Anaerobic Fluidized Bed Reactor, Spring 2017

Clare O'Connor, Evan Greenberg, Peter Martin

February 23, 2021

Abstract

The initial focus of the Spring 2017 Anaerobic Fluidized Bed team (AFB) was to continue developing declogging mechanisms for the reactors, however it was learned that side-stepping declogging was possible by focusing on steady-state operation of the reactors. Thus, the middle of the semester included design of two reactor set-ups designed to determine the fastest hydraulic residence time (HRT) that could feasibly be used. The new designed showed that not enough was known about the treatment process to move forward productively, so an extensive literature search was performed to gather more information necessary for a possible redesign in the fall.

Introduction

Developing sustainable wastewater treatment is an important part of continuing AguaClara's mission to provide clean water for communities where it is limited. By traditional methods, wastewater treatment is financially and energetically expensive. To combat this fact, the Anaerobic Fluidized Bed team (AFB) is working to develop a reactor that uses anaerobic digestion to maximize the removal of organic material in wastewater while collecting biogas, a gaseous combination of mostly carbon dioxide and methane. The biogas can be used to power the reactor as well as meet other power needs. Though the water treated with the AFB reactors will not be potable, with other post-reactor treatments it will be ready for reuse in other capacities.

The goals for the Spring 2017 semester were dynamic and shifted as the semester progressed. Initially, the goal was to develop functional reactors that operated consistently. In order to achieve this, declogging mechanisms needed to be developed. Once the declogging was side-stepped as an issue the focus of the semester then shifted to developing various flow configurations to determine treatment characteristics. At this point, designing new reactors became the goal after the previous reactor design was deemed faulty. A thorough literature search was conducted to design a more effective model that would allow further and more detailed tests to be conducted on the biology and effectiveness of the AFB system.

These improvements will let future teams continue moving forward with research and progress the design evolution of the AFB technology, with the goal of installing an AguaClara AFB within a Honduran village to serve the residents of the community.

Literature Review

Treatment Capabilities

There has been extensive research conducted on the treatment capabilities of AFB reactors over the past few decades. Anaerobic treatment systems, such as an AFB, have been widely used to treat secondary high strength wastewater streams, such as municipal sludge and/or solid wastes, with minimal use as a primary treatment process. But, the use of anaerobic treatment to treat more dilute streams, such as domestic wastewater, can be achieved with a more thorough understanding of the underlying chemical and biological processes involved(Saravanan and Sreekrishnan, 2006). Biogas, which is composed of carbon dioxide and methane, is an important byproduct of the anaerobic digestion of wastewater. Harvesting the biogas can be utilized as a fuel source for heating, cooking, or power generation. Successful biogas production and capture can offset the costs of the treatment process making it much more feasible in low income areas.

AFB reactors are similar to upflow anaerobic sludge blanket (UASB) reactors in that they both treat wastewater using the process of anaerobic digestion. Anaerobic treatment of wastewater decreases the

chemical oxygen demand (COD) and biological oxygen demand (BOD), which are different measures of the oxidation potential of the contents in the water. Pathogen and nutrient reduction is minimal but still present (Nehru, 2001). AFB reactors differ from UASB reactors because there is a higher flow rate and this flow is more evenly distributed. (Shen et al., 2016) The higher upflow rate in combination with the fluidization it causes allows greater interaction between the microbes and substrates in the influent. When fluidized there an increased motility of the support media, or the granules as in AguaClara's AFB reactors, as they move freely within the main body of the reactor. The greater surface area exposed and interacting with the influent is what allows the fluidized bed to function with a shorter retention time than in settled reactors (Marin et al., 1999).

Tests conducted by Switzenbaum and Jewell (1980) on 2" diameter lab scale AFB reactors achieved COD removal efficiencies from 50-70 percent. In warmer temperatures, removal efficiency is increased. This will make implementing AFB reactors in Honduras more feasible due to its warm climate Switzenbaum and Jewell (1980).

Reactor Design Considerations

AFB reactors differ from other anaerobic reactors in several ways, the most important of which is the upflow velocity at which wastewater is rises through the reactor. Because of this higher upflow velocity, AFB reactors are considered high-rate as compared to low-rate reactors such as upflow anaerobic sludge bed reactors, in which the velocity of the fluid is lower. Higher upflow rates come with both advantages and disadvantages. One characteristic shared by high-rate processes is the ability to maintain a short hydraulic retention time (HRT) and have a long solid retention time (SRT) which lets the concentration of the granules in the reactor stay high throughout the treatment process (Hickey et al., 1991).

Determining the support media is one of the first steps in developing a functional reactor as the characteristics of the media, such as density or adsorption capacity, determine other aspects of the reactor design such as the rate needed to maintain fluidization. Several tested materials include sand, activated carbon, zeolites, porous glass beads, and resilient granules, with those of irregular shape recommended (Hickey et al., 1991) due to a more rapid start-up and potentially higher biomass. Hickey et al. (1991) report that sand is the most common carrier used due to its high availability and low cost, however the AFB reactors use microbial granules. The granules differ from support media in that they are clusters of microbes without an added inorganic media to gather around.

In determining the flow condition for operation, consideration must be taken to ensure the upflow rate is high enough to fluidize the granules, but not too high. An upflow velocity that is too high would flush the granules out of the reactor. Washout could also be caused if the fluidized height of the bed exceeds the available height in the reactor. To avoid this the height of settled granule bed should be known and flow rates should be based on a bed expansion of 20-40% (Marin et al., 1999).

The physical shape of the reactor matters significantly. With an angled settling arm, as in Figure 1 solids will remain in the reactor. The height of the reactor also matters; (Hickey et al., 1991) report that an increase from 40 cm to 100 cm in reactor height caused stratification in the thickness of the biofilm around the carrier particles with thinner films towards the bottom of the reactor where shear is the greatest. The height can also influence the gas flux rates, with taller reactors having higher gas flux for the same loading conditions, due to an increase in the mass of granules (Hickey et al., 1991). Another consideration is that of recycling through the system. According to (Hickey et al., 1991) recycling is necessary for a fluidized bed reactor, and according to (Marin et al., 1999) a high recycle ratio is usually employed and can create optimal alkalinity conditions and resistance to sporadic organic overloads. Given that a principle disadvantage of AFBs is in energy cost due to additional pumping from the recycling, the ability to maintain correct alkalinity is a notable advantage given the chemical cost to maintain a correct pH within the reactor (Marin et al., 1999).

