Low Flow Flocculator Spring 2012 Final Report

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Abstract

Open flow flocculators, like those currently used in AguaClara plants, increase in cost for lower flow rates (less than $5\frac{L}{s}$). AguaClara must be able to meet the need of a wide range of community sizes, so scaling the design for low flow plants is crucial. This report specifically analyzes three different scenarios that use obstructions within a pipe to remove the geometric constraints that cause the errors found in the current designs. Two scenarios include placing semi-circular baffles (similar to those in open flow flocculators) within the pipe and maintaining the spacing between and above the baffles or maintaining the area between and above the baffles. The last scenario involves placing balls on a string through the center of a pipe. A table is provided within this report comparing critical values for these flocculators for a 3 L/s plant. An initial comparison of the three options shows that the scenario that maintains area above and between baffles is the most effective with materials. However, discrepancies with calculations in the approach using balls as obstructions ultimately yields the results inconclusive.

Introduction

Flocculation is the process by which small suspended particles are aggregated into larger particles that are able to settle out in a sedimentation tank. This process is traditionally carried out by low speed electric mixers, which create turbulence through which particles collide. AguaClara uses a vertically oriented hydraulic flocculator, which creates collisions between particles in the jet expansions around the corners of obstructions, called baffles, placed in a concrete channel. This design is effective and does not require electricity. However, for construction purposes, the length of the flocculator channels must equal the length of the sedimentation tank and the width of the channels cannot be narrower than the width of the human hip. These constraints make AguaClara's flocculators very inefficient for low flow rates – there are more material costs for flocculators operating at less than 5 L/s than those operating at higher flow rates. This lack of scalability makes the current design impractical. We seek to create a hydraulic flocculator that can be contained within a pipe instead of an open channel. This design has the disadvantage of inaccessibility for maintenance; however, it eliminates the constraints that make hydraulic flocculators ineffective at low flow rates. In understanding where the use of pipe flocculators might be effective, we can implement them to reduce the cost of water treatment at low flow rates.

Literature Review

As mentioned above, the constraints imposed on current flocculators leave little room for a truly efficient flocculator with a low influent flow rate. In creating a flocculator contained within a pipe, many of these spatial constraints are eliminated and a more practical design for a flocculator operating at flows less than $5\,\frac{L}{s}$ can be developed. Though many modifications are necessary, the research and development conducted by AguaClara to date with hydraulic open channel flocculators is highly relevant to these pipe flocculators; many concepts regarding collision potential, energy dissipation, and flocculation efficiency are useful in a low flow flocculation design. We selected an optimal $\frac{H}{S} = 4$ ratio based on CFD Analysis conducted by AguaClara, which corresponds to the highest possible flocculation efficiency (α_ψ) (Figure 1). Additionally, we assumed a maximum energy dissipation of $10\,\frac{mW}{kg}$, which limits the breakup of flocs to an acceptable level, thus creating flocs large enough that they can settle out in the sedimentation tank. We selected a dissipation uniformity constant (α_ε) of two based on the value used in the current AguaClara plants. α_ε refers to the ratio of maximum energy dissipation to average energy dissipation. These selected parameters are described in more detail in the Analysis Section.

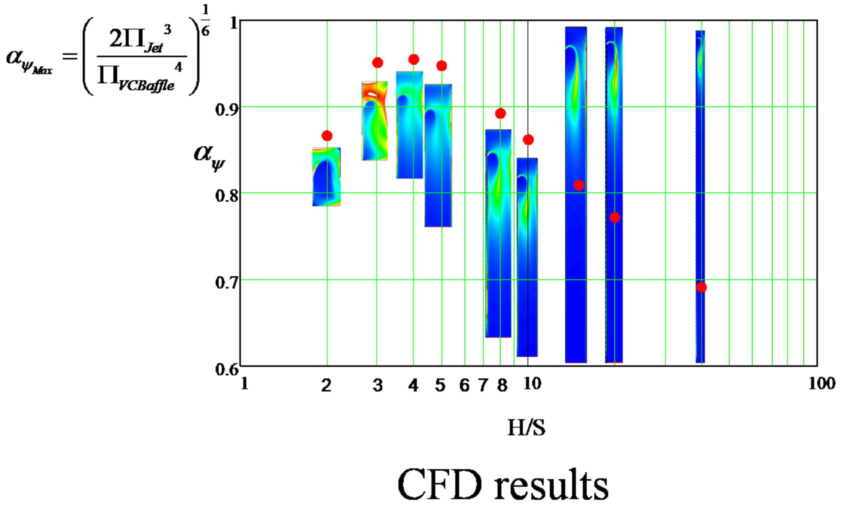

Figure 1: Plot of Flocculation Efficiency Against H/S Ratio for an Open Channel Flocculator

