Ram Pump

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Abstract

AguaClara creates sustainable water treatment plants that are powered entirely from the force of gravity and hydraulic principles, making them completely electric-free. However, since plant outlets are located at much lower elevations than the plant itself, this presents difficulties in transporting treated water back into the plant for filling chemical stock tanks and plumbing. The ram pump is an excellent solution because it utilizes the water hammer effect to pump water to a higher elevation than the source water and does not require electricity. Our ram pump is designed to be augmented in an existing plant in San Nicolas, Honduras, where the 750.0 L stock tanks will need to be filled in 3 hours, corresponding to a flow rate of 70.0 mL/s.

1 Literature Review

1.1 General Performance

Ram Pumps are water pumps that use a hydraulic effect known as the water hammer to provide energy for pumping. Via this hydraulic effect, ram pumps are capable of elevating water from a lower head to a higher head. However, a significant flow rate is necessary for this to happen. The principle of operation is relatively simple although the exact theoretical model for a ram pump is still under development. There are multiple empirical formulations to calculate parameters for the ram pump.

One such equation is:

$$Q = \frac{ESF}{L} \tag{1}$$

where Q=pumping rate; S=drive flow rate; E= energy efficiency; F=height from source; L=height to destination (Jennings).

This equation seems to be one which is most commonly applied to ram pumps. It essentially takes the incoming flow rate and multiples it by the ratio of fall to lift. This would represent the maximum attainable pumping rate in 100% energy efficient system. However, systems in the market tend to be rated in the range of 60% to 80% with the big majority in the lower end. Along with this equation several tables have been produced to identify optimal points.

One of these tables given again by the North Carolina Cooperative Extension Service suggests that the optimal conditions for pumping rate occur when the fall height to the lift height is at a 1:2 ratio (with the drive pipe and delivery pipe not being excessively long). After this the pumping rate increases with increasing drive rate.

1.2 Air Chamber

A very important component for the efficient operation of the ram pump is the air chamber. The purpose of the air chamber is to provide a constant supply of water to the delivery pipe while preventing harmful effects from the water hammer pressure surge. According to the Development Technology Unit at Warwick University, there is a range of volume of air that should be in the air chamber, depending on the volume of water pumped per cycle (each cycle is one opening of the delivery valve). The recommendation they give is that there should be from 20 to 50 times the volume of air in the chamber as compared to the volume of water pumped per cycle. This will mean that the change in pressure after each cycle will have a negligible effect on the pressure of the air chamber, leading to a more continuous delivery flow. One can write the equation in the following form:

$$V_{air} = \frac{cQ\Delta t}{n} \tag{2}$$

where V= volume of air in chamber; c = a constant in the range [20 to 50]; Q = the pumping rate; Δt = time interval; n = number of cycles in the time interval (Warwick University DTU Ram Pump Programme).

1.3 Theoretical Pressure Rise in Ram Pump

Given that the nature behind the operation of the ram pump is based on the water hammer effect and that our ram pump will be connected to the San Nicolas water treatment plant (specifically, the flow will come from the water that leaves the Stacked Rapid Sand Filter), there is a concern that the pressure wave, that is caused by the closing of the waste valve and that travels back up the drive pipe, could in some way affect the operation or integrity of the SRSF portion of the plant. Although we believe this to be negligible it is still essential to look into. In regards to this there is a equation to calculate the pressure surge from the water hammer. The equation is as follows:

$$D = \frac{\triangle VC}{g} \tag{3}$$

where D= the pressure rise in meters; C = speed of an acoustic wave in the fluid in meters per second; ΔV=change in the fluid's velocity; g = the acceleration due to gravity in meters per second squared (Taye).