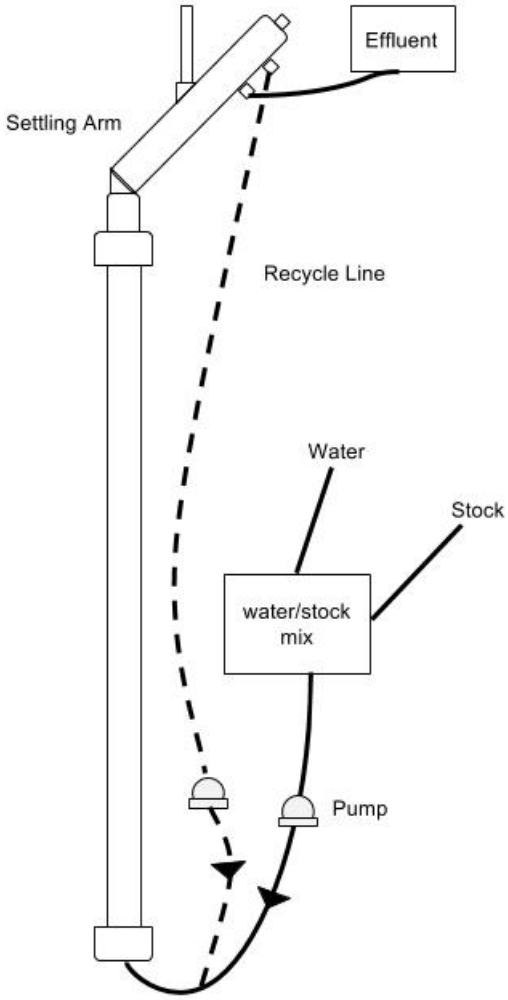

Figure 1: The general reactor set up for one AFB reactor

Characterization of Granular Sludge

The key factor for successful operation of an AFB is the development and maintenance of granular sludge. Granules are well defined conglomerates of microbes and inorganic substituents that comprise the bulk of the fluidized bed of an AFB (Switzenbaum and Jewell, 1980). The granule creation process is not fully known, but the composition of granules has been well documented. The main variability in granules is due to the difference in wastewater composition and available substrate for biological activity, but there are two general components common to most granules: inorganic material, and extracellular polymer (Switzenbaum and Jewell, 1980).

The inorganic material, also referred to as ash, makes up between 10-90% of the dry weight of granules. The main components of ash are calcium, potassium, and iron (Switzenbaum and Jewell, 1980). The importance of calcium and potassium precipitates in granular sludge have been highlighted by their roles in stabilizing individual granules. Experiments which have removed the precipitants have confirmed a decrease in strength of the adhesion of the granules, and in some cases disintegration of the granules, in the absence of calcium and potassium.

The extracellular polymer (ECP) is a structural matrix that is important for developing a well-functioning biofilm for wastewater treatment. Most ECPs are comprised of organic debris, phages, lysed

cells, and other excreted material, along with polysaccharides, proteins, lipids, phenols, and nucleic acids. The ECP matrix can trap nutrients and mediate adhesion of bacteria in the wastewater stream.

Previous Work

Since 2013, AguaClara anaerobic wastewater research teams have been working to develop small-scale models that can be used to test the success of wastewater treatment. However, modeling anaerobic reactors with low HRTs has been difficult in a tabletop size setting. Problems include overflow, head loss, granule washout, and reactor clogging (Maisel Z., 2016).

Of the previously mentioned shortcomings, the issue with granule plug clogging within the reactor has been the prime focus of previous AFB team efforts, as clogging prevented teams from operating reactors continuously without disruption. Granules can form clogs, and biogas production then causes the clogs to rise. The surface tension due to the biogas bubbles and the granule clogs significantly impedes flow. In 2013, the clogs would either break in the settling arm and wash back into the reactor, which was ideal, or they would rise into the gas collection unit or clog the effluent line. The small inner diameters of the tabletop reactors makes this problem difficult to avoid. Fortunately, no evidence of clogging on industrial scales has been found (Maisel Z., 2016).

To combat the cloging issue in the lab-scale reactors some past declogging methods tested include: vibration with back massaging devices purchased from Walmart, a rotating PVC rod inserted into the reactor, using a stir bar in combination with a large magnet to mix the granules, and dropping a heavy object into the reactor to break up clogs (Maisel Z., 2016). In Spring 2017, the already constructed 1" reactors were used so it was very important to consider these clogging problems previous teams have dealt with (Maisel Z., 2016).

The past set up of reactors included four in series, as shown in Figure 2. In one previous design, pumps were installed between each reactor to offset head loss but was discarded quickly due to challenges in coordinating the pump speeds and minimizing head loss (Maisel Z., 2016). It was observed that the error introduced at each pump would aggregate to a significantly high error overall for the system while not necessarily preventing the plugs from forming. The flow rate used in Fall 2016 was about 100 mL/min corresponding to an upflow velocity of 1.8 mm/s in the 1" reactors. These values lead to an HRT of one hour.

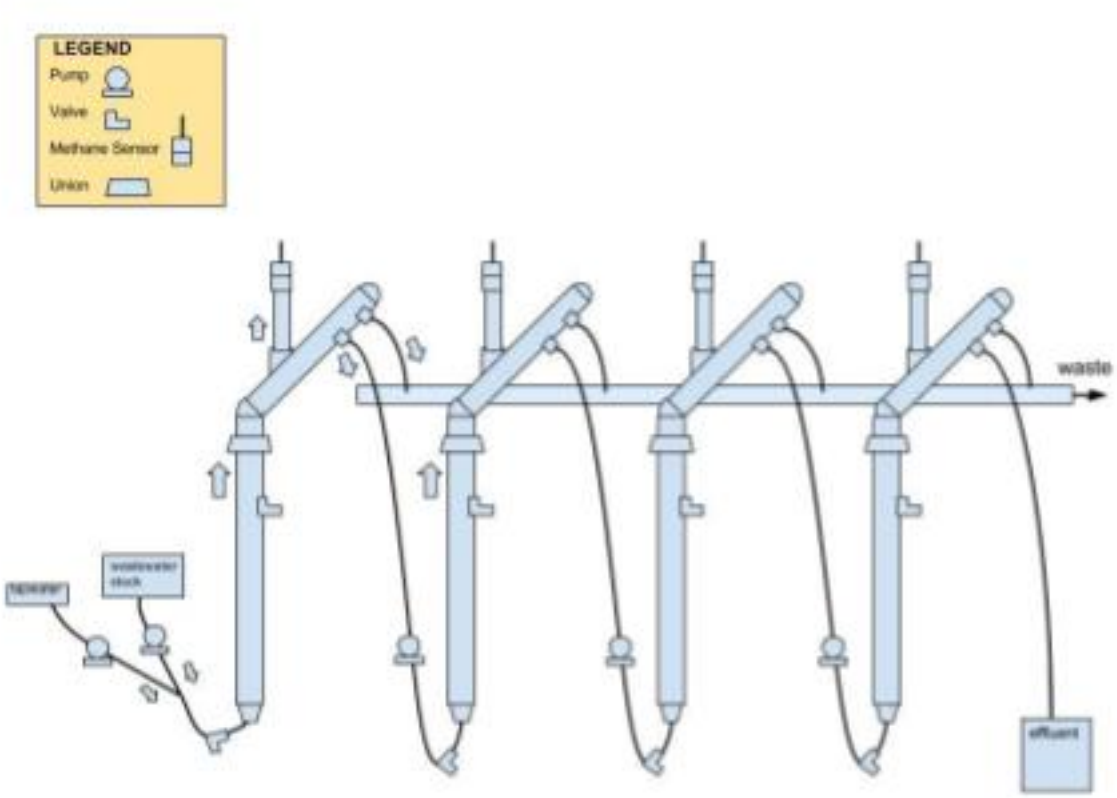

Figure 2: Four reactors in series with the effluent of one leading providing influent for the next. This design was used in Fall 2016, and updated throughout that semester.

