Stock Tank Mixing Team Research Report

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Part I

Introduction

The Stock Tank Mixing team has been charged with the task of designing and fabricating a tool to effectively and efficiently mix stock solutions of coagulant and chlorine. Currently, operators in AguaClara plants utilize a long PVC pipe to mix stock solutions to achieve chemical dissolution, but this method is inefficient and limits the ability of operators to mix large stock tanks. Uniformly mixed stock solutions are required for flocculation and disinfection; this fact is the driving force for creating a mixer to aid the formation of flocs in raw water and improve plant efficiency.

Part II

Literature Review

The Fall 2013 Stock Tank Mixing team (Final Report) designed and tested a small-scale centrifugal pump meant to lift dense solution located at the bottom of a tank to the top utilizing the properties of the fluid pressure gradient. Figure 1 shows the pump inside and outside of the tank. This design attempted to utilize rotational motion to achieve vertical mixing of a stratified solution; while the concept of the pump was sound, experimental results showed high inefficiencies and large discrepancies between conceptual ability and actual outcome.

At best, the pump achieved 4% efficiency; in all tests, actual results were 4% of theoretical and presumed lift values for respective input rotational speeds. Results for tests utilizing different solution densities and comparing theoretical lift to actual lift are depicted in Figure 2. Multiple arm geometries were tested to attempt to explain theoretical and experimental discrepancies but no troubleshooting adjustments produced significant improvements. The major error factor was determined to be drag on the pump's rotating arm fixture, which set up strong circulatory motion in the fluid at the top of the tank. This circulation essentially equated to wasted work input; considering design adjustments, it was noted that any centrifugal pump design would include this rotation. New designs to achieve complete stock solution mixing should take this factor into account; strictly vertical mixing systems provide a plausible alternative to reduce energy lost to circulation.

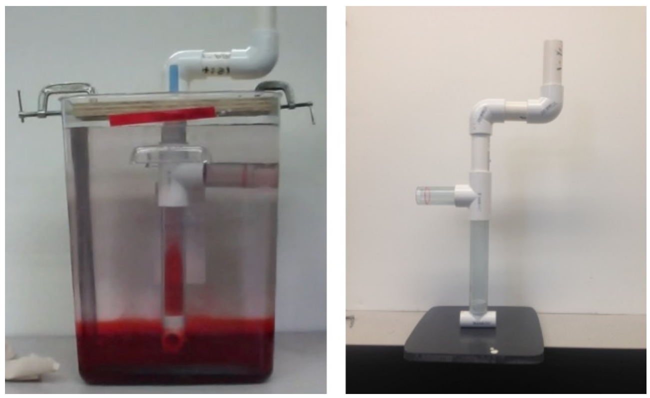


Figure 1: Fall 2013 Small-Scale Centrifugal Pump Inside Tank (Left) and Outside Tank (Right)

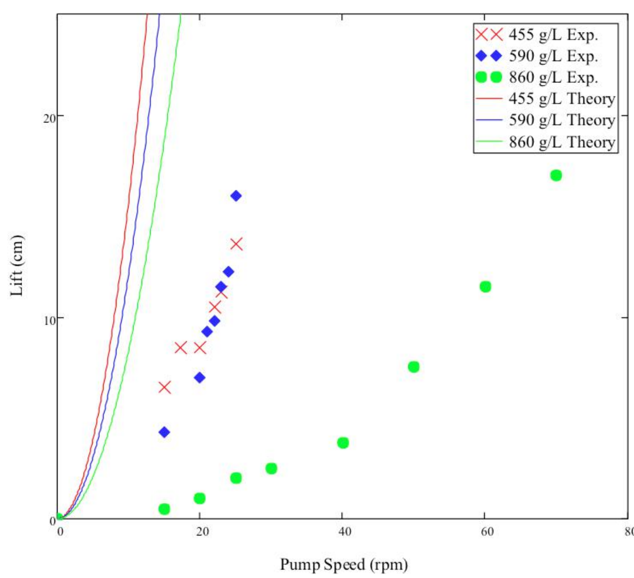


Figure 2: Lift vs. Pump Speed for Fall 2013 Pump

Part III
Methods

1 Vertical Mixer

Building off the conclusion that the rotational pump model would always be inefficient due to fluid circulation, the concept of creating a device that would move up and down through the tank was identified as a better alternative because the motion of the device would be in the same direction as the desired solution mixing.

