Stock Tank Team Research Report

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Part I

Introduction

The Stock Tank Mixing team has been charged with the tasks of purchasing and testing a hydrometer suitable for usage with typical AguaClara stock solution concentrations and designing and fabricating a centrifugal pump (or inventing an alternate method to mix chemical solutions) to uniformly mix the coagulant and chlorine solutions. The hydrometer must be durable and essentially unbreakable (e.g. not glass) to ensure longevity under daily work conditions/non-lab environments. The pump will be a new addition to the AguaClara plant; at present, operators mix the stock tank with a long PVC pipe but have no way of ensuring uniformly dense solution. A uniformly mixed stock solution is instrumental in the success of flocculation and thus the creation of safe drinking water. The combination of a pump to create a homogeneous solution and the hydrometer to confirm solution density will aid the formation of flocs in raw water and improve plant efficiency.

Part II

Literature Review

1 Hydrometer

Currently, AguaClara plant operators have no way of ensuring stock solutions are of uniform concentration. Hydrometers are used to measure the specific gravity of a solution; in the AguaClara model, they can be utilized by plant operators to determine the concentration of stock solutions and verify that the solution at the top of the tank has the expected concentration. Specific gravity is the ratio between the density of a liquid and the density of water, shown in Equation 1 and is the typical scale utilized on hydrometers. Once a relationship between chemical density and concentration is established, the plant operator would be able to extrapolate solution concentration from the hydrometer reading.

$$SG = \frac{\rho_{Liquid}}{\rho_{H_2O}} \tag{1}$$

The Coagulant Management team (`https://confluence.cornell.edu/download/attachments/190483226/Final_Report_Coagulant_Management_Spring2013.pdf?version=1&modificationDate=1368689721000`) measured PACl density as a function of concentration and determined that the required hydrometer should be able to read between 1,000 and 1,200 g/L. Their results are presented in Figure 1. Their data demonstrated a linear relationship, shown in Equation 2.

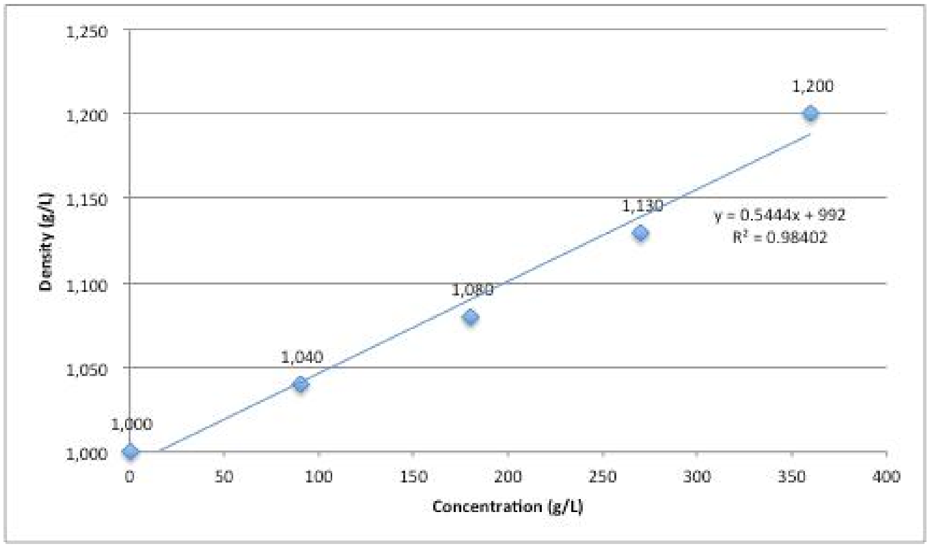


Figure 1: Measured PACl Density vs. Concentration

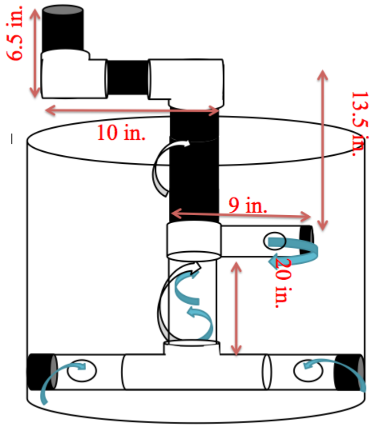
$$\rho_{PACl} = 0.5444 C_{PACl} + \rho_{H_2O} \tag{2}$$

Additionally, it had been determined that a polycarbonate hydrometer will be ideal for usage in the field, as it is unlikely to shatter and poses a low safety risk.

2 Centrifugal Pump

Past teams began the fabrication of a centrifugal pump, which uses the creation of a pressure gradient through rotation to bring the more dense solution located at the bottom of the container to the top. The Coagulant Management team began fabrication of a full-size pump but was unable to test its effectiveness.

A large design obstacle was the need to stabilize the pump; the Coagulant Management team recommended the usage of a bronze flanged bushing, but a design decreasing the usage of metal is preferred due to the fact that the pump will be constantly exposed to water and various chemicals. An illustration and photograph of their pump is depicted in Figures 2 and 3.



Design is not to scale.

Figure 2: Coagulant Management Team Pump Schematic

Figure 3: Coagulant Management Team Fabricated Pump

Part III

Methods

3 Hydrometer

3.1 Hydrometer Purchase

3.1.1 PACl Hydrometer

Given that the typical range of PACl concentration in an AguaClara plant is between 100-200 g/L, the hydrometer required would need to be able to read densities between 1,000 and 1,200 g/L. Based upon industry convention, the most appropriate hydrometer to purchase reads specific gravity between 1.000 and 1.220. There were many polycarbonate hydrometers available within the specified specific gravity range, with prices ranging from approximately \$60-\$100. Based upon the Coagulant Management team's recommendation and product availability, the Krackeler Scientific model was purchased for \$74.