Additional work conducted by the 2013 team involved COD tests which resulted in a decrease of COD between of 0% to 100%, which intuitively requires more validation (Gao G., 2013). Biogas collection and measurement has also been a lingering problem in previous semesters. Volumetric measurement by pressure triggered offgas events has been the primary system of biogas monitoring, but other options have been considered such as methane specific sensors, and external measurement units created by the sensor development team shown in Figure 3.

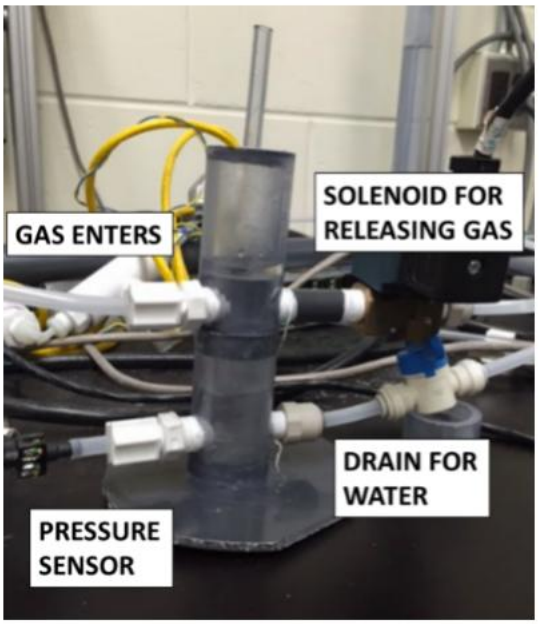

Figure 3: Methane sensors designed by the Sensor team.

These challenges previous teams battled guided the work for the current semester. They indicated the clear need to develop clog prevention and removal methods, change reactor geometry, modify methane collection, and increase frequency of COD and pH testing.

Declogging

Reactor De-Clogging

Before experimentation with the reactors began, the primary focus was developing and implementing methods to reduce granule clogging within the reactors. These efforts were a continuation from previous semesters. The two bench-top methods explored were: crimping the body of the reactors and installing a barbed agitator into the reactors. A review of the original reactor design was done to determine if there were sources of error or adjustments that could be made to remove the potential for clogging.

Procedure

Both the crimps and barbed agitator were tested with sand initially to avoid the challenges associated with granules. Water and air were pumped into the reactors with the declogging mechanisms to simulate operation conditions with gas production. Due to the higher density of the sand compared to granules, a higher flow rate was needed to fluidize the sand as noted in Table 1. After the sand tests, the same tests were conducted with granules at normal operating conditions. To simulate start-up conditions, the granule tests were conducted once the granules became settled and compacted after two days of being left alone.

Table 1: Plug Test Flow Rates of Air and Water (mL/min)

Sand	Granules
350	120

Crimped reactors

Methods

In order to increase the friction from the walls of the reactor on rising plugs, the vertical body of the reactor was crimped or pinched. These crimps acted as obstructions and caused more turbulence due to

expansions and contractions. These factors worked together to to break apart plugs as they rose through the crimped section of the reactor. See Figure 4 for a detailed picture of the crimped reactor with sand partitioned throughout. The crimps were created utilizing a technique previously developed by the 1 L/s Plant fabrication team to produce the pipe flocculator. The PVC reactor was heated up using the PVC welder for approximately four minutes or until it became visibly weak and malleable, then a custom jig was created to squeeze the malleable PVC pipe into the desired shape. See Figure 5 for a visual of the custom jig used to crimp the reactor. Initially only one crimp was placed in the reactor, and two others were later added 6" apart.

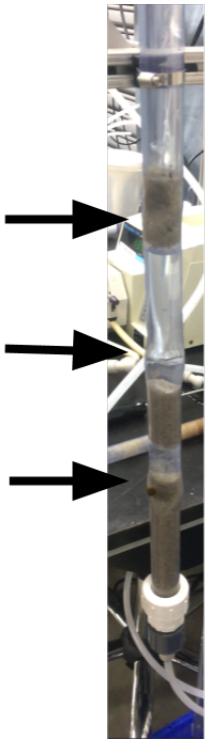

Figure 4: The crimped reactor with sand, in this image clogs of sand formed during start-up but were subsequently broken up once the reactor had been running for several minutes.

Figure 5: Crimping Jig

Results and Analysis

When the crimped reactors were tested with sand, there were very positive results. Plugs would rise up to the crimps and then break apart effectively keeping the bed fluidized and free of plugs. However, once granules were introduced, the clogging recurred. This indicated that the crimped reactors may have needed additional crimp depth to be functional. As the goal was to prevent clogs from forming, this was not determined to be a usable method despite its functionality in breaking many clogs apart.

Barbed Agitator

Methods

Another method explored to reduce clogging was a barbed rod that extended though the length of the reactor. It was attached at the base of the reactor to a spring shown in Figure 6. The spring would oscillate between stretched and compressed positions due to the entire barbed rod being pulled by a rotating arm near the top of the reactor. A picture of the set up is shown in Figure 7. Fishing line connected a rotating pump seen in Figure 8 to the barbed rod and a pulley was used to reduce friction and wear from the continuous movement of the fishing line.

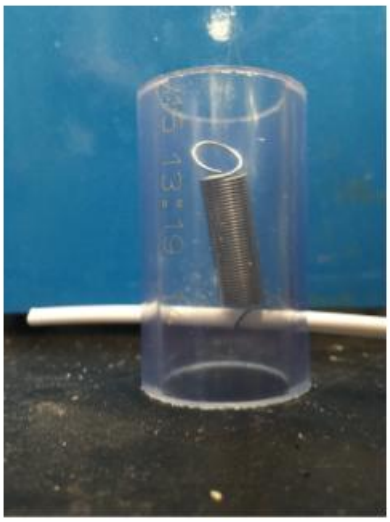

Figure 6: This spring attachment was added to the bottom of the barbed line reactor shown in Figure 7

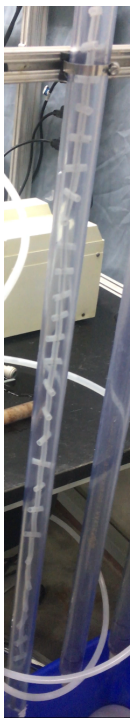

Figure 7: Barbed agitator designed to break up plugs

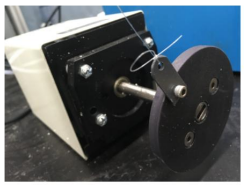

Figure 8: The rotating arm that controls the stretch in the spring of the barbed agitator

Results and Analysis

The Barbed agitator declogging method was effective in breaking up plugs and preventing them from forming. With both sand and with granules, there were no problems with plugs rising up through the length of the reactor. Ultimately this method was not feasible to implement because it required the reactor to be open to atmosphere due to the string that attached the barbed agitator to the rotating arm. Closing and pressurizing the reactor was necessary for proper draining and refilling so the concept of a barbed agitator was deemed unfeasible because the open end of the system would not allow the pressurization to occur.

