AguaClara Cornell Coagulant Dosing Final Report

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Abstract

Coagulant is essential for particle removal during flocculation and clarification in the AguaClara drinking water treatment process. Currently, coagulant dosing is semi-automated, but a fully automated dosing system provides an opportunity to cut down on labor costs which can be a barrier for low-income communities. In order to automate coagulant dosing, a deeper understanding of the particle removal process during clarification is needed. Specifically, the dynamics of the floc filter in AguaClara clarifiers remains largely uninvestigated. The goal of the Fall 2024 Coagulant Dosing team is to better understand the spatial distribution of floc saturation and concentration in the floc filter in order to develop an accurate physical model of clarification. The team is designing and conducting experiments with a miniature version of the clarifier to visualize gradients of floc saturation and concentration in the floc filter. The improved clarification model will then be applied to optimize the automation of coagulant dosing and to guide future plant designs, in collaboration with the Fall 2024 Plantita Subteam.

Introduction

AguaClara water treatment plants currently rely on a semi-automated coagulant dosing system, where an operator manually adjusts the coagulant in response to changing influent turbidity conditions. For small and rural communities, high labor costs associated with a full-time plant operator present a significant barrier to accessing drinking water treatment technology. A fully automated coagulant dosing system may therefore provide significant benefits to these communities. Additionally, coagulant is very expensive and should be used optimally to minimize wastage. Therefore, an automation system that is reliable and accurate is necessary.

Coagulant dosing refers to the process of adding the appropriate amount of coagulant to the influent water stream to facilitate the formation of larger particle aggregates, called flocs, which can be more easily removed compared to smaller primary particles.

Coagulant plays an important role during the flocculation and clarification processes. During flocculation, primary particles attach during shear-induced collisions to form flocs. Coagulant must be present at the contact points between primary particles in order for them to successfully attach. The amount of coagulant during flocculation therefore determines the number of flocs that can form. During clarification, floc sweeping occurs, in which primary particles attach to the pores of suspended flocs as the primary particles flow upwards through the floc filter. The floc filter is a suspension of flocs which forms within the clarifier. The floc filter is maintained by a jet reverser that redirects fluid upwards and resuspends settling flocs. Similar to how coagulant was necessary for particle attachment during flocculation, the amount of coagulant also affects the attachment efficiency of primary particles to flocs during the floc sweeping process. Therefore, accurate coagulant dosing is critical for both flocculation and clarification.

In order to accurately dose coagulant using an automated system, a physical model for the flocculation and clarification processes is necessary. A significant factor that affects primary particle removal during clarification is the average saturation of flocs in the floc filter. Floc saturation refers to the amount of primary particles which a floc has captured relative to the total number of particles which the floc is capable of capturing. Flocs entering the clarifier tend to be very porous, allowing water and primary particles to flow through and become captured within the floc. As a floc captures more primary particles, less water flows through, causing the attachment efficiency to decrease until the floc is fully saturated and unable to capture more primary particles.

In order for a primary particle to be captured by floc sweeping, it must pass through a floc that is not saturated. Therefore, where the flocs are (i.e. the spatial variation in concentration of flocs) and how saturated each floc is both control the effectiveness of floc sweeping. An area with an especially low concentration of flocs or high floc saturation might allow more primary particles to pass through uncaptured, decreasing the efficiency of the clarification process. Reducing the coagulant dosage below the optimal level is expected to reduce the number of flocs formed, resulting in a decrease in floc concentration. If that change occurs over time, a concentration gradient can form where the lower portion of the floc filter closer to the influent is less concentrated than the upper regions. Similarly, since there would be fewer flocs in this region to capture the same number of primary particles, the flocs in this region would become saturated more quickly, creating a saturation gradient. Hence, the spatial variation in floc saturation and concentration of flocs must be evaluated to accurately determine coagulant dosage.

The current clarification model developed by the Spring and Summer 2024 Coagulant Dosing Subteams does not fully account for floc filter dynamics. It assumes that the concentration of flocs is uniform throughout the floc filter, and it does not account for variations in floc saturation within the floc filter. This is a problem because it is unclear what causes floc filter instability and where the current model fails. The spatial distribution of floc states in the floc filter therefore needs to be assessed.

