Upflow Anaerobic Sludge Blanket Reactor, Spring 2016

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Abstract

In addition to AguaClara's vision for providing safe drinking water, our group is attempting to assess the feasibility of implementing sustainable wastewater treatment at the small community scale. The Spring 2016 UASB team is fabricating new, smaller UASB reactors that would potentially be easier to implement at these scales. MathCAD has been used to determine the reactor dimensions based on various constraints including maximum reactor height, hydraulic retention time, and influent chemical oxygen demand (COD) loading rate. Currently a set of four reactors have been fabricated with the newly designed dimensions. A new method of measuring methane production has been developed by other groups in AguaClara focusing on wastewater treatment; these sensors will be applied to the newly build UASBs following their validation. After the methane measuring system is complete and the granules have matured, future groups will characterize reactor performance during periods of applied oxygen stress and/or variations in influent wastewater strength in order to better simulate real-world operating conditions.

Introduction

AguaClara's mission of providing sustainable wastewater treatment necessitates the development of a functional, low-energy or energy-neutral, and compact wastewater systems. The Upflow Anaerobic Sludge Blanket (UASB) reactor is essential to this mission because it offers an efficient means to anaerobically treat wastewater influent. With the new reactors designed this semester, future groups will be able to continue research to assess and improve the feasibility of implementing UASBs in rural regions of developing countries. The team has built on the research of previous teams by designing a new set of reactors. The new design includes features like a smaller reactor volume and labspace footprint, a reduced number of inlet/outlet ports to maintain water and airtightness, an inlet port for a dissolved oxygen probe, a junction in the reactor body to make maintenance much easier, and a head unit capable of being equipped with a methane sensor for more accurate data collection.

Literature Review

Aiyuk et al. (2004) suggest that there is a large need to develop domestic wastewater treatment in developing countries and that such a task is a nontrivial undertaking. There are many constraints for widespread application in the developing world including "simple design, use of non-sophisticated equipment, high treatment efficiency, and low operating and capital costs" to name a few. The UASB reactors have been widely used in the wastewater industry for a number of reasons including simplicity, scalability, and the ability to process a variety of wastewater strengths [1].

Chong et al. (2012) provide an overview of the current state of UASB technology [3]. The typical UASB consists of a cylindrical column and a gas-liquid-solid (GLS) separator with a geometry traditionally similar to a funnel (Figure 1). Wastewater is fed into the bottom of the reactor and the particles separate due to differences in density. The dense sludge forms a bed at the bottom of the reactor and the smaller, more dispersed particles form a blanket above the sludge bed. The reactors are inoculated with bacterial biomass that eventually undergoes a process called granulation that occurs in three main steps: absorption, adhesion, and multiplication. After inoculation and granule formation are complete, the influent COD is converted into biogas, a gaseous mixture consisting mainly of methane (CH_4) and carbon dioxide (CO_2).

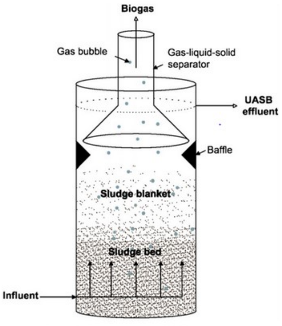


Fig. 1 – Schematic of a UASB reactor.

Figure 1: Schematic of UASB Reactor Chong et. al 2012

Yu et al. (2001) describe granulation as "the process in which suspended biomass agglutinates to form discrete well-defined granules." Bacteria may adsorb or adhere to inert matters, inorganic precipitates, and/or to one another. Once the bacteria are attached to a stable substrate they are free to multiply and eventually form granules. The authors continue on to mention that the microbial cultures formed within a UASB are a complex mixture of microbial species and that their survival and usefulness derive from the way in which the different species coexist and thrive off of one another [7].