Once the declogging issue was addressed, the reactors were able to operate consistently at a steady state. After this, the reactors needed to be configured to achieve the proper operating conditions.

Reactor Configuration and Operation

In running the reactor beyond the initial start-up period, it was seen that plugs did not form at 150 mL/min in a reactor operating independently, rather than in series. This observation allowed advances to be made to understand how the reactors functioned in constant use. Two different modes of reactor set-up were designed to characterize different treatment paths. The clogging issue was not solved in Spring 2017, simply side-stepped in order to study steady-state operation. The two methods that were set-up were a recycle reactor and a batch-style reactor; their set-up is shown in Figures 9 and 10. They were run simultaneously at the same organic loading rate (OLR), so that direct comparisons of treatment could have been made. Additionally, in both reactors, having an aspect of recycling allowed the upflow velocity to be high, ensuring fluidization. Without recycling, the reactors either needed to be in series or be very long to have an HRT long enough to provide any treatment because the reactors are too small to treat the influent if the wastewater only cycles once.

Both reactors were run with clean water to determine that the set-up functioned as it was designed to with granules. However, both were operating at 100% recycle to feed the granules while exact conditions for tests were determined. Each reactor contained approximately 300 g of granules, which filled the reactor about one-third of the way up when settled. Though the reactors were set-up in this configuration, it was realized that there were still too many unknowns to be able to garner much useful data out from tests. In addition, the stock feeding mechanism as set-up in ProCoDA worked well only when the reactors were being run constantly, but in Spring 2017 they were starting and stopping often making adding stock a challenge. If this set-up is to be used again a better intermediate method to add stock should be determined until the reactors are being run constantly for tests.

Recycle

Methods

In the recycle reactor, some variable percent of the total flow was from new influent and the rest from a recycle line. There were separate pumps on each line to control the flow rate of each. The percent of the volume that was being recycled was determined manually by the pumps rates. During initial testing to determine if the set-up worked, two-thirds of the total influent was recycled and one-third was removed as effluent, corresponding with a recycle ratio of 2:1. Given a constant organic loading rate (OLR), HRT, and mass of granules, a higher recycle ratio corresponds with a higher upflow velocity. Tests would still need to be conducted to determine where this optimum recycle ratio is for the AFB reactors. In the literature a large range of recycle percentages exist, with some sources advising a 66% recycle rate (Romli et al., 1994) and others using a 94% at normal operation (Punal and Lema, 2002).

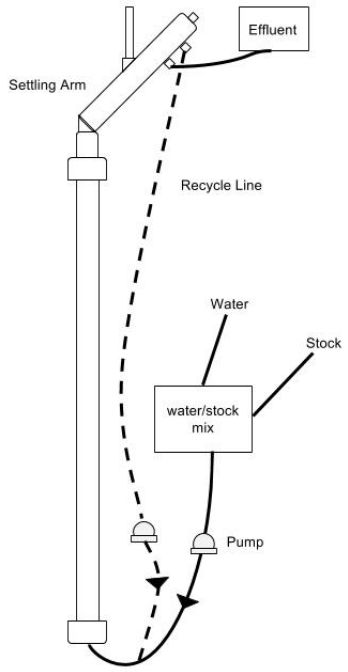

Figure 9: Schematic of recycle reactor

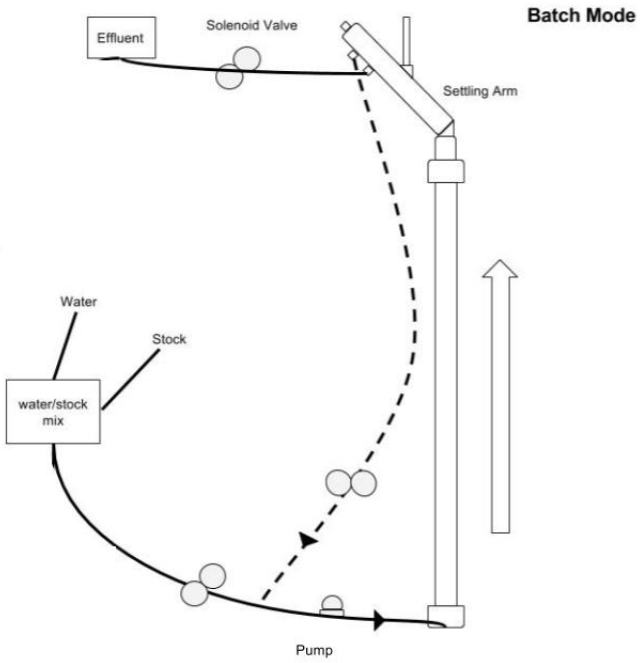

Figure 10: Schematic of Batch mode reactor set-up

Closed Loop Batch Reactors

Methods

The Closed Loop Batch reactor, was run similarly to the recycle, except that it was designed to be run at 100% recycle for a predetermined length of time, every time it was run. Though it was never run fully as intended, the way it would have been run could have revealed useful information. For example, if it were run for a predetermined amount of time, this length of time would be the HRT, making it very useful for determine the minimum HRT needed to provide some treatment. When in use, a volume of influent sufficient to fill the reactor would have been pumped in on start up and would be recirculated until ProCoDA closes certain solenoid valves. At that time, the full volume within the reactor would have been pumped out and new influent would have been introduced to refill the reactor and treat a new batch. As the wastewater in the closed loop batch mode would have been constantly treated, repeated reactors tests using different HRTs would have been able to show the shortest HRT that could yield a decrease in COD. Tests were to be run that would have determined the HRT. This would have been accomplished through running the batch reactor for a given amount of time, perhaps an hour for the first run, and then taking a COD test to determine if there had been a change in COD as compared to the influent. The length of time would have been incrementally increased until a notable change of COD had occurred, and that length of time would then be used as the HRT for the given organic loading rate in the 1" reactors.

Design Calculations

As previously discussed, operation of the AFB reactors has been hindered by continual clogging. After multiple failed attempts at developing a reliable declogging method, it was decided that review of the original reactor design calculations was necessary to determine if declogging could be overcome through a redesign of the system. Although the exact mechanism for reactor clogging remains unclear, it has been assumed that surface tension caused by the small reactor diameter could be a factor. Therefore, the focus of the design calculation review was to determine if reactor sizing could be changed, thus eliminate clogging issues entirely.

Review of Previous Design Calculations

The reactor design established by the Spring 2016 AFB Team, was reviewed for sources of error and improvement. Utilizing a copy of the original MathCAD design file, original design constraints were maintained and all design calculations were re-examined.