1.1 Fabrication

Two designs for vertical mixing were fabricated to determine if a vertical mixing device would be effective and which of the two designs would be the most efficient. The first concept utilized a shallow bucket with small holes in the bottom attached to a long handle that would move vertically in the tank and rest with its base just above the fluid free surface between pump cycles to deposit dense solution from the bottom of the tank to the top of the tank. The second concept utilized a thin PVC plate attached to a long handle that would move vertically within fluid and create turbulence and jets to prompt mixing.

1.1.1 Bucket

Dimensions of the bucket were made based upon proportion assumptions in the actual AguaClara stock tank. The Spring 2013 team had assumed the height of the dense solution would be approximately 33% of the height of the total fluid; subsequently, the height of the bucket was chosen to be around 40-50% of the dense solution height. Additionally, due to tank restrictions at the full scale, it was determined that the base area of the bucket would be 25% of the plan view area of the tank.

Actually constructed bucket dimensions are as follows:

- Base Area: $0.011\, m^2$ (circular)
- Bucket Height: $4\, cm$
- Hole Diameter: $0.4\, cm$
- Number of Holes: 16

The holes were evenly spaced throughout the base and a PVC pipe handle was affixed to the center of the bucket for operation. The final product is shown in Figure 3.

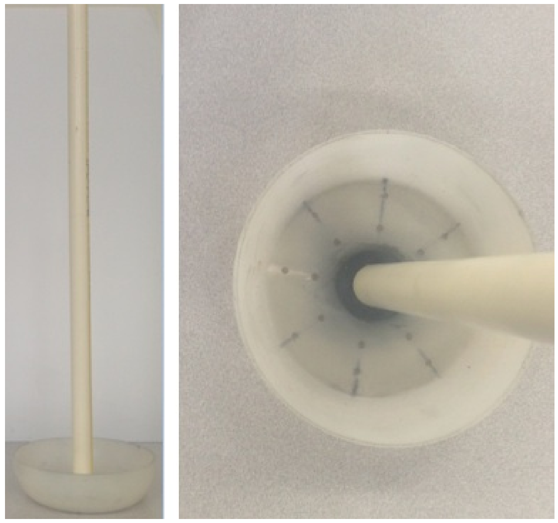


Figure 3: Bucket Mixing Device

1.1.2 Plate

Similar to the bucket design, the plate size was chosen to be 25% of the tank projected area because of full size restrictions. A 0.011 m^2, 0.5" PVC circular plate was cut with a hole in the center for the handle. The final plate mixer is shown in Figure 4.