The complex mixture of bacteria convert the influent wastewater and chemical oxygen demand (COD) into biogas via the process overview in Figure 2 (Mes et al. 2003). The chemical digestion process includes hydrolysis of non-soluble biopolymers into soluble organics, acidogenesis or the conversion of soluble organics into fatty acids and CO_2, acetogenesis in which the fatty acids are converted into acetate (or acetic acid) and hydrogen gas (H_2), and finally, methanogenesis in which the acetate, CO_2, and H_2, are converted into CH_4 gas. Acidogenic bacteria are usually responsible for the hydrolysis and acidogenesis steps, acetogenic bacteria for generation of acetic acid, and methanogenic bacteria for the final conversion into methane [5].

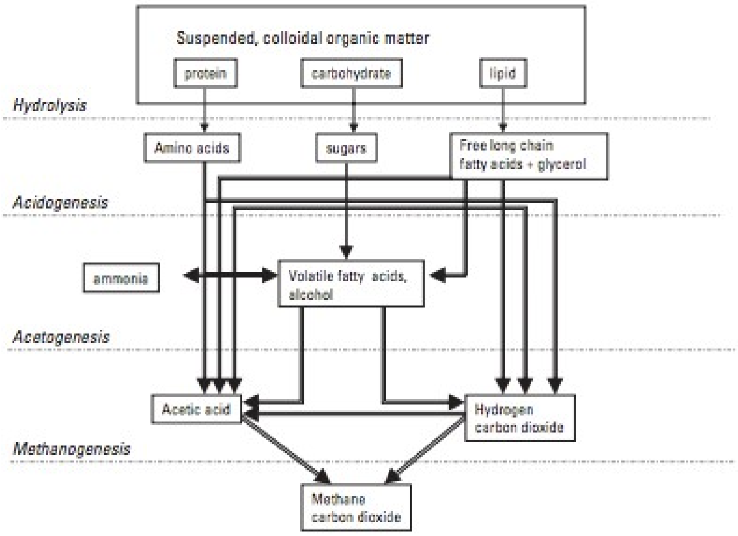


Figure 2: Wastewater to Biogas Chemical Conversion Process Flow Diagram Mes et. al 2003

UASB reactor technology has undergone a number of performance enhancements in the last decade including start-up and granulation characterization, coupling with post-treatment units, and general improvements in operating efficiency. The technology faces limitations when applied in developing countries, most notable of which involves the ability of the reactor to maintain a steady performance in a fluctuating climate [4].

Using the new reactors built this semester, One of the future goals of the group is to examine how anaerobic granules respond to oxygen stress with respect to COD treatment and methane production. The experiments carried out by Botheju et al. (2010) involved bubbling oxygen into UASBs at various rates with respect to percent of overall biogas production [2]. The influent oxygen content was varied from zero to 10 % biogas production rate by volume. The results of the study refuted the conventional perception that oxygen can only be toxic to anaerobic digestion cultures. Instead, the researchers found that, “limited quantities of oxygen can even lead to improved AD [anaerobic digestion] reactor performance under certain operating conditions.” Contrary to the results of Bothejou et al., a review paper by Leitaeo et al. (2006) concluded that oxygen present in UASB reactors can be inhibitory to methanogenesis unless certain facultative bacteria were present in the cultures to process the oxygen [6]. These two contrary results with respect to oxygen stress offer an interesting opportunity to test the phenomena for ourselves in order to probe our system.

It should, however, be noted that the oxygen concentration used by Bothejou et al. was significantly lower than that used by Leitaeo et al. In order to assess the maximum performance enhancement (if any) gained by spiking oxygen into the system, independent experimentation is necessary. Low-cost wastewater treatment technologies have the potential to be exposed to a wide variety of process perturbations in temperature, pH, COD, and oxygen and it is important to understand and quantify how our system may respond to such stresses. It is the goal of the UASB wastewater group to conduct an oxygen stress study either this upcoming summer or next Fall with an experimental design similar to that of Boutheju et al..

Previous Work

The AguaClara Wastewater Group began in the summer of 2013 and three semesters of research with respect to anaerobic wastewater treatment have been conducted to-date. In the summer of 2013 the UASB reactor was first explored; two reactors were constructed and one utilized support media to promote biomass growth. COD removal and gas production were monitored for approximately one month.

