EPA People, Prosperity & the Planet Grant Final Report
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EPA Agreement Number: SU839463
Project Title: AguaClara's Ram Pump for Zero Electricity Drinking Water Treatment
Project Period: December 1, 2018 through November 30, 2019
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Objective of Research:

The AguaClara plants use fluid mechanics principles to eliminate the need for mechanical controls; by reducing the number of moving parts, the AguaClara plants have far fewer failure modes than conventional mechanical plants. AguaClara produces cleaner water with lower capital and operating costs than conventional plants in Honduras, and thus, there is an effort underway to bring AguaClara technologies to the United States. The AguaClara Vertical Ram Pump (ACVRP) was designed and fabricated as a novel inline (vertical pipeline with zero waste) ram pump, which uses potential energy to lift a small amount of water to a higher elevation. While a standard ram pump wastes the water used for energy extraction, the AguaClara ram pump returns that low-energy water for use as potable water by the community. Conventional ram pumps that discharge wasted water to the environment have been researched extensively, but there is no research on AguaClara's vertical-flow, waste-free ram pump (ACVRP). The research goal is to improve the efficiency and ease of use of this design, as the inline ram pump is essential to making AguaClara water treatment plants electricity-free and easy to operate. The purpose of an ACVRP in an AguaClara plant is to lift treated water to water storage tanks at a higher elevation that are used for preparing coagulant and chlorine solutions as well as for the plumbing throughout the plant. Currently, plant operators need to transport this water manually by hauling numerous buckets of water up to these storage tanks. Implementation of an ACVRP would relieve both time and physical burdens from plant operators, promoting better physical well-being of the operators and allowing for their time to be put into other maintenance and improvement of the plant.

Progress Summary/Accomplishments (Outputs/Outcomes):

Force Analysis and Ideal Spring Constant

Efficiency of the ACVRP is defined as the percentage of theoretical flow rate that is actually achieved. The theoretical flow rate is calculated based on dimensions and terminal velocity while the actual flow rate is measured experimentally. In order to optimize the efficiency of ACVRP, a range of ideal spring constants is needed to supply the optimal forces to open and close the valve of the pump, and therefore forces required to toggle the plate valve were calculated.

The drag force from the falling water overcomes the spring force to close the valve while the spring force overcomes the hydrostatic force of the water on the closed plate to open the valve. In order to determine the ideal spring constant and optimal forces, these forces of the water on the plate in the open and closed positions can be used as outer limits. That is to say that the force of the spring on the plate when the valve is open cannot exceed the maximum drag force on the plate or else the valve would never close. Similarly, the force of the spring on the plate when the valve is closed cannot be less than the hydrostatic force of the water on the plate or else the valve would never open. For this reason, the team developed a procedure for finding both of these forces. In order to find the maximum drag force on the plate, the team used a two pulley system connecting the plate valve with a bottle with water in it hanging from the pulley that extends out of the head tank. The amount of water in the bottle was adjusted until the plate was just opened. The weight of the bottle at this instant was equal to the force from the falling water in the drive pipe on the plate. In order to find the hydrostatic force, the height of the water column above the plate was found and the hydrostatic pressure from this height of water was calculated. This pressure was multiplied by the area of the plate to find the force acting on the plate.

Using the determined forces, a range of ideal spring constants were determined. Since Hooke's Law depends on the compression length, Δx, k' was defined as an intrinsic material property of the spring dependent on the actual length of the spring rather than its compression length, such that Hooke's Law could be written as:

$$F = \frac{k'x}{L} \text{ where } k' = kL$$

An equation based on the two forces varying with k' in terms of the spring length, L can thus be derived: $F_o - F_c = \frac{k'}{L}\Delta x$, where in the case of using just one compression spring, F_o is the force required by the spring to open the waste valve at desired time), F_{closed} is the force required by the spring for the waste valve to close at desired time), and Δx is the compression length difference between open and closed states. Thus, a ratio between k' and L can be obtained. Even though the design of the system has changed since these experiments and calculations were performed, this work will inform the team in the future on how to find the desired forces for the new system. The same calculations would be applied for finding the intrinsic k constant for extension springs, and since separate springs are used for keeping the plate opened and closed, calculations should account for two spring constants and their respective changes in length.

