Full Scale Floc Breakup Final Report

David Buck and Meg Fitzgerald

February 22, 2013

Abstract

The objective of this research was to design a floc break up device to test the concept of floc break up at full-scale and improve flocculation performance of the AguaClara plant located in Atima, Honduras. Recent research suggests that using flow constrictions to break up flocs improves performance and reduces settled water turbidity. Using this hypothesis, we designed a device to cause floc break up. We used a perforated plastic sheet which constricts flow and creates many jets, which dissipate energy and break flocs. The proposed design for the prototype for Atima includes 21 orifices and an orifice diameter of 5.1 cm (2"), which results in approximately 9.3 mm of head loss per device and 40% open area. We also determined that the devices should be optimally placed in the flocculator so that water flows upward through them. We plan to attach the devices between the baffles and walls of the flocculator with foam blocks. Our design can be fabricated in Honduras with locally sourced materials, so although the fabrication will require local labor, it does not rely on shipping materials from the United States. We will send our design to Drew Hart in Honduras who will fabricate the perforated plates and test them at full scale.

Introduction

The objective of this research is to enhance the performance of AguaClara flocculators by creating a device that can be used to break up large flocs and reduce the amount of colloids left after flocculation. Flocculation occurs as clay colloids collide and aggregate before they are settled out by gravity in the sedimentation tanks. Small colloids coagulate and grow, forming larger flocs from smaller flocs. However, it is inevitable that at the end of flocculation there are colloids left that have not collided with each other and do not aggregate with larger flocs. The colloids remaining at the end of flocculation require small flocs to aggregate because the larger flocs experience too much shear for small colloids to attach. Previous laboratory data indicates that breaking up these big flocs in the middle of flocculation improves performance because the larger flocs are broken into smaller flocs which allows the remaining colloids to attach and ultimately lowers outflow turbidity.

Previous research in the tube flocculator and FReTA supports the hypothesis that “big flocs are useless” and does not agree with the hypothesis that colloids can attach to all flocs. If this were the case, then high turbidity water would always perform best in flocculation and require a lower retention time. It is presumed that the colloids do not attach to full size flocs because the large flocs experience too much surface shear because surface shear on a floc in a linear velocity gradient is expected to increase linearly with floc diameter. Additional research supports this and shows that breaking up flocs in the middle of flocculation helps improve performance. Previous laboratory experiments with the tube flocculator show that adding flow constrictions significantly decreases the settled water turbidity. This is because the constrictions increase the energy dissipation rate, break up the larger flocs, and allow colloids to attach to the newly created small flocs. However these experiments were performed on a small scale under laminar flow conditions, so further research is needed to implement these findings on a plant-scale turbulent flocculator.

This research team built off of the existing research, and designed a floc breakup device for a full-scale plant. We used perforated sheets with a specific porosity and orifice size to create a high energy dissipation rate to break up large flocs. We chose an energy dissipation rate that breaks the flocs to a specific size that will enhance flocculator performance without hindering settling in the sedimentation tank. After choosing a specific energy dissipation rate we carried out a time analysis to determine the possible number of devices. Using this information and the maximum head loss we determined a set of possible orifice diameters and porosities. After finalizing the design we will send the design to Drew Hart in Honduras who will build and test the floc breakup plates at full scale.

Theoretical Basis of Design

Target Floc Size

The first step in the design process was to determine the size to which flocs should be broken. We found the smallest diameter floc that could be captured by the sedimentation tank plate settlers. This particle size was determined by the designed capture velocity in the sedimentation tank. This mathematical relationship is displayed in Equation 1.

$$d_{particle} = d_0 \left(\frac{18 V_t \phi \nu}{g d_0^2} \frac{\rho_{H_2O}}{\rho_{Floc_0} - \rho_{H_2O}} \right)^{\frac{1}{D_{Fractal} - 1}} \tag{1}$$

Given a capture velocity of $0.12\,{}^{\mathrm{mm}}\!/_{\mathrm{s}}$ the minimum floc size that can reliably be captured is 113 µm.