After detailed inspection, there have been errors found in the calculations used to design the current reactors. It was determined that the flow rate, Q_{Θ}, that was being utilized to control desired retention time and upflow velocity, was set to approximately 50% of the desired Q_{Θ}. This lead to a reduced retention time and lower upflow velocity than originally desired. It was found that increasing the diameter of the reactors from 1" to 1.5" would achieve the required Q_{Θ}, while maintaining desired hydraulic retention time and upflow velocity. Figure 11 shows the preliminary design calculations examined.

Initially it was assumed that the use of larger diameter reactor ($D_{Reactor}$) would lead to a total required reactor length (H_{Column}) impractical for a laboratory setting. Reconsideration of the design shows that a reactor diameter of 1.5", utilizing four reactors in series, all at a height of 1.7 meters tall (as is currently used), can maintain a flow rate of approximately 130 mL/min at a desired upflow velocity of 1.8 mm/s. To check the flow rate against the desired velocity, the continuity equation was applied, and a flow rate determined (Q_Check). As can be seen in Figure 11 below, Q_{Θ} and the Q_Check are within reason, so it can be assumed that necessary upflow for fluidization will be met for a 1.5" diameter reactor.

CONSTRAINTS:

$V_{UpAFB} := 1.8 \frac{mm}{s}$ $\theta_{AFB} := 60min$

VARIABLES:

$N_{column} := 4$ $H_{column} := 1.7m$ $D_{reactor} := 1.5in$

$A_{column}(D_{reactor}) = 1.14 \times 10^{-3} m^2$

$V_{reactor}(N_{column}, H_{column}, D_{reactor}) = 7.753 L$

DESIGN CALCULATIONS:

$Q_\theta := \frac{V_{reactor}(N_{column}, H_{column}, D_{reactor})}{\theta_{AFB}} = 129.21 \cdot \frac{mL}{min}$

$Q_{Check} := V_{UpAFB} \cdot A_{column}(D_{reactor})$

$Q_{Check} = 123.13 \cdot \frac{mL}{min}$

Figure 11: Design calculations adjusted for 1.5" reactor diameter. These calculations show that in a larger diameter reactor the upflow velocity can be maintained and the goal HRT of one hour can also be used assuming there are four reactors.

To test the theory that reactor diameter affects the formation of clogs, a trial 1.5" diameter reactor was constructed. In constructing this reactor, only clear flexible tubing could be located with a 1.5" diameter, as shown in Figure 12. This was connected to the work station with several zip-ties and pipe clamps and also had a series of expanding fittings at the input to connect the influent line, as no appropriate connectors could be located. Upon being run with sand, clogs did not form, so granules were introduced. Due to the increased volume of the reactor the flow rate was increased to 180 mL/min, an increase from 130 ml/min in the 1" reactors. At this flow rate, clogs formed briefly upon startup but fell apart independently after several seconds, and were not observed later in operation. Another observation was that the flexible tubing would allow for clogs to be broken up easily by hand if they were to form, however the flexibility also made attachment to the work station challenging as clamping even slightly too tightly caused deformations in the reactor. Given the relative success of the larger diameter reactor and the resolution of the calculation error, inquiries were made into what else about the reactors is unknown and could subsequently be improved upon.

Figure 12: 1.5 Inch Flexible Tube Reactor

Analysis of Current Methods

Towards the end of the semester little progress had been made with the new reactor set-up because there were too many unknowns. Between the clogging issues and lack of usable data it was clear that existing design would not work. Prior calculations were based on an HRT which might not be accurate and was much lower than any amount found in the literature. There were also questions about the generality of the reactors, such as if somehow the one hour HRT was good enough how would that work if any of the conditions were changed. This question indicated that not enough was known about how the granules actually treat the water and what is the limiting factor in developing the shortest possible HRT. Additionally, in speaking to Professor Ruth Richardson, questions were raised about the possibility of an upflow velocity that was too high, even when that velocity is lower than the velocity required to flush out the granules. She also asked whether, given equal contact time, if there was a difference in treatment between a parcel of water moving through the reactor quickly many times or slowly a few times, and whether either option may cause a gradient of treatment at different heights within the reactor. It was also unknown if more granules in the reactor necessarily meant that more treatment would occur. Though, some of these questions are testable the number of unknown was deemed to warrant a more extensive literature search to learn what exactly happens within the reactor and what the important parameters to keep in mind for treatment.

Additional Literature Review

An additional literature was conducted with emphasis on understanding how granule characteristics affect treatment.

Biofilm Characteristics

The original AFB Design considered hydraulic characteristics, such as HRT, as the basis for development of a reactor model. Although these parameters are necessary to consider, it is important to understand the mass transfer and reactions that occur within the biofilm, and ultimately dictate the treatment capacity within the reactor. Available models have been reviewed in cursory, and discussed in brief in the section following. Understanding of these models should be considered a priority moving forward.

Biofilm mathematical models assume the transformation of an influent substrate within the biofilm as a process transported by diffusion from the bulk liquid, through the biofilm layer. Figure 13 shows a simplified conceptualization of a biofilm system with a concentration profile, where S_{Sb} is the substrate concentration in the bulk liquid, S_{Ss} is the substrate concentration at the liquid-solid interface between the bulk liquid and biofilm, and S_{Sf} is the substrate concentration at the surface of the carrier particle. As can be seen from the concentration profile, the substrate is highest in the bulk liquid, and reduces rapidly within the biofilm. To model the biofilm, it is important to understand mass transfer to and within the biofilm (external and internal mass transfer, respectively), and the reactions occurring within the biofilm layer.