Redesigning System

Reduction of Headloss

In the first couple iterations of the ACVRP, the effluent valve was a ¼" valve located 90° to the drive pipe where the water was falling. The 90° bend that the water takes to enter the high pressure check valve caused unnecessary head loss and hence reduced pumping efficiency. Therefore, the team proposed a new design with the effluent flow first passing through a 1" check valve into the air chamber, then, water exits from an effluent valve located at the bottom of the air chamber. Thus, headloss at the effluent was reduced in relation to the drive pipe, and more energy from the falling water was conserved. Such design has increased the efficiency of the ACVRP from less than 8% to consistently over 50%.

Ease of Adjustment

The redesigned spring system addresses the issue of difficult readjustment of the ACVRP and implements a method that involves minimal deconstruction of the mechanism. The previous design required a check valve at the lower end of the system to be dismantled in order for the compression spring to be adjusted or replaced. This series of actions to make changes to the ACVRP is tedious and often difficult to perform in the conditions that the pump was installed and operates in. The main challenge that hindered adjustment of the pump was that while the mechanism was in operation most of the adjustable parts were submerged. The team created a design that allowed for instantaneous adjustment of the spring constants, while the system is in operation.

This new system involves three external extension springs instead of one internal compression spring. The three external springs are hooked onto three separate threaded eyebolts, which can be moved up or down to adjust the forces being applied on the plate within the lower check valve. All of these springs are attached to a bottom plate that serves to transmit this upward force, through a metal wire rope, to the plate in the check valve. The eyebolts that the springs are connected to are secured by two nuts each to a stationary top plate that restricts the springs from falling into the drive pipe. The two outer springs on the design are longer springs with a low spring rate, this is to apply a relatively constant upward force while the plate is oscillating through its cycle. The current inner spring has a relatively high spring rate compared to the other springs in the system to account for the increased pressure when the plate is "closed" in the check valve. It is attached to its eyebolt with a piece of metal wire that has slack in it when the plate is in the open position. As the plate closes, the wire is pulled taught, the middle spring extends and, thus, exerts an upward force on the plate. This allows the forces corresponding to the open and closed positions to be adjusted individually. This spring system is stationed above the flowing water and is easily accessible in order to raise or lower the effective force transmitted by the springs. Changing the force of the check valve plate is now easier to accomplish because of the greater accessibility to the force applying springs and the greater range of adjustment available.

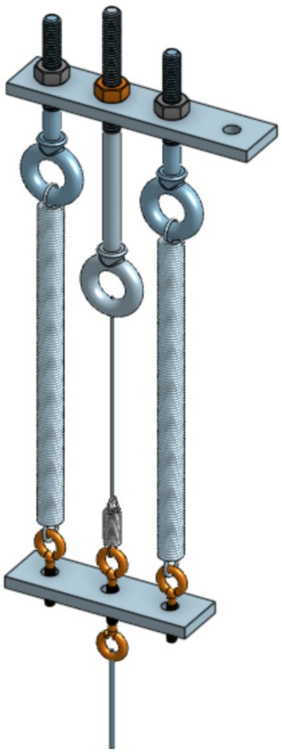

Figure 1: Triple extension spring system, with middle spring to open the valve and the two side springs to close the valve.

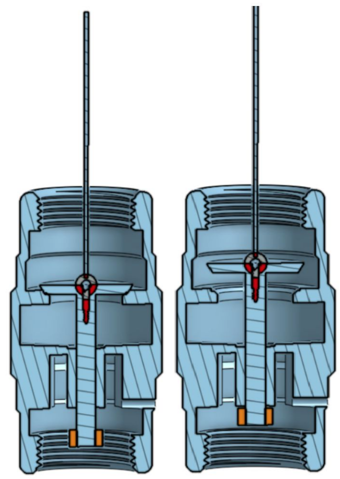

Figure 2: Plate open and plate closed position of valve, where the plate valve is connected to the spring system with a cable that goes through the eyebolt. The limit of plate opening is limited by a nut at the threaded end (as shown by the orange nut).