Literature Review & Previous Work

The article titled, “Simulating the Effect of Blanket Characteristics on the Floc Blanket Clarification Process,” explores accurately modeling the floc blanket clarification process. It takes into account the impact of various floc blanket characteristics on the efficiency and performance of floc blanket clarifiers in water treatment. Past attempts to model this process struggled in accurately reflecting the performance of full-scale treatment coupled with varying operating and influent conditions. Head et al., outlines the key developments in modeling floc blanket clarifiers as well as highlights the significance of a newly proposed mathematical model. The model Head et al. developed is based on a combination of methods. One method is Gould’s theory of the operation of floc blanket clarifiers, which relates the upflow velocity, the settling rate, and position of the floc blanket (Head, 1997). The Bamea-Mizrahi equation, modified for this model, simulates hindered settling, where the settling velocity of particles in the floc blanket decreases as their concentration increases due to particle interference (Head, 1997). This process is integral for understanding the clarifier's ability to separate solids efficiently. Additionally, the Warden and Craft equation helps determine solids loading, the amount of suspended solids entering the clarifier, which is important for optimizing the distribution of floc particles and ensuring effective treatment (Head, 1997). Head’s combined model holds significant potential for practical applications in both operational and design scenarios, including automation of coagulation through assessments of raw water quality changes, optimizing desludging rates, and evaluating optimal wasting tube position. Future research aims to incorporate factors like coagulation conditions and particle size distribution into the model.

The article titled, “Image Analysis of Floc Blanket Dynamics: Investigation of Floc Blanket Thickening, Growth, and Steady State” examines the role of floc blankets in upflow sedimentation tanks to enhance turbidity removal. Using image analysis and turbidity measurements, the study identifies three distinct stages of floc blanket formation: thickening without a visible interface, thickening with an interface, and a steady state. The research finds that floc blanket concentration, rather than height, plays a critical role in turbidity removal. The study highlights how mass transfer between the supernatant and the floc blanket affects formation dynamics and implies changes in floc properties over time. Image analysis is validated as a precise method for real-time monitoring, offering valuable insights into operational control of floc blankets in water treatment plants. Future work will be focused on optimizing performance by gaining a better understanding of floc characteristics and operational conditions.

Previously, the coagulant dose has been set at water treatment plants through the use of streaming current meters. The basis for this decision was because coagulant neutralizes the negative charge of raw water particles. However, it has been found that this does not work because it is the fractional coverage of the primary particles with sticky coagulant nanoparticles that sets the attachment efficiency. This does not require a neutral surface charge.

Coagulant Dose Response and Plantita subteams shared a common goal of lowering operational costs and understanding the interactions between coagulant and primary particles in the past. The Coagulant Dose Response subteam determined a minimum coagulant dose and observed the effects of high coagulant dosage on effluent turbidity in spring 2019. They found that too much coagulant leads to poor floc formation, and coagulant sticks to itself more than the particles. This progress was the foundation of the coagulant dose work done since then and the variables that are being defined now. The Plantita subteam created a new empirical coagulant dosing equation that fit a power law equation in fall 2023. The equation read,

(1)

$$C_{coag} = 81.6T^{0.104} - 72.7$$

where T was influent turbidity. The PACl dose scaled as $T^{0.104}$, which was significantly weaker than the quasi-linear model. The team believed that it was due to a shift in the mechanistic behavior of coagulant when going from low to high turbidity regimes. The Plantita subteam also believed there were other variables that played a role in the coagulant dose equation. This informed the coagulant dosing model made in spring 2024 by the Coagulant Dosing subteam and the modeling of flocculation and clarification done in Summer 2024 by Anjali Asthagiri.