Analysis of Sequential Floc Breakup Events

The number of floc breakup events required for the design depends on the time it takes for broken flocs to return to full size and the residence time of the flocculator. The first step was to determine the number of collisions required to grow from the primary particle size to the final floc size. This is shown in Equation 2, where n is the number of collisions, $D_{Fractal}$ is the fractal dimension 2.3, d_0 is the primary particle size and d_{final} is the target floc size we obtained in Equation 1. Equation 3 gives the particle diameter d_i resulting from: i collisions, the primary particle size and the fractal dimension.

$$n = D_{Fractal} log_2 (\frac{d_{final}}{d_0}) \tag{2}$$

$$d_i = d_0 \cdot 2^{\frac{i}{D_{Fractal}}} \tag{3}$$

Equation 4 presents the time required, t_c, for two particles of size d_{floc} to collide. This time requirement is also a function of the floc volume fraction ϕ_{Floc}. As shown in Equation 5 the floc volume fraction is a function of the floc size, primary particle size, fractal dimension and initial floc volume fraction ϕ_{Floc_0}, which is in turn a function of clay concentration C_{Clay}, clay density ρ_{Clay}, alum concentration C_{PACl} and alum density ρ_{PACl}. This is shown in Equation 6.

$$t_c = \frac{1}{6}\left(\frac{6}{\pi}\right)^{\frac{1}{9}}\left(\frac{d_{Floc}^2}{\varepsilon}\right)^{\frac{1}{3}}\frac{1}{\phi_{Floc}^{\frac{8}{9}}} \tag{4}$$

$$\phi_{Floc} = \phi_{Floc_0}\left(\frac{d_{floc}}{d_0}\right)^{3-D_{Fractal}} \tag{5}$$

$$\phi_{Floc_0} = \frac{C_{Clay}}{\rho_{Clay}} + \frac{C_{PACl}}{\rho_{PACl}} \tag{6}$$

Equations 4, 5, and 6 were then combined to form Equation 7.

$$t_c = \frac{1}{6}\left(\frac{6}{\pi}\right)^{\frac{1}{9}}\left(\frac{d_{Floc}^2}{\varepsilon}\right)^{\frac{1}{3}}\left[\left(\frac{C_{Clay}}{\rho_{Clay}} + \frac{C_{PACl}}{\rho_{PACl}}\right)\left(\frac{d_{floc}}{d_0}\right)^{3-D_{Fractal}}\right]^{\frac{-8}{9}} \tag{7}$$

$$t_{TotalGrowth} = \sum t_c \tag{8}$$

Equation 7 only gives the time for collision between two particles at a given size. The total growth time, $t_{TotalGrowth}$, was found by summing the times of individual collisions of particles of the same size to find the time to grow from a primary to final size. This is shown in Equation 8. To determine the time required for the particles to grow from the broken particle size of 113 µm to the full size of 348 µm, we first calculated the time required for the primary particle to grow to the full size and then subtracted the time required for the primary particle to grow to the broken particle size.

A comparison between the total time required for floc growth, 15 seconds, and the flocculator residence time, 19 minutes, was then used to determine the maximum number of break up points. We found that there can be at most 75 breakup points to ensure time for flocs to reform. This high number lead us to conclude that head loss was our main constraint on number of break up devices. As such we used trial and error to see what number of break up devices lead to a feasible design solution.

Energy Dissipation Rate

We calculated the desired energy dissipation rate from the design floc diameter Equation 9. It is an empirical equation that was determined by previous research using FReTA to compare the average floc size with energy dissipation rate through a laminar flow tube flocculator (Tse, 2009). Although the empirical relationship was determined using a laminar flow bench-scale flocculator using alum as the coagulant, we assumed the relationship applies to a full-scale turbulent flocculator using poly aluminum chloride.

$$d_{floc} = \frac{75\mu\mathrm{m}}{\left(\frac{\varepsilon_{max}}{W/kg}\right)^{\frac{1}{3}}} \tag{9}$$

The energy dissipation rate required to break flocs down to a diameter of $133\,\mu m$ was calculated to be $300\frac{mW}{kg}$.