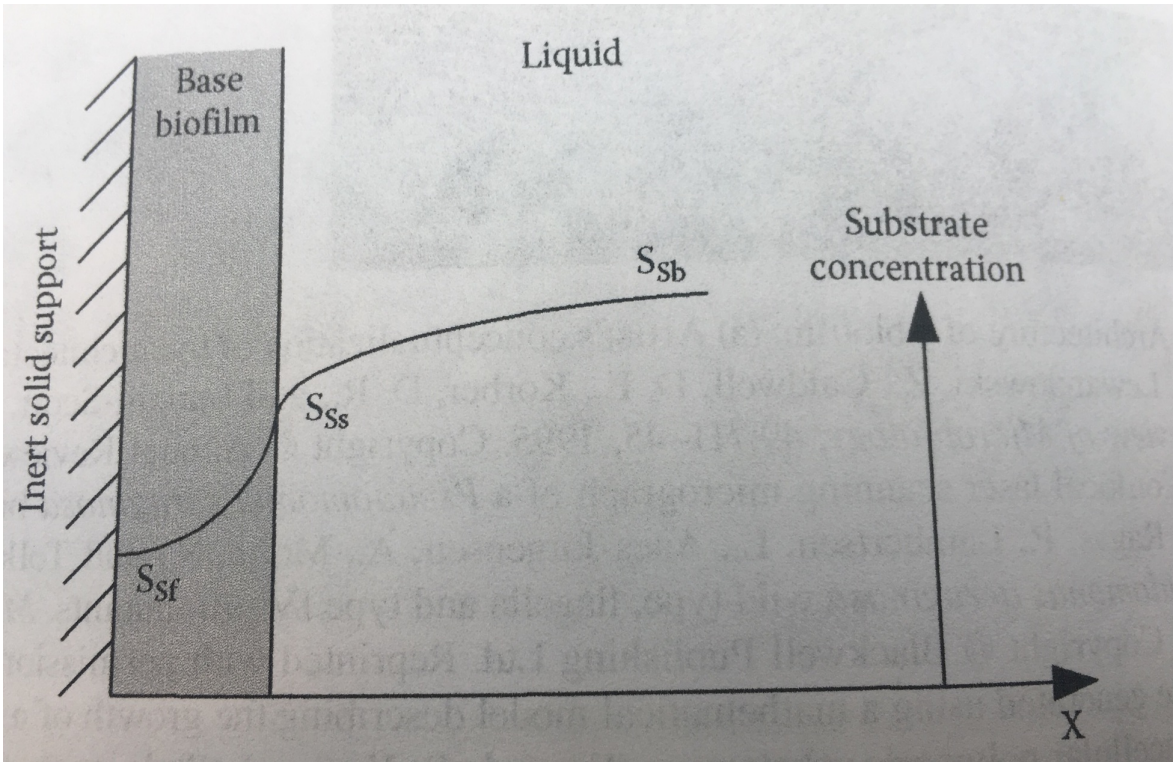

Figure 13: Biofilm Model

Hydrodynamic Characteristics

Once the physical features of the reactor carrier particles, or biogranules in this instance, have been characterized, it is imperative to develop a sound understanding of the hydrodynamic characteristics of the fluidized bed reactor. As the biofilm continues to change (increase size, mass, composition, etc.) during reactor operation, so does the corresponding behavior of the hydrodynamic characteristics.

Mass Transfer

Several approaches have been developed to model external mass transfer, with the following differences; utilization of a diffusivity coefficient, D_w, or utilization of a liquid phase mass transfer coefficient k_L. Both models require knowledge of the thickness of the boundary layer, L_w, to determine the substrate flux from the liquid to the solid phase (flux is quantified as the mass per unit area-time) (Saravanan and Sreekrishnan, 2006). The use of the liquid phase mass transfer model allows for the use of readily available parameters (such as particle density, and size), as opposed to the diffusion equation which requires more stringent laboratory experiments for parameter determination. Therefore, the liquid phase mass transfer shall be utilized for this project. Flux into the biofilm has been defined as follows:

$$J_s = k_L(S_S b - S_S s)$$

Where:

$$k_L = \frac{D_w}{L_w}$$

Mass transfer within the biofilm (i.e. internal mass transfer) can be readily characterized by Fick's first law that defines free diffusion within an aqueous solution.

$$J_f = D_w \frac{dS_S b}{dS_S s}$$

Combining mass transfer with a reaction term can be accomplished in several ways, for the purpose of this report, a pseudoanalytical approach has been selected (Saravanan and Sreekrishnan, 2006). This approach combines numerical solutions into simple algebraic expressions that allows for understanding of mass transfer and reaction kinetics.

Biofilm Kinetics

In order to achieve the goal of developing a more effective wastewater treatment system, the kinetics of anaerobic wastewater degradation must first be understood. The rate at which wastewater is processed by the granules is likely the limiting factor in AFB reactors so several models has been researched. Many models are variations of simple kinetic models that have been adjusted based certain parameters. One such model that was verified experimentally was a zero-order kinetic model. Diez et al. (1999) used the zero-order kinetic model in a batch style AFB reactor, and consistently observed that COD removal occurred according to this model until organic matter was depleted.
Using another model is understood that substrate removal kinetics can be modeled for a biofilm system using a derivation of the classical Monod model for microbial growth.

$$R_t = \frac{4}{3}\rho\pi k_0(r_p^3 - r_m^3)$$

Where R_t is the observed rate for the first order rate expression, ρ is the density of the particle, k_0 is the first-order rate constant, and r_p and r_m are the radius of the biogranule and the biofilm, respectively.

Revised Mathcad Model

With the new information gained through the extensive literature review, new design parameters were determined and with them, a new model was generated. These parameters included the kinetic rate of wastewater degradation along with upflow velocity and hydraulic retention time which were previously included in the previous design model. The new model design was initially similar to the previous design model in that the size and dimensions of the reactor were first determined using the organic loading rate, and upflow velocity. The hydraulic retention time is then established by these parameters. After this, the solids retention time (SRT) and volatile suspended solids (VSS) concentration are established which are essential for proper kinetic modeling. The steps for this design were influenced by the works of Tchobanoglous (2014). The redesigned Mathcad code can be found in Part III of the appendix. The redesign yielded the following:

$$\tau = \frac{V_L}{Q} = 3.35hr$$

Where:

$$V_L = 0.017L$$

$$Q = 5\frac{mL}{hr}$$

Utilizing kinetics for anaerobic sludge treatment (similar to that used for upflow anaerobic sludge blanket systmes), an SRT was determined utilizing the following equation:

$$S = \frac{K_s(1 + (k_d) * SRT)}{SRT * (Y * k - k_d) - 1}$$

Where:

$$S = desiredefluentCOD$$

All other parameters are kinetic parameters and can be found in the Mathcad file located in Appendix III. The SRT was adjusted until S reached the desired concentration. As of right now, the S is about 100 days, which is unfeasible. The design is currently being reviewed by the team.

Conclusions

Though it was determined that some the declogging methods were effective, especially a widening of the reactors to 1.5", these options were bypassed in favor of exploring the steady-state treatment capability of the reactors. Though the treatment capabilities were never determined, the two reactor set-ups, batch and recycle, will be useful tools in the future do accomplish this goal. Characterizing and improving reactor capabilities did not occur this semester because it was determined that it would require a more in-depth understanding of the limiting steps of AFB reactors. A more comprehensive literature review was conducted and with it, a new reactor design model was generated.

Future Work

Moving forward, the team still needs to gather more information and data in order to design an effective system for lab-scale tests. Both physical and biological parameters need to determined for use in the newly generated design model. Future teams will need to examine and characterize the size, shape and structure of the granules. Physical parameters such as size, density, porosity, and resistance to shear forces will all be useful parameters needed in the new design model. Once these parameters are established, the reactor geometry and hydraulic characteristics can be calculated to design an AFB reactor that can be used for further experimentation. Experimentation will be conducted to test the validity of the defined parameters. Gathering the data for the parameters of the new model, fabricating new reactors according to these parameters, and testing the design to prove functionality would be great tasks for the next semester's team, to complete. Once the system is tested and operational, then the parameters can be pushed to the limits and the room for improvement can be explored.

References

Diez, V., Garcia, P. A., and Fdz-Polanco, F. (1999). Evaluation of methanogenic kinetics in an anaerobic fluidized bed reactor (AFBR). *Process Biochemistry*, 34(3):213–219.

Gao G., Gokarn M., G. W. M. D. R. Z. L. (2013). Anaerobic wastewater treatment. research project, fall 2013.

Hickey, R., Wu, W.-M., Veiga, M., and Jones, R. (1991). *The start-up, operation and monitoring of high-rate anaerobic treatment systems (PDF Download Available).*

Maisel Z., Martin P., G. E. V. D. (2016). Anaerobic fluidized bed (afb), fall 2016.