3.1.2 Chlorine Hydrometer

Typical chlorine solution concentrations utilized in AguaClara plants were employed to determine the required hydrometer specific gravity range. Assuming 6 lbs of calcium hypochlorite ($Ca(ClO)_2$) are used in 55 gallons of chlorine solution (metric equivalents of 2.72 kg $Ca(ClO)_2$ and 208 L of solution) and utilizing the property that the density of calcium hypochlorite is 2.35 $\frac{g}{cm^3}$, total mass of water and chemical was calculated to be 210.56 kg. Therefore, solution density was calculated to be $\frac{Mass_{Soln}}{Volume_{Soln}} = \frac{210.56kg}{208L} = 1.012\frac{kg}{L}$. However, considering that when chemicals dissolve they occupy less volume in the water matrix, the density of the resulting solution is likely to be slightly higher than this estimate. Assuming the calcium hypochlorite occupies no volume in the solution, a “maximum” density can be projected to be $\frac{Mass_{Soln}}{Volume_{Soln}} = \frac{210.56kg}{207.88L} = 1.013\frac{kg}{L}$. The resulting density range for AguaClara chlorine solutions would require a hydrometer with a smaller range than the Krackeler Scientific model purchased for PACl in order to achieve low error margins; polycarbonate hydrometers with the desired small range are currently unavailable commercially. A glass hydrometer from Cole Parmer with a 1.000-1.050 SG range and 0.0005 divisions was purchased for \$33.50 to perform initial tests on hydrometer effectiveness in measuring chlorine solution density.

3.2 PACl Density vs. Concentration Relationship

The purchased Krackeler Scientific hydrometer was tested with PACl solutions whose concentrations varied from 50-200 g/L to extend the relationship between density and concentration. Concentration was determined by utilizing a known mass of PACl and adding water until total volume reached 1,000 mL. This measurement was made in 1,000 mL volumetric flasks using an electronic balance to decrease measurement error. After the solution was fully mixed, the solution was poured into a wide mouth container and the density was measured using the hydrometer. Results are given below, in Figure 4.

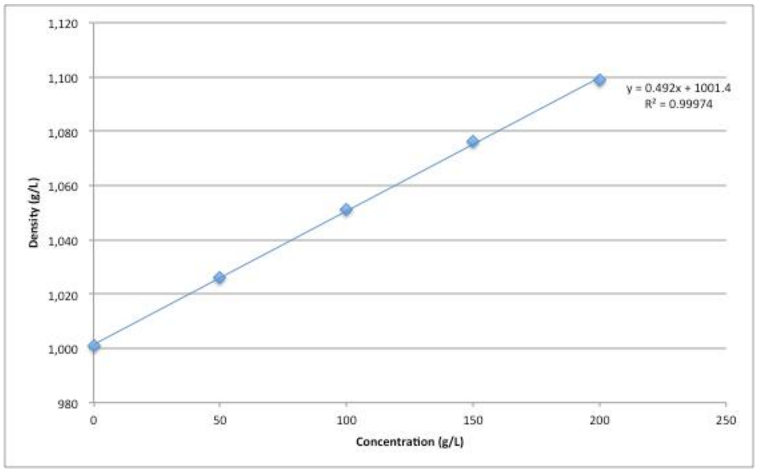


Figure 4: PACl Density vs. Concentration - Experimental Results

3.3 Sugar Density vs. Concentration Relationship

Since preliminary centrifugal pump tests utilize sugar solution in lieu of PACl to decrease environmental impact and cost, the sugar density and concentration relationship was tested. 0, 50, 100, and 150 g/L solutions were tested following the same procedure detailed with the PACl tests. Results are reported in Figure 5.

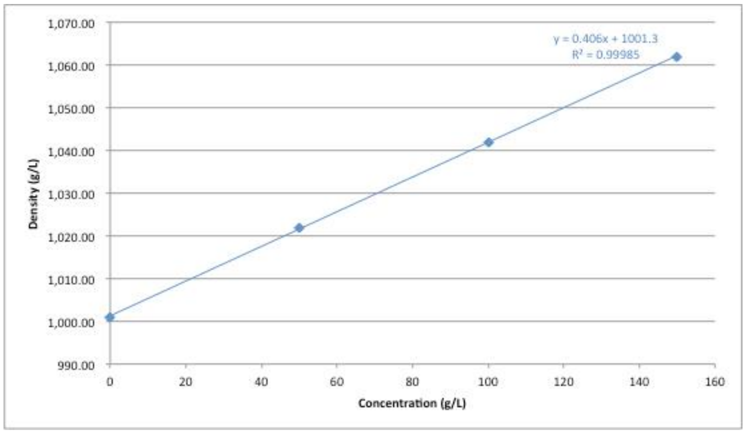


Figure 5: Sugar Density vs. Concentration

4 Centrifugal Pump

4.1 Pump Fabrication

Using the general schematic and design elements of the pump created by the Coagulant Management team, a smaller "test-size" pump was fabricated using 1" PVC pipe to fine tune design and better examine solution mixing. The rotating arm is 11.5 cm long and 20 cm above the base. The arm dimension is based upon the maximum size allowable in the test tank and the vertical location places the arm just below water surface level. An important design addition is the usage of a 1/2" PVC plate that secures the pump at the bottom of the container instead of the recommended brass joint. The exclusion of metal allows this new design to be utilized for more corrosive solutions, namely chlorine. The plate provides increased stability and its weight holds the pump upright. The tee fitting at the bottom of the pump is screwed to the plate to keep the pump centered, and the adjoining pipe has been designed to slip around the stationary tee fitting. The PVC plate with the pump connected is shown in Figure 6.

Another feature added to the pump design is a stabilizing board at the top of the stock tank. Since a major concern is the pump stability during horizontal rotation, this feature has been included to ensure the pump remains centered and upright. The board has three holes: one on each end to allow attachment to the tank with clamps and another in the center for the pump. A close-up of this design is shown in Figure 6.