Though many calculations can mimic those from which current AguaClara flocculator technology is based on, fundamental changes in geometry make modification to these calculations imperative.

Pipe flocculators have been constructed for wastewater treatment purposes but are significantly different from this proposal in their approach and construction. These flocculators are simply a series of pipes connected by bends where the collisions take place. Coagulant is dispersed inside one of the beginning pieces of the pipe and the raw water is flocculated around the bends (see http://www.gosansa.com/esp/aguas/stork/brochures/BrochureB2.pdf). The companies that create these flocculators have not made the mathematical or scientific logic behind their processes and construction available to the public. This approach of flocculating the water is very different from a flocculator using obstructions in a pipe.

Analysis

By placing obstructions in a pipe, there are two processes which could produce flocculation: flow expansions/contractions and severe direction changes in the flow path. AguaClara currently uses direction changes around baffles to cause collisions between particles in a fluid. The open flow vertical flocculators used by AguaClara route flow around baffles with consistent spacing above, below and between the baffles. A rectangular parcel of fluid with a constant area perpendicular to the flow travels through the flocculator without undergoing any expansions or contractions. Spacing is always conserved around corners and the cross-sectional area that the flow sees also remains constant. Creating a flocculator inside of a pipe using semi-circular baffles closely mirrors the current designs but cannot maintain both of the following scenarios: (1) The spacing above and between baffles could be maintained, which results in flow expansion and contraction. (2) The areas above and between baffles could be maintained to reduce these additional losses.

Using baffles creates the most abrupt changes in flow, but it is not certain if this is the most ideal or effective design for a low flow flocculator. Therefore, a third scenario was analyzed using balls within a pipe to represent the case where the flow does not abruptly change directions and all flocculation occurs because of expansions in the flow path. In examining the three extreme cases of baffles with equal spacing, baffles with equal area, and balls as obstacles, the most efficient flocculation mode can be determined.

Figures 2 and 3 provide a simple overview of the baffle scenario.

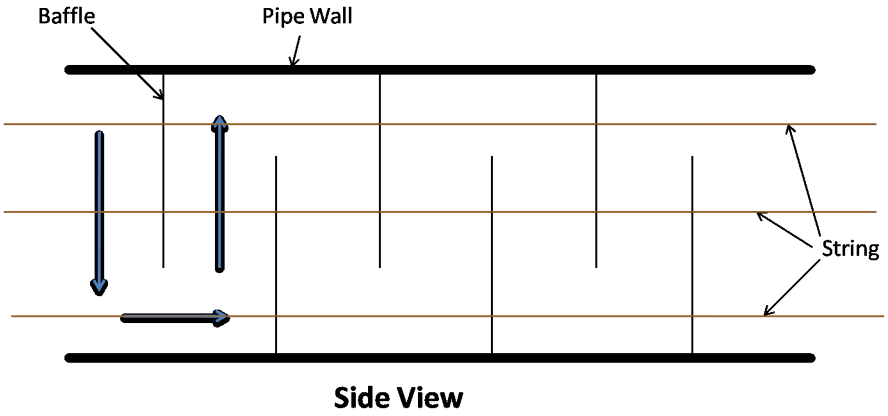

Figure 2: Simple diagram of a low flow flocculator using baffles.

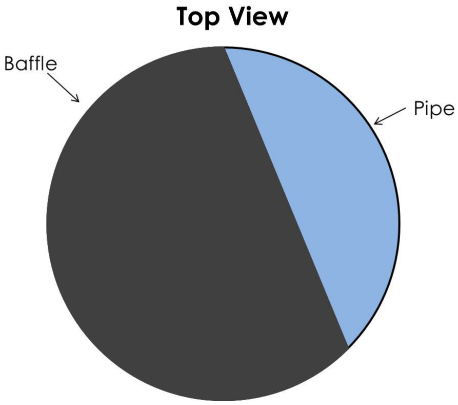

Figure 3: View of a Baffle within the Pipe Flocculator from the End of the Pipe.