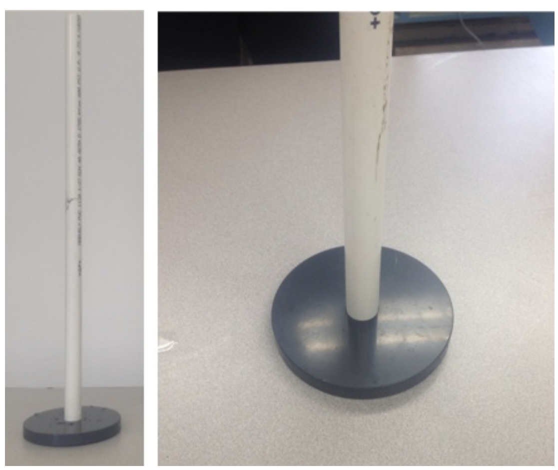


Figure 4: Plate Mixing Device

1.2 Density Trials

Each mixing device was tested in a 22 L rectangular tank with a stratified sugar solution. The sugar solution was dyed red to provide qualitative cues of mixing effectiveness. Following the assumptions of the Spring 2013 team, the stratified solution utilized was 33% dense solution and 66% water. In the bucket trial, the tank was filled with a stratified solution composed of 6 L of 500 g/L sugar solution and 12 L of water. In the plate trial, the tank was filled with a stratified solution composed of 5 L of 500 g/L sugar solution and 10 L of water. In both cases, the density of the solution was recorded after every 5 pumps, and pumping was cut off at 30 repetitions. A repetition for the bucket mixer was defined as bringing the mixer from the bottom of the tank to just above the free surface, after which the bucket was allowed to empty completely before being brought back to the bottom of the tank. A repetition for the plate mixer was defined as bringing the mixer from the bottom of the tank to the top of the dense solution surface, and then plunged back to to the bottom of the tank immediately.

2 Water Injection

In addition to utilizing the newly designed mixers to ensure a uniformly concentrated stock solution, a test injecting the total volume of water into the bottom of the stock tank containing the total volume of dense solution was performed. The concept behind this experiment was to observe if injecting low density fluid into high density fluid would provide substantial mixing and decrease required operator manual input. Especially because it is hoped that the RAM pump will be used to deliver clean water to the stock tanks in full size plants and will provide sufficient energy to pump water into the bottom of the tank, utilizing already available energy to potentially reduce operator labor would further optimize the mixing process.

2.1 Test Tank Injection

Design feasibility was tested by injecting 12 L of water into 6 L of 500 g/L red sugar solution. A 1/4" outer diameter steel pipe was affixed with an elbow at the outlet and secured to inject water into the bottom of the stock tank; this made the jet size approximately 1/4" in diameter. A peristaltic pump was affixed with two pump heads to provide an effective flow of 760 mL/min for the injected fluid; this value is within the range the RAM pump can provide at actual plants. After the entire volume of water was injected into the tank, the plate mixer was utilized to complete mixing. The test setup is shown in Figure 5.

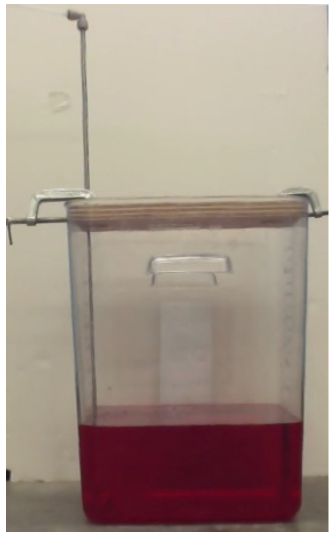


Figure 5: Water Injection Test Setup

The original design for delivering water to the stock tank utilized a pipeline running from the RAM pump that deposited water above the free surface of the solution in the stock tank. The goal of an optimal injection system design would be to minimize the additional head required from the original "pipeline-drip" design. In the injection system, head could come from the actual injection process through the orifice or the required pumping to move the water to the base level of the tank. These two values are defined in Equations 1 (injection via orifice) and 2 (pumping).

Constants and terms utilized in Equations 1 and 2 are as follows:

- H represents head
- Q represents injection fluid flow
- A_{or} represents the area of the orifice/jet
- h_{FS} represents the height of the solution in relation to the bottom of the tank, calculated when the injection process has been completed
- ρ represents fluid density
- $\Pi_{VC} = 0.62$ (Vena contracta factor)

Head due to injection and pumping height differential is calculated in Equations 1 and 2. A visualization of the terms utilized is shown in Figure 6.

$$H_{Injection} = \frac{1}{2}\left(\frac{Q}{A_{or}\Pi_{VC}}\right)^2 \tag{1}$$

$$H_{Tank} = \frac{\rho_{Final} h_{FS}}{\rho_{H_2O}} - h_{FreeSurface} \quad (2)$$

