Venturi Spring 2012 Final Report

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The purpose of a venturi is to create a low pressure zone_in the contraction of a pipe that can be used to pull fluid from another location into the existing flow against the force of gravity. AguaClara can use this technology to implement floc recycle and decrease the necessary size of the flocculator. A pipe will transport heavily flocculated and turbid water from the floc hopper in the sedimentation tank to the horizontal section of the rapid mix pipe_that leads into the flocculator. A venturi constructed in this horizontal portion of the rapid mix pipe_will pull this turbid water from the floc blanket into the incoming plant flow and thereby increase the incoming turbidity. The flow of the turbid water transported from the floc blanket to the rapid mix pipe is dependent upon difference in head at the end of the system compared to the head in the throat of the venturi. By recycling the turbid water, a greater floc volume fraction will_be present at the beginning of the flocculator to increase collisions and thereby reduce the amount of time that the water must spend in the flocculator; this, in return, will reduce the size of the flocculator and reduce material and construction costs.

Literature Review

Venturis are currently available on the market for water pumping applications; however they are either quite expensive and not necessarily optimized for our purposes (too small or not enough suction). The venturi works by using a contraction in a pipe to increase the velocity in that section. Because more energy is devoted to velocity in this contraction, the pressure decreases. If the pressure is below atmospheric pressure, it creates suction which can draw in water from another pipe (Figure 1). We need to determine the ratio of cross-sectional areas between the contraction and the expansion to build a venturi that can recycle floc water at the most efficient rate. Simple manipulation of the energy equation can determine this relation (Equation 5).

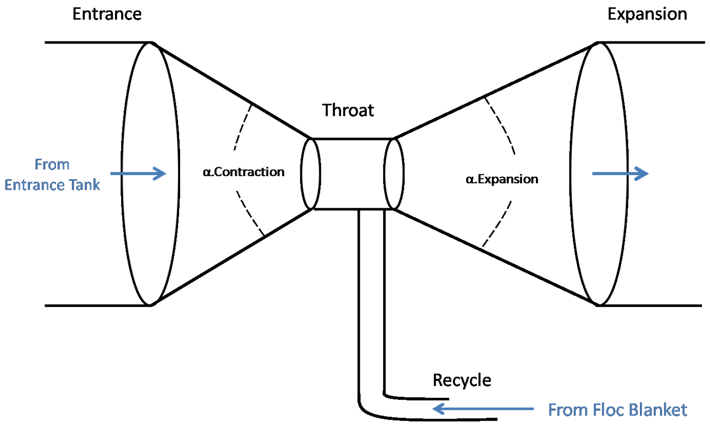

Figure 1: Design of Proposed Venturi. This figure shows the complete layout of the venturi. Water flows from left to right, and recycled water is taken up in the small recycle tube.

To integrate a venturi into the rapid mix pipe of an AguaClara plant, it was necessary to determine the amount of recycled water that must be drawn into the venturi. According to Karen Swetland, this flow rate of the recycle pipe can be approximated based on Figure 2. By knowing the turbidity entering the recycle pipe, the concentration can be determined and thus the flow rate can be calculated (1)

