Ram Pump

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May 2, 2013

Abstract

AguaClara plants are driven entirely by gravity. This makes it difficult to provide treated, running water in the plants to fill chemical stock tanks and to provide bathroom service as the outlet of the plant is below where the water is needed. The Ram Pump team aims to optimize a ram pump with a drive flow rate of about $0.1\,L/s$ to pump a minimum of $0.01\,L/s$ of treated water to the stock tanks and bathrooms in an AguaClara plant, $5.15\,m$ above the plant outlet. A hydraulic testing facility and ram pump with drive and delivery pipes of 3/4" were built to test and optimize the ram pump while simulating a delivery height of $7.15\,m$. We have produced several correlations between ram pump head and efficiency at various flow rates and show that for a given ram pump design, there is a delivery head and flow rate that result in optimum ram pump efficiency. Ram pump design will need to be optimized to produce maximum efficiency given design constraints.

1 Literature Review

A ram pump is a cyclic water pump that takes in water at one pressure and flow rate and pumps it out it at a higher pressure and lower flow rate. Thus, the pump uses momentum from a relatively large amount of water from an elevated source to pump a relatively small amount of water to a higher elevation. A ram pump typically operates at only 10% efficiency. About 90% of the water from the drive pipe flows out of the pump as it builds momentum. In an AguaClara plant, the water used for a ram pump would be bypassed from the distribution tank and this "wasted" water would simply be returned to the distribution tank.

A ram pump consists of two moving parts: a waste valve and a delivery check valve (Figure1). A drive pipe supplies water to an elevation higher than the source. The air chamber cushions the hydraulic pressure shock when the waste valve closes, and improves the pumping efficiency by allowing a more constant flow through the delivery pipe.

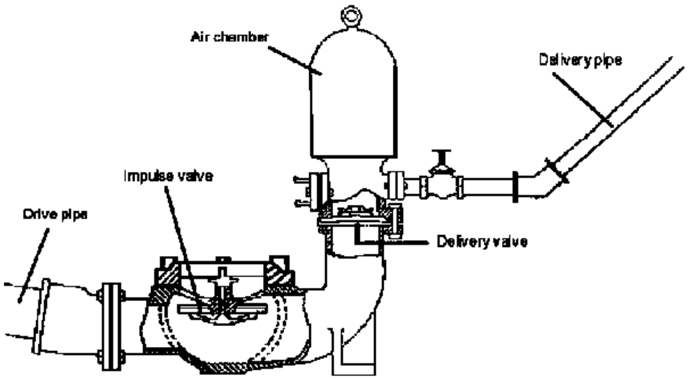

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Figure 1: Schematic of hydraulic ram pump

1.1 Clemson University

Clemson University provides information online to those wanting to build their own hydraulic ram pump. Their documentation includes designs, parts lists, typical hydraulic ram specifications, test installation information, operation instructions, trial performance data, and troubleshooting information. This information is supplemented with image-by-image explanations of how a hydraulic ram pump works and short movies of an operating ram pump. Clemson's design used a $1\frac{1}{4}\,inch$ Schedule 40 PVC drive pipe, with $4\,ft$ of elevation above the pump and $12\,ft$ of elevation from pump outlet to delivery outlet.

Clemson's online information provides guidelines for the size of the air chamber in a ram pump: it should be 20-50 times greater than the volume of water pumped per cycle in order to provide a more continuous flow through the delivery pipe as well as to dampen the pressure shocks in the pump. Other guidelines suggest that the inlet pipe length should be between 150 and 1000 times the inlet pipe diameter. In addition, the drive pipe should be as rigid and as straight as possible to maximize pumping efficiency and thus allow for higher pumping heights. To achieve a maximum flow and pressure the suggestion is that the check valve should be in a vertical position.

Lastly, the Clemson design suggests placing bicycle inner tubes inside the pressure chamber during assembly in order to prevent water-logging or air-logging. The addition of inner tubes would eliminate the need for a snifter valve, which allows air to be re-introduced to the ram during operation. Snifter valves can be problematic and allow the addition of too much air, ceasing pump operation.

1.2 Warwick University

The Development Technology Unit (DTU) at Warwick University designed several ram pumps for use in developing countries in the late 1980s and early 1990s, primarily intended for water distribution to small villages and for small-scale irrigation projects. Their website contains ram pump performance specifications, parts design notes, and manufacturing notes.

According to the Warwick University technical documentation on ram pump installation, shorter drive pipes result in higher ram pump operating frequencies. Higher frequencies can lead to inefficiency in pumping and increased wear on components. Drive pipes should be as straight as possible and if gradual bends are necessary, they should be firmly anchored. The DTU document contains detailed information and diagrams regarding construction and performance and will be a useful source for this team. The DTU also has a paper about performance comparison of DTU and commercial hydraulic ram pumps, which can be useful for the team to compare perfomance versus cost and decide if it is better to build a ram pump or buy a commercial and run the tests.

