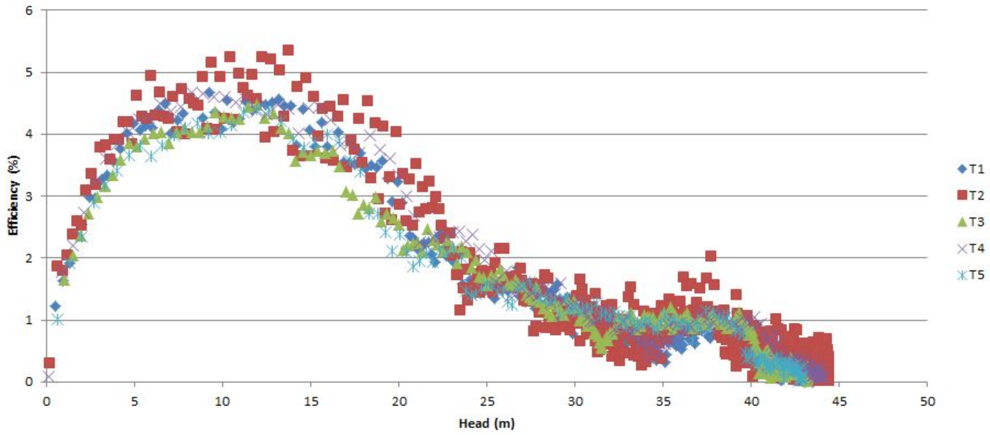


Figure 16: This graph shows how efficiency changes according to head.

Discussion

The efficiency test is important in that this comparison of energies takes both flow rate and head into account. Although flow rate tends to decrease with increased head, flow rate and hydraulic head are not perfectly inversely proportional at all heads. Efficiency relates the two and produces values that can in turn be plotted against head.

Distribution Piping

The team's next step was to add distribution piping to the bottom of the ram pump to simulate the setup in a treatment facility. In an AguaClara water treatment plant, the ram pump is intended to be part of a closed system in which the treated water flows through the hydram and is either pumped back to the top of the plant or continues on to the distribution tank, because any potable water created cannot be wasted. The working hydram is to be connected in-line with the pipe that carries clean, chlorinated water from filters to the distribution tank instead of depositing the pump waste to an unenclosed container like the pump waste bucket that is currently used.

Figure 17: In order to simulate a completely submerged ram pump, distribution piping was added to the bottom of the apparatus using flexible plastic tubing and a barbed adapter fitting.

The hydram initially did not function when the threshold test was attempted with the distribution piping in place. Consultation with Professor Weber-Shirk led the team to the hypothesis that the distribution pipe addition prevented the pump from functioning because the amplitude of the plate within the check valve was too large. With the addition of the distribution piping, the pathway of water was extended and considerably more mass could be retained in the system while the pump was running. However, the driving force moving the water through the system was the same as it was before the addition because the initial energy of the system remained the same. According to Newton's Second Law, F = ma, when force is constant and mass increases, acceleration decreases. Thus, the velocity of the water pushed through the ram pump was lower with the addition of the distribution pipe. With this lowered velocity, water passing the wide opening between the plate and the check valve constriction did not have the force to pull the plate down and close the check valve.

The solution of this was to adjust the nuts within the pump to decrease the plate's amplitude. When the maximum distance between the plate and the constriction is reduced, the opening through which water passes is reduced. Therefore, the velocity of the fluid can be increased, and the plate can be pulled over the check valve constriction to make the ram pump function again. This new nut distance was referred to as the new configuration.

4.4 New Configuration

When the pump ceased to function after the addition of the distribution piping, the team hypothesized that a smaller plate amplitude would allow the check valve to close more easily and enable the pump to complete its cycles.

The ram pump was taken apart and the nut was reconfigured to 18.24 mm (0.718 in) below the top rod from its original position of 24.36 mm (0.959 in). This new position of the nut and collar was referred to as the new configuration and permitted the pump to resume its performance. This distance was chosen because the Spring 2016 found it to be optimal for pumping to 8 m of head, the team's zone of interest. Threshold and efficiency tests were also run in this new configuration without piping in order to serve as a comparison.