Currently, it is defined that

(2)

$$C_{clarified} = C_{flocculated} e^{-k_c \frac{C_{coagulant}}{C_{influent}}(1-P_{floc\ saturated})^{2/3} h_{floc\ blanket}} \ where\ k_C = k'\beta \frac{\pi r^2_{floc} C_{floc\ blanket}}{m_{floc}}$$

(3)

$$C_{flocculated} = \left(\frac{C_{coagulant}}{k_{pf} C_{influent}} + C_{influent}^{-2/3}\right)^{-3/2} \text{ where } k_{pf} = \frac{3}{2\pi k k' G\theta} \left(\rho \frac{\pi}{6}\right)^{2/3}$$

(4)

$$P_{floc\ saturated} = \frac{C_{flocculated} - C_{clarified}}{q(C_{influent} - C_{clarified})}$$

(5)

$$C_{coagulant} = C_{coagulant\ added} - \lambda C_{DOM}$$

The value of the constant, k_c, (see equation 2) suggests there is a critical component missing from this clarification model. When fitting the model to Plantita data collected by Kim Yang in 2023, the fitted and theoretical values of k_c are orders of magnitude off—with 0.002 as the theoretical value and 100 as the fitted value. The major assumptions of this model are that flocs in the floc filter are at their steady-state saturation, the concentration in the floc filter is a constant, and the floc filter is uniform/well-mixed. The discrepancy in the value of k_c may be due to incorrect assumptions. Further investigation into the distribution of floc saturation and concentration in the floc filter is therefore needed to determine whether or not these assumptions are valid.

Methods

A comprehensive set of experimental methods and imaging techniques were designed to investigate the dynamics of the floc filter at different length scales. To control influent turbidity, white kaolin clay will be mixed with water at different concentrations, and a solution of polyaluminum chloride will be used as coagulant. In order to examine the long-term stability of the floc filter under varying turbidity and coagulant conditions as well as the transient time-scale for the floc filter to reach steady-state, experiments will be conducted with combinations of constant and fluctuating influent turbidity and coagulant dose. The clarified turbidity response will be measured to indicate the performance of flocculation and clarification.

<u>Experiment Design Feature I: Colored Primary Particles</u>

In order to investigate the spatial distribution of floc saturation in the floc filter, a stream of colored primary particles will be added to the flocculator effluent before entering the clarifier. As floc sweeping occurs in the clarifier, the colored primary particles will adhere to the flocs in the floc filter. The extent to which a floc is saturated is hypothesized to be related to the fractal dimension of the floc. Different-sized collisions between the floc and primary particles during floc sweeping in the clarifier increases the floc's fractal dimension and saturation. Therefore the relative coloration of a floc may indicate its saturation state. Imaging the color gradient of the entire floc filter may provide insights into the spatial distribution of average floc saturation.

In order to implement colored primary particles, research was conducted to explore various organic dyes and colored clays. Primary particles are typically 1-100 μm in diameter and have a negative surface charge. Key criterion when determining optimal compounds was the similarity of their particle size and charge characteristics to primary particles. Rose kaolin clay, Red-40 and Reactive Red were identified as good initial candidates, having diameters of 25-35 μm, 60-100 μm and 53-180 μm respectively and negative surface charge.

Experiment Design Feature II: Imaging

In order to image the floc filter, a horizontal camera apparatus will be designed, similar to that described in Hurst et al., 2013 but using reflected light instead of transmitted light in order to additionally visualize floc filter coloration (see section above). As described by Hurst et al., 2013, this imaging setup can be used to estimate floc filter concentration and growth rate. Previous work by Hurst et al., 2013 and Hurst et al., 2014 used this setup to investigate constant influent and coagulant dose conditions. Expanding on their work, the effects of fluctuating coagulant dose and influent turbidity on floc filter concentration and growth rate will be investigated.