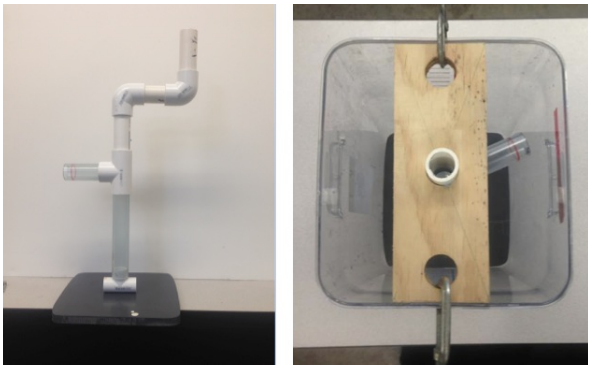


Figure 6: Pump Stabilizing Design Additions - Left: PVC Stabilizing Plate, Right: Wood Stabilizer (Handle Removed)

4.2 Lift vs. Pump Speed Testing and Uniform Mixing

4.2.1 Open Pipe Arm

Finding a relationship between solution lift in the central tube of the pump and pump speed was a first step in assessing if this design can be scaled up to full-size given the limitation of human power input to rotate the pump. The theoretical relationship between lift and pump speed was established utilizing Equations 3 and 4, where ρ is density, V is pump linear velocity at the tip of the rotating arm, ω is pump angular velocity, g is the gravitational constant, h is lift height, and r is rotation radius (which in this case is 11.5 cm). These equations relate pressure differential and potential energy and the final relationship is shown in Equation 5.

Equation 3 shows the relationship of potential energy to the linear velocity of the pump tip, utilizing lift and concentration changes.

$$\rho_{ConcSoln} V^2 = 2g\Delta h \Delta \rho \tag{3}$$

The velocity of the tip of the rotating arm is obtained from the angular velocity and the circumferance of the circle, shown in Equation 4.

$$V = \omega(2\pi r) \tag{4}$$

The direct relationship between pump angular velocity and lift is shown in Equation 5.

$$\omega = \frac{1}{2\pi r}\sqrt{\frac{2gh\left(\rho_{ConcSoln} - \rho_{Water}\right)}{\rho_{ConcSoln}}} \tag{5}$$

Tests to measure lift of the centrifugal pump were conducted with high density sugar solutions. Red Dye #40 was added to allow visual differentiation between the sugar solution and water. A stratified solution was created by making a dense sugar solution and placing it in a container with an outlet tube fixture. This container was placed at an elevation where the free surface was higher than the free surface of the test tank and the outlet tube was placed at the bottom of the test tank. The tank was filled until the dense solution just covered the pump inlet. This setup is shown in Figure 7.

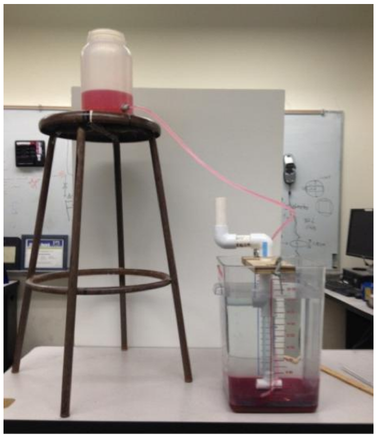


Figure 7: Stratified Solution Setup

Once the inlet to the pump was fully covered, solution lift in the central pipe was measured versus operating rpm. The pump was rotated by hand and the angular velocity was regulated by listening to a metronome. A comparison of results from tests run with 455 g/L (1.185 SG), 590 g/L (1.240 SG), and 860 g/L (1.350 SG) sugar solution is shown in Figure 8.

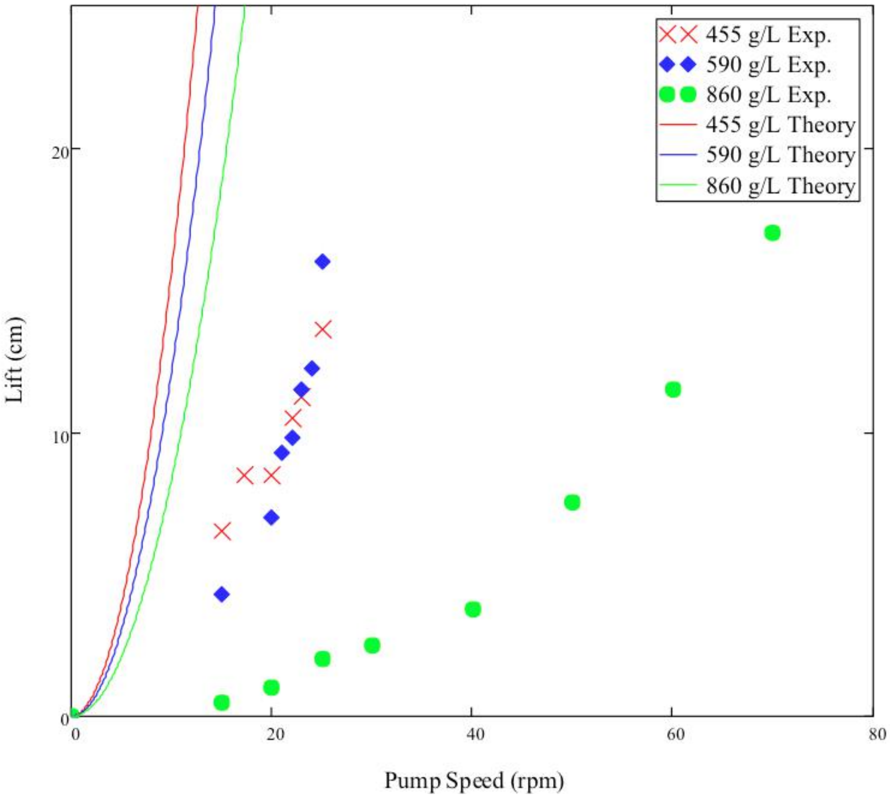


Figure 8: Lift vs. Pump Speed Findings - 455 (1.185 SG), 590 (1.240 SG) and 860 (1.350 SG) g/L sugar solution comparison.