1.4 Theoretical Maximum Flow per Cycle

The following is the calculations for the theoretical maximum volume of water that would go from the drive side through the check valve to the delivery side per cycle, assuming ideal check valve conditions and no backflow. This value represents the maximum amount of water pumped per cycle and allows us to calculate the efficiency of our pump.

$$v = \frac{Q}{A} \tag{4}$$

v = fluid velocity (m/s); Q = drive flow rate (m^3/s); A = cross sectional area of pipe (m^2)

$$m = \rho \mathrm{lA} \tag{5}$$

m = mass of water in pipe (kg); ρ = water density (kg/m^3); l = length of pipe (m)

$$M = mv = \rho \mathrm{lQ} \tag{6}$$

M = water momentum (kg*m/s)

$$F = \frac{\Delta \mathrm{M}}{\Delta \mathrm{t}} = \frac{-\rho l Q}{\Delta t} = ma \tag{7}$$

F = force on water (N); ΔM = change in momentum (kg*m/s); Δt = time interval from closing of valve to opening of valve (s); a = acceleration (m/s^2)

$$a_{avg} = \frac{-Q}{A\Delta \mathrm{t}} \tag{8}$$

Here it is assumed that the acceleration might not be constant but that it will be linear. These are the equations that will be used to derive the formula for our calculation.

$$X(t = \Delta \mathrm{t}) = \int (\int \mathrm{a\ dt})\ \mathrm{dt} = \frac{-Q}{2A\Delta \mathrm{t}} t^2 + \frac{Q}{A} t = \frac{Q}{2A} \Delta \mathrm{t} \tag{9}$$

The process above describes the length that a fluid particle will move from the time that the waste valve closes to the time when the waste valve opens again. It is assumed that the moment the particle comes to rest corresponds to the moment that the waste valve opens again and that t=0 corresponds to the time when the waste valve closes. The calculation begins by integrating our average accelearation (a constant) with respect to time. The solution is subject to initial condition V(0)=Q/Apipe and X(0)=0. Then t=Δt is plugged into equation (9) to find the position of the particle when it comes to rest. Thus the particle has traveled a given distance and so too have the particles around it. Lastly, if this displacement is multiplied by the cross-sectional area of the pipe, the volume element that moves into the delivery section of the ram pump will be obtained and thus the amount of water pumped per cycle. The element is described below:

$$V_{cycle} = XA \tag{10}$$

V_{cycle} =volume of water pumped per cycle (m^3); X = displacement per cycle (m).

1.5 Power

Power was used as general metric to determine the effectiveness of the ram pump. The following equation was used calculate it:

$$Power = \rho ghQ$$

g = acceleration due to gravity (m/s^2) ; h = headloss (m); ρ and Q as defined previously

2 Introduction

In accordance with AguaClara's core values of sustainability and electricity-independence, the ram pump utilizes only gravity and hydraulic principles to raise water to higher elevations using the momentum of water falling from a shorter elevation. Through spring check valves that only open when the pressure is high enough, the ram pump allows the water hammer to build up and then uses that pressure to drive the process. Thus, no external power is needed to pump the water up to a higher altitude.

The ram pump is incredibly essential as it will allow filtered water from a lower elevation to be pumped back into the plant for use in chemical stock tanks and bathrooms. The current design is geared towards implementation in San Nicolas, Honduras, where the pumping requirement is 70.0 mL/s and the delivery head is 7.0 meters. The existing apparatus has been improved by constructing a space-efficient head loss generating system, a recycling system that pumps water from the waste bucket to the drive tank, and by adding sensors at various points in the appartus to accurately measure head loss and pressure at those positions. The goal is to optimize the function between when the ram pump valve closes and when it opens, which can be controlled by weights and springs, respectively, and to conduct enough experiments to construct a preliminary mathematical model that describes ram pump performance.