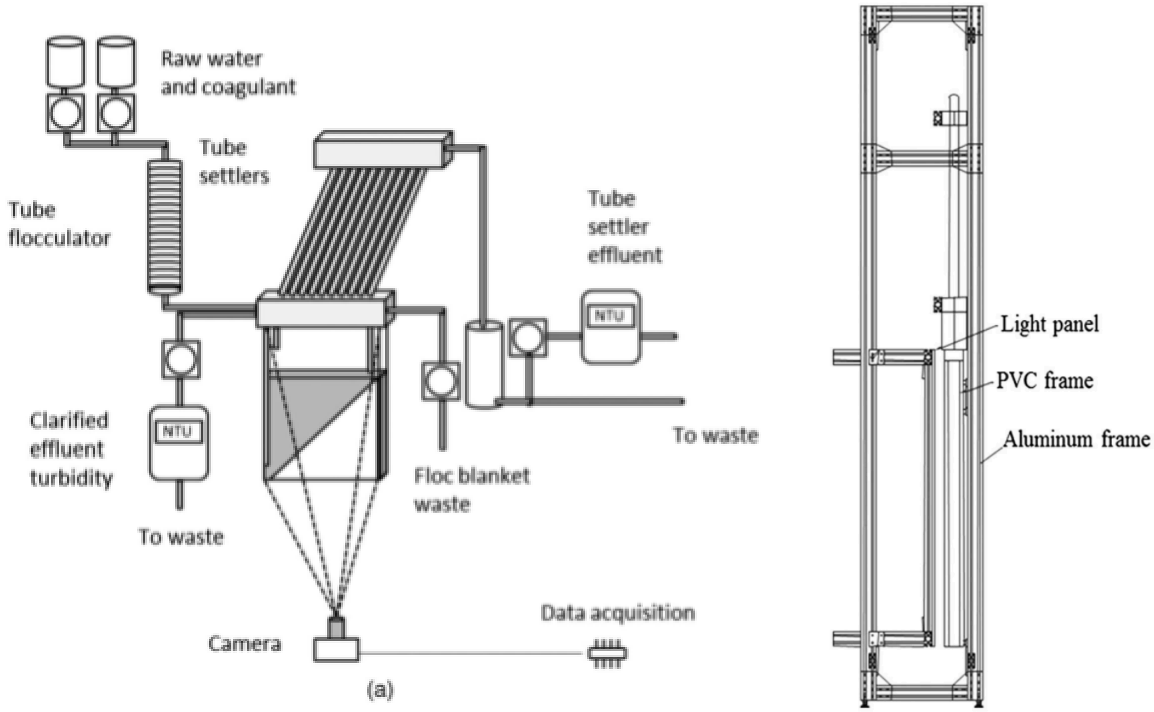


Figure 2. Figures from Hurst et al., 2013 illustrating setup for imaging floc filter concentration and growth using a camera and a backlight LED panel. Instead of using transmitted light, this research study will use a light source at the front to image reflected light.

<u>Experiment Design Feature III: Miniature Clarifier</u>

A miniature version of the clarifier will be designed and built to conduct experiments with a small floc filter, requiring minimal time for floc filter formation and thus enabling efficient experimentation. In the future, the imaging-compatibility and portability of this apparatus may also allow for micro-scale visualization of individual flocs and their interactions with coagulant and primary particles. The clarifier will be built with a glass panel for imaging.

Results/Analysis

Experiment Design Feature I: Colored Primary Particles

Rose kaolin clay as a colored primary particle stream was explored first. An initial jar test experiment was conducted using rose kaolin clay to determine whether rose colored flocs can be visualized after they sweep rose primary particles. First, white kaolin clay was mixed with water and approximately 10 mL of coagulant was added. The mixture was swirled causing white flocs to form. A pinch of rose kaolin clay was mixed with water in another cup to create rose primary particles. About 50 mL of the white floc mixture was added to the top of the rose primary particle mixture. The mixture was observed periodically over 3 hours as the white flocs settled. A control sample of only rose primary particles was set aside as well. Figure 1 depicts the water column after the flocs settled. The settled flocs were rose-colored, suggesting they swept the primary particles. However, the primary particles in the control sample also settled to the bottom, indicating the results of this experiment are inconclusive. More experiments will be conducted to determine whether rose kaolin clay can provide spatial information regarding primary particle removal via floc sweeping and ultimately saturation state.

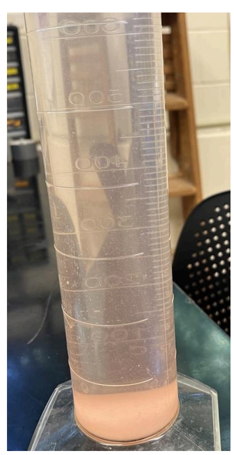


Figure 1. Settled flocs became rose-colored after sweeping rose primary particles, leaving behind cleaner water towards the top.