The 860 g/L test was also utilized to identify pump success in creating a uniform solution. The stratified solution was pumped for three minutes at 90 rpm, after which an initial density reading was taken. Additional density readings were taken 5, 10, and 15 minutes after pumping was completed, with results shown in Figure 9.

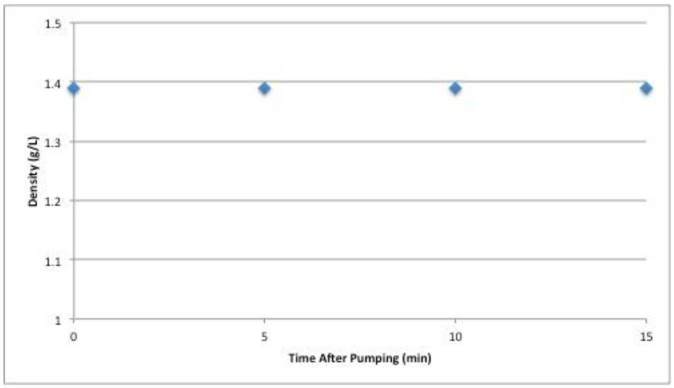


Figure 9: Density vs. Time After Pumping

4.2.2 Trailing Elbow on Arm

A possible reason for the great discrepancy between experimental results and theoretical prediction in the open arm pump could be flow in and out of the tip under conditions of no net flow. The pump was refitted to include a trailing elbow on the end of the arm so fluid being pumped would be released into a low pressure zone, thus decreasing the likelihood of interference. The adjusted arm design is depicted in Figure 10.

Figure 10: Pump with Elbow on Arm

The lift vs. pump speed relationship was tested following the same procedure as the open end arm test with sugar solutions at 455 g/L (1.185 SG), 590 g/L (1.240 SG), and 680 g/L concentration (1.277 SG). The results from these tests are depicted in Figure 11. After evaluating the results, the trailing elbow setup was found to be less efficient than the initial open arm setup.

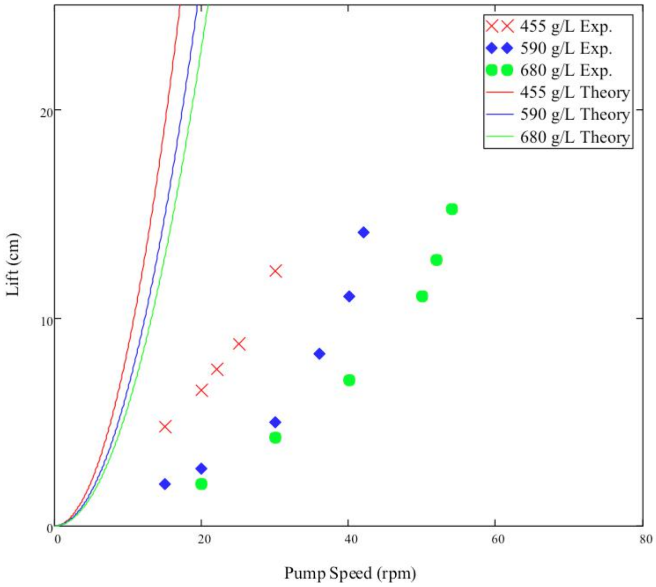


Figure 11: Lift vs. Pump Speed Findings - Trailing Elbow on Arm

4.2.3 Error Troubleshooting and Baffle Trials

Possible sources of the discrepancy between theory and the measured values were then explored. Leakage through the rotating tee, fluid rotation in the tank, and leakage through the arm joint were identified as possible problems. These issues were rectified by increasing the volume of concentrated solution put into the stratified solution so it completely covered the entire tee and the rotating joint at the bottom of the pump, performing tests with a baffle, and gluing all joints to eliminate any leaks. A baffle was fabricated to sit beside the pump without interfering with the arm (pictured in Figure 12). The baffle was designed to reduce overall fluid rotation in the tank. Results of tests run utilizing 335 g/L (1.137 SG) and 650 g/L (1.264 SG) concentrated sugar solutions with and without the baffle are shown in Figure 13.