To determine the appropriate spacing and pipe diameter for both scenarios of the baffle analysis, some assumptions were made based on optimal values used in the current AguaClara open flow flocculators. The ratio of the pipe diameter to the spacing above the baffles ($\frac{H}{S}$ ratio) was assumed to be 4:1. Past research by AguaClara indicates that this ratio gives the most uniform, and hence most efficient, energy dissipation rate. This $\frac{H}{S}$ ratio allowed for the use of equations dominated by viscous processes, and corresponded to a collision potential efficiency (α_ψ) of 0.95 and an energy dissipation uniformity (α_ε) of 2. Additionally, the collision potential ($\psi_{FlocBod}$)of $100\, m^{\frac{2}{3}}$ and a maximum energy dissipation of$10\ \frac{mW}{kg}$ were selected based on their use in AguaClara plants. From these values, the average energy dissipation ($\bar{\varepsilon}$) is $5\ \frac{mW}{kg}$.

The first scenario analyzed, the Distance Correlation, maintained equal spacing above and between the baffles (Figure4).

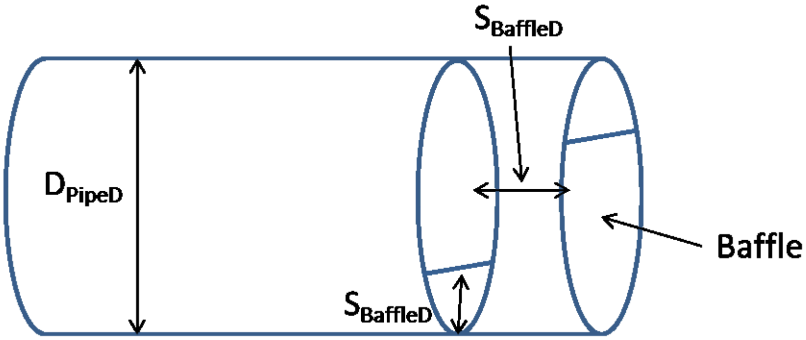

Figure 4: The dimensions and layout for the distance correlation.

To determine the design for this flocculator, the pipe diameter necessary to maintain the assumptions listed above was calculated based on Equation 1 from the current AguaClara plants and Flocculation Notes.

$$S_{Baffle} = \left(\frac{K_{Baffle}}{H\varepsilon_{Max}}\right)^{\frac{1}{3}} \frac{Q_{Plant}}{W} \tag{1}$$

Where S_{Baffle} is the baffle spacing, $K_{Baffle}$is the minor loss coefficient due to the baffles, H is the height of the channels in the current AguaClara flocculator, $\varepsilon_{Max}$is the maximum energy dissipation, Q_{Plant} is the flow rate in the flocculator and W is the width of the channels in the current AguaClara flocculator. To adapt this equation to pipe flow, H and W need to be correlated to the pipe diameter (Equations 2 and 3).

$$H = D_{Pipe} \tag{2}$$

$$W = \overline{D_{Pipe}} = \frac{\pi}{4} D_{Pipe} \tag{3}$$

These relationships can be substituted into Equation 1, and if $\frac{H}{S} = 4$ is assumed, D_{Pipe} can be calculated based on known and assumed variables (Equation 4).

$$D_{Pipe} = \left(\frac{K_{Baffle}}{\varepsilon_{Max}}\right)^{\frac{1}{7}} \left(\frac{4Q_{Plant}HtoS_{Ratio}}{\pi}\right)^{\frac{3}{7}} \tag{4}$$

The necessary pipe diameter and baffle spacing were then calculated; these values, in addition to those found from all of the following equations, are summarized for a 3 $\frac{L}{s}$ plant in Table 9.