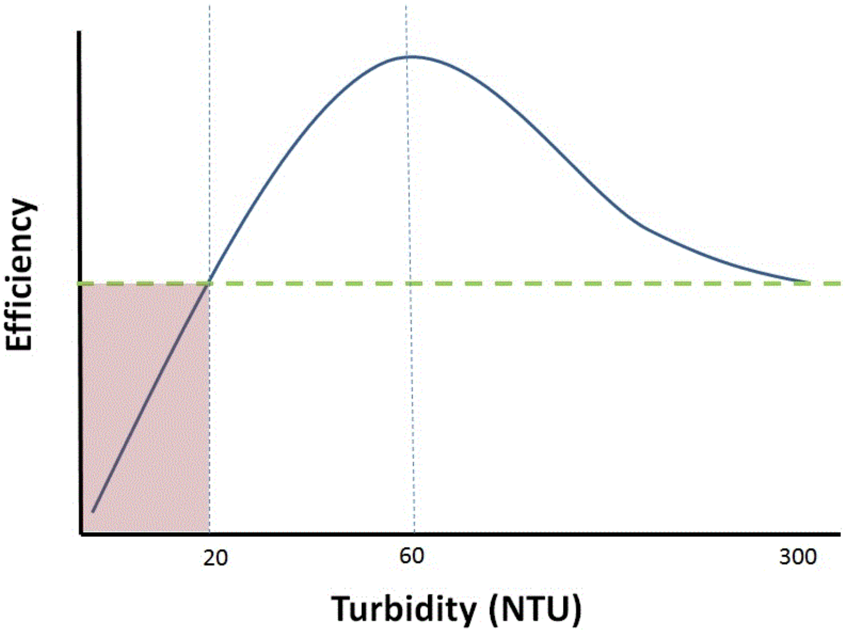

Figure 2: Flocculation_efficiency_curve. Shows the relative efficiency of a flocculator in treating influent water at different turbidities. The red box denotes the low range efficiencies that floc recycle could eliminate. The turbidities listed on the x-axis are best approximations by Karen Swetland, and should be revised based on further research.

Flocculation is least efficient with low turbidities, so by increasing the influent turbidity above the sub-optimal range, we can shorten the flocculator significantly (denoted by the red area in Figure 2). Karen gave us some starting values upon which we based our calculations. The minimum desirable turbidity of water entering the plant was assumed to be around 65 NTU. The concentration of the recycled water was assumed to be around 4 $\frac{g}{L}$_entering the transport pipe. The AguaClara Turbidimeter team from Summer 2011 developed graphs to translate NTU to mg/L of clay. This information was helpful in setting up a mass balance to hit our target of a 65 NTU minimum plant inflow turbidity. Yet, the turbidity of the water coming out of the floc blanket was out of the scope of their experiment and thus our value of 4 $\frac{g}{L}$ was obtained from an estimate by Monroe Weber-Shirk._

Another important factor in floc recycling is keeping flocs suspended in the recycling pipe. The post-sedimentation flocs will be highly turbid and will need some momentum in the recycle pipe to avoid settling. To prevent sedimentation in the pipe, a scouring velocity must be maintained. This scouring velocity can be modeled as the velocity inside the flocculator:0.148 $\frac{m}{s}$ for a 12 $\frac{L}{s}$ plant.

A venturi is essentially a gradual contraction funneled into a throat followed by a gradual expansion. The head losses in the venturi were the minor head loss through the contraction, the minor head loss through the expansion and the major head loss through the throat. The head loss coefficient for the expansion was calculated from the A.H. Gibson Equations (Gradual Expansion). The loss coefficient for the contraction was best estimated as $K_{Contraction} = 0.07$, as referenced from "Fluid Mechanics 6th Edition" by Frank M. White. These values are only valid for a venturi with a cylindrical contraction. An AguaClara venturi might be fabricated by deformation of a cylindrical pipe, which could skew these head loss estimates. However, due to a lack of information on minor loss coefficients for irregular contractions, the determined values serve as a starting point for calculations.

Analysis

In determining whether the venturi is feasible for an AguaClara plant, a set of calculations were constructed. First, the flow rate that the venturi would need to draw out of the recycle pipe was determined. . As mentioned in the *Literature Review* section, the concentration that will ideally enter the flocculator, $C_{Flocculator}$, is set to a concentration of $100\,\frac{mg}{L}$, or a turbidity of $65\,NTU$.On the other side of the plant, the concentration of the floc blanket, $C_{Recycle}$, is currently estimated at $4\,\frac{g}{L}$. From the graphs generated by a previous AguaClara Turbidimeter team in Summer of 2011 that relate turbidity to kaolin clay concentration, the incoming_turbidity values could be converted to concentrations. To eliminate the least efficient turbidities from the flocculator, the turbidity of $0\,NTU$ water needs to be increased to near $65\,NTU$ (2). By using these concentrations, a mass balance can be created to determine the the flow rate needed in the transport pipe, $Q_{Recycle}$. The equation is expressed by:

$$Q_{Recycle} = \frac{Q_{Plant}(C_{Flocculator} - C_{Plant})}{C_{Recycle} - C_{Flocculator}} \tag{1}$$

Next, to determine the area of the floc recycle pipe (Figure 3) necessary to prevent settling of the flocs in the pipe, it was necessary to find a certain velocity to scour the flocs. As mentioned in the *Literature Review* section, the scouring velocity may be best estimated as a value close to the velocity in the flocculator. After determining this velocity, the minimum area and nominal diameter of the transport pipe necessary for that particular plant flow rate was found. The length of the floc recycle pipe is a sum of the width of the sedimentation tank, the width of the flocculator and half the length of the horizontal portion of the rapid mix pipe. Half of the length of the horizontal portion of the rapid mix pipe was chosen as a viable length because it can be assumed that the entrance of the recycle pipe into the throat of the venturi will occur halfway through the rapid mix pipe.