In the Fall of 2013, six reactors were constructed. Three of the six reactors were UASBs and the other three were Anaerobic Fluidized Bed Reactors (AFBRs). The Fall 2013 group began operation of these reactors, but was unable to collect a significant amount of gas production data due to leaks in the reactors and the lengthy startup time required for steady state operation. The group proposed a new gas chamber sealing method based on the coupling of a pressure sensor with Process Controller that would potentially only release accumulated biogas once a certain gas pressure had been reached. The group developed mathematical models for particle fluidization and settling within the reactor. These models helped the group reach the conclusion that both fluidization velocity and settling velocity increase as granule diameter and density increase. Finally, the Fall 2013 group used confocal microscopy and chemical staining in an attempt to characterize the granules within the reactor. The group was able to identify regions within the granule involved in active DNA and RNA synthesis as well as groups of aggregated methanogens.

The Spring 2014 group split into three subgroups: a UASB operation improvement group, a gas production and collection improvement through design and scaling modification group, and an aerobic treatment options group. Gas chromatography was used to monitor the amount of methane produced by the reactors throughout the semester. The Spring 2014 group faced several problems with respect to reactor performance: inconsistencies between theoretical and experimental gas production, inconsistent COD feed concentration delivery, and vessel leakage. These issues were provided as explanations as to why the experimental data did not match theoretical predictions for biogas production. In an attempt to fix the air tightness issue, the group used two methods to identify leaks in the reactors. The first method involved filling the reactors with water, sealing the reactors, and monitoring any change in water level over a few weeks. The idea was that a noticeable change in water level would only occur if the reactor were not airtight. The group's second air-tightness test was to fill the reactor with air and submerge it underwater and observe whether or not bubbles would escape the reactor. The identified leaks were at first repaired by reapplying Teflon tape and covering joints with parafilm, but this eventually proved unsuccessful. The group eventually took to sealing the connections with epoxy for reactors 2.4 and 2.5. Reactor 2.4 remained airtight throughout the semester, but reactor 2.5 began to leak a few weeks into operation. It was speculated that methane loss may have been due to dissolved methane leaving the reactor in the liquid phase.