3 Methods

3.1 Apparatus

Water from the overhead drive tank(1) (a) (with 2.05 m of head measured from the ground to the waterline) enters the drive pipe (b) and gains momentum as it falls. The overflow weir (b) in the overhead drive tank prevents water from overflowing. The spring check valve is initially closed (i) while the waste valve (e) is initially open. As water flows through the drive pipe, and flow speed builds up, the waste valve closes. This produces the water hammer and forces water through the check valve. Then the pressure surge from the water hammer dissipates causing the waste valve to open up once more. Waste water from the ram pump valve, which is treated water in actual plants and will be distributed, is then pumped to the recycle tank (m) in our set-up via the waste-to-recycle pump (h). A flow rate sensor (g) along the way records the waste flow rate in process controller. From the spring check valve, water is then pushed into the air chamber (j), which comprises of a bike tire and stabilizes the water flow; the bike tire compresses when water enters and then pushes down on the water surface, allowing water to be delivered at a steady rate rather than in pulses. Then, water is delivered through our 7.0 m head delivery system (l). The sections of the delivery system going up add up to the desired head of 7.0 m, and as water flows, the up sections will fill with water while the down sections will involve free falling water, implying that the pressure is (almost) constant in these sections. Thus, the head accumulates and simulates the 7.0 m head encountered in the plant in San Nicolas. A flow rate sensor (m) is attached after the delivery system to record the delivery speed before water falls back into the recycle tank. Lastly, to reuse the water during our experiment, water from the recycle tank is pumped up to the overhead drive tank via an electric pump (n); the flow rate from the pump is controlled by a manual valve (o) in order to maintain a stable water level in the overhead drive tank.

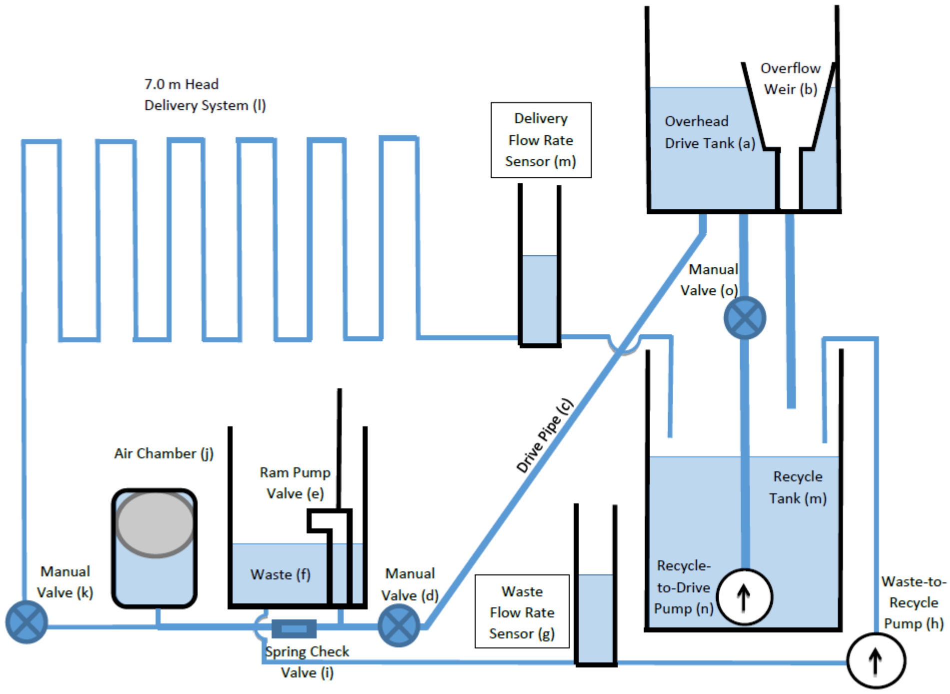

Figure 1: Overview/Schematic of Ram Pump Apparatus

Below are actual photos of our apparatus.