The average velocity within the pipe is defined by the plant flow rate divided by the average cross sectional area between two baffles (Equation 5).

$$\bar{v} = \frac{Q_{Plant}}{\frac{\pi}{4} D_{Pipe} S_{Baffle}} \tag{5}$$

where $\bar{v}$ is the average velocity though the flocculator. The residence time between two baffles can be calculated using the volume between the baffles and the plant flow rate (Equation6).

$$\theta = \frac{(D_{Pipe})^2 \frac{\pi}{4} S_{Baffle}}{Q_{Plant}} \tag{6}$$

Where θ is the residence time between each baffle. The residence time leads to calculation of the collision potential per baffle as defined by Equation 7.

$$\psi_{Baffle} = \alpha_{\psi}\theta\bar{\varepsilon}^{\frac{1}{3}} \tag{7}$$

Where ψ_{Baffle} is the collision potential per baffle, α_{ψ} is the collision potential efficiency. Collision potential is a geometric property of the flocculator. It is a measure of the ability of the flocculator to provide collisions between particles. If a target number of collisions are needed for effective flocculation, and the collision potential per baffle is known, then the number of baffles needed within the flocculator can be found using Equation8.

$$N_{Baffles} = \frac{\Psi_{FlocBod}}{\Psi_{Baffle}} \tag{8}$$

Where $N_{Baffles}$ is the number of baffles, $\psi_{FlocBod}$ is the collision potential that the flocculator must provide.

The length of the pipe can be determined from simple algebra given the number of baffles and spacing between them using Equation9.

$$L = (N_{Baffle} + 1)S_{Baffle} + NT \tag{9}$$

Where L is the length of the flocculator and T is the thickness of the baffle material.

The total residence time in the flocculator can then be determined using the number of baffles and the residence time between each baffle (Equation 10).

$$\theta_{Total} = \theta N_{Baffles} \tag{10}$$

The head loss for this scenario includes only minor losses; major losses are insignificant (~0.2% of the total losses). The minor losses result from flow around the baffles in addition to the expansions and contractions the flow sees while moving between the different cross-sectional areas above baffles and between baffles. The minor loss coefficient for sudden expansions (K_{ex}) was calculated using Equation 11. A clear equation to calculate the minor loss coefficient for the contraction (K_{con}) was not available as it appears that these values are generally determined experimentally. Additionally, the contraction head loss is minimal compared to the expansion head loss, so minor losses due to contractions were assumed to be 0.

$$K_{ex} = (1 - \frac{A_{in}}{A_{out}})^2 \tag{11}$$

where A_{in} is the area above the baffle and A_{out} is the cross-sectional area at the center of the space between two baffles based on $\overline{D_{Pipe}}$ and S_{Baffle}.

To verify these calculations, the maximum and average energy dissipation were recalculated using Equations 12 and 13:

$$\bar{\varepsilon} = \frac{K_{Baffle}\bar{v}^2}{2\theta} \tag{12}$$

where $\bar{\varepsilon}$ is average energy dissipation.

$$\varepsilon_{Max} = \frac{K_{Baffle}\overline{v}^3}{D_{Pipe}} \tag{13}$$

where ε_{Max} is the maximum energy dissipation. Since the initial assumption was that maximum energy dissipation was 10 $\frac{mW}{kg}$ and that average energy dissipation was 5 $\frac{mW}{kg}$, any deviation from these values at the final stage of calculations indicated an error in the algorithm. However, the model was able to accurately reproduce these values, indicating consistency in our mathematical assumptions.

In the second scenario analyzed, the area between the top of a baffle was set equal to the rectangular area between the baffles at the center of the pipe (Area Correlation) (Figure 5) . The spacing over each baffle is designated by S_{Over} and the spacing between baffles is designated by $S_{Between}$. The pipe diameter and the spacing between the baffles remain the same from the Distance Correlation. A very similar method can be used to determine the design parameters for this scenario. The area over a baffle, as well as the spacing between baffles, can be determined geometrically. Again, head loss for this scenario only included minor losses from the baffles. Using the same algorithm described above, the average velocity, residence time, collision potential per baffle, number of baffles and pipe length were calculated for a 3 $\frac{L}{s}$ plant (Table 9).