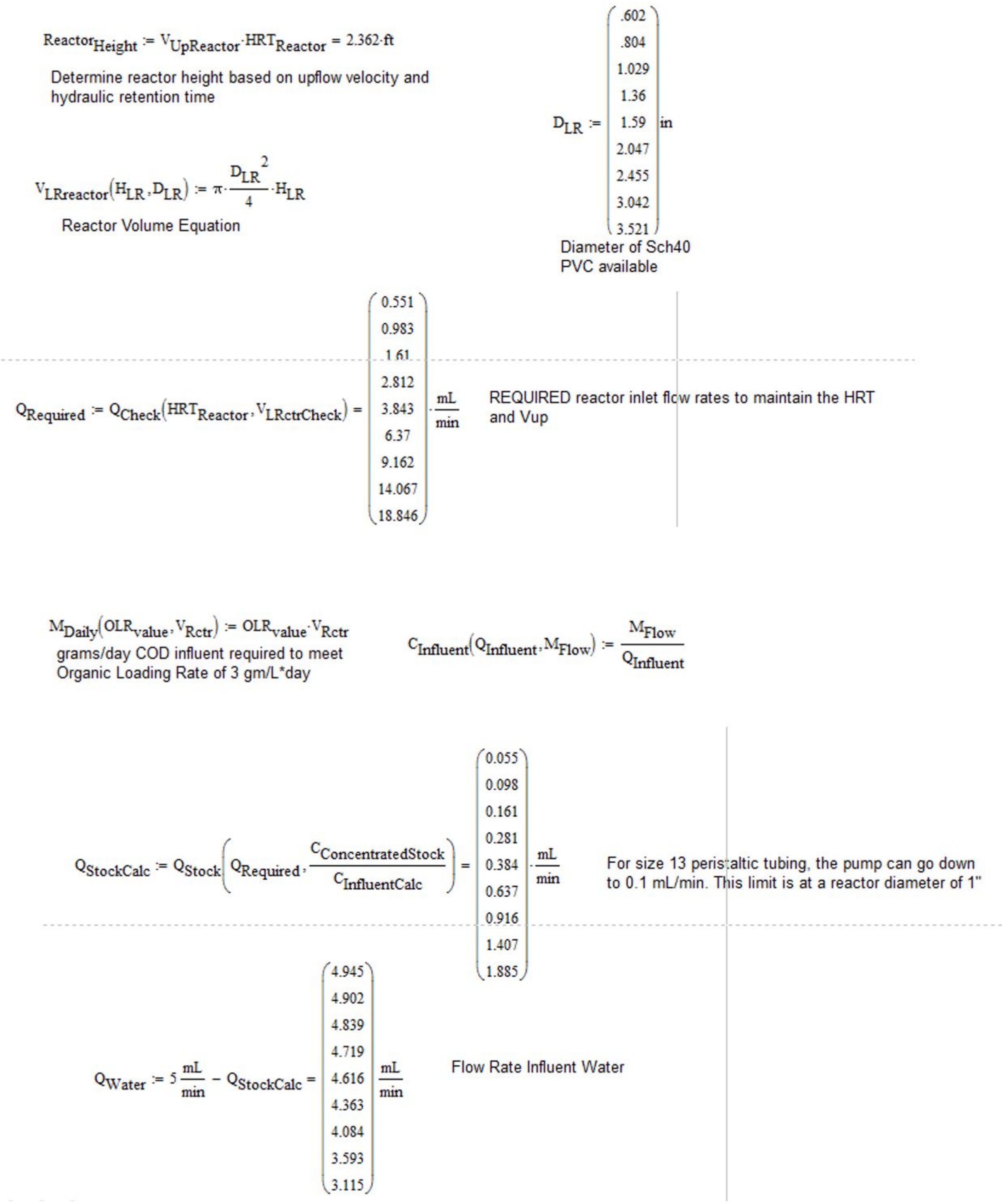
A common theme of the wastewater group has been the difficulty associated with sealing the reactors not only watertight, but airtight as well. The lengthy start-up time has also been an issue that has interfered with the collection of data during previous semesters. Additional time and resources will be devoted to making sure these issues are minimized in this upcoming Spring semester. In order to prevent this issues from occurring in the future, the team has designed and build a new set of reactors. This new reactor design attempts to minimize the potential for leakage by minimizing the number of reactor ports and includes a separable junction to separate the reactor at its midpoint for easy servicing.

Methods and Discussion

First Iteration

At the beginning of the Spring 2016 semester, the group moved from the teaching lab to the AguaClara work station. The new workspace is significantly smaller than that of the teaching lab. The large UASB reactors from previous semesters didn't fit well in the space, were prone to falling over due to their top-heavy design, and are too tall to mount on the lab bench and access safely during operation. The two UASB reactors from last semester were damaged during the move from the teaching lab to the new working area and have been rendered unusable. In order to determine if the remaining UASB reactors are usable for experimentation this semester, the team tested the reactors for water and air tightness. All 3 of the remaining (undamaged) UASB reactors leaked water from various valve or plug connections. As a result of the constraints that came with the new lab space, the team fabricated smaller scale UASB reactors that would be easier to work with.

During the design phase of this semester, the team came to the conclusion that the reactors will be constricted by a few parameters including lab space, required hydraulic retention time, and organic loading rate. The reactors may not be taller than the working space available to the team (about 3.5 ft). The hydraulic retention time was chosen to be fixed at values common to literature in order to mimic industrial UASB technology. Organic loading rate was chosen from literature values to mimic a medium strength wastewater influent. With these confining parameters, the following dimensions were established. The reactor height and influent flow rates and concentrations were computed as demonstrated in Figure 3.



$$\text{Reactor}_{\text{Height}} := V_{\text{UpReactor}} \cdot \text{HRT}_{\text{Reactor}} = 2.362 \cdot \text{ft}$$