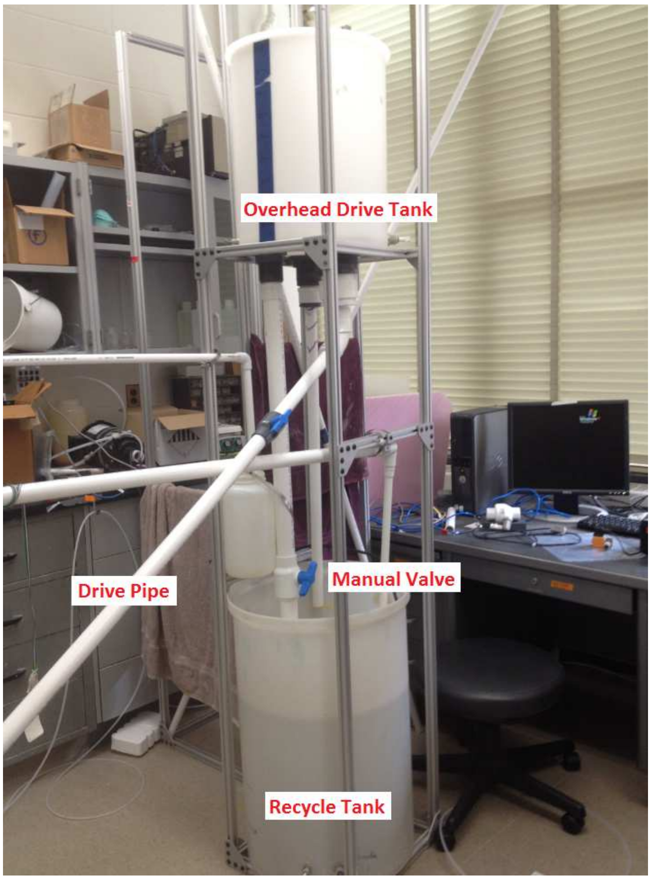

Figure 2: Overhead Drive Tank and Recycling System

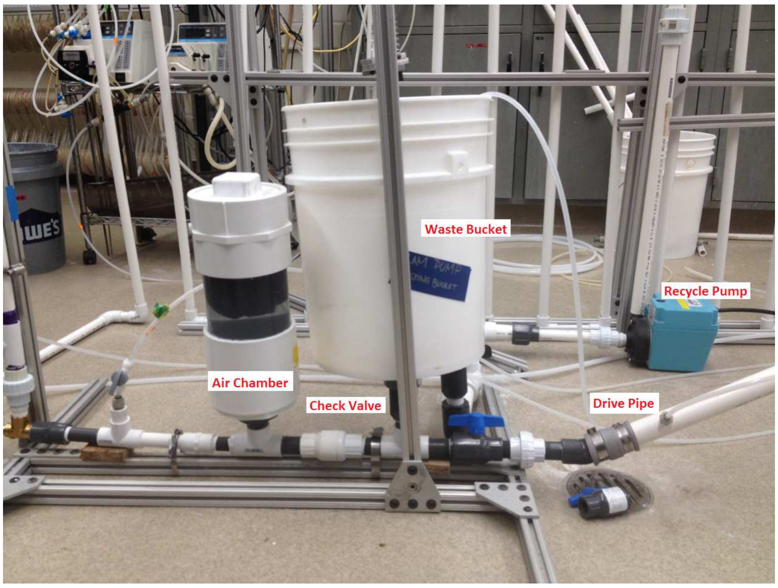

Figure 3: Ram Pump Set Up

Figure 4: Waste Bucket

Figure 5: Head Loss Generating System

3.1.1 The Head Loss System

The head loss system is a crucial part of the experiment because it needs to be set at 7.0 meters in order to calculate the amount of pressure needed to pump the water up to that height and to adjust weights and springs in the ram pump. The system is composed of PVC piping and is glued to prevent air from entering the system. A 200 kPa pressure sensor is attached at the beginning of the head loss device and one is attached at the end to calculate the difference in head. An air tube is also inserted at the beginning to pump in a slight amount of air to obtain the correct amount of head loss.