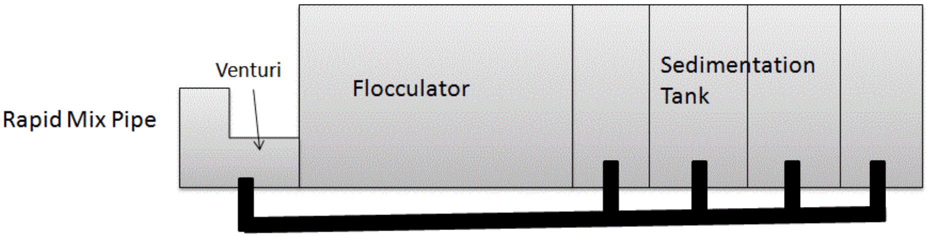

Figure 3: Floc Recycle System. This side view of the plant shows the location of the floc recycle pipe with respect to the overall plant layout.

To see if the venturi has the actual capability to transport water from the floc recycle pipe into the rapid mix pipe, it was necessary to compare the head at the end of the system (end of recycle pipe) to the head in the throat; the water will flow from the sedimentation tank through the recycle pipe and up into the throat of the venturi if the pressure at the end of the recycle pipe is greater than the pressure in the throat. Because water flows from high to low pressure, the water from the floc blanket will be "pushed" through the recycle pipe and into the venturi. This difference in head between the throat and the end of the system is defined as $h_{difference}$:

$$h_{difference} = h_{EndOfSystem} - h_{Throat} = 0.05\,m \tag{2}$$

where

$$h_{EndOfSystem} = \frac{P_{Entrance}}{\rho_{water} g} - HL_{Total} \tag{3}$$

and

$$h_{Throat} = \frac{P_{Throat}}{\rho_{water} g} \tag{4}$$

Where$h_{EndOfSystem}$ refers to the remaining head at the end of the plant. This head is the original head at the entrance to the venturi, $\frac{P_{Entrance}}{\rho_{water} g}$, minus the total head loss in the plant, or HL_{Total}. The definition of HL_{Total} will be described in the upcoming paragraphs.

To determine the most efficient, workable venturi system, $h_{difference}$ will be a small positive value. This indicates that there is slightly more head at the end of the system, $h_{EndOfSystem}$, than at the throat of the venturi, h_{Throat}, and thus water will be successfully recycled into the throat of the venturi. Yet, because no head is wasted, water will flow into the throat with barely any velocity left. To insure this best case scenario, $h_{difference}$ was set to the value of a $SafetyFactor$, or $5\,cm$. This will mean that the head at the end of the system is $5\,cm$ higher than the head in the contraction. Water will successfully be pushed into the throat of the venturi with a slow velocity upon entrance.

To find the head in the throat and the entrance to the venturi, it is necessary to find the pressure in the throat and the entrance to the venturi. These pressures can be found from the help of the Bernoulli Equation (Equation 5).

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \tag{5}$$

This equation can be rearranged to solve for the pressure in the throat as:

$$P_{Throat} = -1 \left[\left(\frac{1}{2} \rho_{Water} \right) \left(V_{Contraction}^2 - V_{Entrance}^2 \right) - p_{Entrance} \right] \tag{6}$$

where the $P_{Entrance}$ refers to the pressure in the entrance to the venturi (Equation 7).

$$P_{Entrance} = \rho_{water} g \left(h_{RapidMix} + HL_{Venturi} \right) \tag{7}$$

where $h_{RapidMix}$ is the head in the rapid mix pipe, which refers to the vertical height of the water column in the rapid mix pipe. The pressure in the entrance tank also includes the head loss incurred by the venturi. Thus, the pressure in the entrance tank must make up for the head loss in the venturi, or $HL_{Venturi}$. This head loss in the venturi can be calculated by the sum of the minor losses in the contraction and the expansion of the venturi (Equation 8).