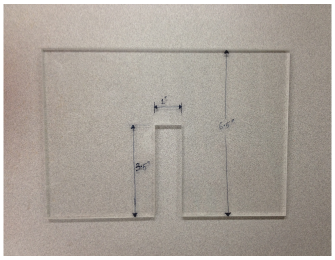


Figure 12: Baffle for Test Tank

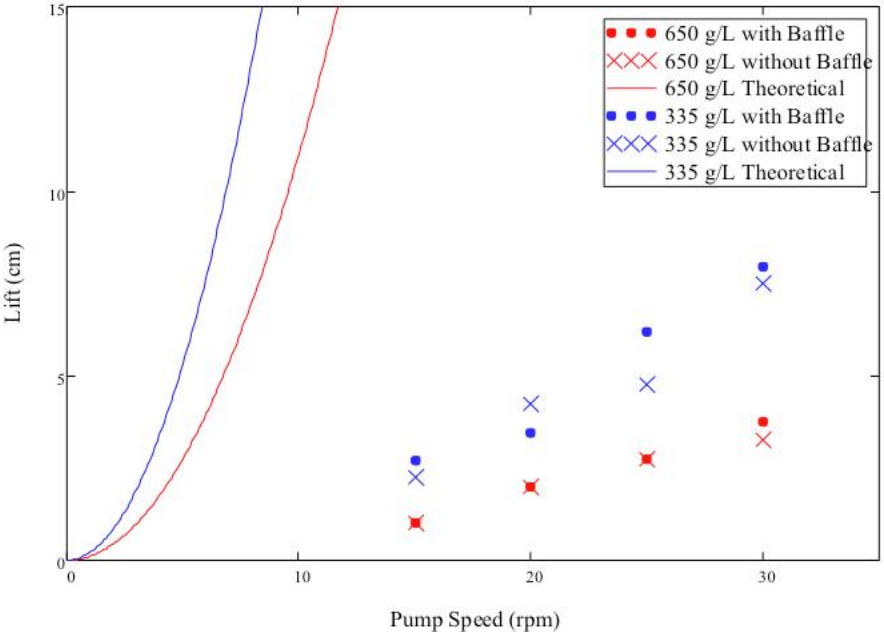


Figure 13: Lift vs. Pump Speed Findings - Baffle Tests

The 650 g/L trial showed almost no difference in performance between tests with and without the baffle, indicating that fluid rotation is likely not the source of error for a very dense solution. The 335 g/L trial had some disparity between baffle and baffleless tests, but the difference still does not explain the primary source of error; however, it can be inferred that fluid rotation due to pumping affects lower density solutions more than higher density solutions. Additionally, these tests show that it is likely that a baffle would not be necessary in a full scale model with this current general pump setup.

To further troubleshoot the theoretical curve, pressure differential between the tip of the pump arm and the core of the pump at arm elevation was calculated using Equation 6, where h represents fluid lift and $\Delta\rho$ represents change in density between the concentrated sugar solution and water. The pressure differential for all tests performed at the same pump speed should be the same and results are depicted in Figure 14.

$$\Delta P = h_{lift}\Delta\rho \tag{6}$$

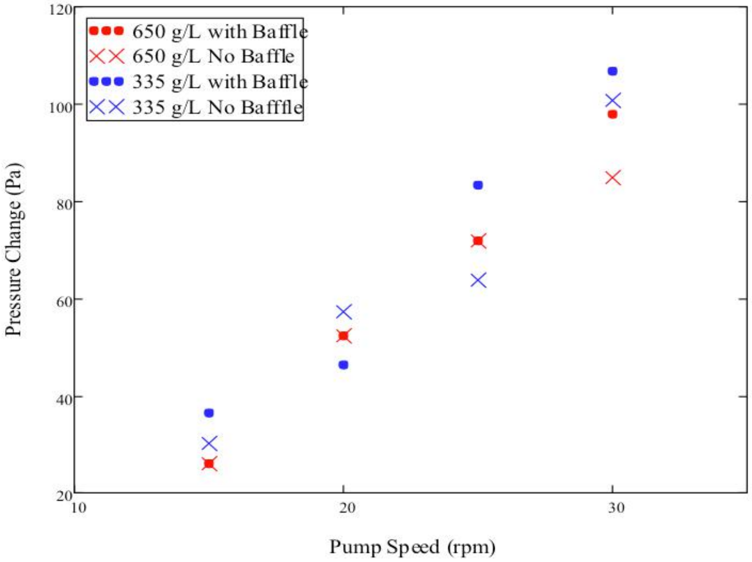


Figure 14: Suction generated by the rotating pump as a function of rotational speed. The results converge for the different solution densities.

As made evident by Figure 14, experimental findings were self consistent. Figure 15 displays lift versus pump speed findings with theoretical expectations at 4% efficiency, suggesting that the pump operates at incredibly low efficiency.

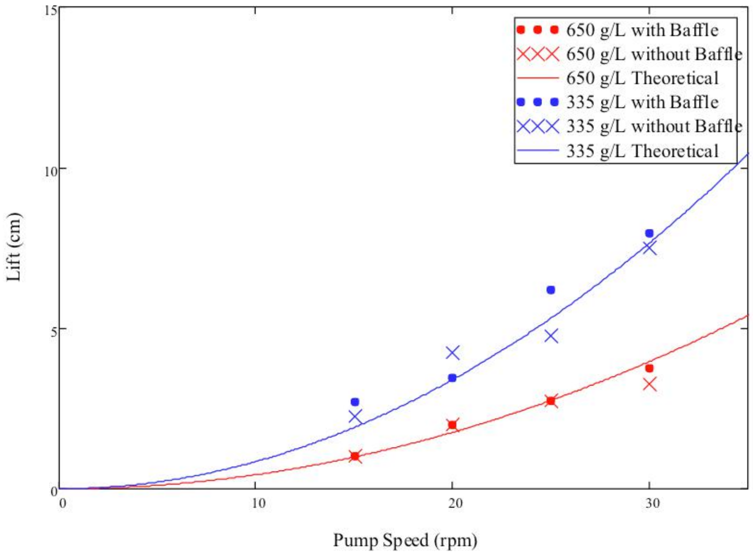


Figure 15: Lift vs. Pump Speed Findings with 4% Theoretical Curve

4.2.4 Straw Fixtures in Arm

To continue to determine the source of high inefficiency, further tests were performed with 9 0.5 cm diameter straws filling the pipe arm; this design addition is meant to greatly decrease flow circulation in and out of the pump arm tip and improves the arm length-diameter ratio. Results from a trial utilizing 605 g/L (1.247 SG) sugar solution are depicted in Figure 16.