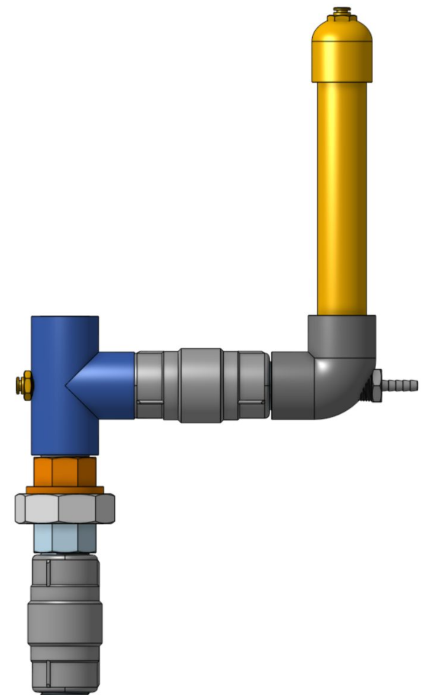

Figure 3: Overview of the ACVRP: The triple extension spring system is located in the stock tank and is connected to the plate in the check valve (Figure 2) located at the bottom of the assembly shown here. The effluent of the ACVRP is located at the bottom of the air chamber (yellow).

The support structure of the new spring design also has an adjustable height component as a way to make the replacement of springs of various sizes easier. Because of this design the metal wire connected to the check valve plate does not need to be replaced when springs are changed in height, rather the support height can be changed to accompany the necessary spring length.

Lab Apparatus

During the period of funding, the research team fabricated a new experimental apparatus for the testing of the ACVRP. The apparatus had to be shorter so that the adjustment mechanism, which is now at the top of the apparatus, could be easily accessed. The design, similar to the previous one, involves a head tank, drive pipe, collection tank, waste valve, sump pump, air chamber and other smaller components. An aspect that differs in this lab setup is the addition of a throttle valve on the pipe that pumps water up to the head tank. Currently the team only has a sump pump that is able to pump water at one speed, so being able to adjust the flow rate of the water going into the head tank allowed for a faster and more controlled flow of water. The addition of a throttle with an on/off valve allowed the team to make a one-time adjustment to the flow rate that controls the amount of head from the bottom of the ACVRP to the top of the water while still having the ability to close this pipe when needed. This helped keep the calculated head level constant and made determining the necessary spring force for the opened and closed check valve plate more precise.

The new lab apparatus is also integrated into the team's lab bench in order to reduce the amount of floor space occupied in the shared laboratory. The head tank is situated over the lab bench and pipes leading to the sump pump and collection tank are fitted through holes drilled into the lab bench. An 80-20 structure contains the head tank and fixes the whole structure to the team's lab bench. The new apparatus was created mainly to consolidate the space in the laboratory and make a more compact model of the Ram Pump system.

Evaluation

Economic Feasibility

AguaClara focuses on designs and solutions that are sustainable for their context. AguaClara plants are specifically designed to be electricity free, use locally available and inexpensive resources for the communities that the plants serve (currently in Honduras and Nicaragua), and require inexpensive maintenance procedures. These have been the foremost considerations of the team while designing the ACVRP. Most of the entire system is comprised of traditional water and plumbing materials including check valves and PVC pipes and accessories. The other components include extension springs, metal rope, and aluminum plates, all of which are low cost and easily accessible for AguaClara plants. The integration of an ACVRP into an AguaClara plant is also a low cost process and does not require any special components or skills.