$$HL_{Venturi} = HL_{Expansion} + HL_{Contraction} \tag{8}$$

where $HL_{Expansion}$ can be modeled as:

$$HL_{Expansion} = \frac{K_{Expansion} (V_{ThroatWithRecyclewater})^2}{2g} \tag{9}$$

where $V_{ThroatWithRecycleWater}$ is the throat velocity of the water from the entrance tank mixed with the recycled water. Equation 10 defines the head loss coefficient for the venturi expansion, $K_{Expansion}$.

$$K_{Expansion} = 2.61 (1 - \frac{A_{Throat}}{A_{Entrance}})^2 sin \frac{\alpha_{Expansion}}{2} \tag{10}$$

where $\alpha_{Expansion}$ is the angle of expansion that will be described in more detail in the following paragraphs. Also, $K_{Expansion}$ can be written as a function of A_{Throat}, which will be solved for in the upcoming steps.

To get the second loss in the venturi, the head loss in the contraction was modeled as:

$$HL_{Contraction} = \frac{K_{Contraction} (V_{Entrance})^2}{2g} \tag{11}$$

where $K_{Contraction}$ was determined to be equivalent to 0.07, as mentioned in the *Literature Review* section.

Next, to determine the total head loss in the plant, it is necessary to sum up all the separate head losses incurred in the system (Equation 12).

$$HL_{Total} = HL_{Flocculator} + HL_{Recycle} + HL_{Expansion} + HL_{Elbow} + HL_{EntranceIntoRecycle} + HL_{Exit} \tag{12}$$

This total includes the expansion of the venturi, the flocculator, the sedimentation tank, the recycle pipe and the entrance in and exit out of the recycle pipe. In this calculation, the head loss in the sedimentation tank is ignored because the majority of head losses incurred in the sedimentation tank are from the flow exiting through the launder. Because this venturi system does not involve the launder because flow exits from the bottom of the sedimentation tank, it is safe to assume that the head loss in the sedimentation tank, HL_{Sed}, is zero.

The head loss through the flocculator, or $HL_{Flocculator}$, was calculated as:

$$HL_{Flocculator} = \frac{HL_{Floc}}{N_{FlocChannels}} \tag{13}$$

where HL_{Floc} is the head loss in the flocculator for some flow rate and $N_{FlocChannels}$ is the number of channels in that flocculator. Because floc recycle will theoretically reduce the length of the flocculator, only one flocculator channel will be necessary if floc recycle is successful. Thus, the head loss incurred in the flocculator will be the head loss in the flocculator for one channel.

Next, $HL_{Recycle}$ describes the major head loss in the recycle pipe. This major loss is a function of the flow rate through the plant, the diameter of the recycle pipe, the length of the recycle pipe, the kinematic viscosity of the water and the roughness of PVC pipe. Regardless of the flow rate, the head loss in the recycle pipe is extremely small. For a $12\,\frac{L}{s}$ plant, for example, the head loss through the $8.3\,m$ pipe is $5.5\,mm$.

While $HL_{Expansion}$ has been described previously,HL_{Elbow} is the head loss from the elbow in the recycle pipe that makes a turn for the pipe to meet the throat of the venturi (Equation 14).

$$HL_{Elbow} = \frac{K_{Elbow}(V_{Recycle})^2}{2g} \tag{14}$$

K_{Elbow} can be best estimated as 0.04, a value taken from *Fluid Mechanics 6th Edition* by Frank White.

$HL_{EntranceIntoRecycle}$ is the head loss from the entrance of the water into the recycle pipe from the floc blanket in the sedimentation tank (Equation 15).

$$HL_{EntranceIntoRecycle} = \frac{K_{EntranceIntoRecycle}(V_{Recycle})^2}{2g} \tag{15}$$

where $K_{EntranceIntoRecycle}$ is best modeled as:

$$K_{EntranceIntoRecycle} = (\frac{1}{Pi_{VC}} - 1)^2 = 0.376 \tag{16}$$

where Pi_{VC} is the vena contracta coefficient of 0.62.