Orifice Size and Porosity Design

Four major concepts are used in the development of the floc break up apparatus design. These concepts are head loss through a contraction, continuity, vane contracta and energy dissipation in a jet. These concepts are represented generally by equations 10, 11, 12, and 13 respectively.

$$h_e = \frac{V_{Jet}^2}{2g}\left(1 - \frac{A_{Jet}}{A_{out}}\right)^2 \tag{10}$$

$$Q = VA \tag{11}$$

$$\Pi_{VC} = \frac{A_{Jet}}{A_{Perforation}} \tag{12}$$

$$\varepsilon_{Breakup} = \frac{\left(\Pi_{Jet} V_{Jet}\right)^3}{D_{Jet}} \tag{13}$$

The geometry of the orifice jet expansion is shown in Figure 1

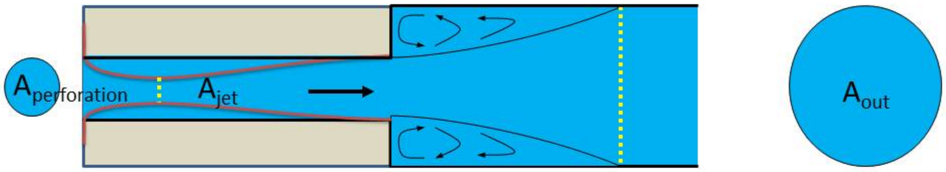

Figure 1: Flow Through Orifice and Jet Expansion

We set a constraint of maximum head loss of 5 cm through the entire flocculator for floc breakup because there are only 10 cm of freeboard and we want to ensure that the water does not over-top the baffles. Using 5 breakup devices allows a maximum of 10 mm of head loss through each breakup device. We used this head loss to determine a lower bound for porosity. The relationship between head loss and porosity is developed below.

Where η is the fraction of open area in the plate and can either be interpreted over the entire flow area between flocculator baffles or over the area corresponding to one perforation.

$$\eta = \frac{N_{Orifices} A_{Perforation}}{A_{Plate}} = \frac{A_{Perforation}}{A_{Out}} \tag{14}$$

We rewrote V_{Jet} as a function of porosity and known parameters as shown in 15.

$$V_{Jet} = \frac{V_{Floc}}{\eta \Pi_{VC}} \tag{15}$$

Substituting 10, 12, 14, and 15 into we obtain head loss as a function of porosity. This relationship is shown graphically in Figure 16

$$h_e = \frac{V_{Floc}^2}{2g}\left(\frac{1}{\eta \Pi_{VC}} - 1\right)^2 \quad (16)$$

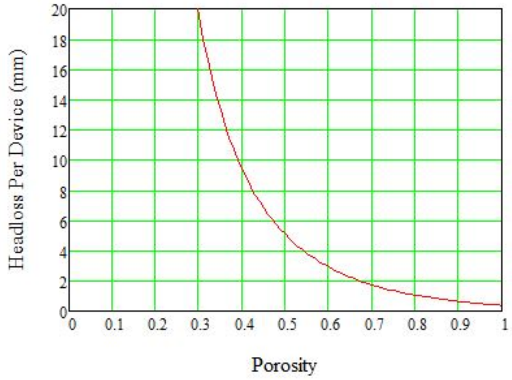

Figure 2: Head Loss per Device vs Porosity

We set a maximum head loss and porosity as our constraints, and used the target energy dissipation rate of $300\frac{mW}{kg}$ to find a suitable orifice diameter. We determined a maximum head loss per device to be 10 mm, which gives 0.39 as a lower bound for porosity. This relationship is shown in Figure 2.

The next step was to determine the orifice size and number of orifices based on the energy dissipation rate within the range of desired porosities. We chose the minimum porosity, because it maximizes head loss per device, ensures that streamlines bend as a jet, and requires fewer orifices to be drilled. The relationship between number of orifices and porosity at varying orifice diameters is shown in Figure 3. This shows that with a larger orifice diameter, fewer orifices are needed. It also shows that for a given orifice diameter, porosity increases with number of orifices.