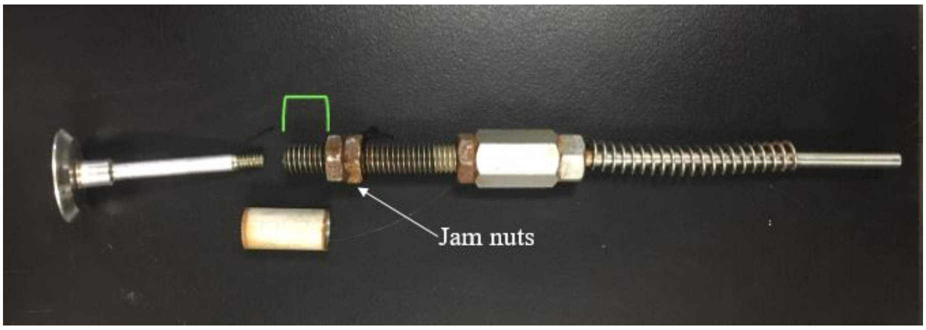


Figure 18: The length indicated in green shows the distance between the top of the rod and the nuts. The placement of the nuts determines the length of spring compression and therefore the amplitude of the check-valve plate. When the distribution pipe was added and the pump ceased to function, the nuts were placed closer to the top of the rod to decrease plate amplitude and increase the velocity of water passing through the check valve.

4.4.1 Results

For a head of 8 meters, a flow rate of 8 mL/s can be obtained. The flow rate obtained when the distribution pipe is not attached and the collar is placed 18.24 mm below the top rod can be described by the following polynomial, found using a best-fit line on Excel:

$$y = (-8E - .05)x^5 + 0.0051x^4 - 0.1318x^3 + 1.6547x^2 - 10.755x + 35.65 \quad (4)$$

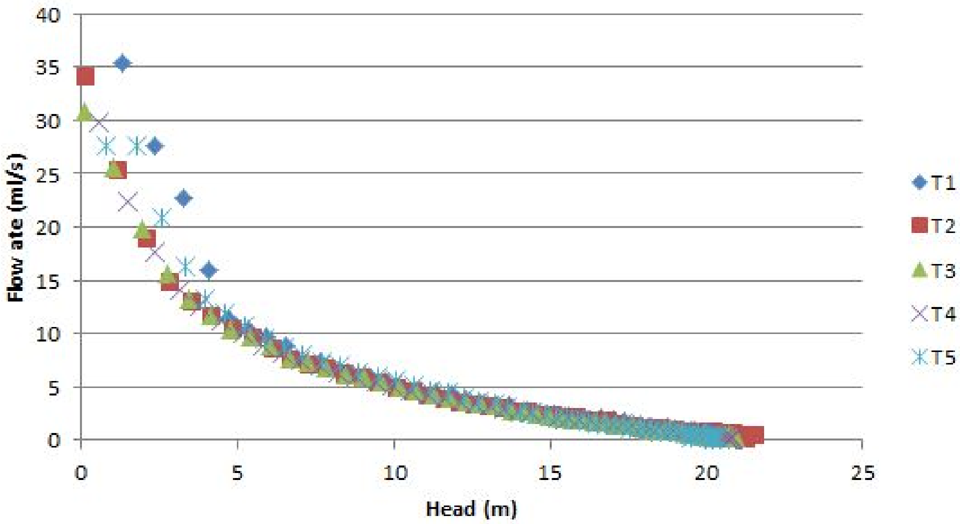


Figure 19: This graph shows the change in the flow rate versus head for a collar placed 18.24 mm below the top rod. Notice that all five tests have a similar flow rate at 8 m of hydraulic head, the team's zone of study.

For a head of 8 meters, an efficiency of 11.8% can be obtained. The efficiency obtained when the collar is placed 18.24 mm below the top rod can be described by the following equation, which was found using a best-fit line on Excel:

$$y = 0.0013x^3 - 0.0891x^2 + 0.9321x + 8.764 \tag{5}$$

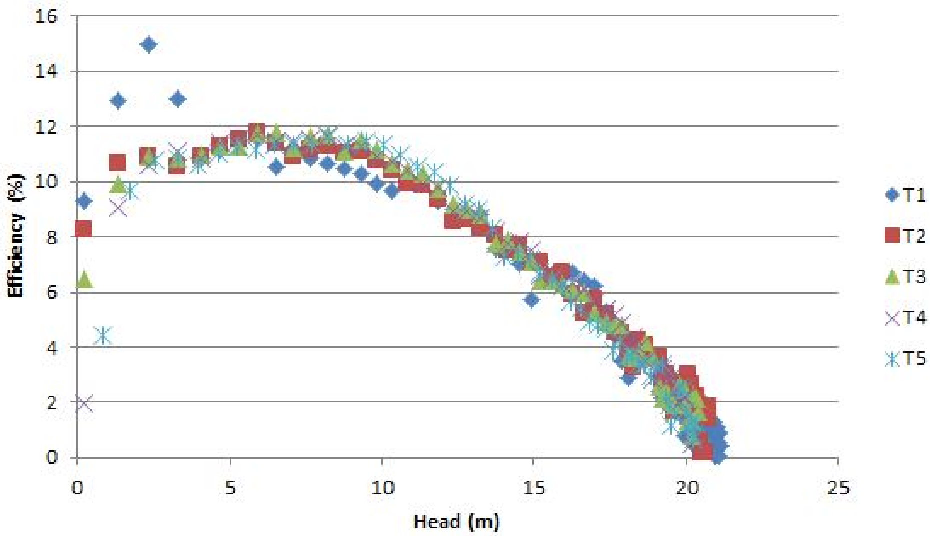


Figure 20: This graph shows the change in the efficiency versus head for a collar placed 18.24 mm from the top rod. Notice that the various tests have similar efficiency values at 8 m of hydraulic head, the team's zone of study. This is also the point of maximum efficiency on the graph. Note that the efficiency has improved from the previous configuration.

4.4.2 Discussion

Plotting efficiency and flow rate based on the data obtained, the maximum efficiency is at 8 meters of head, the team's particular zone of interest. Overall, both the efficiency and the flow rate of the system improved with the new collar configuration. At 8 m of head in the old configuration, the flow rate was about 5 mL/s with an efficiency around 4.3 %. At 8 m of head with the new configuration, the flow rate was about 8 mL/s with an efficiency of 11.8 %. However, it was observed that the water did not climb as high in the air chamber as it did before the movement of the collar. This means that the maximum head that water can be elevated to is lowered as plate amplitude is decreased.

4.5 Effect of Distribution Piping

After observing the behavior of the pump at the new configuration, the next step was to determine how attachment of the distribution piping would influence flow rate and efficiency.

4.5.1 Results

For a head of 8 meters, a flow rate of 3.7 mL/s can be obtained. The flow rate obtained when the distribution pipe is attached and the collar is placed 18.24 mm below the top rod can be described by the following equation, which was found using a best-fit line on Excel:

$$y = (1E-.05)x^6 - 0.0011x^5 + 0.0321x^4 - 0.4847x^3 + 3.8804x^2 - 15.829x + 29.286 \quad (6)$$

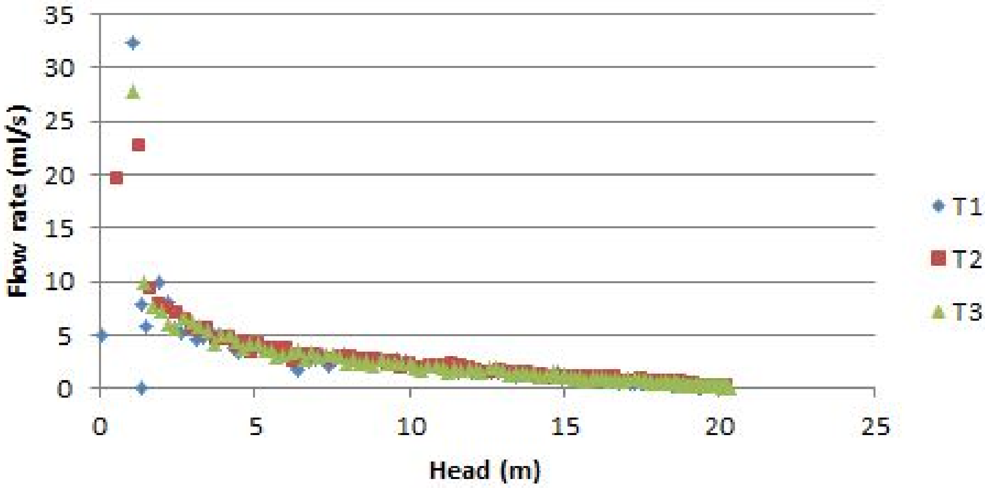


Figure 21: This graph depicts the relationship between flow rate and head after the distribution piping was inserted.

For a head of 8 meters, an efficiency of 5.97% can be obtained. The efficiency obtained when the distribution pipe is attached and the collar is placed 18.24 mm below the top rod can be described by the following equation, which was found using a best-fit line on Excel:

$$y = -0.0349x^2 + 0.5688x + 3.65866 \tag{7}$$

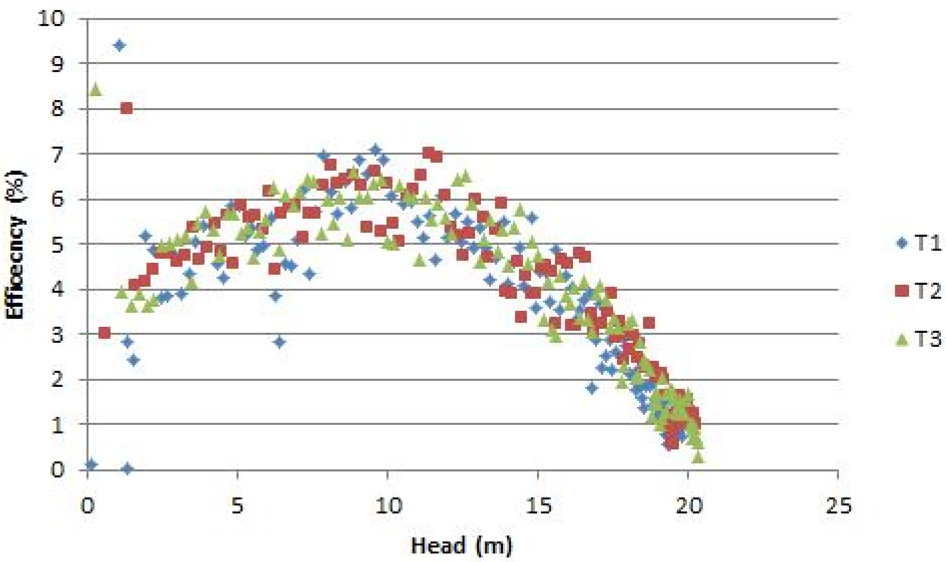


Figure 22: This graph represents the efficiency of the system at different heads after the addition of distribution piping.

4.5.2 Discussion

The effect of adding the distribution piping as explained earlier in the report is clearly represented in the data. Before the distribution piping was added, the new configuration gave a flow rate of about 8 mL/s and an efficiency of 11.8 % at 8 meters of head. However, once the distribution piping was added to this new configuration, the pump gave a flow rate of 3.7 mL/s and an efficiency of 5.97% at 8 meters of head. With the piping in place, both the flow rate and efficiency were reduced by about half. These results support our initial hypothesis that the extra mass added to the system would decrease the acceleration, and therefore velocity, of the water in the system.

Pump Troubleshooting

One week after the data from the threshold and efficiency tests were gathered, the pump stopped functioning. When each test was initiated, the pump would get stuck and stop pumping water. Closing and reopening the drive pipe valve would get the pump to work again, then stop a few pump cycles later. However, removing the distribution piping and allowing the water to flow freely through the waste valve caused the pump to function normally. This led the team to believe that there was a vacuum developing below the check valve, preventing the plate from opening again after several cycles. This hypothesis aligns with the Spring 2016 team's predictions on the effects of a distribution pipe on the ram pump.

For the following three weeks, the team tried several methods. First, an additional opening in the distribution piping was created to expose the system to atmospheric pressure (Figure 23). Next, the plate amplitude was manipulated in the hopes that the problem was a simple matter of the check valve being unable to close correctly. Then two washers were added — one between the check valve and metal collar, and one between spring and the lowest nut on the rod — in an attempt to prevent jamming of parts during pump cycles. Lastly, a second air chamber was added behind the distribution piping (Figure 26). This final setup, with a few minor modifications, was successful in getting the pump to work efficiently with the distribution pipe in place.

4.6 Opening in the Distribution Pipe

After the threshold and efficiency tests were performed with the distribution pipe in place, an opening was installed. A two meter, vertical tubing was attached to this opening to prevent water from leaking out of the system. The hypothesis was that bringing the system back to atmospheric pressure would increase the velocity of the water in the system, and consequently increase flow rate. However, the pump did not function at all after this actualization.