Finally, HL_{Exit} describes the head loss in the pipe from the water leaving the recycle pipe into the throat of the venturi (Equation 17).

$$HL_{Exit} = \frac{K_{Elbow}(V_{Recycle})^2}{2g} \tag{17}$$

and K_{Elbow} equals1, as referenced from *Fluid Mechanics 6th Edition* by Frank White.

As a result of the calculation of HL_{Total}, $h_{EndOfSystem}$ can be determined and thus $h_{difference}$ can be fully calculated. Now, the only missing variable is the necessary area of the throat, or A_{Throat}. The following equation was derived through the previous equations listed that involve A_{Throat}.

$$h_{difference}(A_{Throat}) = -HL_{Total(A_{Throat})} - \frac{V_{Entrance}^2 - V_{Throat(A_{Throat})}^2}{2g} \tag{18}$$

Because all the variables in this equation are already known for besides A_{Throat}, A_{Throat} can be determined through the “Find” function, as described here:

$$Find\, A_{Throat}(h_{difference}) = Find(A_{Throat}) \tag{19}$$

Through this function, A_{Throat} is now found as the maximum throat area that successfully recycles water through the venturi with $h_{difference} = 0.05\, m$.

By assuming that the throat pipe will be cylindrical, the diameter of the throat, d_{Throat}, can be found (Equation 20).

$$d_{Throat} = (\frac{4A_{Throat}}{\pi})^{\frac{1}{2}} \tag{20}$$

To determine the length of the venturi in reference to the length of the rapid mix pipe, a group of calculations were compiled. The length of the contraction is a function of the angle of contraction and the diameters of the throat and the entrance pipe. Meanwhile, the length of the expansion is a function of the angle of expansion and the diameters of the throat and the entrance pipe. Together with the length of the throat, the length of the venturi, $L_{Venturi}$, can be calculated (Equation21).

$$L_{Venturi} = L_{Contraction} + L_{Throat} + L_{Expansion} \tag{21}$$

where

$$L_{Contraction} = \frac{(d_{Entrance} - d_{Throat})}{2} tan \frac{(180deg - \alpha_{Contraction})}{2} \tag{22}$$

and

$$L_{Expansion} = \frac{(d_{Entrance} - d_{Throat})}{2} tan \frac{(180deg - \alpha_{Expansion})}{2} \tag{23}$$

Also, L_{Throat} is assumed to be equal to $2d_{Recycle}$. Then, the remaining space in the rapid mix pipe can be calculated (Equation 24).

$$Space_{RemainingInRMPipe} = L_{RMHorizontal} - L_{Venturi} - 2SafetyFactor \tag{24}$$

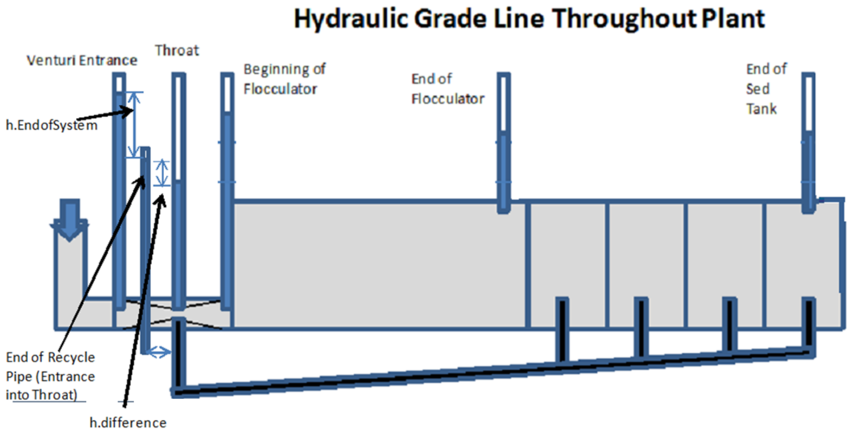

Figure 4: Illustrates the hydraulic grade line throughout the plant. Piezometers lie above each section of the plant to portray the static liquid pressure in that part. $h_{difference}$ and $h_{EndOfSystem}$ are described in the picture as the difference in two different heads in the plant.

where $L_{RMHorizontal}$ is the length of the horizontal portion of the rapid mix pipe and $SafetyFactor$ is set to $5\,cm$, as described previously. The geometry of the venturi can be seen in 5.