2 Introduction

A ram pump uses the momentum from a large amount of water falling a short distance to overcome the potential energy required to raise a small amount of water, and can therefore be used to pump small amounts of water to higher elevations without the use of electricity. In an AguaClara plant, the ram pump would be used to pump water to the stock tanks and bathroom facilities by using the momentum of water flowing from the plant to the distribution tank. The water could either be pumped directly into the stock tanks and restroom facilities, or could be pumped into a storage tank elevated slightly above the stock tanks and restroom facilities and retrieved as needed.

The previous ram pump team designed a ram pump that can be used specifically for AguaClara's Las Vegas plant, where the maximum available head is $2\,m$, corresponding to a required pumping elevation is$7.15\,m$. The details of the ram pump are described in the Apparatus section. The pump is designed to move $0.01\,L/s$ using the available head, which would be sufficient to fill both the coagulant and chlorine storage tanks ($750\,L$ and$208\,L$ respectively) at the Las Vegas plant, as well as supply the bathroom and allow for other miscellaneous uses. The ram pump was designed for an inlet flow rate of about $0.1\,L/s$, which is the maximum available flow in our test apparatus, and will reduce the cost of the pump by using smaller diameter pipes and pump dimensions, and require that less water be diverted from the plant effluent.

Our goal for this semester is basically to modify and improve the ram pump from last semester by installing a pressure relief valve, adding a flow rate measurement device and improving the existing check valve or buying a new one. Various parameters of the ram pump were tested in order to optimize it's performance and deliver water to an equivalent height of 7.15 meters. In addition, we continued research on evaluating the possibility of buying a commercial ram pum or the possibility to build an in-line ram pump. Another goal was to build a stable device to collect water from the wasting valve so that the 'wasted' water can return to the distribution tank.

3 Methods

3.1 Apparatus

the ram pump design was based on Clemson University's design for a homemade hydraulic ram pump [Clemson University, 2012]. The length of the drive pipe is $3.66\,m$ or $12\,ft$. Using Clemson's guideline that the ratio of drive pipe length to drive pipe diameter should be between 150 and 1000, that the diameter of the drive pipe was calculated to be between $0.12\,in$ and $0.96\,in$. Thus, a drive pipe diameter of $0.75\,in$ inner diameter was built. The delivery pipe will have an inner diameter of $0.5\,in$. A diagram of the ram pump is given in Figure 2.

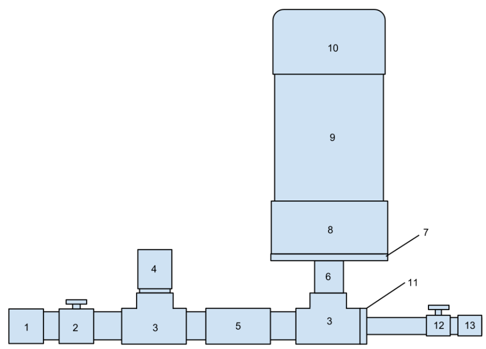

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Figure 2: Schematic of our preliminary ram pump, which is based on Clemson University's design. Numbered parts are described below.

The parts required for our ram pump are:
(1) $\frac{3}{4}$" union
(2) $\frac{3}{4}$" valve
(3) $\frac{3}{4}$" tee
(4) $\frac{3}{4}$" check valve – this will serve as the waste valve and will shut once the water has a reached a high velocity, forcing water through the second check valve
(5) $\frac{3}{4}$" check valve – by closing once the water's velocity has decreased this will prevent water from flowing back out of the pump and will retain the air pressure in the pump's air chamber
(6) $\frac{3}{4}$" by 4" nipple
(7) 4" by $\frac{3}{4}$" bushing
(8) 4" coupling
(9) 4" by 24" PVC pipe
(10) 4" PVC glue cap
(11) $\frac{3}{4}$" by $\frac{1}{2}$" bushing
(12) $\frac{1}{2}$" valve
(13) $\frac{1}{2}$" union

All connectors between fittings are threaded pipe nipples of at most 2" in length. Inflated bike tires are inserted into our air chamber to cushion the water hammer shock waves, provide a steady flow of water through the delivery pipe, and prevent the chamber from filling completely with water.

3.1.1 Check Valves

The check valves used in the pump are PVC valves with a spring-close design. These valves are certified by NSF International for use with drinking water. While the check valve numbered (5) in the diagram operates in the manner intended by the manufacturer (a sufficiently high velocity forces it to allow water to flow through), the check valve that serves as the waste valve (4) does the opposite. The waste valve was modified so that it would initially be in an open position, which means that the water flowing through it will close it at a sufficiently high velocity. When the waste valve closes (4) the water will be forced through the other check valve (5).