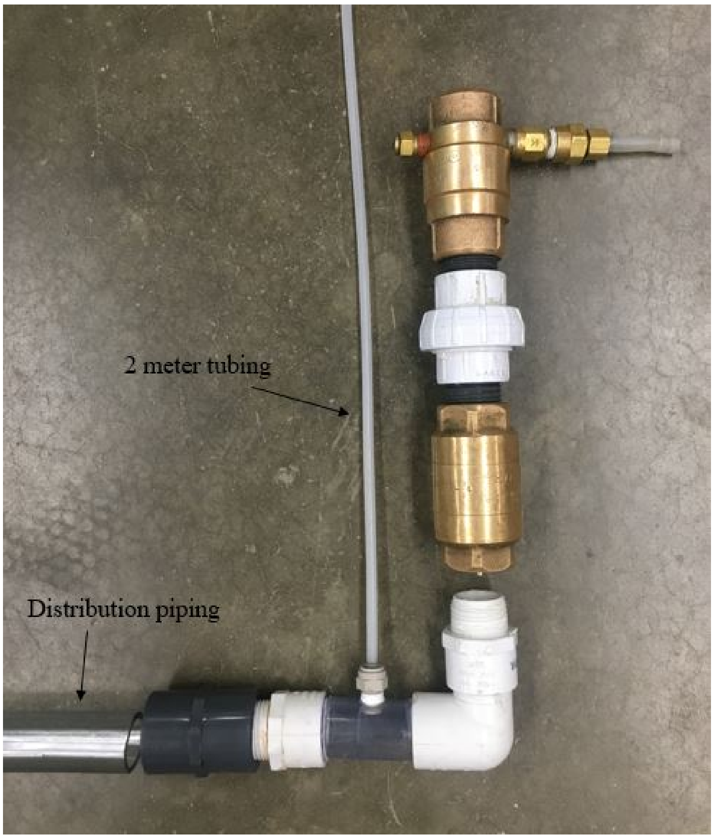


Figure 23: To bring the system back to atmospheric pressure, a small opening was added to the distribution pipe. A two meter, vertical tubing was attached to this opening to prevent water from leaking out of the system.

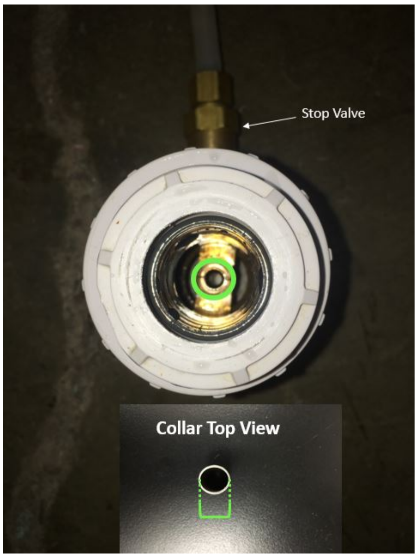
4.7 Change in the Collar Distance

Initially, it was thought that the pumped stopped functioning because the addition of the distribution piping decreased the velocity of the water running through the system. In an attempt to resolve this, the placement of the nuts from the check-valve plate was changed from 18.24 mm to 12.70 mm (0.718 in to 0.5 in).

It was determined by subsequent tests that the pump functions most consistently when the nuts are placed at 12.70 mm under the current conditions. However, the pump would still stop occasionally. After several days of adjusting the nuts, it was concluded that this modification alone would not resolve the issue.

4.8 Jam Prevention

Another hypothesis to explain why the pump was not functioning was that the metal collar and spring fit over the rod were getting jammed due to incompatibility of parts. The metal collar was visibly rusted, and its edges were fraying. This was a point of concern because the excess metal had the potential to catch on the bottom of the check valve. To address this problem, a washer was added between the check valve and the problematic collar. Because the diameter of the washer's opening was smaller than the diameter of the collar's opening, the washer would keep the two parts separated.



(a) This is the collar placed on the top of the threaded portion of the rod, as seen from above. It appeared that as the collar rusted, it was getting caught on the bottom of the check valve. This was exasperated by the loose fitting of the collar over the rod and check valve.

(b) A washer was added between the check valve and the problematic collar, to prevent the pump from jamming. Note that the diameter of the washer's opening is smaller than that of the collar, to effectively screen the edge of the collar from the check valve.

When the pump was being disassembled, it also became apparent that the top of the spring was getting caught on the lowest nut on the rod. To prevent this, a second washer was placed between the nut and the spring.

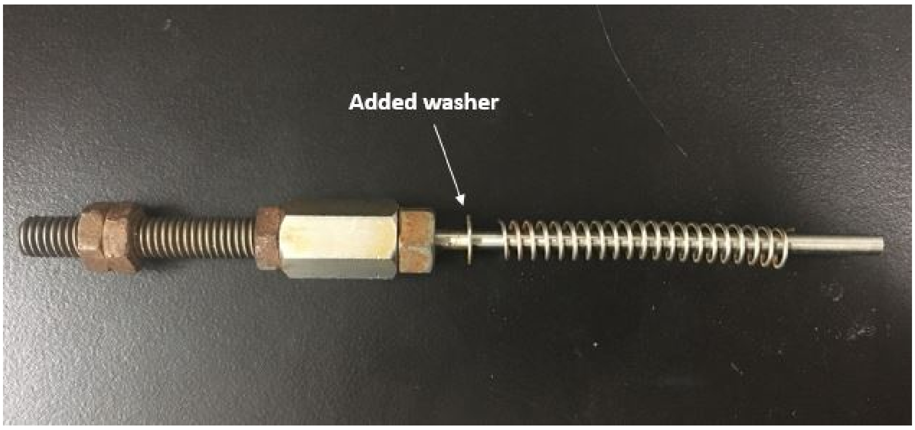


Figure 25: It appeared that the end of the spring was getting caught on the bottom nut. Another washer was placed between the two parts in order to prevent jamming.

