AguaClara Cornell Coagulant Dosing

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Kayla Stephenson (ks929)
Alex Gardocki (rag325)
Christine Berlingeri (cnb53)
Ulises Balbuena Figueroa (umb5)
Anjali Asthagiri (aa2549)

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 large-scale 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. 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, "Investigating Floc Blanket Dynamics for Improved Turbidity Removal in Water Treatment" 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 previously 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. However, the Plantita subteam 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)

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

(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. White kaolin clay will be mixed with water at different concentrations to simulate influent turbidity, 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.

Experiment Design Feature I: Colored Primary Particles

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.

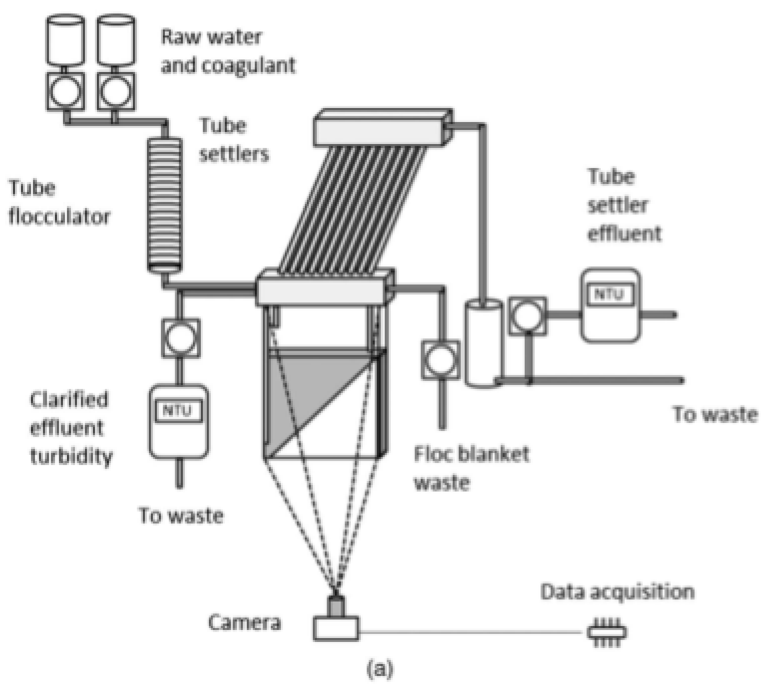
In order to implement colored primary particles, research was conducted to explore various organic dyes and colored clays. Primary particles are typically 1-100 μm in diameter and have a negative surface charge. Key criterion when determining optimal compounds was the similarity of their particle size 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.

Rose kaolin clay 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 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 blanket 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.



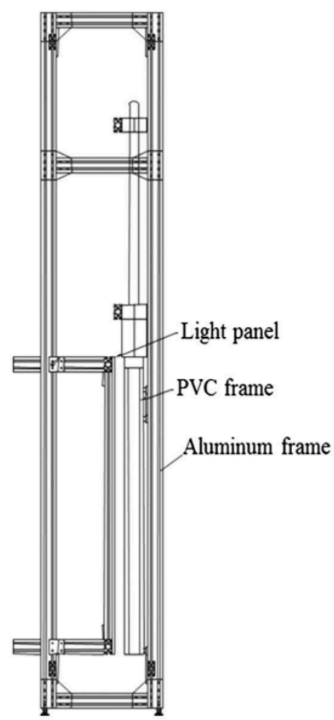


Figure 2. Figures from Hurst et al., 2013 illustrating setup for imaging floc filter concentration and growth using a camera and a backlight LED panel. Instead of using transmitted light, this research study will use a light source at the front to image reflected light.

Experiment Design Feature III: Miniature Clarifier

Furthermore, a miniature version of the clarifier will be designed and built to conduct experiments with a small floc blanket, requiring minimal time for floc blanket 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 metal frame, acrylic panels, and a glass panel for imaging. See Figure 2 for a schematic of the design.