Results

As described in the *Analysis* section, $h_{difference}$ was set to a value of $5\,cm$ to ensure that the head at the end of the system (after expansion, flocculator, sedimentation tank and recycle pipe), $h_{EndOfSystem}$, is $5\,cm$ higher than h_{Throat}, the head in the throat of the venturi. Because $h_{difference}$ is positive, water from the floc blanket will be successfully recycled back into the throat of the venturi. In the MathCad document titled “Venturi_2.0”, the user can pick a desired flow rate of the plant and the program will generate a feasible venturi system based on defined difference in head, $h_{difference}$. The program uses the equations described previously in the *Analysis* section to generate all of the necessary specifications of a working venturi system installed in an AguaClara plant. For example, if the user desires a $12\,\frac{L}{s}$ plant, the *Summary* section of the “Venturi_2.0” document will output all of the attributes of the AguaClara plant that utilizes a workable venturi and a successful floc recycle system (6) Whether the flow rate is desired at $5\,\frac{L}{s}$ or $60\,\frac{L}{s}$, the document will generate a workable venturi system that implements a successful floc recycle program in the plant (there are some discrepancies that will be explained in the *Future*

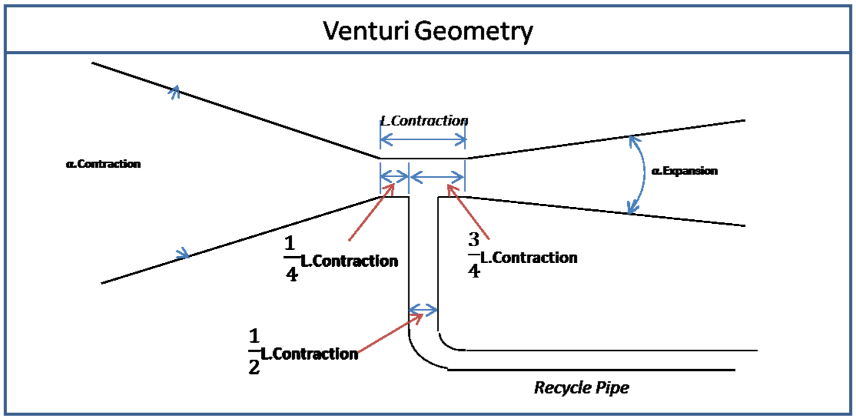

Figure 5: Portrays the geometry of the venturi; not to scale. Assumptions were made considering the positioning of the recycle pipe on the throat of the venturi and the length of the venturi in terms of the recycle pipe ($L_{Throat} = 2d_{Recycle}$).

Work section).

As the flow rate increases, the length of the venturi does not fit into the rapid mix pipe as easily. Thus, angles of contraction and expansion, $\alpha_{Contraction}$ and $\alpha_{Expansion}$, respectively, are set up as inputs in the top of the document. As the flow rate increases, the user is given instructions to continue to increase $\alpha_{Expansion}$ by $1\,degree$ until the length of the venturi, $L_{Venturi}$, is less than the length of the horizontal portion of the rapid mix pipe, $L_{RMHorizontal}$. When this is true, the variable $Space_{RemainingInRMPipe}$ will be positive. Originally, $\alpha_{Expansion}$ is set to the optimal value of $7\,degrees$ while $\alpha_{Contraction}$ is set to $60\,degrees$. $\alpha_{Expansion}$ is ideally low so that most of the kinetic energy in the throat is converted back into a higher pressure. On the other hand, since there is little to no head loss in the contraction, the value of $\alpha_{Contraction}$ is set to a fairly high value and is instructed to stay constant. Yet, $\alpha_{Expansion}$ may need to increase above $7\,degrees$ as the flow rate increases and $L_{RMHorizontal}$ decreases in length.