Determine reactor height based on upflow velocity and hydraulic retention time

$$D_{LR} := \begin{pmatrix} .602 \\ .804 \\ 1.029 \\ 1.36 \\ 1.59 \\ 2.047 \\ 2.455 \\ 3.042 \\ 3.521 \end{pmatrix} \text{in}$$

Diameter of Sch40 PVC available

$$V_{\text{LRreactor}}\left(H_{LR}, D_{LR}\right) := \pi \cdot \frac{{D_{LR}}^2}{4} \cdot H_{LR}$$

Reactor Volume Equation

$$Q_{\text{Required}} := Q_{\text{Check}}\left(\text{HRT}_{\text{Reactor}}, V_{\text{LRctrCheck}}\right) = \begin{pmatrix} 0.551 \\ 0.983 \\ 1.61 \\ 2.812 \\ 3.843 \\ 6.37 \\ 9.162 \\ 14.067 \\ 18.846 \end{pmatrix} \cdot \frac{\text{mL}}{\text{min}}$$

REQUIRED reactor inlet flow rates to maintain the HRT and Vup

$$M_{\text{Daily}}\left(\text{OLR}_{\text{value}}, V_{\text{Rctr}}\right) := \text{OLR}_{\text{value}} \cdot V_{\text{Rctr}}$$

grams/day COD influent required to meet Organic Loading Rate of 3 gm/L*day

$$C_{\text{Influent}}\left(Q_{\text{Influent}}, M_{\text{Flow}}\right) := \frac{M_{\text{Flow}}}{Q_{\text{Influent}}}$$

$$Q_{\text{StockCalc}} := Q_{\text{Stock}}\left(Q_{\text{Required}}, \frac{C_{\text{ConcentratedStock}}}{C_{\text{InfluentCalc}}}\right) = \begin{pmatrix} 0.055 \\ 0.098 \\ 0.161 \\ 0.281 \\ 0.384 \\ 0.637 \\ 0.916 \\ 1.407 \\ 1.885 \end{pmatrix} \cdot \frac{\text{mL}}{\text{min}}$$

For size 13 peristaltic tubing, the pump can go down to 0.1 mL/min. This limit is at a reactor diameter of 1"

$$Q_{\text{Water}} := 5 \frac{\text{mL}}{\text{min}} - Q_{\text{StockCalc}} = \begin{pmatrix} 4.945 \\ 4.902 \\ 4.839 \\ 4.719 \\ 4.616 \\ 4.363 \\ 4.084 \\ 3.593 \\ 3.115 \end{pmatrix} \frac{\text{mL}}{\text{min}}$$

Flow Rate Influent Water

Figure 3: MathCAD calculations used to determine Parameters

The up-flow velocity is much lower than that of standard UASB reactors, but this has been determined to be acceptable because the team is not looking to fluidize the biomass bed. The new AguaClara High Rate UASB (HRUASB) team is assessing a number of UASBs in series and utilize a fluidized bed during operation. Our team has initially chose to maintain low flow rates and a packed bed reactor operation in order to compare (with the HRUASB team) the performance of packed vs fluidized bed reactors. The team was initially worried that we would not be able to find a pump capable of producing the necessary low flow rate and that the solids in the feed medium would clog the small diameter tubing. A single-speed pump capable of producing the necessary flow rate was eventually acquired and after thorough testing, there was been no sign of clogging or inconsistent pumping. Unfortunately, a comparison with the HRUASB team has not been achieved due to a lengthy reactor construction period in the semester. It is our hope that the two systems will be compared in the future when all methane sensors, and potentially dissolved oxygen probes, are online. To compare the two systems, methane yield, COD tests, and biomass culture density could be assessed to determine which reactor geometry is capable of generated the most energy and treated the highest amount of influent COD. The parts for these new reactors were salvaged from the previous reactors where possible and new parts were ordered if they could not be found in the lab. The fabrication process began with the team receiving training in the necessary fabrication techniques that included PVC cutting, sanding, adhering, and threading. Caution was taken in the fabrication process to ensure no permanent and costly errors were made. With these skills the team began assembling reactors. The team designed and built one reactor first to learn where improvements could be made. It was determined that in order to achieve an effluent freefall lower than the head unit water level, an outlet hole should be drilled in the outlet pipe; the first reactor was equipped with a plug and push-to-connect joints, this was changed for the following three reactors. The team also constructed supports on the lab bench and used zip-ties to mount the reactors to minimize the possibility of the reactors falling over and breaking again. The head unit of the first reactor was equipped with a septa for gas sample collection, a solenoid valve to enact offgas events, and a pressure sensor to determine the gas pressure and trigger said offgas events using process controller. The constructed reactor with its dimensions can be seen in the picture below.