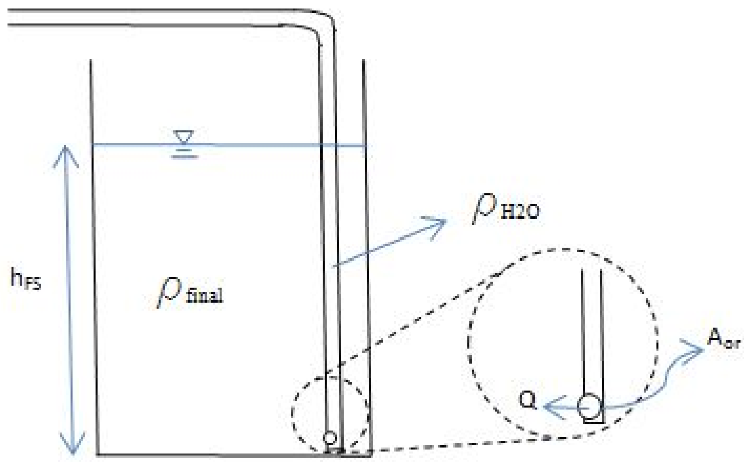


Figure 6: Visualization of Head Terms for Equations 1 and 2

Utilizing Equation 1, the head due to lost kinetic energy at the injection point in the test tank system was found to be 2.1 cm. Head resulting from injecting the less dense water into the dense solution was calculated as 1.9 cm using Equation 2. The total head loss was thus calculated to be 4 cm.

Additionally, the energy supplied by injection was calculated and compared to the theoretical minimum amount of energy needed for full mixing to quantitatively support if injection aided the mixing process. Minimum energy required to mix the solution was calculated by finding the difference between the potential energy of the stratified solution (Equation 3) and the potential energy of the fully mixed solution (Equation 4). The energy provided by injection was calculated by summing the potential energy delivered from the height differential of the injection process (Equation 5) and the kinetic energy of the water exiting the orifice (Equation 6). Assumptions and terms utilized in these calculations are as follows:

- 33% of the total volume before mixing is the volume of the dense solution, 66% of the total volume before mixing is the volume of water
- h represents the height of the top of the fluid interface measured from the datum at the bottom of the container; note that this height changes with time as injection proceeds

- Vol represents volume
- PE represents potential energy
- KE represents kinetic energy

The initial and final potential energies of the fluid in the tank are calculated using Equations 3 and 4. These equations calculate the energy of the stratified (initial) and fully mixed (final) solutions. A visualization of the terms utilized is shown in Figure 7.

$$PE_{Initial} = \left[\rho_{Soln}\frac{h_{Soln}}{2}Vol_{Soln} + \rho_{H_2O}\left(\frac{h_{H_2O} - h_{Soln}}{2} + h_{Soln}\right)Vol_{H2O}\right]g \tag{3}$$

$$PE_{Final} = \rho_{Final}\frac{h_{Final}}{2}\left(Vol_{Final} + Vol_{H_2O}\right)g \tag{4}$$