Technical Effectiveness

In order to evaluate the performance of the ACVRP, its effluent is connected to an air chamber that can be pressurized to simulate a specific height of water corresponding to the height in an AguaClara plant to which the ACVRP will have to pump. As the ACVRP pumps water into the air chamber, a pressure sensor monitors the pressure in the air chamber and communicates to a data acquisition software which runs a peristaltic pump to pump water out of the air chamber to keep the pressure constant. The data acquisition system calculates the flow rate coming out of the air chamber, which is the flow rate that the ACVRP is pumping. Using this system, the team was able to compare the flow rate from the previous design to that of the current design. It is important to note that the previous data was collected using an older lab apparatus that provided about 2 m of driving head to the ACVRP while the new lab apparatus only provides about 1.5 m of driving head. However, even with less energy coming from the water the maximum flow rate increased from 20.25 mL/s with the old design to 26.74 mL/s. If the new design's maximum flow rate were scaled by a factor of 1.33 to find what the flow rate would be if the ACVRP still had 2 m of driving head, the resulting flow rate is 35.65 mL/s. These results yield a 76% increase in flow rate. Additionally, this data was also collected before optimizing the spring system so there is potential for the flow rate to increase. Graphs of flow rate data acquired through experimentation with the old and new designs are shown below. It is important to note that the experiments that were performed on the two different systems were not the same but they both yield flow rate profiles of their respective systems that can be compared.

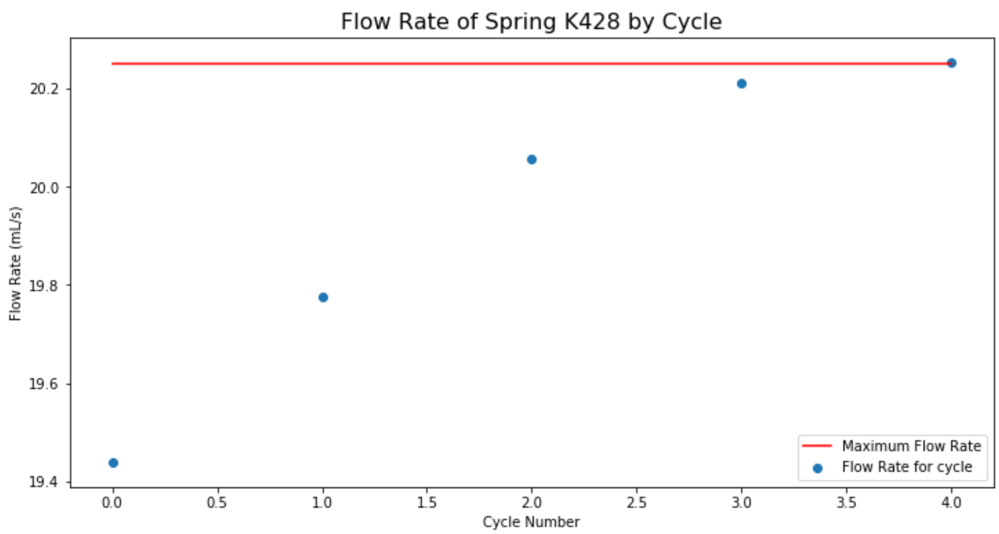

Figure 3: Graph of Flow Rate vs. Cycle for the old ACVRP design.