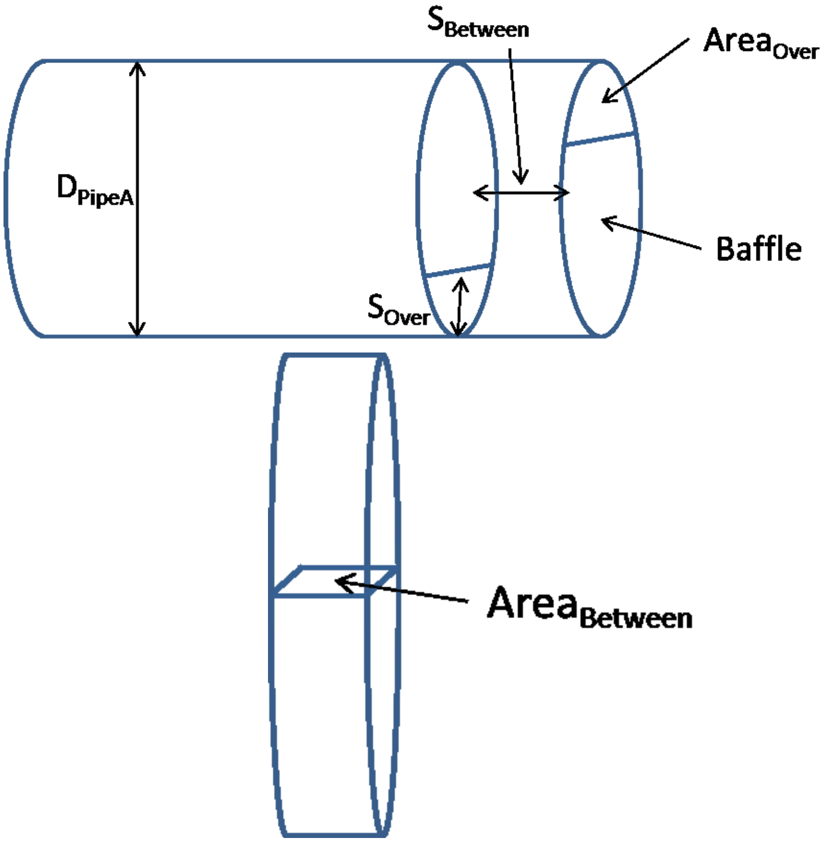

Figure 5: The dimensions and layout for the area correlation.

For the the third scenario, where balls were used as obstructions, a ratio between the cross-sectional area of the ball to the cross-sectional area of the flocculator (Π_{Ball}) was set to 0.6. This geometry most closely mimics that of an open channel vertical flow flocculator. As water flows around a baffle, a vena contracta forms that confines the bulk of forward flow to an area equal to 40% of the total cross-sectional area (Figure 6). To replicate this flow path, balls are assumed to obstruct 60% of the pipe. This assumption also implies that there is no vena contracta as water flows around the balls.

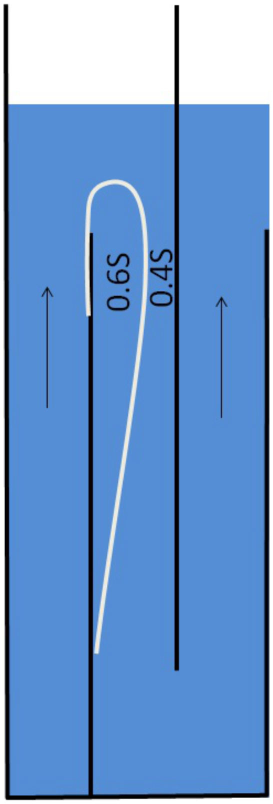

Figure 6: Representation of vena contracta for water flowing around a baffle

Using this rationale, the diameter of the ball was determined algebraically using Equation 14:

$$d_{Ball} = [\Pi_{Ball}(d_{Floc})^2]^{0.5} \tag{14}$$

where Π_{Ball} is the ratio of the cross sectional area of the ball to that of the pipe, d_{Floc} is the diameter of the flocculator, and d_{Ball} is the diameter of a ball. Another major assumption in the model is that the optimal spacing between balls would allow the doughnut-shaped jet passing each ball to expand fully before hitting the next obstruction. A jet expands$10\,units$ along its width for every $1\,unit$ it expands along its length. Since the jet must expand the radius of a ball, this gives a relation between the radius of the ball and the center-to-center spacing between balls:

$$S_{Ball} = r_{ball}(ratio_{expansion} + 1) \tag{15}$$

where $S_{Ball}$is the center-to-center spacing between balls, $r_{Ball}$is the radius of a ball, and $ratio_{expansion}$is the ratio of jet expansion along its length to expansion along its width $(10:1)$.