3.2 Hydraulic Testing Facility

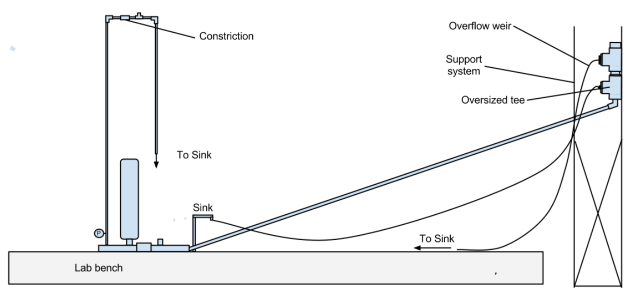

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Figure 3: Schematic of our modified hydraulic testing facility

A hydraulic testing facility will be used to perform tests on the ram pump by providing drive flow rate, drive head and delivery head. The hydraulic testing facility design is shown in Figure 3. Water from the sink will provide the drive flow rate to the ram pump and will flow through flexible tubing from the sink faucet head to an oversized tee with the top open to the atmosphere. This oversized tee simulates a drive tank and creates an open system. A second tee and flexible tubing leading to the drain is located above to serve as an overflow weir; any water from the sink that cannot pass through the ram pump will exit through the overflow weir. The head loss through the overflow weir and tubing at maximum sink flow rate must be low enough so that all excess water can flow through the overflow weir and tubing with the available head. There is about

$3\,cm$ of available head above the overflow weir and $1.4\,m$ of head to drive the overflow water through the flexible tubing. Calculations indicate that a 1" inner diameter tube can be used for the overflow tubing and will be able to evacuate all excess water in the worst case scenario with the available head. An extra length of pipe was added above the tee to provide excess head in the case of overflow. A support system created from 80/20 frames and flexible couplings supports the tees. Because we are using the sink as our supply of water to the pump, we are required to elevate this flow to a point $1.4\,m$ above the pump. This is accomplished by running water from the sink through 3/8" flexible tubing into the oversized tee fastened to the 80/20 support system above the pump.

The delivery pipe is a $2\,m$ long $1/2\,inch$ diameter pipe with a tee at the top of the pipe to create an open system. Water pumped up the delivery pipe will travel down another pipe either into the drain or into a flow rate measurement device. A valve is placed at the bottom of the delivery pipe which can be tightened to create a constriction and to increase the delivery head of the pump. A pressure sensor is placed at the bottom of the delivery pipe below the constricting valve so that the pump head can be measured.

A stand was designed for the ramp pump out of 80/20 bar so that the pump can be placed on any flat surface or supported above the sink, as it is in our current setup. With the pump positioned directly above the sink, water from the wasting valve can fall directly into the drain. The pump itself is mounted to a single bar, with a parallel bar attached on either side. Vertical bars are mounted to provide support for the air chamber and delivery pipes. The position of any of the bars can be adjusted to provide support for different sized air chambers and ram pumps.

3.3 Waste Valve Collection

The ram pump should be able to be tested when the waste valve is not located directly above a sink or drain. A device to collect water leaving the waste valve and directing this water to a drain therefore needs to be fabricated. Two options were considered for the waste valve water collection system. In the first option, a large bucket or collection vessel would be placed beneath the ram pump, with flexible tubing connecting the bucket to the nearest drain. The frame of the ram pump stand would rest on the edges of the bucket or collection vessel. This design is relatively simple, would not require any further modification to the existing ram pump, and has a large collection volume. However, placing the ram pump stand directly on a bucket would result in decreased stability, which would lead to a decrease in efficiency.

A second option was considered for collecting water from the waste valve. In this option, a bucket would be placed below around the base of the wasting valve but above the body of the ram pump, around the pipe nipple connecting the $3/4\,inch$ tee and wasting check valve. This option proved to be more stable and allowed for greater mobility of the ram pump.

3.4 Ram Pump Operation

Once the ram pump is running, ram pump operation should be automatic and should only require occasional observation by an operator to ensure that the check valve is not stuck and the pump is running smoothly. However, the ram pump will require special attention during start up, because the pump needs some back pressure to begin working. According to Clemson University, the valve at the back end of the ram pump (valve 12 in 2) should be initially closed. While the valve is closed, the pump should be manually started several times to remove any air from the ram pump piping. Because the ram pump air chamber is not currently air-tight, air will also need to be removed from the air chamber during ram pump start-up. During manual start-up, the wasting valve will need to be pushed open after it closes–Clemson recommends manually opening the check valve 20 to 50 times to begin normal operation. Once adequate pressure builds up in the system, around four meters of head, and the pump begins operation, the back valve can be slowly opened. If the valve is open before it has enough back pressure, the check valve won't work automatically. The pump should run for about 30 seconds with the valve closed after it starts, after which the valve must be opened. Clemson recommends a discharge pressure of no less than 10 psi , which can be monitored with the pressure sensor at the base of the delivery pipe. Once we have a better idea about how our ram pump performs, we will revise the start-up and operating procedures to allow for simplicity, efficiency, and ease of operation.