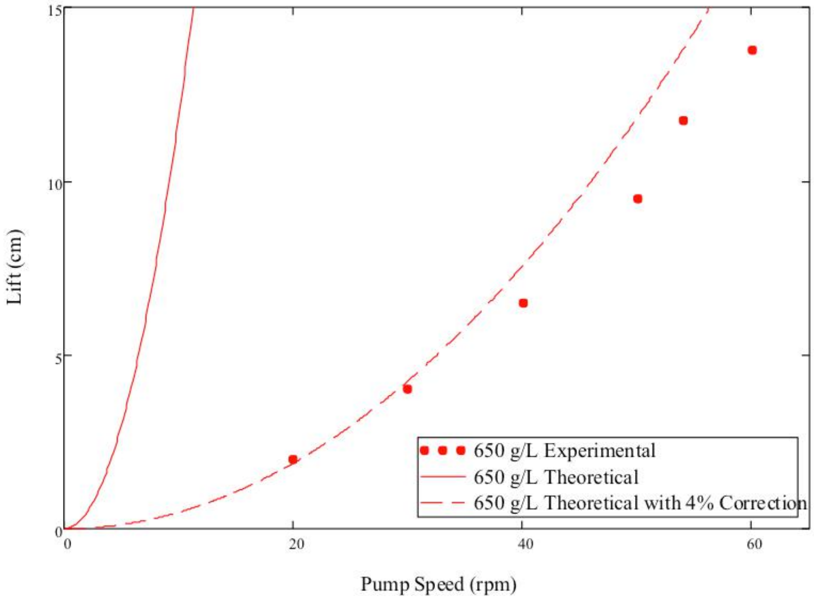


Figure 16: Straw-Filled Arm Test with 605 g/L (1.247 SG) Sugar Solution

The increased L/D ratio proved to not be the source of inefficiency, as the 4% efficiency correction matched the experimental results. The centrifugal pump also became less efficient as the rotation speed increased. This drop in efficiency may be due to increased rotation of the fluid in the tank. This would also explain the inability of this pump setup to actually discharge dense solution from the end of the arm.

4.3 Flow and Torque Power Requirements

Building upon the idea of testing dense solution lift versus pump speed, calculating total power required to move the pump due to flow and drag on the arm is essential in determining the feasibility of the given pump design at the full scale. Equations 7, 8 and 9 detail the calculations and assumptions required to determine flow through the arm, summarized in Equation 10. All relevant dimensions are depicted in Figure 17. The minor loss coefficient was set at K=3.5 and takes into account loss during fluid directional change. Note that

HL is head loss, ρ is fluid density, D is pipe diameter, A is pump tip area (the area over which fluid can flow out of the tip), V is pump tip velocity, g is the gravitational constant, and η is pump efficiency.

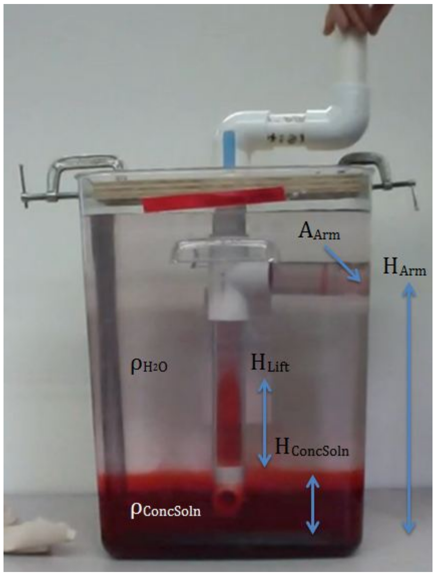


Figure 17: Head Loss Dimensions

$$H_{Lift} = \frac{\rho_{ConcSoln}}{\rho_{ConcSoln} - \rho_{H_2O}} \frac{(2\pi r\omega)^2}{2g}\eta \tag{7}$$

$$HL_{Lift}\rho_{ConcSoln} = HL_{ConcSoln}\Delta\rho \Rightarrow HL_{Lift} = \frac{H_{Lift} - (H_{Arm} - H_{ConcSoln})}{\frac{\rho_{ConcSoln}}{\rho_{ConcSoln} - \rho_{H_2O}}} \tag{8}$$

$$A_{Arm} = \pi r^2 = \pi \frac{D_{Arm}^2}{4} \tag{9}$$

$$Q_{Tip} = VA = \sqrt{\frac{HL_{Lift} \cdot 2 \cdot g}{K_e}} A_{Arm} \tag{10}$$

Once the flow through the tip of the arm was determined, total head loss through the pump was calculated (Equation 11) and converted into input power requirement (Equation 12). Note that ω is the pump angular velocity, L is the length of the pump arm, and that pump efficiency (4%) has already been considered through the lift height.

$$HL_{Pump} = \frac{V^2}{2g} = \frac{(2\pi\omega L_{Arm})^2}{2g} \tag{11}$$

$$Power_{Flow} = \rho_{ConcSoln} \cdot g \cdot Q_{Tip} \cdot HL_{Pump} \tag{12}$$

Drag on the rotating arm is also part of calculating total power requirement; Equation 13 details the calculation of torque, where one half of the drag coefficient (C_d) is multiplied by the final solution concentration, linear velocity of the pump squared ($2\pi r\omega$, where r represents arm length), differential area (drD_{Arm}, where D_{Arm} represents outer diameter) and arm length. Note that the drag coefficient was set at 1.2 in all numerical calculations. The torque equation (Equation 13) is then integrated over the length of the arm to give total torque due to the arm; this integration is summarized in Equation 14.

$$T = \frac{1}{2} C_d \rho_{Final} (2\pi r\omega)^2 (drD_{Arm}) * r \tag{13}$$

$$T = 2C_d \rho_{Final} \pi^2 \omega^2 D_{Arm} \int_0^{L_{Arm}} r^3 dr = \frac{2}{4} C_d \rho_{Final} \pi^2 \omega^2 D_{Arm} L_{Arm}^4 \tag{14}$$

Equation 15 shows the summarized relationship of power lost due to drag.

$$Power_{Drag} = T \cdot \omega = \frac{1}{2} C_d \rho_{Final} D_{Arm} \pi^2 \omega^3 L_{Arm}^4 \tag{15}$$

Given these theoretical conclusions, total required power can be calculated by summing power requirements from the flow and drag components. Analysis was done comparing different pipe sizes available in Honduras for pump power versus pump speed in the full size 750 L tank to be used in San Nicolas. The comparison is shown in Figure 18.