Variable	*Description*	*Value*
$d_{EntranceNom}$	*Nominal pipe diameter of the rapid mix pipe*	$8\,in$
$h_{Entrance}$	*Head at the entrance of the venturi*	$1.739\,m$
d_{Throat}	*Diameter of the throat in the venturi*	$9.863\,cm$
A_{Throat}	*Area of the throat in the venturi*	$76.401\,cm$
$DiameterRatio$	*Ratio of the entrance pipe diameter to the venturi throat diameter*	2.055
h_{Throat}	*Head at the throat of the venturi*	$1.62\,m$
HL_{Total}	*Total head loss in the plant, from expansion in venturi to end of recycle pipe*	$0.069\,m$
$HL_{Venturi}$	*Total head loss in the venturi*	$0.013\,m$
$HL_{PercentageFromExpansion}$	*Percentage of head loss in the venturi that comes from the expansion*	96.138%
$L_{Venturi}$	*Horizontal length of the venturi*	$1.046\,m$
$\alpha_{Contraction}$	*Angle of contraction in the venturi*	$60\,deg$
$\alpha_{Expansion}$	*Angle of expansion in the venturi*	$7\,deg$
$Space_{RemainingInRMPipe}$	*Horizontal space remaining in rapid mix pipe with venturi enclosed inside (with SafetyFactor)*	$4.3\,cm$
$L_{Recycle}$	*Horizontal length of the recycle pipe*	$8.383\,m$
$d_{Recycle}$	*Diameter of the recycle pipe*	$3\,in$
$h_{difference}$	*Difference in HGL between end of recycle pipe and throat of venturi*	$5\,cm$
V_{Throat}	*Velocity in the beginning of the throat of the venturi*	$1.571\,\frac{m}{s}$
$V_{ThroatWithRecycleWater}$	*Velocity in the throat with the water from the entrance tank and the recycled water*	$1.611\,\frac{m}{s}$
$V_{Entrance}$	*Velocity in the entrance of the venturi*	$0.372\,\frac{m}{s}$

Figure 6: Table of the specific attributes of the most feasible and constructable venturi system at a flow rate of $12\frac{L}{s}$

Future Work

Many assumptions were made within our initial calculations and compilation of necessary equations. Before finalizing the results on the venturi's feasibility at various flow rates, it is important to optimize current values. In particular, more accurate values for turbidity from the sedimentation tank and the desired influent turbidity for the flocculator must be determined. Also, the actual head loss of the venturi will need to be calculated because the shape of the contraction may be more rectangular than circular depending upon construction techniques. Further calculations may need to be performed concerning the expansion, throat, and contraction of the venturi using a flattened PVC pipe rather than fully cylindrical pipes.

The program "Venturi_2.0" fails to create a successful venturi system and floc recycle program at some particular flow rates. At flow rates of $3\,\frac{L}{s}$ and below, the source code is not able to calculate the height of the water column in the rapid mix pipe. Because this value is unknown, the pressure and head in the entrance to the venturi cannot be found, and thus the program cannot run. Also, the program fails to work at flow rates between $40\,\frac{L}{s}$and $55\,\frac{L}{s}$. If the user inputs a flow rate in this range, the program calculates the inner diameter of the rapid mix pipe as $0\,m$. Because of this, the area in the rapid mix pipe cannot be determined and thus the velocities are not known as well. This prevents the Bernoulli Equation from being properly executed. It is believed that the source code may not be able to determine the inner diameter of Schedule 40 pipe at $40\,\frac{L}{s} - 55\,\frac{L}{s}$ for some reason. It is recommended that these failures be looked at further to help optimize the program.

It is important to note that all of the calculations performed in the analysis are based on a successful system running at steady state (water flowing from the sedimentation tank, through the recycle pipe and into the throat). Thus, further calculations must be done that correspond to plant start-up. Initially, there is no recycled water running through the flocculator and thus the calculations would be different when the recycle water is added to the plant flow rate.

Additionally, the angles of contraction and expansion must be optimized to produce the most efficient venturi that is still constructable inside the existing rapid mix pipe. Since the plant will require extra head to compensate for the head losses incurred in the venturi, determining how to decrease this added head will help feasibility of construction. One of the final steps will involve constructing the most feasible and workable venturi system and implementing it into an AguaClara plant. At this point, not much is known on methods of constructing the venturi's expansion, contraction and throat. It is recommended to build the throat through methods of pipe squishing, but not much is known about how to still get the desired throat area through this method. Different fabrication methods for the venturi contraction, throat and expansion construction will need to be tested. Lastly, it will be necessary to develop a better idea of the hydraulic methods to combine flocs from the sedimentation tanks. Ideas have been posed on how to pull recycled water from various bays, but it is not quite known how this will affect the activity of the floc blankets.