Experiment Design Feature III: Miniature Clarifier

Two versions of the miniature clarifier were developed with the goal of making it modular and watertight. Given an upflow velocity of 1 mm/s (typical for AguaClara clarifier designs), the clarifiers were designed with heights around 4-5 inches to ensure a residence time that is less than 3 minutes. This will enable rapid experimentation, minimal time for floc filter formation, and fast response to changes in influent conditions. Key design parameters, including a diffuser angle of 50°, a plate settler angle of 60°, and a plate settler diameter of 2.5 cm, were based on standard AguaClara clarifier specifications (4). The use of an overflow weir and floating plate settlers mimic the designs described in Hurst et al., 2013.

The first clarifier was designed to be modular, made entirely out of rubber, screws, bolts, and laser-cut acrylic. To construct the sides of the clarifier, pieces of laser-cut acrylic and rubber were layered and sandwiched between two outer faces. Depending on the desired width of the clarifier, the number of layers can be altered. The bottom of the clarifier was prototyped with a rubber gasket sandwiched between the side panels and a bottom acrylic piece that has a hole for an influent tube. Initial tests with water indicated that the side interfaces were watertight, however the interface at the bottom of the clarifier was not. Further design modifications are necessary to develop a watertight seal for the bottom interface. See Figure 2 for a schematic of the design.

A second clarifier was designed, made from a resin-printed piece, an ABS 3D-printed piece, glass, rubber, screws and bolts. Compared to the first design, this design is not modular; however it contains only one interface that needs to be watertight rather than several interfaces.

As expected, initial tests suggest this clarifier is more watertight than the first clarifier and may enable preliminary experimentation. See Figure 3 for a schematic of the design.

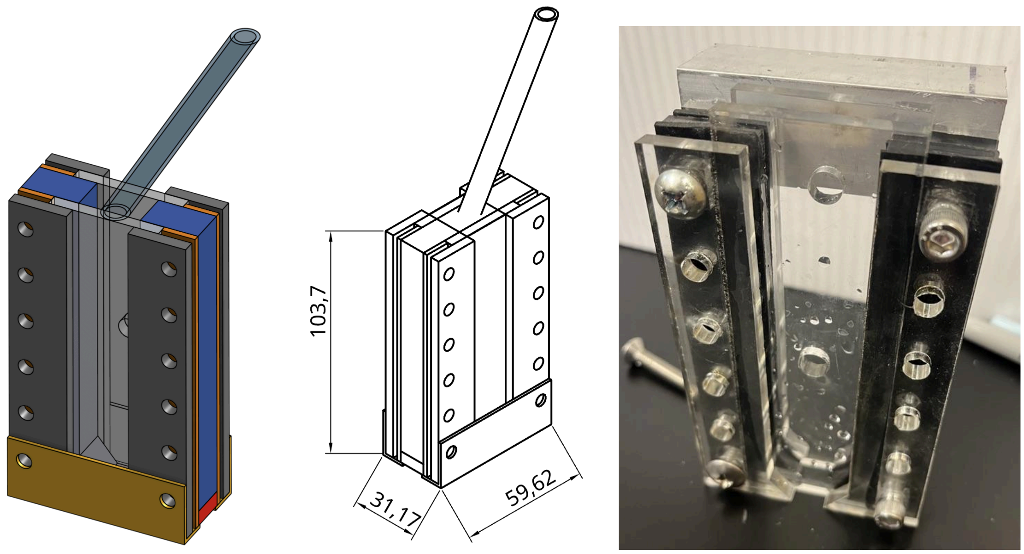


Figure 2. CAD and image of the modular clarifier.