Marin, P., Alkalay, D., Guerrero, L., Chamy, R., and Schiappacasse, M. C. (1999). *Design and startup of an anaerobic fluidized bed reactor*, volume 40 of *Wastewater Anaerobic Treatment.*

Nehru, M. (2001). Upflow anaerobic sludge blanket reactor–a review. *National Environment Engineering Research Institute.*

Punal, A.and Roca, E. and Lema, J. M. (2002). An expert system or monitoring and diagnosis of anaerobic wastewater treatment plants. 36(10):2656–2666.

Romli, M., Greenfield, P. F., and Lee, P. L. (1994). Effect of recycle on a two-phase high-rate anaerobic wastewater treatment system. *Water Research*, 28(2):475–482.

Saravanan, V. and Sreekrishnan, T. (2006). Modelling anaerobic biofilm reactors - a review. *Journal of Environmental Management*, 81(1):18.

Shen, Q., Galdi, S., and Maisel, Z. (2016). Expanded granular sludge bed (egsb) team report.

Switzenbaum, M. S. and Jewell, W. J. (1980). Anaerobic Attached-Film Expanded-Bed Reactor Treatment. *Journal (Water Pollution Control Federation)*, 52(7):1953–1965.

Tchobanoglous, G., B. F. L. . S. H. D. (2014). *Wastewater engineering. treatment and reuse.* New York: McGraw-Hill.

Appendix

Part I
Semester Schedule

Task Map

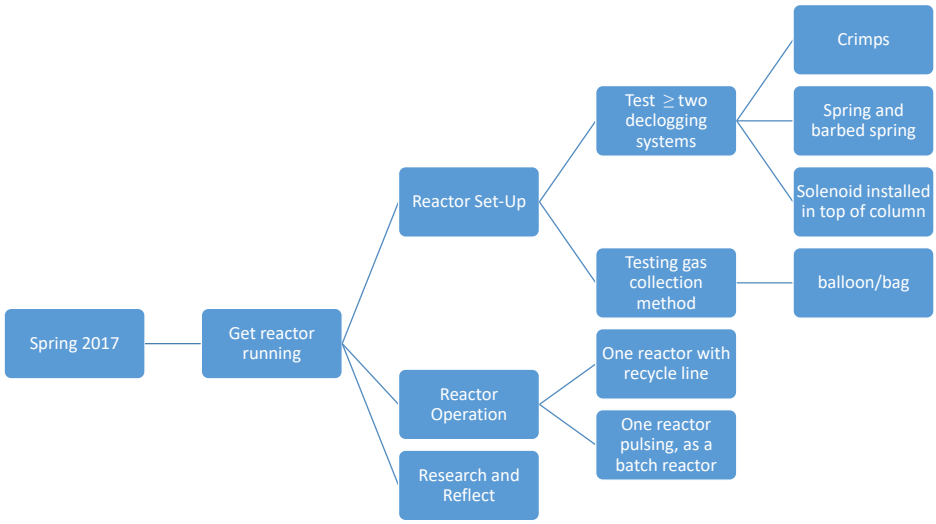

Figure 14: Spring 2017 AFB Task Map

Task List

1. Reactor Setup (3/4)
   (a) Declogging Mechanisms (2/25)
      i. Crimped Reactor System - The team shall develop a pilot reactor that consists of "crimped" sections along the length of the reactor. There shall be several different iterations of this design in order to determine if frequency of crimps, or depth of crimp, can prevent clogging. Once crimped, the reactors shall be put into service utilizing construction sand as a media, under the assumption that if clogging can be prevented in sand, it can be prevented in biogranules. If clog prevention is successful, the team shall focus efforts on modifying the full reactor system. Team should seek guidance from 1 L/S on how to crimp reactors, similar to the 1 L/S flocculator system.
      ii. Spring and Barbed Rod System - The team shall develop a pilot reactor that utilizes a barbed tension wire with spring attachment, to provide continuous declogging within the reactor. The spring shall be secured at the base of the interior of the reactor, and the barbed tension wire shall be connected to an external pump using high strength fishing wire. Once secured in place, various pump speeds and frequencies shall be tested to find an optimal operating point. Similar to the Crimped Reactor System, construction sand shall be utilized as a media for trial purposes.

(b) Modified Reactor System - (2/25)

i. Enclosed Reactor Design - The team shall modify the current reactor system such that the entire reactor is pressurized from the influent line to the point of effluent discharge. The reactor gas collectors and overflow ports shall be sealed off using either plugs, or PVC glue and caps. Once the system has been sealed, it shall be operated utilizing tap water only, to determine the headloss across the system. If headloss is insignificant, the system shall be filled with granules and put into operation.

2. Reactor Operation

(a) Batch Reactor - (2/18)
A new single reactor shall be built and dedicated to experimental operation as a batch reactor system. The team shall build the new reactor, and design a batch process to identify potential benefits to operating the reactors in non-continuous flow states.

(b) Pulse Input Reactor - (2/18)
A new single reactor shall be built and dedicated to experimental operation using a pulse input flow. The team shall build the new reactor, and design a pulse flow pattern to identify potential benefits of a pulse flow system. This shall include developing a ProCoDA design to control the pulse input.

(c) Effluent Recycle Line - (3/15)
The team shall design and build an effluent recycle line to assist with increasing flow through the reactor, and balancing pH and microbe communities.

3. Research and Reflect
Literature review and reactor design research shall be conducted by the team, in order to determine if alternate reactor configurations should be considered for future AFB teams. Evaluation of the current design shall be weighed against alternate configurations to make recommendations. If time permits, the team shall move to fabricate the alternative reactor.

Report Proofreader: Team proof reader shall rotate amongst team members throughout the semester.

Part II
Manual

Experimental Methods

Synthetic Wastewater Recipe

The figure below lists all chemical ingredients used to develop a synthetic wastewater stock recipe that yields a strength of approximately 5,000 mg/L of COD. Utilizing a 5 liter carboy located on a magnetic stir plate, each ingredient should be measured accurately and then added to the carboy. After all dry ingredients have been added, four liters of pure water should be measured accurately and added to the carboy. Once all ingredients are in the carboy, a magnetic stir bar should be added to the carboy, and run the magnetic stir plate on high for 30 minutes, allowing all ingredients to dissolve into solution. The mixture is stored at 20 degrees Celsius.

Table 2: Synthetic waste water stock recipe to produce 4L

Ingredient	Amount
Urea	6400 mg
NH4Cl	800 mg
Peptone	1200 mg
MgSO4	1580 mg
KH2PO4	1220 mg
FeSO4•7H2O	80 mg
CaCl2•2H2O	480 mg
Glucose	16400 mg
Yeast Extract	3600 mg
vegetable Oil	2000 mg
CuCl2•2H2O	40 mg
MnSo4•H2O	8 mg
NiSO4•6H20	20 mg
ZnCl2	20mg

Chemical Oxygen Demand (COD) Tests

Prior to conducting COD tests, the following items should be gathered:

- COD vials (i.e CHEMetrics, Hach) with range suitable for wastewater being tested.
- Digester block capable of heating sample to 150°C (The oven located within the 1st floor teaching lab has been utilized in lieu of a digester block.)
- Personal protective equipment for handling of chemicals and high heat items.
- Fume hood with working ventilation for sample preparation.
- Spectrophotometer for sample readings.