3.1.2 Spring to Swing Check Valve

In an effort to increase the delivery flow rate, the spring check valve is replaced with a swing check valve since it offers less resistance. However, the flow rate decreased from 13.7 mL/s to 12.5 mL/s even with a lower head loss. This suggests that the spring check valve is more suitable for the purposes of this experiment.

3.2 Experimental Methods

The goal is to maximize the ram pump delivery rate by achieving the optimal range of velocities and time intervals between each cycle. At the beginning of each cycle when the waste valve is initially open, the water velocity first begins to gain speed and approaches a limiting value. During this period, the goal is to close the valve before the water velocity reaches this limiting value, where drag forces between the water and the pipe walls become significant sources of head loss. At this point, the valve shuts close and the water experiences a substantial deceleration and approaches zero velocity. Right before the water reaches zero velocity, there is an inherent inefficiency where water from the delivery system begins to flow back into the drive pipe. The goal in this period is to open the waste valve and start the cycle again before this inefficiency comes into play. Essentially, the team isis looking to affect these two phenomenon through appropriate modifications of the waste valve. This will be done through springs or added weights, or a combination of the two. In order to avoid the weights from sliding down the waste valve,the valve is modified and inserted a circular nut that can be moved up and down the valve and tightened at any position. The approach to find the optimal modification will be done by continuous refinements of clever trial and error that are guided by aforementioned ideas.

In addition, the effects of the air chamber will be looked at on delivery performance. The team plans to adjust the volume of air inside the chamber and also explore different materials and ways to adjust this volume. Some of the proposed ideas include bike tires, snifter valves, and pressure gauges. Details were mentioned in the literature review section and will guide the experimentation with the air chamber.

To monitor and record the data from various points of the ram pump system, Process Controller and Easy Data will be implemented. The software will record the head loss and pressure at different points in the system. Though it is possible to utilize process controller to measure the delivery flow rate, the set-up is too time intensive and would have detracted from actual experimentation. Instead, the team opted to measure the delivery flow rate manually with a graduated cylinder and a stop watch; to minimize errors, this measurement will be repeated three times and will use the average flow rate. From these data, the system can be continuously modified to increase performance and to provide grounding for a mathematical model that governs the ram pump cycle.

4 Analysis

4.1 Head Loss System Set-Up

A crucial part of the set-up is the head loss system, which provides the 7.0 meters of head loss needed to simulate actual parameters in Honduras. Thus, before starting the experimentation phase on the ram pump, it is necessary to ensure the system actually achieves 7.0 meters of head loss. Sensors were added in at the very beginning (right after the air chamber) and the end (after the last up-flow pipe) of the system to accurately measure the head loss generated throughout the system.

For the initial trial, the pump was left to run continuously for about 500 seconds 6. The first horizontal stretch of the graph indicates that the system generates about 240.0 cm of head loss; however, the sensor was not zeroed properly, and after taking this difference into account, the actual head loss is closer to 470.0 cm. At around 150 seconds, air was pumped into the system with the inlet at the beginning of the delivery pipe in order to increase head loss. Also around this time, the ram pump stopped working continuously and instead delivered water intermittently. As a result, the effect on head loss of adding air into the system was inconclusive. Nevertheless, the team decided that changing head loss by pumping air into the system is unreliable because the air flow rate is adjusted by manually turning the "air" valve in lab, making replicating the same flow rate difficult and imprecise. As a result, it was concluded that it is optimal to simply add more turns to the head loss system to achieve the desired constant head loss of 7.0 meters.