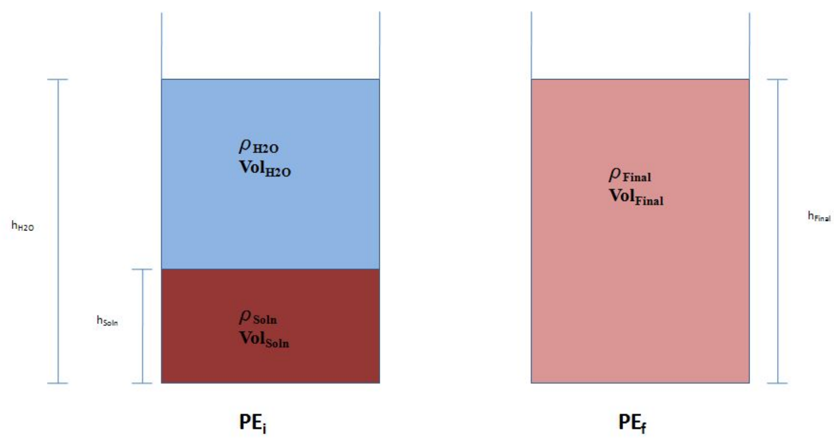


Figure 7: Visualization of Potential Energy Terms for Equations 3 and 4

The potential and kinetic energies associated with the injection process are calculated using Equations 5 and 6. Reference Figure 6 for a visualization of the input terms.

$$PE_{Injection} = h_{FS} \cdot \rho_{H_2O} \cdot Vol_{H_2O} \cdot g \tag{5}$$

$$KE_{Injection} = \frac{1}{2}\left(\frac{Q}{\Pi_{VC}A_{or}}\right)^2 \rho_{H_2O} \cdot Vol_{H_2O} \tag{6}$$

The proportion of assumed energy provided by injection and assumed required energy is calculated using Equation 7.

$$\Pi_{Energy} = \frac{PE_{Injection} + KE_{Injection}}{PE_{Final} - PE_{Initial}} \tag{7}$$

The 22 L test tank setup utilizing sugar solution had a $\Pi_{Energy} = 17$. Thus, the energy input provided by injection was 17 times the theoretical energy required to mix the two solutions.

2.2 Optimal Procedure Test

Assuming the injection method would be viable at full scale, optimal procedures needed to be tested and determined. These tests were meant to mimic the procedure for mixing chemicals in the stock tank. The stock tank will first be partially filled before adding chemicals to avoid crystallization and to ensure full dissolution. After adding the entire mass of chemicals, the remaining volume of water could be injected. These tests were meant to determine the required initial volume of water and the best procedure.

The test setup utilized a 1000 mL graduated cylinder and added 110 grams of PACl to 200 mL, 300 mL, and 400 mL of the total 1000 mL of water used to make the solution; this concentration mimics that which is being used at San Nicolas. The remaining volume of the 1000 mL of water to be added was injected into the bottom of the graduated cylinder, after which the solution density was measured. In two of the trials, the PACl was mixed with the initial water volume using a long tube before the remainder of the water was added. Note that there was no mixing with the plate mixer because of the narrow opening of the 1000 mL graduated cylinder.

2.3 Full Size Injection Calculation

Projected head due to injection in the full size 750 L Rotoplas stock tanks was set at 50 cm due to RAM pump limitations. Utilizing Equation 1 and an assumed flow of 7 mL/s, the required A_{or} was found to be 3.6 mm^2, meaning the diameter of the jet should be 2.14 mm. Total head difference from the original RAM pump setup, including that which is lost in bringing water to the bottom of the tank, was found to be 54.3 cm. Using the process outlined in Section 2.1, $\Pi_{Energy} = 20$, proving the injection method provides much more energy than is theoretically needed to mix the solution.

Part IV

Analysis and Conclusions

3 Vertical Mixer Density Trial Results

Figure 8 shows the hydrometer density reading of the tank corresponding to number of pump repetitions for the bucket and plate trials. The plate trials show a much higher recorded density before significant mixing occurred because of the lower volume of solution utilized; the hydrometer measurement recorded the density of the water as well as the sugar solution because of the lower solution height. This error can be accepted as an experimental flaw, and the subsequent density readings can be accepted as reasonable. As shown by Figure 8, the bucket and plate mixers both achieved complete mixing around approximately 30 repetitions; this argues that both setups are equally effective, efficient, and viable. However, it must be noted that the plate test required less time because there was no waiting period between pumps like in the bucket test. Additionally, the plate test did not require the operator to bring the device in and out of the fluid over the entire height of the solution while the bucket test did. Thus the stroke amplitude was lower for the plate test than for the bucket test and the velocity was higher for the plate test than for the bucket test.