The addition of the washers appeared to lessen jamming, so the washers were kept in the ram pump for the duration of the semester. However, the pump was still inconsistent at best. Cycles would run smoothly while the effluent valve was completely closed, but any slight opening of this valve would slow and stop the pump, and it was still unclear why this occurred.

4.9 Second Air Chamber

Next, the team hypothesized that the submerged pump created vacuums under the check valve plate every time it completed a cycle. In order to prevent the formation of this vacuum, a second air chamber was introduced. This air chamber was placed behind the distribution pipe and next to the ram pump exit (Figure 26).

Figure 26: A second air chamber was installed next to the ram pump exit and behind the distribution piping in order to eliminate the vacuum effect.

The empty air chamber serves to oppose the creation of a vacuum below a closed plate, by allowing water below the ram pump to be drawn into the would-be vacuum. It also serves to prevent the entrapment of air directly below the plate.

At this point, it was discovered that the pump needed to be primed before it could function. To accommodate for this, a new procedure for the threshold test was devised. Rather than simply closing the effluent valve and opening the drive pipe to start the test, the new procedure required several minutes to set up before any data could be logged.

First, the effluent valve was closed, the loose end of the distribution pipe was lifted out of the water in the pump-waste collection bucket, the drive pipe was opened to allow water to flow through the distribution pipe, and then the distribution pipe was submerged when no air pockets were visibly present. Next, the drive pipe valve was opened and closed repeatedly until the ram pump functioned. From here, the procedure for running as threshold test could be performed as usual.

4.9.1 Results

For a head of 8 meters, a modest flow rate of 5 mL/s can be obtained. The flow rate obtained when the distribution pipe and second air chamber are attached, and the collar is placed 12.70 mm below the top rod can be described by the following polynomial that was found using a best-fit line on Excel:

$$y = -8.411lnx + 23.088 \tag{8}$$

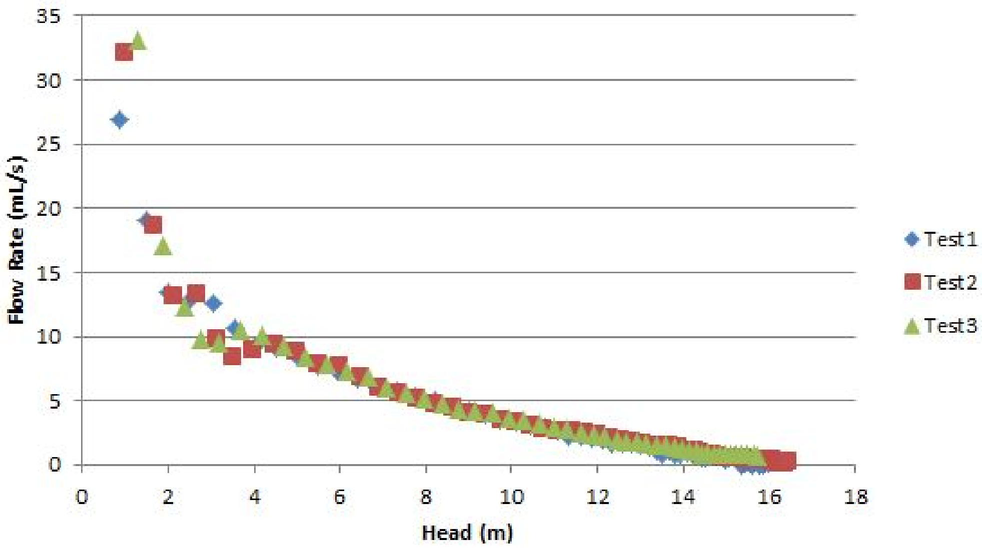


Figure 27: This graph depicts the relationship between flow rate and hydraulic head after the distribution pipe and the second air chamber were inserted. Note that while the maximum head that pumped water can attain is lower with the addition of the air chamber, the flow rate at 8 meters of head remains at 5 mL/s.

Unlike with previous setups, an accurate efficiency test of the ram pump system with the second air chamber in place was unable to be obtained due to the complications involved in priming the pump.