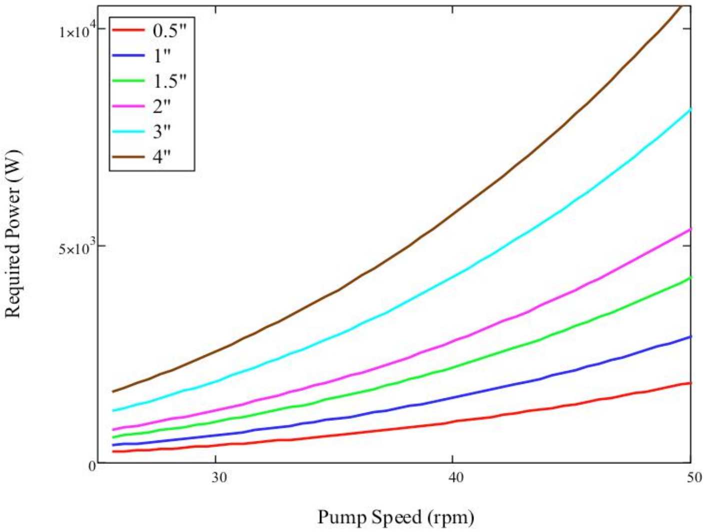


Figure 18: Theoretical Required Power vs. Pump Speed for Varying Pipe Sizes

Total power required for a 1.5" pipe size is shown in Figure 19, visualizing how power lost to drag is the dominating factor. The high total power value is due to the low pump efficiency which causes high required pump speed. Until the source of the low efficiency can be identified, the only design constraint that can be controlled to decrease required power is the drag coefficient. A streamlined body has a drag coefficient of 0.04, the lowest coefficient possible for the pipe arm. Utilizing the coefficient of 0.04, a 1.5" pipe pump with 75 W of input (considered to be maximum human power) could be run at approximately 27.5 rpm and completely mix the 750 L of solution in the tank in about 15 minutes.

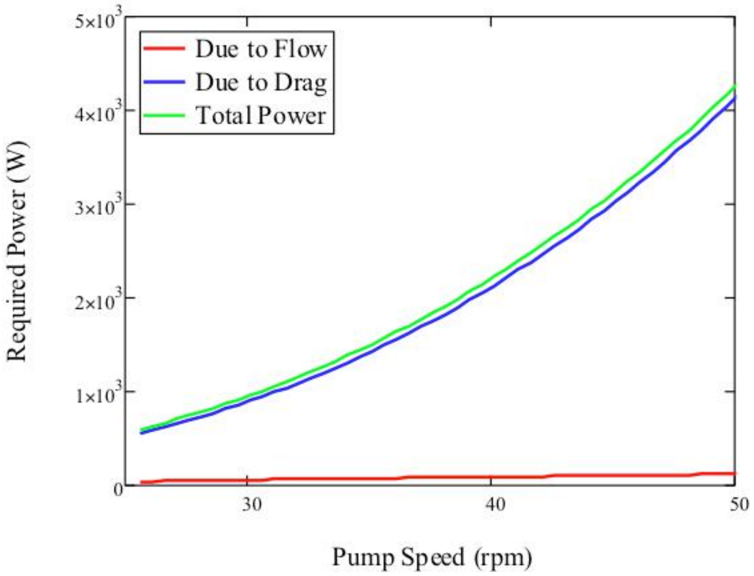


Figure 19: Required Power Breakdown for 1.5" Pipe Size

Part IV

Analysis and Conclusions

5 Hydrometer

5.1 Hydrometer Purchase for PACl and Chlorine

The purchased Krackeler Scientific hydrometer has been utilized in all density vs. concentration tests, as well as pump tests, and it has consistently read the same densities as previously purchased glass hydrometers. Given that all PACl solutions that will be created in Honduras are within range and that the polycarbonate is durable, there are no restrictions that would keep it from usage in actual plants and its addition to the treatment process will undoubtedly positively influence plant efficiency.

The glass Cole Parmer hydrometer for chlorine solutions currently fulfills the initial goal of obtaining a tool to properly analyze solution uniformity. Further research or special requests should be made to obtain a more durable hydrometer in the future. Other possible solutions include fabricating a polycarbonate hydrometer specific for the AguaClara chlorine solutions if no commercial alternatives are viable or utilizing a different type of measurement device.

5.2 PACl Density vs. Concentration Relationship

The governing equation for density and concentration, given from results, is displayed in Equation 16. From the graph of results (Figure 16), all data points were very closely linearly related with an R^2 of 0.999. With this relationship, plant operators should be able to easily and successfully extrapolate solution concentration from hydrometer density readings. Figure 20 shows PACl concentration based upon hydrometer readings (density); this graphic will be a helpful reference for plant operators.