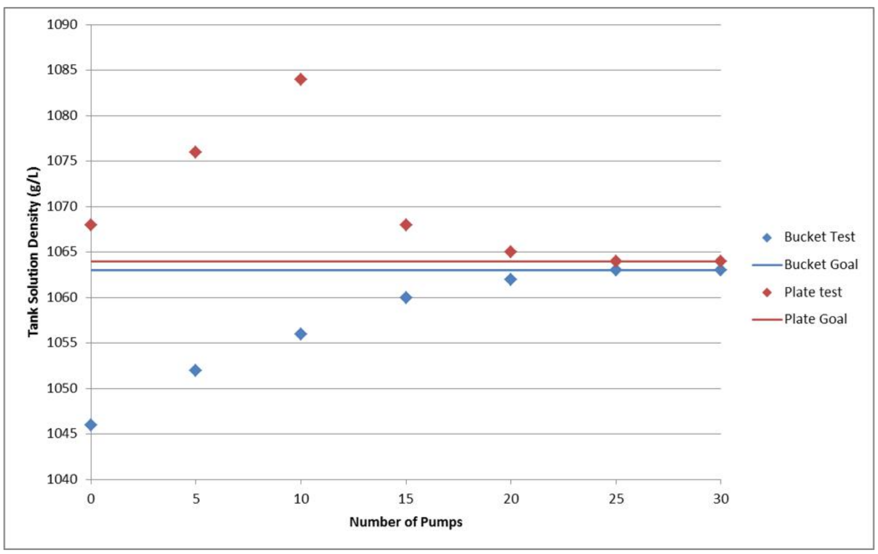
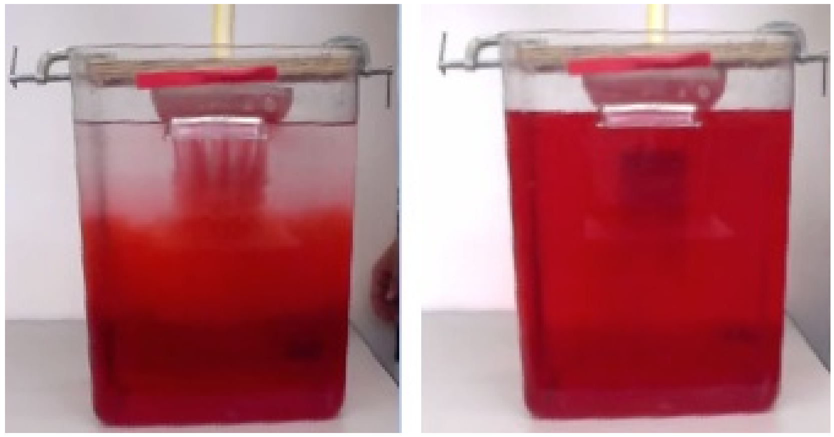
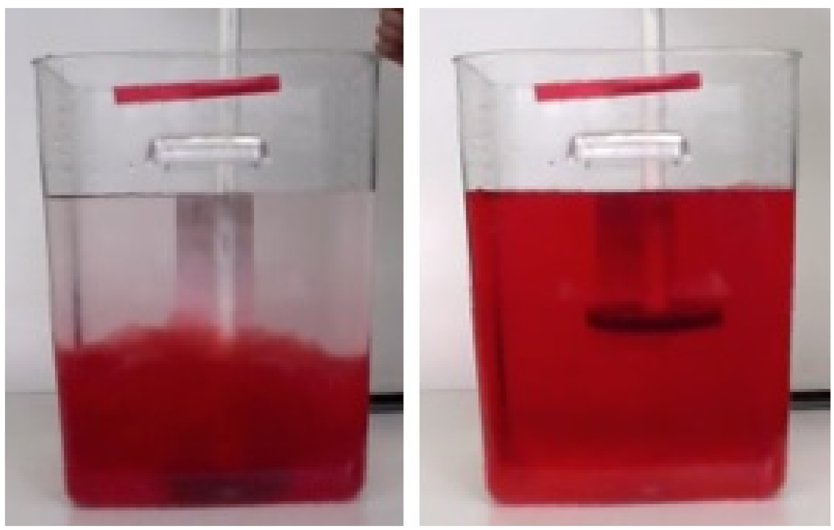