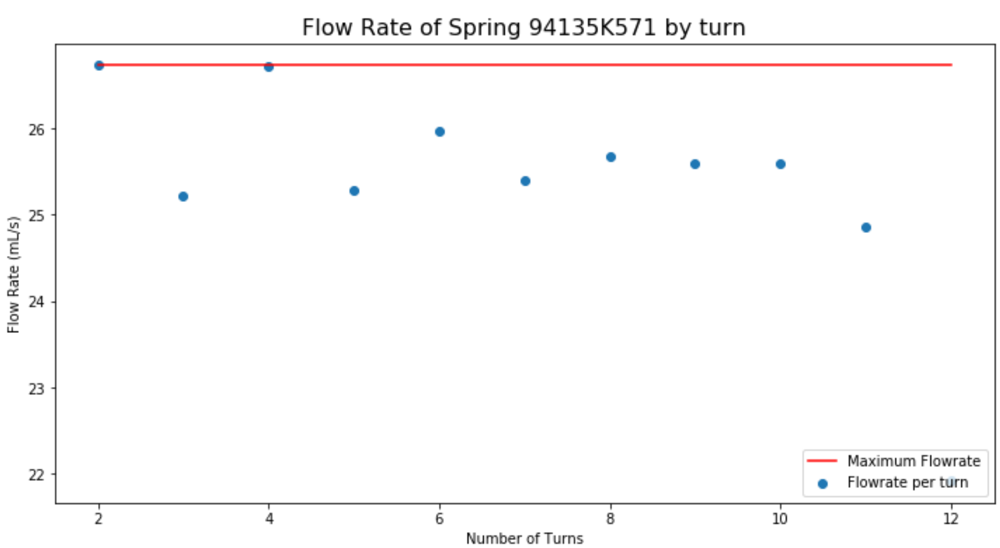

Figure 4: Graph of Flow Rate vs. Number of turns of the middle eyebolt nut (adjusting middle spring force) for the new ACVRP design.

The team was able to compare the current performance of the ACVRP to the needs of a few specific AguaClara plants as well. The plants have water storage tanks that the operators fill with water every few days. The team gathered information on the size of the tanks and the frequency with which the operators fill the tanks. With this information, the team was able to calculate the needed flow rate from an ACVRP for each of these plants. It was clear that the ACVRP with its current performance could provide the needed flow rate at several of the medium-sized plants. However, larger plants would need a higher flow rate than what the current performance could provide. The team is optimistic that with further testing and experimentation the performance of the ACVRP can be improved to the necessary level of these plants.

Environmental and Health Benefits

The ACVRP will provide a hands-off alternative to plant operators hauling several buckets of water up a flight of stairs to the chemical stock tanks and water storage tanks for plant plumbing. This will promote the physical well-being and health of the plant operators by taking this physical burden off of them. Plant operators will also have the time that would be put into this task to focus on other maintenance and improvement of the plant, which is providing clean water to its community.

The ACVRP differs from traditional hydraulic rams in that it is an inline- zero waste pump. Traditional hydraulic rams waste a significant portion of the entering water in order to function. The ACVRP does not waste water but instead allows it to continue on its path to the storage tank from which it will be distributed to the community. Not only does the ACVRP not waste water but since the water running through it was just treated, it is also not wasting the plant resources such as the coagulant and chlorine that was necessary to treat the water.

Publications/Presentations:

Pang, C., Storch, A., Hunter, P. (2019). Ram Pump Final Report, Fall 2019. Retrieved from https://github.com/AguaClara/ram_pump/blob/master/Fall%202019/RamPump2019Fall.ipynb.

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Future Activities

Currently, the use of eyebolts to adjust springs has been a good short-term solution for the working prototype of the new spring system however the team has observed several issues with this design that they plan to resolve in the future. First, the two outer eyebolts need to be adjusted individually so it is difficult to ensure that they are at the same height. Second, the oscillation of the ram pump imparts high impacts on the structure and causes it to shake. The subsequent movement of the eyebolts allows the nuts holding them in place to loosen and they can easily move from their original position. To solve this problem, the team has been using two nuts in each required location but this makes adjustments more tedious and time consuming. Finally, a very small change in height of the eyebolts can make a significant difference in the pump flow rate. For these reasons, the team hopes to develop an adjustment system to replace the eyebolts that can translate a large rotation into a small translation (potentially using a gear system) that can adjust the outer springs together and the middle spring separately. This system must also be able to withstand the movement of the entire structure and remain in place. This system must be quick and easy to use and intuitive.

In the future, the team also plans to perform further testing to explore the relationship between different inner and outer spring forces and the performance of the pump. The team currently evaluates performance as the flow rate of water being pumped by the ACVRP. The results of these tests will inform the team for producing a protocol for choosing springs and adjusting them based on AguaClara plant parameters, specifically the hydraulic head available and the height the water needs to be pumped to. The team has seen generally improved results with the implementation of the new spring system but has not yet had the opportunity to quantitatively describe these improvements.