4 Cost Analysis

Several commercial ram pumps are available for purchase, whose performance and capacity are comparable to the ram pump we are designing. To evaluate the possibility of purchasing a commercial ram pump for use in an AguaClara plant, a cost estimate for AguaClara to construct its own ram pump was made and compared to the cost of various commercial ram pumps that meet our requirements. The additional time and materials that are required for AguaClara to construct its own ram pump, the expected lifetime and reliability of each option, and possible complications involved with either option were also evaluated.

4.1 Ram pump cost

Ram Pump Item	Quantity	Price
3/4" union (threaded)	1	
3/4" valve (low-pressure PVC and CPVC ball valves) (NPT, threaded)	1	
3/4" tee	2	
3/4" spring check valve ("quiet close valve") (NSF certified PVC check valve) (threaded)	1	
3/4" swing check valve ("high flow valve") (NSF certified PVC check valve) (threaded)	1	
3/4" nipple, threaded on both ends	1	
3/4" nipple, threaded on one end	5	
3/4" by 2" bushing, Male NPT Threaded End (A) × Female NPT Threaded End (B)	1	
2" by 4" bushing, Male Unthreaded Pipe End (A) × Female NPT Threaded End (B)	1	
4" coupling	1	
4" diameter PVC pipe, length 24" (Standard-Wall Clear PVC Unthreaded Pipe, 5 ft.)	1	
4" PVC glue cap	1	
3/4" by 1/2" bushing Male Unthreaded Pipe End (A) × Female NPT Threaded End (B)	1	
1/2" union	1	
1/2" nipple, threaded on both ends	2	

The total cost of parts for a ram pump constructed by AguaClara will be $99.80. Additional costs will be associated with PVC glue and bike tires for the air chamber, which are optional. Construction of an AguaClara ram pump will not require a significantly different time investment than the purchase of a commercial ram pump, because each will require assembly of the parts. Investing in more expensive and more reliable check valves will also significantly increase the cost of the ram pump, but should greatly improve the reliability of the ram pump and may eliminate the need for the purchase of a commercial ram pump.

4.2 Check valve analysis

4.2.1 Main types of Check Valves

- Swing check valve: A swing check valve is a check valve in which the disc, the movable part to block the flow, swings on a hinge or trunnion, either onto the seat to block reverse flow or off the seat to allow forward flow. Swing check valves can be installed in both horizontal and vertical position. They are not suitable for pulsating flow.

- Tilting disk check valve: These valves can be installed in horizontal and vertical line. They provide a quick closing response and are particularly suited for pulsating flows with compressible fluids.

- Ball check valve: is a check valve in which the closing member, the movable part to block the flow, is a spherical ball.

- Dual plate wafer check valve: employs two- spring- loaded plates hinged on a central hinge pin. When the flow decreases, the plates close by the action of torsion spring before flow reversal takes place.

- Disc check valve: The single disc check valve (Wafer type disc check valve) Consist of four main components: the body, a disc, a star guide and a spring. The disc check valves are opened by the pressure of fluid and closed through compression spring as soon as flow stops thus preventing reverse flow.

4.2.2 Check valve application in an AguaClara ram pump

For the wasting check valve we have the constraint that it needs to be initially open, but close when the momentum of the water flowing through it is high enough. Our check valve is not working as it should be because it is sticking and we have to open it manually to get the pump to cycle. Clemson's website "Homemade Hydraulic Ram Pump" recommends that the waste valve should always be brass (or some metal) and not plastic. They mentioned that experiences with plastic or PVC swing check valves have shown that the "flapper" or "clapper" in these valves is very light weight and therefore closes much earlier than the "flapper" of a comparable brass swing check. This in turn would mean lower ram pump capacities and lower pressure heads.

The check valve that we are currently using is a PVC check valve with a modified spring-close design. This PVC check valve is not very reliable and often gets stuck either open or closed, resulting in suspension of ram pump operation. To solve this check valve problem we can either buy a new brass check valve, as recommended by Clemson University, or build our own check valve. Brass check valves typically cost between \$10 and \$70 while PVC check valves typically cost between \$7 and \$30. One $\frac{3}{4}\,in$ brass swing check valve from Master-Carr costs \$16.35, while a PVC spring check valve from McMaster-Carr costs only \$7.30. It is clear that the brass one is substantially more expensive but based on research it seems to compensate because of the good functionality and durability. Homemade check valves seem to be relatively cheap to construct– the parts for a homemade check valve would typically cost around \$4. However, constructing a homemade check valve would require significantly more time investment and would be more likely to result in errors that would reduce ram pump reliability and functionality.