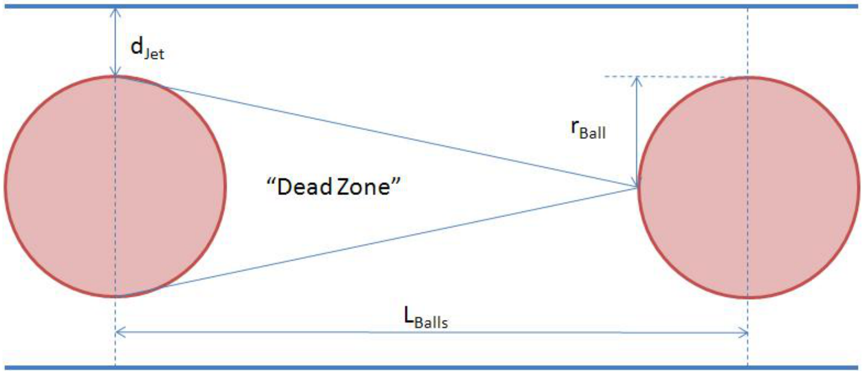

Figure 7: Control Volume View Between Two Ball Obstructions in a Pipe Flocculator

An active control volume was determined by subtracting the volume of a ball and the cone-shaped volume of the dead zone from a cylinder of water in the control volume (Figure 7). This is the volume of water that sees forward movement by the flow. The average velocity of the jet was found using Equation 16:

$$\bar{v} = \frac{QS_{Ball}}{V_{Control}} \tag{16}$$

where Q is the plant flow rate, S_{Ball} is the center-to-center spacing between balls, and $V_{Control}$ is the active control volume between 2 consecutive balls. The average energy dissipation was found using Equation 12, where S_{Ball} is substituted for d_{pipe}. This series of equations gave 4 equations and 4 unknowns, and a value for d_{Ball} could be determined algebraically (Figure 8).

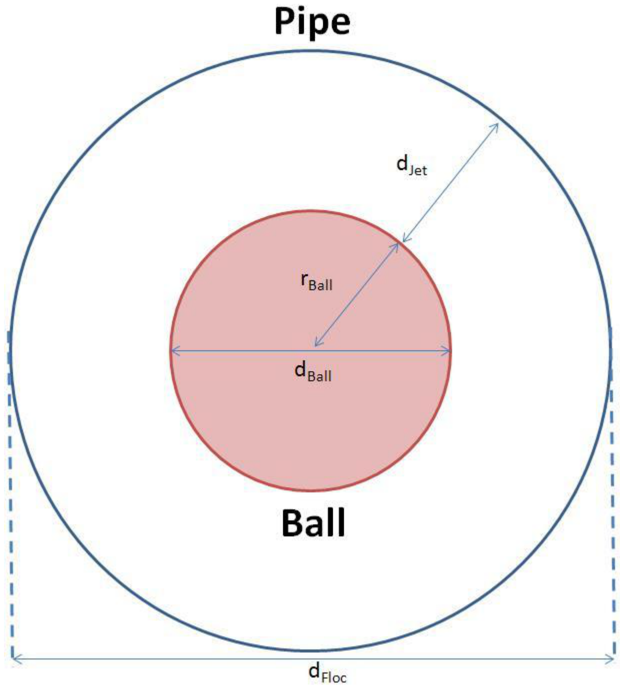

Figure 8: Cross-Section of a Pipe Flocculator Across a Ball Obstruction

The residence time between balls (θ) was defined as the active control volume,$V_{Control}$, divided by the plant flow rate, Q. It then followed that the collision potential per ball and the number of balls could be calculated using Equation 7 and Equation 8. The minor head loss assumed by each ball was calculated using Equation 11, where A_{in} was calculated from d_{Floc} and A_{out} was calculated using the area of the doughnut-shaped expansion (Figure 8). The total length of the flocculator was determined by multiplying distance between balls (S_{Ball}) with the number of balls (N_{Balls}). Using this system of equations, a preliminary design was calculated using a flow rate of $3\frac{L}{s}$; the results are shown in Table 9. Furthermore, the maximum energy dissipation was recalculated using Equation 13 to ensure consistency throughout the algorithm. This energy dissipation was calculated to be 21 $\frac{mW}{kg}$ despite the initial assumption that maximum energy dissipation is only 10 $\frac{mW}{kg}$, indicating a potential inaccuracy in the calculations.