Keywords: Gravity-powered pump, hydraulic ram pump, AguaClara Vertical Ram Pump (ACVRP), drinking water treatment, plant plumbing; sustainable; green engineering; gravity; physics; accessible; economical; portable; zero waste; reuse

Executive Summary:

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Objective

AguaClara Cornell is a multidisciplinary engineering team based at Cornell University that develops sustainable water treatment technology. The AguaClara plant design is gravity-powered, electricity-free, and scalable to fit the needs and size of any community. A subteam of AguaClara Cornell is developing the AguaClara Vertical Ram Pump (ACVRP), and inline zero waste pump that utilizes the energy in flowing water to pump a portion of that water to a higher elevation. While a conventional ram pump wastes the water used for energy extraction, the ACVRP allows this water to continue to the plant's storage tank to then be distributed for use by the community. The ACVRP will be implemented in AguaClara plants to pump clean water up to storage tanks that hold water for the plant plumbing and diluted chemicals for chemical dosing of the water. Currently, the transportation of water up to the storage tanks is a burden placed on the plant operators. The team is currently working to improve the design of the ACVRP to increase efficiency and ease of use as well as perform experiments to gain a better understanding of the physics behind the ACVRP and how to make adjustments to improve performance.

Progress Summary/Accomplishments (Outputs/Outcomes)

Force Analysis and Ideal Spring Constant

Efficiency of the ACVRP is defined as the percentage of theoretical flow rate that is actually achieved. The theoretical flow rate is calculated based on dimensions and terminal velocity while the actual flow rate is measured experimentally. In order to optimize the efficiency of ACVRP, a range of ideal spring constants is needed to supply the optimal forces to open and close the valve of the pump as shown by the positions in figure 1, and therefore forces required to toggle the plate valve were calculated.

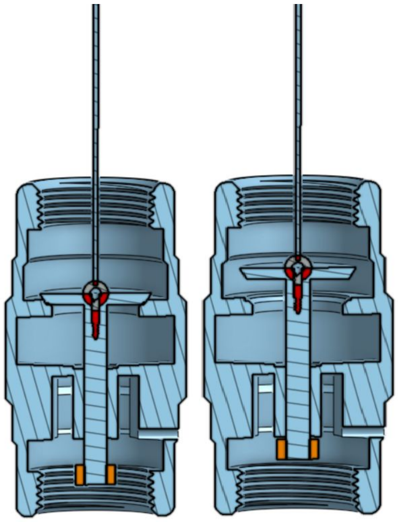

Figure 1: Plate open and plate closed position of valve, where the plate valve is connected to the spring system with a cable that goes through the eyebolt. The limit of plate opening is limited by a nut at the threaded end (as shown by the orange nut).

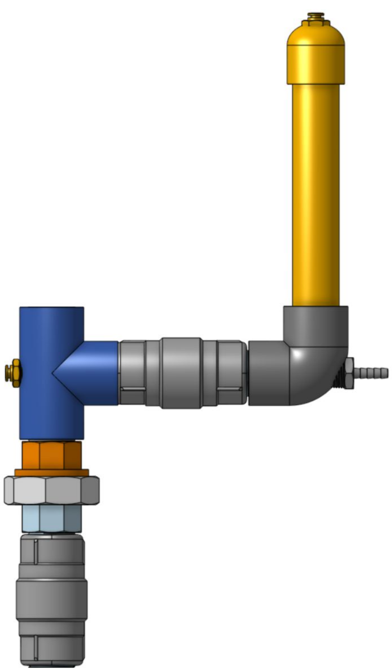

Figure 2: Overview of the ACVRP: The triple extension spring system is located in the head tank and is connected to the plate in the check valve (Figure 1) located at the bottom of the assembly shown here. The effluent of the ACVRP is located at the bottom of the air chamber (yellow).

The team developed a procedure for finding both of these forces. In order to find the maximum drag force on the plate, the team used a two pulley system connecting the plate valve with a bottle with water in it hanging from the pulley that extends out of the head tank. The amount of water in the bottle was adjusted until the plate was just opened. The weight of the bottle at this instant was equal to the force from the falling water in the drive pipe on the plate. In order to find the hydrostatic force, the height of the water column above the plate was found and the hydrostatic pressure from this height of water was calculated. This pressure was multiplied by the area of the plate to find the force acting on the plate.