4.3 Commercial Ram Pumps

Searching for distributors of ram pumps online has proved to be discouraging, primarily due to the high price of these ram pumps. For reference, one provider, Rife Hydraulic Engine Mfg Co. Inc., sells ram pumps that can reach a maximum elevation of 500 ft – for thousands of dollars. The ram pump which most closely corresponds to the specifications of ours is \$565[RIFE Ram Pumps]. After further research, we found 2 models cheaper than the Rife ram pumps, but each costs significantly more than the pump we built. The first one is a 1" drive diameter ram pump from B&L ram pumps, built with essentially the same materials and parts as our ram pump, for a cost of \$195 [?]. The second one is a stainless steel ram pump from AIRES ram pumps, with a cost of \$230

[AIRES Ram Pumps]. Unless we determine that it would be advantageous to have a ram pump built from material other than PVC for durability issues, it would not be cost-effective to purchase a ram pump and we should instead focus on purchasing or designing a better quality check valve, which would greatly impact the ram pump's performance.

After weighing the options, we decided that building a homemade ram pump would better suit our goals of reducing expenses and ensuring availability in Honduras. The ram pump will be easier and cheaper to make here at Cornell and doing this ourselves will make it easier to revise the design. The commercial ram pumps might be more expensive to ship to Honduras.

5 Experiments and Results

5.1 Ram pump delivery head and ram pump efficiency

The efficiency of a ram pump is given by the relationship

$$\eta = \frac{(Q_{delivery} \cdot h)}{(Q_{drive} \cdot H)} \tag{1}$$

where $Q_{delivery}$is the delivery flow rate, $Q_{drive}$is the drive flow rate, h is the delivery head, and H is the drive height.

We want to determine if there is a correlation between ram pump delivery head and ram pump efficiency, and if so, determine a relationship between the two parameters. If there is a correlation between the two parameters, we will need to ensure that head is kept constant when testing other parameters of the ram pump. However, if the efficiency remains constant as delivery head varies, we can assume that efficiency is independent of head and we will not need to keep the delivery head constant as we are varying other parameters to determine their effects on ram pump efficiency. We hypothesize that there will be a correlation between ram pump delivery head and ram pump efficiency, because the ram pump needs a certain minimum back-pressure to begin operation. We think that once this minimum head is achieved, efficiency will continue to increase as delivery head increases.

An initial experiment was conducted to determine the effects of delivery head on ram pump efficiency by measuring the delivery flow rate at various delivery heads. The delivery head was measured using a pressure sensor at the base of the delivery pipe and pressure data was collected using EasyData data collection software. Delivery head was varied by altering the "openness" of a valve at the base of the delivery pipe. Flow rates were measured manually by measuring the time required to fill a $0.5\,L$ graduated cylinder with the flow. Throughout this experiment, the delivery flow rate remained at $0.141\,L/s$. Delivery flow rates were measured at delivery heads of $3.5\,m$, $5\,m$, $11\,m$, and $13\,m$, and ram pump efficiency was calculated according to Equation 3. Ram pump efficiencies at each head are presented in Figure 4.