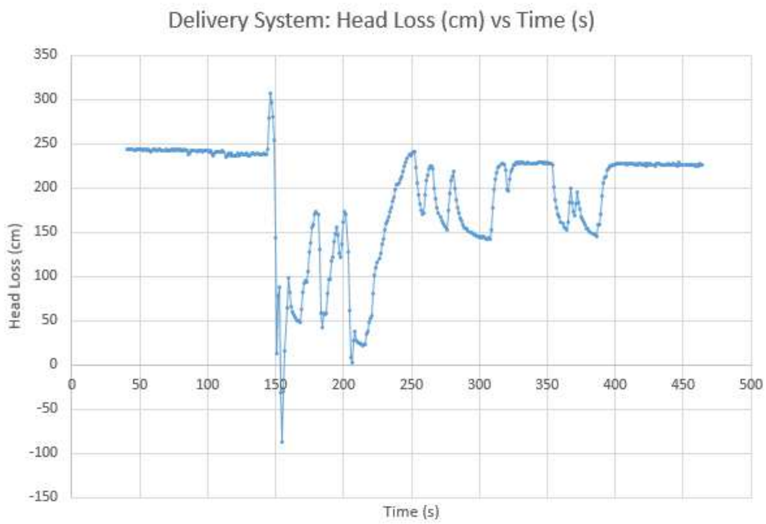

Figure 6: Head Loss Generated by Delivery System Over Time - Initial

After implementing the change of adding more pipes to the head loss system, the following results were obtained 7. As the graph indicates, it took about 120.0 seconds for the system to exceed the desired head loss of 7.0 meters, but once it did, the head loss stayed fairly constant at above 7.0 meters. The excess head loss generated above 7.0 meters provides a safety buffer between lab and plant implementations. This result shows that the system is successful at fabricating comparable head that will be pumped against in Honduras. The head loss being measured correspond to the pressure difference between the first up-flow pipe and the end of the head loss system where it is open to the atmosphere.

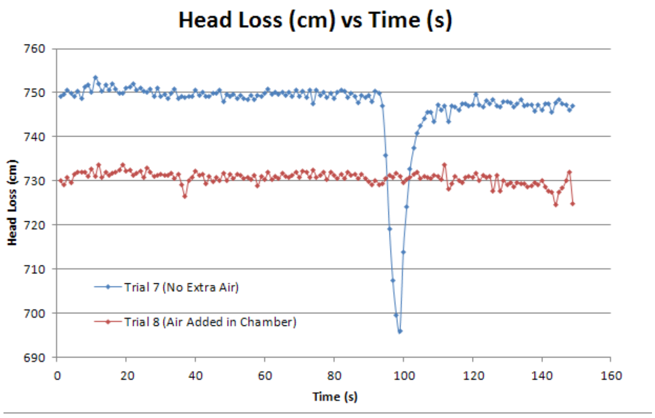

Figure 8: Head Loss (cm) vs Time (s) for Trials 7 and 8

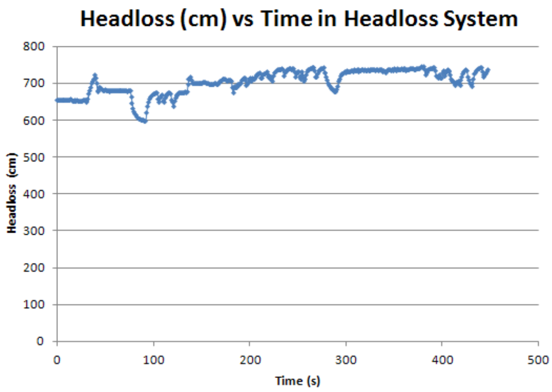

Figure 7: Head loss Generated by Delivery System Over Time - Post-Adjustment

4.2 Volume of Air in Air Chamber vs Delivery Flow Rate

During trials 1 (corresponds to trial 7 in data) and 2 (corresponds to trial 8 in data) , the amount of air was modified in the air chamber drastically to gauge the effect of this modification on the delivery flow rate. Trial 1 is the control trial where the air chamber only has the tire in it with no extra air added, and trial 2 has a substantial amount of extra air pumped into the chamber via the air valve on the lab benches.