Using the determined forces, a range of ideal spring constants were determined. Since Hooke's Law depends on the compression length, Δx, k' was defined as an intrinsic material property of the spring dependent on the actual length of the spring rather than its compression length, such that Hooke's Law could be written as:

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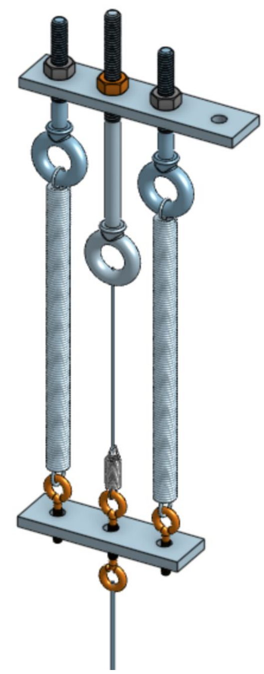
Even though the design of the system has changed since these experiments and calculations were performed, this work will inform the team in the future on how to find the desired forces for the new system. The same calculations would be applied for finding the intrinsic k constant for extension springs, and since separate springs are used for keeping the plate opened and closed, calculations should account for two spring constants and their respective changes in length.

Redesigning of System

Ease of Adjustment

The redesigned spring system addresses the issue of difficult readjustment of the ACVRP and implements a method that involves minimal deconstruction of the mechanism. The previous design required a check valve at the lower end of the system to be dismantled in order for the compression spring to be adjusted or replaced. This series of actions to make changes to the ACVRP is tedious and often difficult to perform in the conditions that the pump was installed and operates in. The main challenge that hindered adjustment of the pump was that while the mechanism was in operation most of the adjustable parts were submerged. The team created a design that allowed for instantaneous adjustment of the spring constants, while the system is in operation.

This new system involves three external extension springs instead of one internal compression spring. The three external springs are hooked onto three separate threaded eyebolts, which can be moved up or down to adjust the forces being applied on the plate within the lower check valve.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All three springs are attached to a bottom plate that serves to transmit this upward force through a metal wire rope, to the plate in the check valve as shown in figure 1. The eyebolts that the springs are connected to are secured by two nuts each to a stationary top plate that restricts the springs from falling into the drive pipe. The two outer springs on the design are longer springs with a low spring rate to apply a constant upward force while the plate is oscillating through its cycle. The current inner spring has a higher spring rate compared to the outer springs in the system to account for the increased pressure when the plate is “closed" in the check valve. It is attached to its eyebolt with a piece of metal wire that has slack in it when the plate is in the open position. As the plate closes, the wire is pulled, the middle spring extends and, thus, exerts an upward force on the plate. This allows the forces corresponding to the open and closed positions to be adjusted individually. This spring system is stationed above the flowing water and is easily accessible in order to raise or lower the effective force transmitted by the springs. Changing the force of the check valve plate is now easier to accomplish because of the greater accessibility to the force applying springs and the greater range of adjustment available.

The support structure of the new spring design also has an adjustable height component as a way to make the replacement of springs of various sizes easier. Because of this design the metal wire connected to the check valve plate does not need to be replaced when springs are changed in height, rather the support height can be changed to accompany the necessary spring length.

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Publications and Presentations

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Future Activities

In the future, the team plans to develop a more refined design for the spring system. While the general three spring design has proven to work well, the team would like to iterate on this design to create an adjustment mechanism to replace the eyebolts. The new mechanism should be able to make very fine adjustments to the heights of the springs, move the two outer springs together, and be both robust and easy to use.

The team also plans to continue experimenting with how different adjustments of the springs affect the efficiency of the ACVRP. Since the three spring design is a recent change, currently little is known about how best to adjust the springs for optimal performance. The goal is to be able to develop an adjustment procedure that the plant operators can follow to ensure they are getting the maximum flow rate from their ACVRP.

Keywords: Gravity-powered pump, hydraulic ram pump, AguaClara Vertical Ram Pump (ACVRP), drinking water treatment, plant plumbing; sustainable; green engineering; gravity; physics; accessible; economical; portable; zero waste; reuse