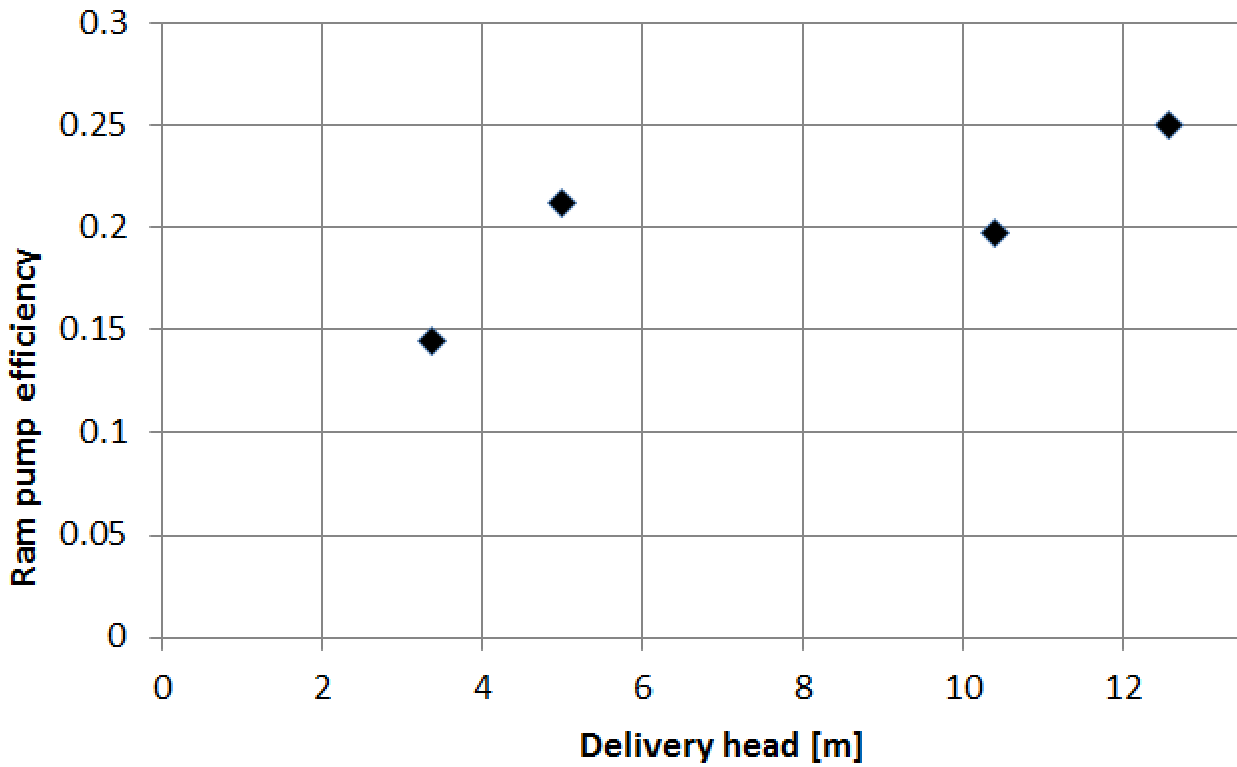


Figure 4: Ram pump efficiency at various delivery heads at a drive flow rate of 0.14 L/s.

Figure 5: Ram pump efficiency vs. delivery head at a drive flow rate of 0.15 L/s.

As can be seen in 4, there appears to be a slight positive correlation between ram pump efficiency and delivery head. This hypothesis is supported by the fact that, at a certain minimum delivery head, the ram pump fails. At a delivery flow rate of $0.141\,L/s$, this minimum head is around $3\,m$. Because of this minimum head required, we believe that, in general, the ram pump will operate at higher efficiencies with a higher delivery head and that decreasing the head will, in general, negatively impact ram pump performance.

A second experiment to determine the ram pump efficiency at various delivery heads was performed at a drive flow rate of $0.15\,L/s$ after adding a needle valve to the delivery pipe. The needle valve will give us better control of the delivery head, so we achieve a desired head more easily and can therefore easily test the pump at more delivery head values. Because the flow rate is only slightly higher than the $0.141\,L/s$ tested previously, we expect similar efficiencies to the efficiencies calculated in this experiment. Results for this experiment are shown in 5.

The efficiencies presented in 5 indicate that ram pump efficiency does increase up to a head of around $12\,m$, as predicted by the first experiments. However, the efficiency significantly drops at a delivery head of $16\,m$, suggesting that there may be an optimal ram pump head at which the pump achieves maximum efficiency. There may be an optimal ram pump head for each delivery flow rate, below which ram pump efficiency increases with delivery head, and above which efficiency will decrease. Additionally, for a given delivery head, there may be an optimal input flow rate that will result in maximum ram pump efficiency. If there is an optimal input flow rate for a given head, this flow rate can be used for the ram pumps in AguaClara plants to achieve maximum efficiency, where the delivery head is fixed by the pump location in the plant, but input flow can be varied. More data will need to be collected to determine an exact correlation between ram pump efficiency and head at various flow rates, and the range over which the correlations are applicable.

5.2 Ram pump performance and drive flow rate

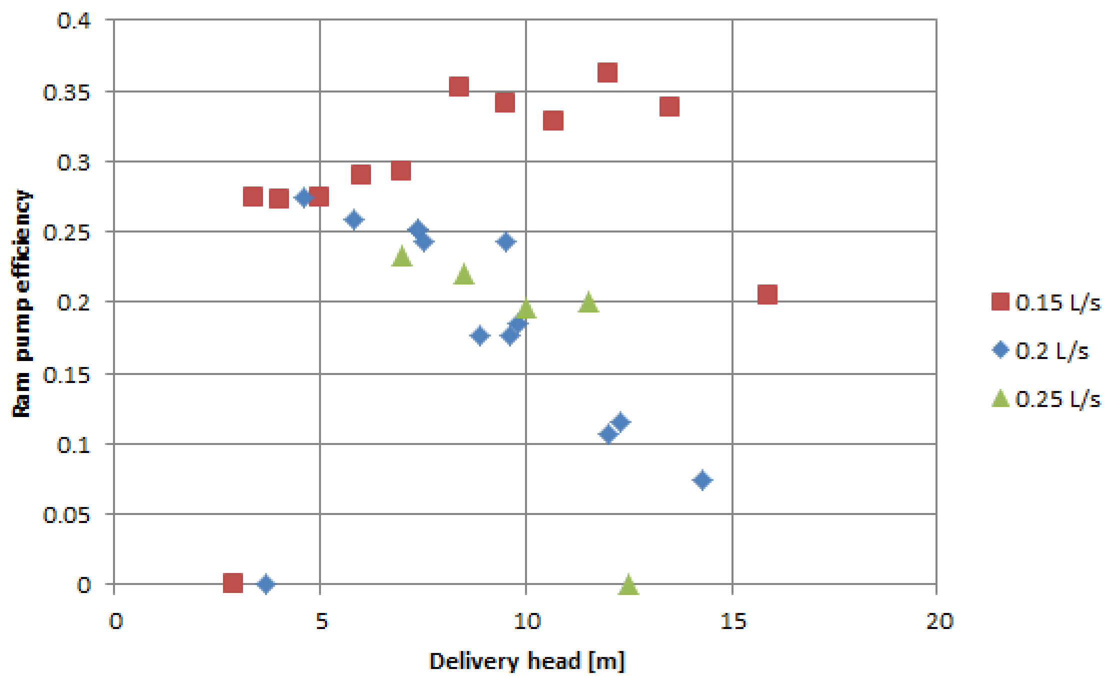
Experiments were run to measure delivery flow rates at various delivery heads at drive flow rates of $0.15\,L/s$, $0.2\,L/s$, and $0.25\,L/s$. We predict that these flow rates will be able to provide the delivery flow required for AguaClara plants of $0.01\,L/s$. We previously hypothesized that different drive flow rates, there will be different optimal delivery heads that result in maximum ram pump efficiency. We want to see how ram pump efficiency relates to ram pump flow rate at each of the heads tested. Results are given in figure 6. Points where ram pump efficiencies are shown to be zero are points where the ram pump and wasting check valve failed.