4.9.2 Discussion

Of the four modifications made to direct the pump to cycle at regular intervals, only the addition of a second air chamber in line with the distribution pipe had any large impact on the pump. The air chamber is effective because it opposes the creation of a vacuum below the pump, and prevents the entrapment of air below the check valve. However, with this addition, the pump needed to be primed before beginning its cycles. This involves manually stimulating the pump by repeatedly opening and closing the check valve to aid the pump in pushing water through the drive pipe in order to remove air pockets. A threshold test taken after second air chamber addition shows that while maximum hydraulic head decreased from slightly over 20m to 16m, flow rate at 8m of head remained at about 5mL/s. An accurate efficiency test was unable to be obtained due to the complications of priming.

4.10 Threshold - Efficiency Test

After running the two tests as independent procedures, the team suggested the possibility of doing both at the same time. The procedure of this test is almost identical to the steps necessary to do each test separately, except that the effluent valve is completely closed. With this disposition, threshold and efficiency graphs can be obtained simultaneously. This is because the data is recorded in a unique, correlated setting with the same parameters.

In this test, efficiency can be obtained as a function of the head, in comparison with the former procedure where the pressure was kept constant. This allows one to identify the maximum values of efficiency on the graph. Just as in the former threshold test, the change in pressure inside the air chamber was used in order to obtain the flow rate and the pressure against the water being pumped. This new test makes it possible to obtain the efficiency with a changing pressure.

4.10.1 Results

When the new test was performed, it was found that a nut position of 12.70 mm yields a 5 mL/s flow rate at 8 m of head. This can be seen by the following graph that represents the threshold test portion of the new method.

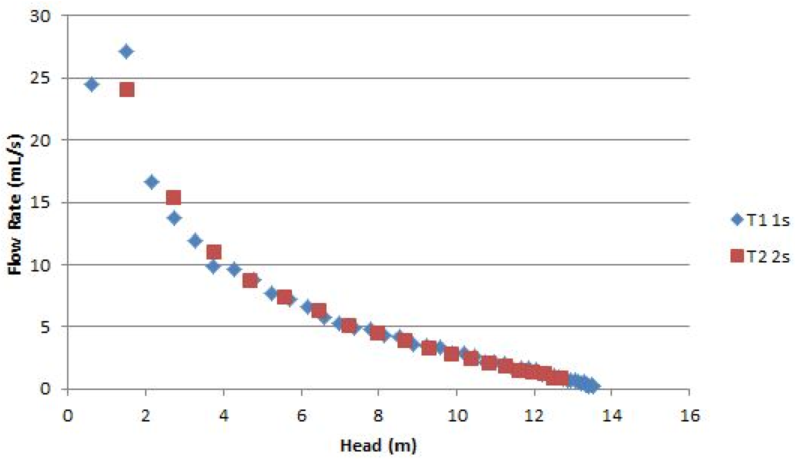


Figure 28: This graph of flow rate versus head was obtained utilizing the two in one Threshold-Efficiency test.

The respective efficiency test graph can be obtained as well. It was found that at 8 m of head, the ram pump has an efficiency of about 10 %.

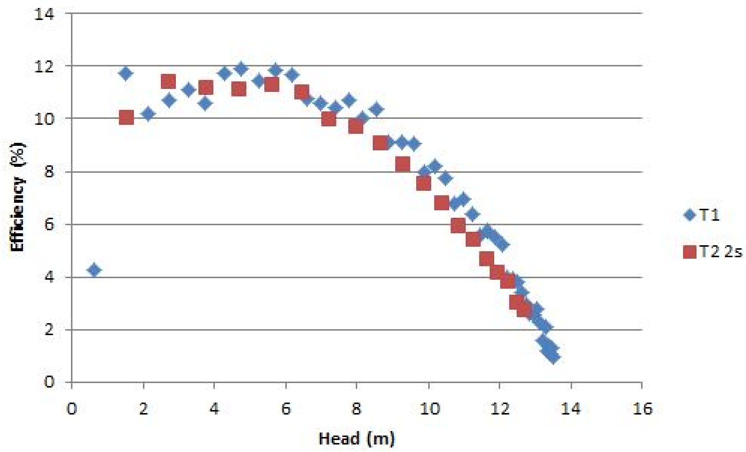


Figure 29: This graph of efficiency versus head was obtained utilizing the two in one Threshold-Efficiency test.

4.10.2 Discussion

After analyzing the resulting graphs obtained from the new test, it is clear that both the threshold and efficiency can be obtained accurately. Comparing Figure 28 with Figure 27, the graphs are essentially identical, giving a flow rate of 5 mL/s at a head of 8 m. Although there was no standalone efficiency test performed with the final nut configuration and air chamber addition, the resulting efficiency from this test at 8 m of head is about twice that of Figure 22 when the nuts were placed at 18.24 mm below the top rod.