Figure 8: Tank Solution Density (g/L) vs. Pump Repetitions

Visualizations of initial and final solutions in both cases can be seen in Figure 9; although qualitative in nature, the color dispersion is indicative of mixing.



(a) Bucket Test (Click for Video)



(b) Plate Test (Click for Video)

Figure 9: Initial (Left) and Final (Right) Solutions for Density Trials

4 Water Injection Results

4.1 Test Tank Injection Results

Figure 10 shows the measured density of the stock tank immediately following complete water injection (0 pump repetitions) and after utilizing the plate mixer for 30 repetitions and compares injection results to the plate test previously performed without injection. It clearly shows that water injection was incredibly effective in mixing the stock solution and almost achieves goal density, requiring very little manual work to reach final density. The positive results from this trial suggest that combining water injection with manual mixing is the most efficient method to achieve uniformity in stock solutions.

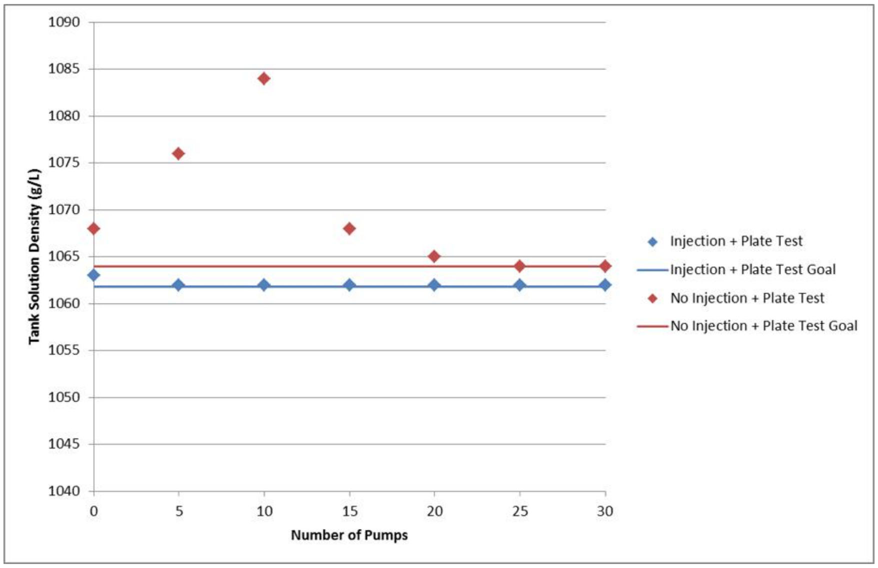


Figure 10: Water Injection Density (g/L) vs. Pump Repetitions

4.2 Optimal Procedure Test

Results from the 1000 mL graduated cylinder tests are shown in Figure 11. Tests utilized initial volumes of 20%, 30%, and 40% of total water volume. None of the experimental setups achieved the density goal because there was no "finishing mixing" with the plate mixer and the density measured was the least dense solution at the top of the graduated cylinder. Additionally, poor performance is likely due to error related to the imprecision of the peristaltic pump in terms of fluid volume measurement and the impact of the small container on mixing ability. The sharp edges at the bottom of the graduated cylinder trapped PACl granules and limited mixing ability; while this also exists in the full-size stock tank, its proportional influence is very low in comparison with this test case. From the results, it can be seen that an initial water volume of 40% of the total volume with mixing achieves the best performance, but it only differs from utilizing 30% of the total volume by 2 g/L. Since a minimum initial water volume is preferred to maximize the effectiveness of the injection process, it was determined that the optimal procedure would be to inject 30% of the total water volume into the stock tank before adding chemicals, and then adding the remaining 70% after crude mixing to encourage dissolution.