Collect samples in glass bottles. When it is necessary to preserve samples for storage, acidify to pH$\leq$ 2 with concentrated sulfuric acid. Store preserved samples at 4°C for no longer than 28 days after collection.

1. Dilute samples based upon spectrophotometer range.
2. Preheat digester block (or oven) to 150°C.
3. Remove cap from vial, and pipette 2.00 mL of diluted sample into vial. Wear gloves, as contents of vial will become hot.
4. Securely replace vial cap, and invert 10 times to mix contents of vial.

5. Wipe vial, and place into oven rack. Repeat for all samples to be tested.
6. Once all samples are prepped, and oven has reached desired temperature, place oven rack into oven and allow vials to heat for 2 hours.
7. After 2 hours, turn off oven, and allow vials to cool to room temperature before handling.
8. While samples are cooling, start spectrophotometer and spectrophotometer software. Refer to instrument specific instructions for start-up.
9. Wipe exterior of sample vial, and place into spectrophotometer sample compartment for wavelength reading.
10. If applicable, calibrate readings based upon range, and recalculate COD concentration to account for dilution.
11. Shut down all laboratory equipment accordingly, and dispose of COD vials in accordance with lab specific procedures.

Part III
Mathcad Preliminary Design

SPRING 2017 - NEW DESIGN FOR FUTURE TEAMS

$Q := 5\frac{mL}{hr}$

$COD := 550\frac{mg}{L} = 0.55\frac{kg}{m^3}$

$sCOD := 475\frac{mg}{L} = 0.475\frac{kg}{m^3}$

Assumed values based upon average quality for domestic wastewater

$TSS := 55\frac{mg}{L}$

$VSS := 35\frac{mg}{L}$

$L_{org} := 4\frac{kg}{m^3\cdot(day)}$

From recommended values

$E := 85\%$

Effectiveness factor

Determine reactor volume based on the design organic loading rate

$Vn := \frac{Q\cdot sCOD}{L_{org}} = 0.014\,L$

$V_L := \frac{Vn}{E} = 0.017\,L$

Liquid volume

$vn := 1\frac{mm}{s}$

Determine reactor dimensions

$A_{reac} := \frac{Q}{vn} = 1.389\times 10^{-6}\,m^2$

$D_{reac} := \sqrt{\frac{A_{reac}\cdot 4}{\pi}} = 0.052\cdot in$

$H_L := \frac{V_L}{A_{reac}} = 12.071\,m$

HRT - Hydraulic Retention Time of Reactor

$\tau := \frac{V_L}{Q} = 3.353\cdot hr$

Determine Reactor SRT

Based on 90% removal

$$CODtarget := COD \cdot 0.90 = 0.495 \frac{kg}{m^3}$$

$$mumax := 0.25 \frac{g}{g \cdot day}$$

$$Y := 0.08$$

$$k_d := 0.03 \frac{g}{g \cdot day}$$

$$K_s := 360 \frac{mg}{L}$$

$$k := \frac{mumax}{Y} = 3.617 \times 10^{-5} \frac{1}{s}$$

Estimate solids retention time

$$SRT := 3.7day$$

$$S := \frac{K_s \cdot (1 + k_d \cdot SRT)}{SRT \cdot (Y \cdot k - k_d)} = 0.491 \frac{kg}{m^3}$$

Adjust SRT until S is less than or equal to CODtarget

Estimate X.Tss in biomass zone

$$X_{TSS} := \frac{Q \cdot VSS \cdot SRT}{Vn} = 1.091 \frac{kg}{m^3}$$

Part IV
ProCoDA Method File

States

To run the Closed Loop Batch reactor and recycle reactor:

- OFF - Resting state of ProCoDA. All sensors, relays, and pumps are turned off.
- Manual Startup- In this state, the reactors are are filled and recycle lines are primed to ensure no air is pumped through the system. The Effluent valve is closed while the others remain open. The recycle line is manually detached to allow air to clear out of system as water fills it. Once the recycle line is primed, it is manually reattached to the system for normal operation. Manual startup will ideally only need to be used once.
- Batch Operation - In batch operation, the influent and effluent line valves are closed. The valve on the recycle line is open, allowing effluent to leave the reactor. This allows the batch to continually run through the reactor. The time is yet to be set.
- Refill - The solenoid valve on the effluent line is open as is the one at the influent line. The valve on the recycle line is closed, this allows the reactor to refill with new wastewater. The time is yet to be set.

Set Points

- Hydraulic Retention Time - Here, you should list the set points used in your method file and explain their use as well as how each was calculated.

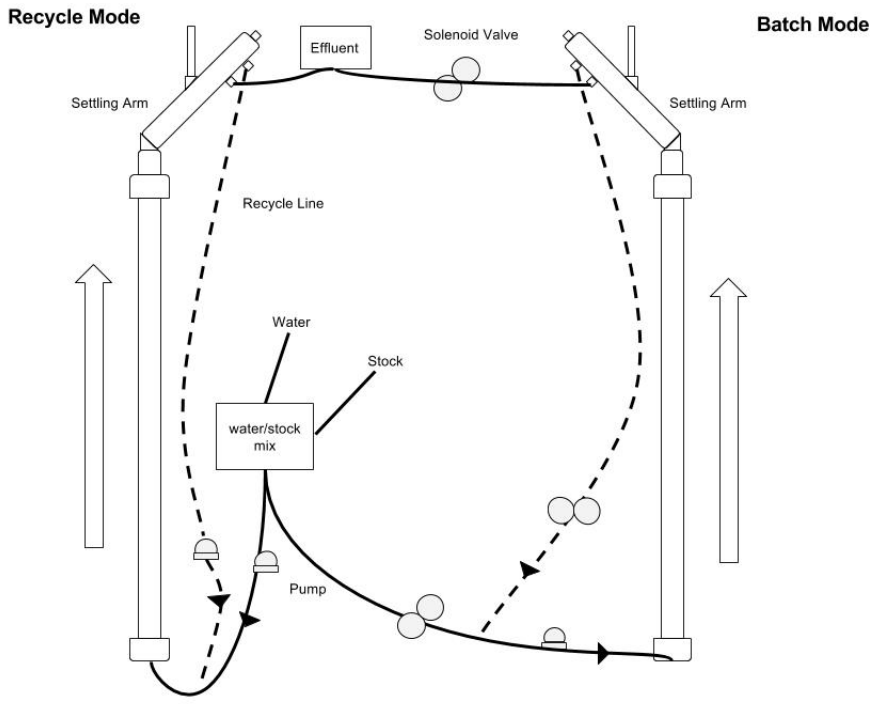

Figure 15: Schematic of set-up of valves and pumps to run the batch and recycle reactors simultaneously using ProCoDA