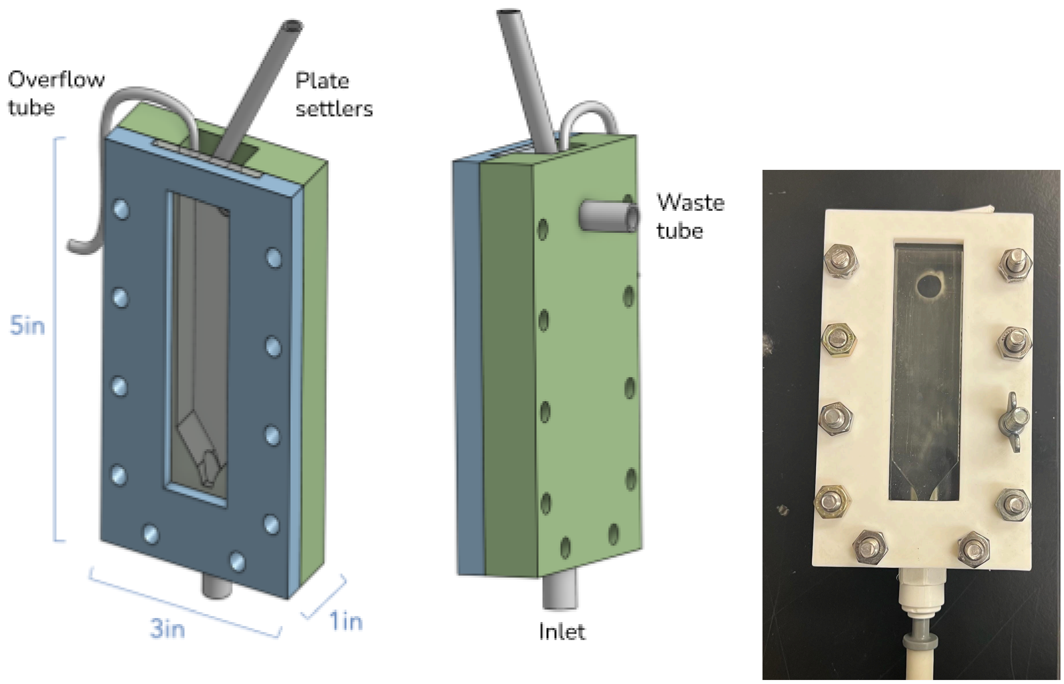


Figure 3. CAD and image of the resin-printed clarifier.

Further experiments are needed to evaluate whether these small-scale clarifiers can replicate trends observed in full-scale clarifiers. A specific concern is whether the reduced vertical mixing in small-scale clarifiers, due to their narrower width, will significantly alter the spatial distribution of floc filter concentration and floc saturation. Testing varying widths using the modular clarifier may provide insights into this effect. Additionally, the reduced height of the floc filter in these designs is expected to lower overall clarification performance. However, as long as the turbidimeter can detect these smaller changes in turbidity, this limitation should not impede the goal of studying trends in floc filter dynamics and clarification performance under varying influent conditions.

Conclusions/Future Work

Conclusions

Initial testing indicates that flocs can be dyed using colored primary particles, as seen in Figure 1. This shows promise for the visualization of floc saturation with reflected light. While a modular miniature clarifier design has not yet been achieved, the current resin-printed model is sufficient to begin experiments. This will allow for the measurement of the spatial variation in floc saturation and concentration within the floc filter under different coagulant dosages and turbidity conditions, yielding a greater understanding of floc filter dynamics. Ultimately, this will enable reliable automation of coagulant dosing, decreasing labor costs and improving the accessibility of AguaClara water treatment technology.

Future Work

Currently, the resin-printed clarifier is not modular, and the acrylic, modular clarifier is not water resistant. Moving forward, a small-scale, modular, water resistant, clarifier that meets the criteria set will be fabricated. This will allow for experimentation and high resolution visualization of the floc filter. Experiments will be conducted in the miniature clarifier to determine the performance of flocculation and clarification, measure floc size distribution, understand key variables, and validate assumptions made.

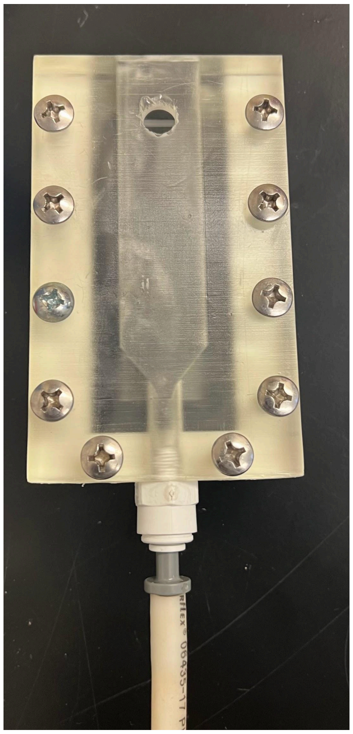
Additionally, influent and clarified turbidity, particle size distribution before and after clarification, and DOM concentration will be collected during these experiments. Using the methods from the literature review, video recordings of the floc filter will also be taken and used to analyze temporal variations in floc filter concentration. This analysis will be expanded to examine color gradients in the floc filter to evaluate floc saturation. Regression models will reveal the correlations between the data collected. Furthermore, mathematical models will be developed and fit to the experimental data.