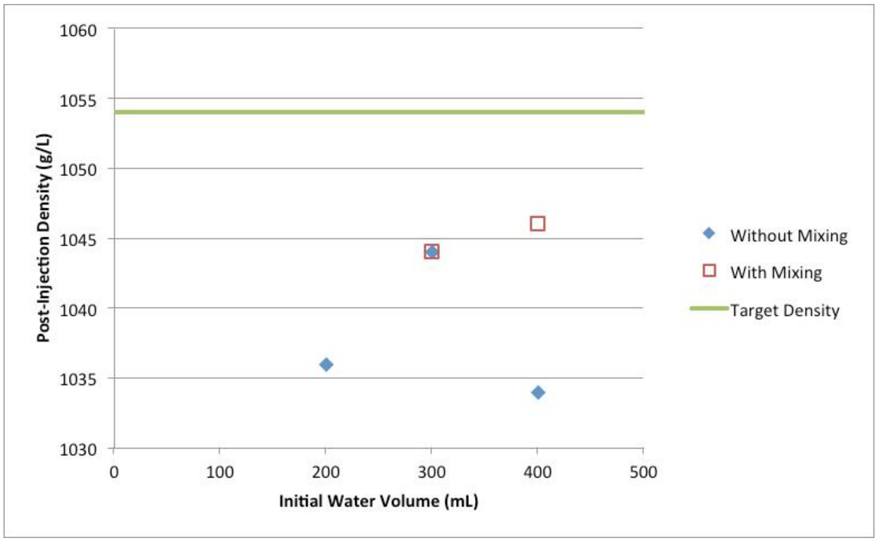


Figure 11: Small-Scale Optimal Procedure Test Results

4.3 Full Size PACl Specifications

As shown by the calculations done in Section 2.3, the limitations of the RAM pump would require the injection orifice has a diameter of 2.1 mm. This could be achieved by affixing a cap to the end of a PVC pipe connected to the RAM pump pipeline and drilling an appropriately sized hole into the side of the pipe. Necessary adjustments for individual plant structures would need to be made, but the actual structure inside the stock tank would only require a vertical pipe with an orifice at the bottom of the tank. The orifice diameter would need to be adjusted based on the ram pump flow rate.

Part V
Future Work

Vertical mixing with the plate mixer in tandem with tank bottom-level water injection is an efficient method for achieving uniformly mixed solutions. The plate mixer has proven to be the best design for a manual mixer due to its high efficiency, rapid mixing time, and low construction cost. Plate mixers could be fabricated of wood or plastic and should utilize a plate area as large as can be accomodated by the tank opening. It is important to note that the plate must be affixed to the bottom of the handle to maximize final velocity.

Water injection also greatly reduces required energy input and takes advantage of available energy from the ram pump. The design procedure specified in this report provides numerical details for 110 g/L PACl solutions made in the 750 L Rotoplas tanks; however, the general design framework can be easily adjusted for other situations. Required infrastructure would include a PVC pipeline connected to the ram pump that has its outlet at the bottom of the stock tank. The pipeline would be terminated with a cap with a hole drilled into the side to create an injection orifice.

The optimal solution will be to use water injection to provide initial mixing in the stock tank and then use a plate mixer to finish the mixing process. Operators can use an appropriate range hydrometer (for 110 g/L of PACl, product #1202-2540PL) to confirm that they have provided adequate mixing.

Future work should include implementing these design additions at San Nicolas to test effectiveness and make appropriate adjustments. After making necessary changes, the mixer and injection pipelines should be added to the design code.