For trial 1, the average head loss is 738.4 cm with a standard deviation of 1.4 cm. The dip at around 100 seconds was caused by the ram pump stopping because the waste valve mechanism got stuck; the spring was adjusted right away and the pump resumed working. The data points around this manual error were considered outliers and were not included to calculate the average

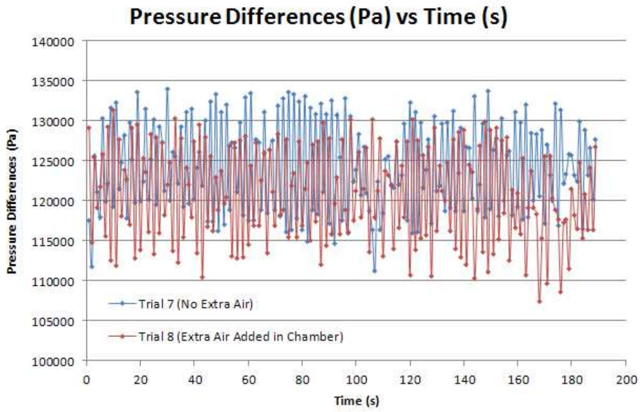

Figure 9: Pressure Differences (Pa) vs Time (s) for Trials 7 and 8

head loss mentioned above. For trial 2, the average head loss is 722.8 cm with a standard deviation of 11.0 cm. The two trials had similar head losses.

For trial 1, the average pressure difference across the check valve (between the drive and the delivery side) is 122.3 kPa with a standard deviation of 6.1 kPa; for trial 2, the average pressure difference was 119.9 kPa with a standard deviation of 7.3 kPa.

The delivery flow rates were manually measured with a graduated cylinder and a stop watch three times for each trial; the values were then averaged to give 14.1 mL/s for trial 7 and 16.7 mL/s for trial 8.

Comparing the two trials, adding more air into the air chamber only had a minimal effect on delivery flow rate, increasing it by 2.6 mL/s . This slightly higher delivery flow rate for trial 2 can be easily attributed to the lower head loss (722.8 cm in trial 2 instead of 738.3 cm in trial 1) that needed to be overcome, meaning that the volume of air in the air chamber is not a significant factor of delivery flow rate in our system. However, it is suspected that since the head loss system is itself a large air chamber (due to the air columns in the downward components), the effect of increasing the volume of air in the chamber on delivery flow rate is inconclusive. Further testings with a different lab set up will need to be carried out if the team wishes to study this variable in depth.

4.3 Commercial (Davey Ram Pump) vs AguaClara Ram Pump

In order to further research and acquire information to improve the flow rate of our system, the teamwanted to study how the commercial ram pump works and if some of its properties can be used to the team's advantage. The model that was ordered is the "RIFE Improved Davey Ram Pump (DRP). the team first modified the piping coming into and out of the ram pump so that it could slide right into our current set up so the same delivery head could be simulated. Upon the first test, water was dispersed throughout the lab because the commercial ram pump does not have a 'waste' water return system. Therefore, in order to capture the water coming out of the commercial pump and avoid damaging our lab, the team modified a Sterilite plastic container to hold the pump and cut holes of the appropriate diameters on the sides for the drive and delivery pipes. Lastly, a PVC pipe was inserted and connected to an electric pump that will recycle the water back into our source tank. With the commercial ram pump, the team is looking to acquire a significantly higher flow rate than we are currently obtaining. As of now, the flow rate is approximately 25 mL/s.

Below are pictures and schematic of the commercial ram pump.

Figure 10: Commercial Ram Pump

The Delivery Rates of the AguaClara and the Commercial Pump are as follows:

AguaClara Pump

Head loss (cm)	Delivery Rate (mL/s)	Power (W)
476.21	17.56	0.8203
655.74	12.48	0.8028
722.82	16.70 (sp valve)	1.184
738.35	14.11 (sp valve)	1.022
766.73	6.187	0.4653

Commercial Pump

Head Loss (cm)	Delivery Rate (mL/s)	Power(W)
529.22	25.84	1.342
602.84	26.81	1.586
679.21	24.67	1.643
733.54	20.18	1.452