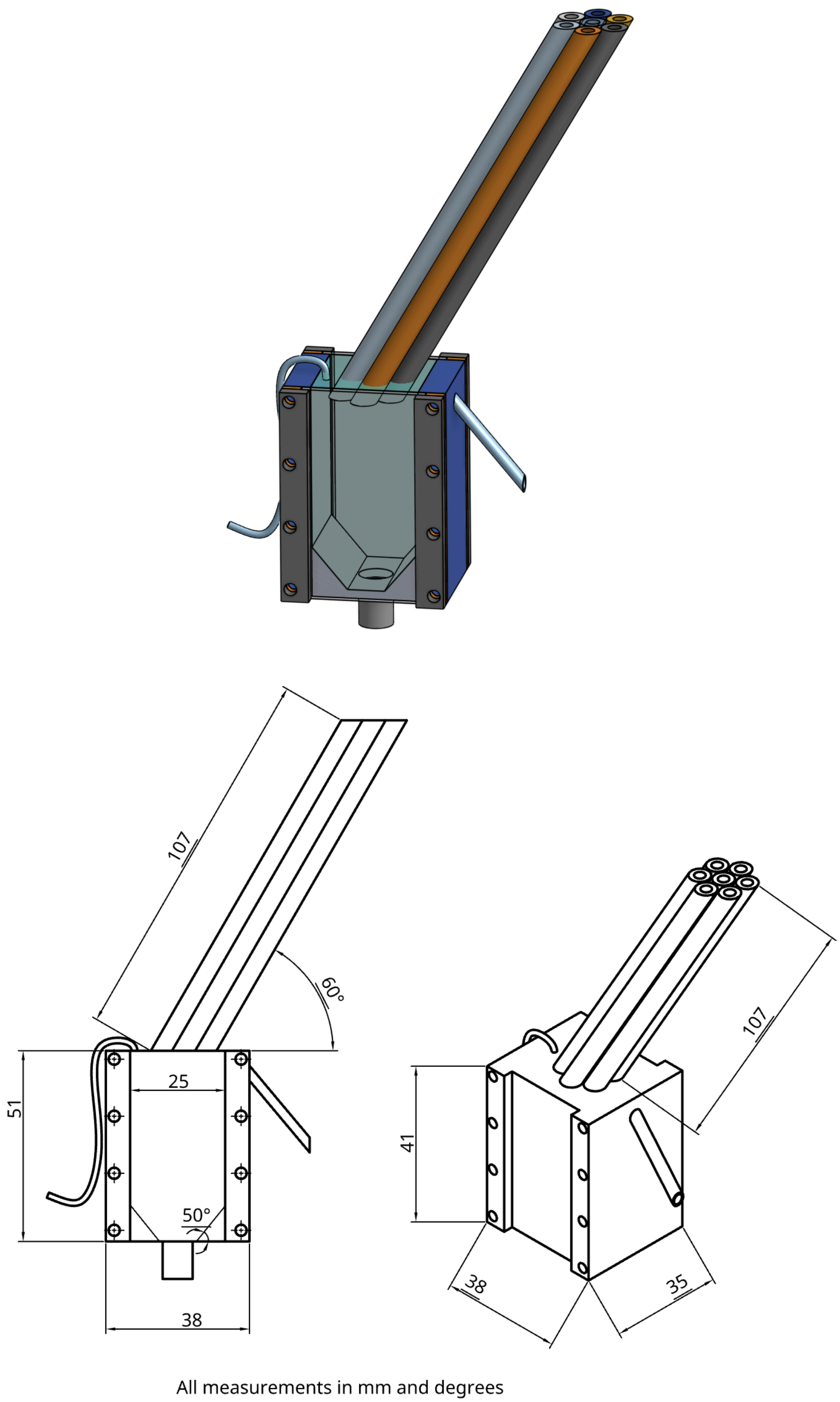


Figure 2. CAD and schematics of the miniature clarifier.

References

1. Head, R., Hart, J., & Graham, N. (1997). Simulating the effect of blanket characteristics on the floc blanket clarification process. *Water Science and Technology*, *36*(4). https://doi.org/10.1016/s0273-1223(97)00422-8.
2. Hurst, M., Weber-Shirk, M., & Lion, L. W. (2014). Image analysis of floc blanket dynamics: Investigation of floc blanket thickening, growth, and Steady State. *Journal of Environmental Engineering*, *140*(4). https://doi.org/10.1061/(asce)ee.1943-7870.0000817.
3. Hurst, M., Weber-Shirk, M., Charles P., & Lion, L. W. (2013). Apparatus for Observation and Analysis of Floc Blanket Formation and Performance. *Journal of Environmental Engineering*, *140*(1). https://doi.org/10.1061/(ASCE)EE.1943-7870.0000773.