5 Conclusions

After comparing results from the cup and timer method and threshold test, it was apparent that the prior is an inconsistent and inaccurate means of acquiring flow rate that is subject to human error. The threshold test delivers consistent data relating flow rate to head in a single test, granting the team a reliable means of tracking the behavior of the pump. The efficiency test further complements this finding, allowing the team to determine what head yields the greatest efficiency. Combining these two tests into one gave the team a single method for determining flow rate and efficiency for a range of heads that is both accurate and dependable.

The addition of the distribution pipe prevented the pump from running as effectively as the original configuration, and a large portion of this semester was spent trying to get the pump to function with the distribution pipe in place at least as well as it did before the pipe was added. To address the problem, the team created an opening in the distribution pipe, changed the amplitude of the plate, added washers to prevent the inner mechanism of the pump from jamming, and attached a second air chamber in line with the distribution piping. Of these adjustments, the addition of the air chamber proved most effective. By preventing the formation of a vacuum under the check valve, water was better able to move through the distribution piping.

6 Future Work

Moving forward, the team will continue to work towards maximizing the efficiency of the pump with the distribution piping. Furthermore, the addition of a snifter valve would allow long term usage of the apparatus without constant moderation by plant operators. Due to the effectiveness of the pump, replicating the latest design to be brought to Honduras in January of 2017 is an ideal goal for the team as well. Moreover, sharing the means necessary for others to replicate the ram pump is a top priority. This entails recreating the union collar design on AutoCAD with the proper dimensions and required materials clearly stated.

References

Aggarwal, P. and Guzman, J. (2016). Ram Pump, Spring 2016. Technical report.

Hofkes, E. and Visscher, J. (1986). Renewable Energy Sources for Rural Water Supply.

Inthachot, M., Saehaeng, S., Max, J. F. J., Müller, J., and Spreer, W. (2015). Hydraulic Ram Pumps for Irrigation in Northern Thailand. *Agriculture and Agricultural Science Procedia*, 5:107–114.

Semester Schedule

Task Map

The following is a diagram of what the team wishes to accomplish this semester. The main focus is to make the ram pump system more compact and secure, to develop an efficient method for calculation of flow rate, to measure the efficiency of the pump, and to attach distribution piping to the pump.

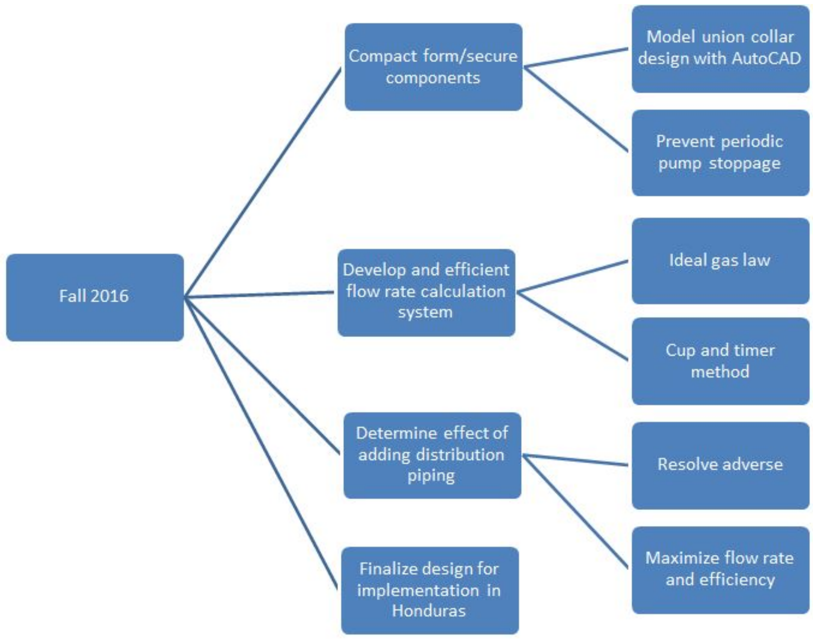


Figure 30: Task Map Fall 2016

Task List

1. Create an effective flow rate calculation system (Javier, Sept 16) - Compare the ideal gas law, Bernoulli's Principle for incompressible fluids, and cup and timer method to determine which is most productive in yielding reliable data. - Completed

2. Model the Union-Collar design on AutoCAD (Chris, Oct 20)- This will allow for the ramp pump design to be replicated in the future - In progress

3. Test submerged ramp pump (Luna, Nov 1) - Attach the distribution piping and observe if any adverse effects come about - Completed

4. Resolve the adverse effects that arise from the ram pump addition (Chris, Javier, Luna, Dec 2) - Completed

   Report Proofreader: Luna Oiwa