From a slightly more technical perspective various differences have been identifiedbetween the designs of both systems. The first and most noticeable design difference is the size. The DRP is substantially smaller and more simple than the current AguaClara pump and yet both share the same key components, namely, the drive pipe intake, the waste valve, the check vale, the air chamber and the pipe delivery output. The next main similarity is that both control the frequency of cycles, which suggests that this is an important part of any ram pump device. The DRP uses an adjustable screw to control the length that the waste valve has to travel to close, while the AguaClara ram pump uses a set of weights and springs to control the opening and closing of the waste valve. However, the similarities end here. It becomes evident that even though both use the same fundamental components they have been arranged in very different manners. The DRP is what would be defined as a "Front End Mount". Front End Mounted pumps havethe check valve component located in front of the waste valve component as opposed to the "Back End Mount" where the check valve is behind the waste valve (as in the AguaClara set up). Also, notice that the naming takes the waste valve as the "origin" since it is in effect the heart of the ram pump and the rest is defined in relation to this origin. This set up is quite interesting and might suggest experimenting with different locations of the check valve with respect to the waste valve. Another difference, granted the team is as of now unfamiliar with its importance or effect in performance, corresponds to the shape of the air chamber. DRP uses an air chamber that seems to be modeled after a sphere. Regarding the control mechanisms for frequency of the cycles, the DRP makes use of an adjustable displacement of the waste valve. One can adjust the length that the water has to push the waste valve to get it to close and thus control in this fashion the frequency of the cycles. It makes no use of varying masses and provides a mass of 476 grams which the water has to push up. Also, important details that are needed to drive attention to is the fact that the waste valve, the check valve, and the air chamber are connected to the same pipe, and that the DRP is made of metal rather than plastic like the AguaClara ram pump (will not shake as violently, aka dissipation of energy).

5 Conclusion

After a semester of conducting experiments, collecting data, and making comparisons to a commercial ram pump, it is concluded that even though the AguaClara ram pump is functional, it is not the most efficient model. The delivery rate of the AguaClara model is significantly lower, achieving a maximum of 17.56mL/s at a head loss of 4.76m, and does not meet demanded flow rate of 70 mL/s. The team believes that the under-performance stems from a variety of reasons, primarily due to the set up of the pump. The components of the model are currently spread out relative to one another, resulting in an increased dissipation of energy and a lower efficiency as compared to the Davey Ram Pump. In the AguaClara pump, when the waste valve closes, the pressure waves are split and travel to both the check valve and to the drive pipe. In the DRP, the waste valve is located after both the check valve and the drive pipe and channels all the pressure waves back towards the source in a single stream. Furthermore, the proximity of the check valve to the waste valve and the fact that the check valve is embedded into the drive pipe maximize the water hammer effect. Therefore, the positioning of the check valve relative to the waste valve plays a significant role towards increasing the water hammer effect and the delivery rate. Another reason for the low delivery rate in the ram pump model is that the AguaClara air chamber had a single pipe that both takes in and pushes out the water while the DRP air chamber takes in the water through the check valve intake and pushes the water out through the delivery pipe. The DRP set up directs water in one direction only and thus the velocity of the water is maintained at a higher value. After taking all these factors into account, the team decided that the best approach would be to construct a new model that incorporates these findings in order to maximize the flow rate.

6 Future Work

After a semester of experimentation, the team has identified the appropriate direction in which to proceed. It is now clear that the new ram pump should take on a more compact form, in which all components (waste valve, check valve, air chamber) should be all closer and more directly connected to one another. The team has created a new preliminary setup, taking into account the aforementioned considerations. In the first run the new setup demonstrated impressive results suggesting that the recommened path proved to be correct. However, further documentation of the set up is needed since barely one trial was taken. Of course the setup can be continued to be improved by implementing more of the outlined considerations, such as the dual tubing in the air chamber or properly securing all components, but in no way limited to these.

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