Figure 9: Summary of Theoretical Values Attained by 3 different Pipe Flocculator Designs at $3\frac{L}{s}$

Variable	Description	Distance Correlation	Area Correlation	Balls as Obstacles
$S_{Between}$	Spacing Between Two Baffles/Balls	$8.9\,cm$	$8.9\,cm$	$65.6\,cm$
S_{Over}	Spacing above a Baffle/Spacing between Ball and Pipe Wall	$8.9\,cm$	$12.6\,cm$	$1.7\,cm$
d_{Pipe}	Pipe Diameter	$36\,cm$	$36\,cm$	$15\,cm$
$\bar{v}$	Average Velocity	$0.12\,\frac{m}{s}$	$0.12\,\frac{m}{s}$	$0.21\,\frac{m}{s}$
θ	Residence Time Between Baffles	$2.9\,sec$	$2.9\,sec$	$3.1\,sec$
ψ_{Baffle}	Collision Potential per Baffle/Ball	$0.48\,m^{\frac{2}{3}}$	$0.48\,m^{\frac{2}{3}}$	$0.48\,m^{\frac{2}{3}}$
$N_{Baffles}$	Number of Baffles/Balls	210	210	209
L_{Pipe}	Length of Pipe	$19.2\,m$	$19.2\,m$	$137\,m$
θ_{Total}	Total Residence Time	$10.3\,min$	$10.3\,min$	$10.8\,min$
H_{Total}	Total Head Loss	$32\,cm$	$31\,cm$	$20\,cm$
d_{Ball}	Diameter of Ball	N/A	N/A	$11.9\,cm$

The difference between the distance and area correlations is minimal and only manifests itself within the spacing above the baffles and in the head loss. Both situations maintain the desired energy dissipation and produce reasonable velocities, collision potentials and residence times. However, both of these scenarios differ significantly form the third case with balls as obstructions, which requires a much longer, thinner pipe length and a much higher average velocity through the flocculator. However, due to the discrepancy in the maximum energy dissipation check for the ball scenario, the results should be analyzed further before a final conclusion is reached on which design is optimal.

Conclusions

Our model produced feasible, but not completely ideal results. The ball obstruction option requires significantly more pipe material than the other two options, but there are indications that the algorithm used to arrive at this conclusion is flawed. The distance correlation situation seems to be the best option at low flow rates. For this option, at $3\,\frac{L}{s}$ the pipe would be $36\,cm$ in diameter and $19.2\,m$ long, containing $210\,baffles$. These numbers are a promising start, since they are not completely unreasonable. However, the assumptions made in the shift of geometry from an open channel to flow in a circular pipe need to be evaluated in depth before a final solution is determined. This can be done with a sensitivity analysis of all assumed parameters.

Future Work

The balls as obstructions scenario requires further analysis and refinement. We speculate that the use of an "active control volume" approach might be skewing the results, and that the "dead zone" is taken into account by flocculation efficiency (α_{ψ}), as in the current open flow flocculator designs (see Figure 7). This might explain why the maximum energy dissipation is inconsistent. In addition to modeling this scenario with confidence, a sensitivity analysis should be conducted to test the sensitivity of all three models to the major assumptions we made, such as α_{ψ}, α_{ε}, and $\prod_{Ball}$. A price comparison should be made between the models to determine for what flow rates they are more economical than the current open flow flocculator. A full analysis of constructability needs to be carried out for each design that takes into account the materials used, construction process, and maintenance requirements. Along with this construction analysis, a method for seeing inside the flocculator needs to be developed so that the operator can ensure proper floc formation. Finally, a prototype flocculator of the most feasible design should be built to verify that calculated values actually correspond to physical flocculator performance.