While there is an optimal efficiency of $0.35\,L/s$ at a drive flow rate of $0.15\,L/s$, the efficiency results at the higher drive flow rates of $0.2\,L/s$ and $0.25\,L/s$ do not show similar maximums. These efficiencies decrease with increasing head, showing a maximum efficiency at the lowest operating delivery head. At a drive flow rate of $0.2\,L/s$, the efficiency decreases from almost 30% to below 10%. The decreasing efficiencies at higher flow rates may be due to the fact that the our ram pump was designed for flow rates closer to $0.01\,L/s$, or because there is not enough weight on our wasting check valve. Increasing the weight on the check valve may help to improve ram pump efficiency at higher flow rates, but more experiments should be run to test this hypothesis.

7shows the measured delivery flow rate versus ram pump head for the same set of experiments. Because of the efficiency decline observed at higher flow rates of $0.2\,L/s$ and $0.25\,L/s$, the delivery flow rate above heads of $9\,m$ is greater for the lowest drive flow rate of $0.15\,L/s$ than for the two higher drive flow rates. These results show the importance of making ram pump design choices that maximize efficiency for the desired head.

5.3 Additional Observations

The head measured by the pressure sensor was found to directly correlate to the water level in the air chamber. The more water floods the chamber, the more back pressure is built-up. We have recorded heights at intervals of head recorded, which serve as accurate estimates of ram pump delivery head.



0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Ram pump efficiency
0
5
10
15
20
Delivery head [m]
0.15 L/s
0.2 L/s
0.25 L/s

Figure 6:

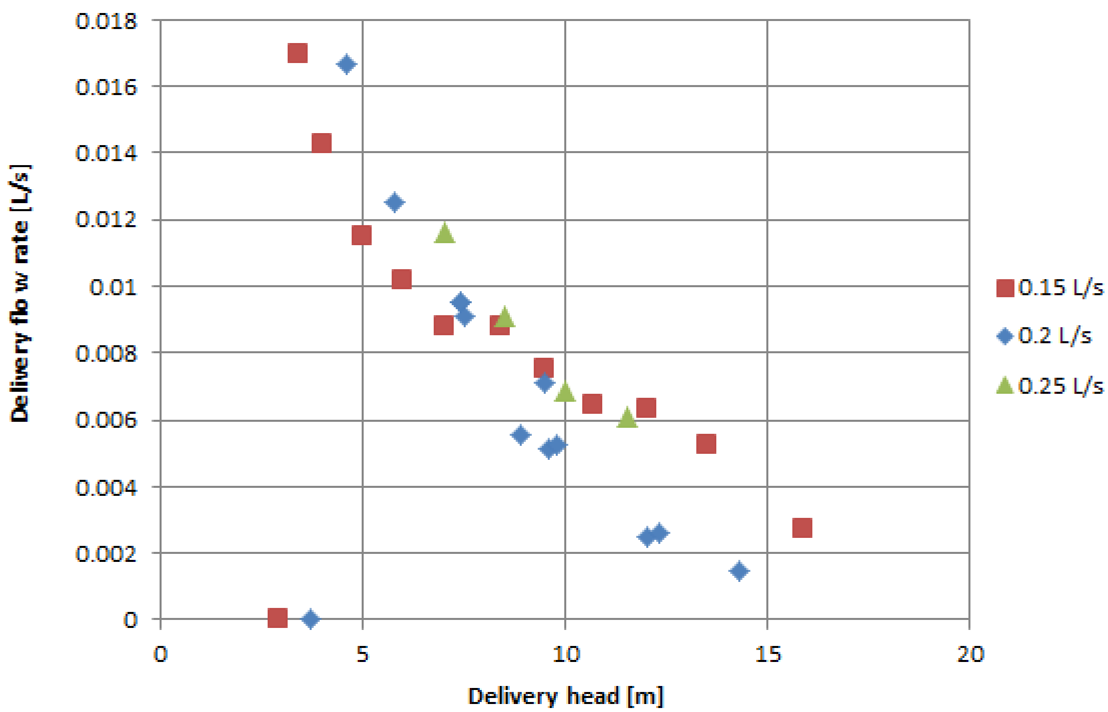

0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
15
20
Delivery flo w rate [L/s]
Delivery head [m]
0.15 L/s
0.2 L/s
0.25 L/s

Figure 7:

Once the back pressure is built up enough to start to slowly open the back valve, the head immediately drops, slowly starting to level out, generally. Upon leveling out, the ram pump starts to build up back pressure again, so measuring flow rates for a specific head is challenging because the head is quite variable. This problem may be resolved with the modification which is discussed in the following section regarding measuring the flow rate automatically.

6 Future Work

6.1 Check Valve

The check valve is one of the most important parts of the Ram Pump. The one that we are currently using, PVC, works at determined pressure levels and is inconsistent. It is not very reliable. According to Clemson University, brass check valves are more durable and have a better functionality. At the end of this semester, a brass check valve was purchased and testing was planned, but it was not able to be modified to be initially open. So, more in depth studies should be done in regards of check valves, efficiency of different types and more accurate results of the relation between pressure and check valve functionality.

6.2 More stable structure

The current structure that we have needs to be more stable. At high pressures it shakes a lot. In our last experiment, on May 1st, the delivery flow was tested for the same head with and without holding the drive pipe (to reduce the shaking) and the delivery flow was higher when the pipe was held. This means that the stability has influences efficiency. Changes should be made to reduce this lack of stability.

6.3 Apparatus improvement

The delivery valve was changed from a ball valve to a needle valve to have a better control of the head. By changing this valve we had to improvise an apparatus, which has caused several leaks.

6.4 Test different parameters

Different parameters should be tested to verify how and if they affect efficiency in order to optimize performance. These include drive pipe length, angle and diameter, air chamber size and orientation, and delivery pipe diameter and angle. Different style control valves and different pump configurations will also need to be tested.

6.5 Automatic flow rate measurement

The means of measuring flow rates through the pump also needs modification. Currently, we are required to measure the velocity of water going into the drive pipe and out of the delivery pipe manually, by means of a bucket test. One means of measuring the delivery flow rate is through an automated bucket tests. The delivery pipe in the hydraulic testing facility would drain to a cylindrical container, and a pressure sensor at the bottom of the container would be used to measure the rate at which the container fills up with water. A solenoid valve located at the bottom of the container would open once the height of water reaches the top of the container, allowing the container to drain and the process to begin again.

6.6 Run tests to determine the effects of various parameters on pump efficiency

Additionally, tests will be run to determine the effects of several other pump parameters on pump efficiency, with the goal of optimizing ram pump performance and delivering water to an equivalent height of $7.15\,m$. Parameters to test in future semesters include drive pipe length, angle, and diameter, air chamber size and orientation, and delivery pipe diameter and angle, with focus on optimizing ram pump efficiency at AguaClara plant conditions.

6.7 Compile research

Ultimately, a list of ram pump design guidelines based on research results should be compiled. These guidelines provide a parts list, operating procedure, and other design guidelines to those looking to build a ram pump with various drive and delivery heads and flow rates. Additionally, we want to create a comprehensive ram pump design Mathcad sheet that will summarize the relationship between design parameters.

7 Conclusions

This semester was very informative as we learned a lot about the ram pump technology through experimentation. At the start of the semester, for example, we knew the air chamber was necessary and that it served the function of "stabilizing" the pump and providing an air cushion such that the flow was regulated. Once the check valve started working and the ram pump succeeded in pumping water, the correlation between water flooding the air chamber and back pressure became clear. The importance of making the entire apparatus water tight was also made clear by the ram pump's inability to function with the multitude of leaks it was experiencing early in the semester.

We have also determined that we will build our own ram pump because of the financial viability of that option. It also allows us to alter the design as much as efficiency requires.

Going in with the goal of determining which parameters impact efficiency, we have found that efficiency varies a lot with conditions such as flow rate. Ultimately, we were able to achieve a maximum of efficiency of 35%. The bottom line at the end of the semester, however, is that this ram pump is viable. The goal at the start of the semester was to deliver 0.01 L/s to a height of 7 meters given a flow rate of 0.1 L/s from the plant. After experimentation, we have confirmed that this ram pump is functional. All that remains is to work on making the pump even more efficient and more resilient to changes in flow rate.

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