We used equation 17 for orifice diameter as a function of energy dissipation and number of orifices.

$$D_{Orifice} = \left(\frac{4Q_{Plant}\Pi_{Jet}}{\varepsilon_{max}^{\frac{1}{3}}\pi N_{Orifice}}\right)^{\frac{3}{7}} \frac{1}{\sqrt{\Pi}_{VC}} \quad (17)$$

These plots helped us narrow down our solution. We rewrote equation 17 to give number of orifices as a function of diameter. This allowed us to ensure that the orifice diameter is a standard size of a drill bit.

$$N_{Orifices} = \frac{4Q_{Plant}\Pi_{Jet}}{\varepsilon_{max}^{\frac{1}{3}} D_{Orifice}^{\frac{7}{3}} \Pi_{VC}^{\frac{7}{6}}} \quad (18)$$

Then we proceeded to input orifice diameters in increments of 1/16 inches, obtain a number of orifices, and then check that the porosity was in the given

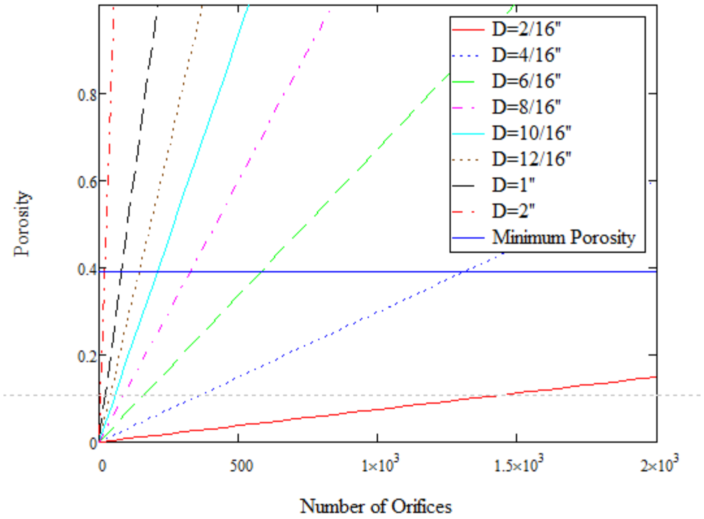

Figure 3: Porosity vs Number of Orifices at Varying Diameters

Figure 4: Diameter of Orifice vs Number of Orifices

bounds as given by equation 14, that the head loss was below the maximum head loss per device and that the energy dissipation was equal to the target energy dissipation rate of 300 mW/kg.

Atima Design Solution

Assumptions

Using the methodology outlined in the Theoretical Basis of Design Section we developed a specific solution for Atima that could be used for full scale testing. In performing these calculations we made a number of assumptions about the inflow turbidity of the plant, the concentration of coagulant dose, and our target final floc size. We designed for the average turbidity of the plant at Atima, which is 8 NTU and then converted that to an initial clay concentration using the empirical relationship 1 $NTU = 1.5$ mg/L clay. We assumed that the PACl dose was 2.43 mg/L , which was the average concentration in the plant from March 17th to April 15, 2013. This could change depending on the type of coagulant, variations in turbidity or plant flow rate. Finally, we assumed that our target final floc size would be the smallest size that can be captured by the sedimentation tank, which is 0.133 µm.

Constraints

We set constraints on our design to avoid the possible failure modes. Our first was that the energy dissipation rate through the device was high enough to break the flocs to a size that could be captured by sedimentation tank. We found that the energy dissipation rate through the device should be 300 mW/kg. We set an upper and lower bound on the porosity. We set the maximum porosity through the effective area of the device (which excludes the area covered by the foam attachments) to 50% to ensure that the streamlines through the device bend as a jet. The lower bound for porosity is determined by the maximum head loss through the device. We set maximum total head loss through the flocculator equal to 5 cm. There are only 10 cm of freeboard between the water level and the top of the baffle and we did not want to create so much head loss that water over-topped the baffles. This maximum head loss became our main constraint on number of devices. After determining that there could be a maximum of 75 devices, we needed to use trial and error to find what number of break up devices gave us a reasonable upper bound for head loss and lower bound for porosity. We determined that 5 break up devices gave us a maximum of 10 mm of head loss per device. As shown in Figure 2, this maximum head loss gives 39% as the lower bound for porosity. We checked to ensure that our final design solution met these constraints.