Manual

See the "modular version" and "resin-printed version" tabs at this link for the CAD in OnShape.

Resin-Printed Clarifier

The rapid prototyping lab constructs a resin-printed miniature clarifier through 3D-printing the CAD design with resin and ABS. Resin is used for the main holder piece, while ABS is used for the top cover piece. A 10 in x 12 in glass is cut using a glass cutter to be 1.6 in x 4.5 in. Rubber pieces are cut out of a Neoprene Rubber Sheet that is 1/16 inches thick. 10 screws and bolts (⅜ in diameter, 2 in long) are used to hold together the resin, ABS, glass and rubber pieces. A push-to-connect fitting is screwed into the bottom of the clarifier with Teflon tape, and the tube is connected to the push-to-connect fitting via a tube insert.



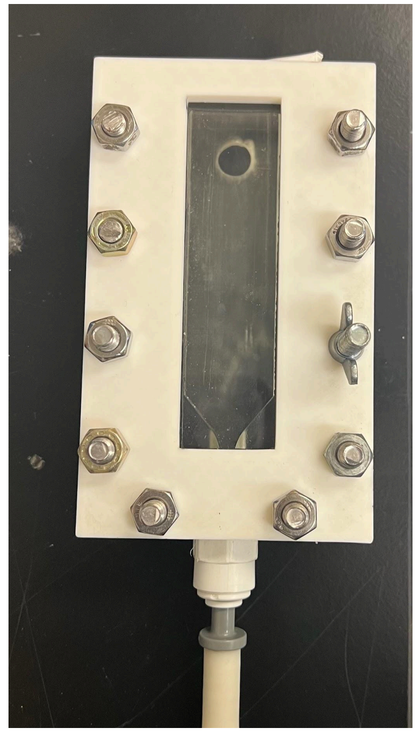


Figure 3. Back of resin-printed clarifier

Figure 4. Front of resin-printed clarifier

Modular Clarifier

The Rapid Prototyping Lab laser cutter is used to cut the acrylic for the sides of the modular clarifier, following the CAD design. Rubber pieces are cut out of a Neoprene Rubber Sheet that was 1/16 inches thick. Both acrylic and rubber pieces have holes that are 6.35 mm in diameter. Screws and bolts (⅜ in diameter, 2 in length) are used to fasten hold the acrylic and rubber pieces together. To test watertightness of the bottom interface, clamps are used between the top of the clarifier and the table to press the clarifier into the bottom rubber and acrylic pieces.

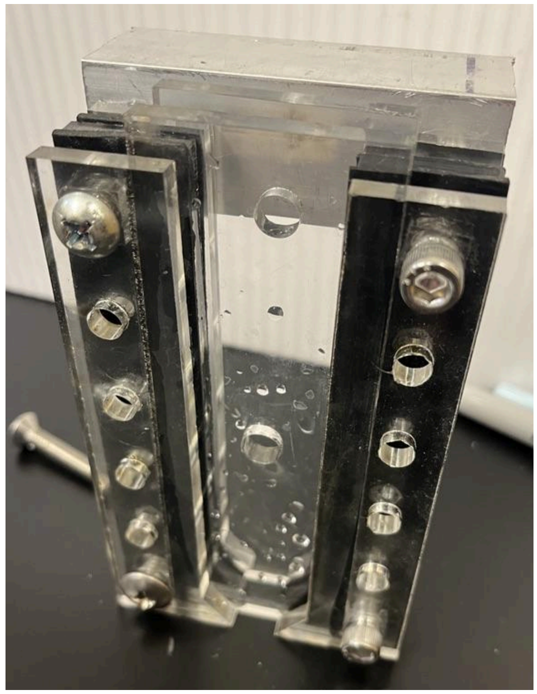


Figure 5. Fabricated modular clarifier.

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