$$\rho_{PACl} = 0.492C_{PACl} + \rho_{H_2O} \qquad (16)$$

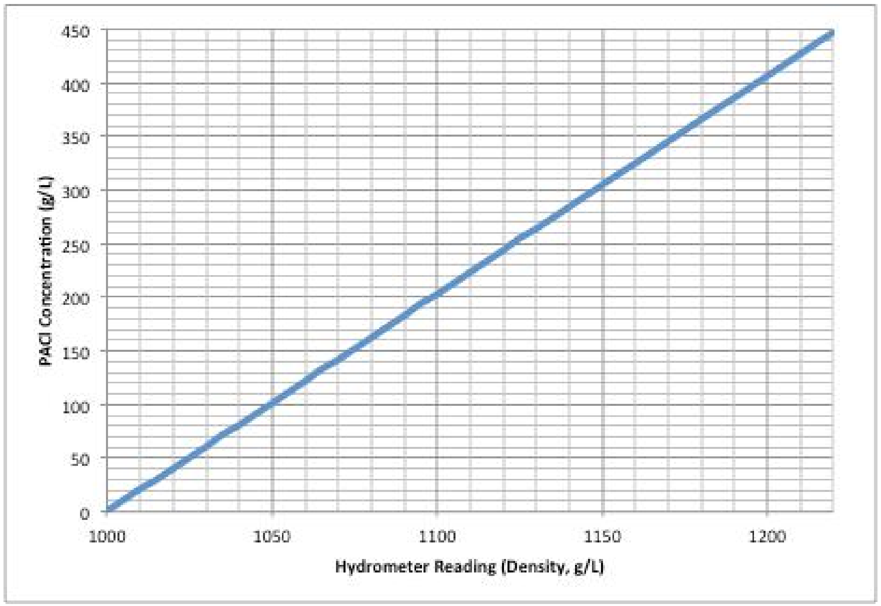


Figure 20: PACl Concentration vs. Hydrometer Readings Reference Graph

5.3 Sugar Density vs. Concentration Relationship

The found governing equation for sugar density and concentration is given in Equation 17. The nearly perfectly linear data (shown in Figure 5) produces a solid relationship between sugar density and concentration and confirms the testing procedure utilized in PACl tests.

$$\rho_{Sugar} = 0.406C_{Sugar} + \rho_{H_2O} \tag{17}$$

6 Centrifugal Pump

6.1 Pump Fabrication

Based upon experience using the small-scale pump in testing, it has been determined that the above-mentioned design additions are sufficient to secure the pump and are simple enough to be easily constructed in Honduras. If this general design is carried through to the full-scale model, it is suggested that the PVC plate be welded to the bottom of the tank to ensure no highly concentrated solution gets trapped beneath the plate. Additionally, a 1" PVC plate is suggested in full-scale models to account for increased tank size.

6.2 Lift vs. Power Testing and Uniform Mixing

The pump successfully mixed all stratified solutions, but the low efficiency presents difficulties for scaling this technology for use in water treatment plants. Given the great discrepancy between theory and laboratory measurements for open pipe arm tests, there is clearly a factor for which the theoretical calculations did not account. Testing with a trailing elbow at the end of the arm showed even lower efficiency than the open arm setup. Filling the rotating arm with straws to reduce circulation did not change the efficiency and proved that the low L/D ratio was not the source of inefficiency. All other error factors considered were addressed in pump setup (gluing possible leaky joints and adding a baffle to reduce fluid circulation) and retested; findings show there is likely another component that has not been accounted for because the 4% efficiency did not change significantly.

The most likely source of inefficiency is that the rotating arm has significant drag and the drag on that arm sets up a strong circulatory motion in the fluid at the top of the tank. This rotating fluid causes a direct decrease in efficiency. If the fluid at the top of the tank rotates at the same speed as the rotating arm, then the ability of the centrifugal pump to lift dense fluid will decrease to zero. The baffle designed may not have helped enough because it only stopped fluid rotation in the bottom of the tank where fluid rotation was not significant. The fluid rotation at the top of the tank at the elevation of the rotating arm was unaffected by the baffle.

Listed below are potential options for pump redesign and adjustment:

1. Design an enclosed centrifugal pump to eliminate rotation of the fluid in the tank.
2. Invert the pump and place the rotating element at the bottom of the tank. Use baffles above the rotating element to reduce fluid rotation in the tank. Pump low density solution into the bottom of the tank.
3. Reduce the drag on the rotating element to improve efficiency.
4. Use a rotating curved blade to either impart a vertical velocity or a radial velocity to the dense solution at the bottom of the tank.
5. Inject the water that is being used to fill up the stock tank into the bottom of the tank so it can mix through the dense solution. This could be an optimal design for alum, as the solid chemical settles at the bottom of the stock tank.

6.3 Flow and Torque Power Requirements

Total power requirements based on theoretical calculation were shown to be highly influenced by pump efficiency, and thus pump speed. If the pump efficiency can be improved, pump speed could be greatly reduced and appropriate pipe size can be quantitatively selected. With the current setup, a 1.5" pipe diameter could be utilized if the drag coefficient were drastically reduced. Regardless of efficiency improvement based on design changes, the pump arm should be adjusted to include a geometry with a lower drag coefficient than the current value of 1.2.

It is also important to consider how much of the shaft power would be utilized in pumping the fluid and how much would go into overcoming drag on the rotating arm. Understanding how energy is being utilized in the system even under idealized conditions would indicate if the rotating centrifugal pump idea is worth pursuing. The energy that is spent on drag is not only wasted input, but it also sets up fluid rotation that reduces the pumping action. Therefore, if the power that is wasted on overcoming drag is significant, there is no chance of creating an efficient rotating arm centrifugal pump.

Part V

Future Work

7 Hydrometer

With the consistent results found for PACl density and concentration and the proven proper functioning of the Krackeler Scientific hydrometer in multiple tests, the experimental density and concentration relationship (Equation 16) and purchased PACl hydrometer should be sent to Honduras for actual usage.

However, if any plants decide to use a different type of coagulant or chemical in the future, further testing and additional research to find an appropriate hydrometer (if the purchased model is not in range) is recommended. Additionally, if an appropriate hydrometer for chlorine cannot be procured, then chlorine concentrations will need to be measured using an alternate approach.

8 Centrifugal Pump

All tests indicated the very low efficiency of 4% for the current pump setup, essentially deeming the design unscalable for full-size usage. Future work should include identifying the source of this inefficiency, regardless of if this general design is still pursued. Ideally, this design should be adjusted to greatly reduce the power lost to drag. However, if the efficiency issue cannot be resolved, other designs including reversing the flow of water and using rotating blades or baffles should be explored.