Attachment to Flocculator

We analyzed the optimal placement and attachment method for the floc break up device. We will place the device horizontally in the flocculator between two baffles. We will use foam blocks to wedge the device in between the baffles and walls of the flocculator channel. The width of the foam attachment will be 0.5 inch around the entire perimeter of the break up device. The device will rest on top of the horizontal PVC pipes that are used to keep the baffles in place. It will be close enough to the top that it will be easily removable by the plant operator should a clogging event occur. We will place the device so that the water is flowing up through the perforations. We chose to orient the sheet this way, rather than have the water flow down over the sheet because flow is more uniform on this side of the baffle. On the downward flow side of the baffle, the flow expansion and vena contracta create eddies and less uniform flow. Figure 5 gives a visual representation of the flow path of water, in blue, and the placement of the floc break up device, in red. Our model is based on uniform flow through the device, so placing the device on the uniform side will ensure greater consistency in performance. The foam can be made of either polyurethane or polyethylene. As with the plate material, the foam selection will be determined based on materials availability in Honduras.

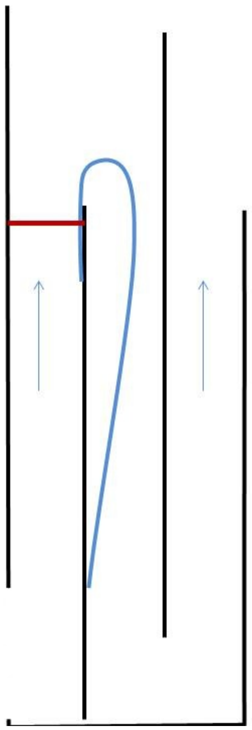

Figure 5: Placement of Floc Break up Device

Final Design

No research has yet been conducted to determine the relationship between the number of devices and flocculation performance. There have also been no studies indicating where in the flocculator the device would be the most effective, but from our understanding of flocculation, the break up device is needed less in the beginning of flocculation because there are enough small flocs to aggregate and not as many large flocs have formed. We also chose not to put floc break up devices on the last channel because we still want the flocs to have time to form into medium and large sized flocs so that they can be easily removed by the sedimentation tanks. As such, we recommend installing them in the middle two channels. We chose five break up devices because it gives a reasonable lower bound for porosity.

We input orifice diameters that are in increments of drill bit sizes, 1/16-inch, into Equation 18 to determine the associated number of orifices that would need to be drilled. Then we input the orifice diameter and number of orifices into Equations 14, 16, and 13. We checked that the design solution gave an acceptable porosity, head loss, and energy dissipation rate.

Our design solution consists of five break up devices that each have 21 2-inch diameter holes drilled into them. The head loss through one device is 9.3 mm and it has a porosity of 40%. The effective porosity of the plate, which does not account for area covered by the foam, is 49%. The energy dissipation through the device is 300 mW/kg

We do not have the capacity to test our full design in the Cornell laboratory, but will send our design to the plant in Atima, Honduras where it can be fabricated and tested.

Device Fabrication

The device will be fabricated in Honduras using local materials and labor. A large orifice size was chosen to reduce the number of holes required for drilling. Also, a hole size corresponding to a drill bit size was chosen to ensure ease of fabrication. The plate will be made of chemical resistant polypropylene or PVC depending on what is locally available. The plates will be stacked together and a plank of wood placed on either side. Holes can be drilled straight through the wood and all the plastic sheets at the same time. No holes will be placed on the outer 0.5 inch perimeter of the plate to allow room for attachment to the plant as described in the Attachment to Flocculator section.

Future Work

1. The next step is to have a meeting with Drew to discuss fabrication techniques in Honduras and testing strategies.

2. Drew will test the floc break up devices in Honduras