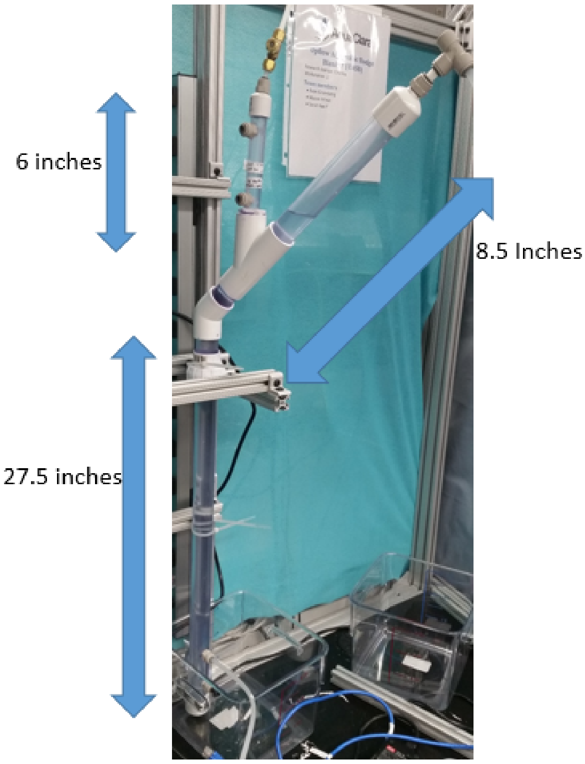


Figure 4: Prototype UASB design

After constructing the first reactor, the team was informed by Monroe that new methane sensor technology may be available, so the head units for the next three reactors did not include the septa, pressure sensor, or solenoid valve. The methane sensors are currently in fabrication by the HRUASB team and will potentially be equipped to the UASB team reactors during this summer. The new methane sensor can be attached directly to the head unit and allow for the continuous monitoring of methane production without the previously required build-up and off-gas of biogas. Effluent methane will leave the reactor and be mixed with a constant flow rate of air at a T junction. This methane-air mixture will then travel to an electronic methane sensor that produces a voltage reading. The methane concentration can be calculated based on a calibration curve created from known concentrations.

The reactors were inoculated April 27th with a biomass volume equal to 2/3 the vertical reactor height. Water and stock tanks were setup beneath the lab bench, connected to peristaltic pumps, and pumped into the bottom of the reactors at the required flow rates. The four effluent lines were combined into two effluent lines and each line was fed into a 4 gallon waste holding tank. The methane sensors have not been fabricated this semester and the reactor head units are currently open to the air at a push-to-connect junction. Due to the lengthy construction period and the late inoculation date during this semester, the team chose to focus on monitoring the newly built reactors for design flaws during operation as opposed to fabricating new methane sensors.

Discussion

After operating the newly designed reactors, the team has noticed several areas in which the reactors performed well and several areas where reactor performance can be improved. The reactors were sized very appropriately and gave the team no issues in the small space they were allotted. The reactors were easy to secure to the frame built on the table and were never in risk of falling over or getting in the way of other people walking around the lab. The newly designed union in the body of the reactor was another largely beneficial element of the new design. With the ability to disassemble the reactor, the team had much fewer difficulties during inoculation and cleaning out the reactors. There were also aspects of the new design that proved to be problematic. The smaller diameter made it more difficult for gas to navigate its way up through the densely packed granules. As a result, large gas pockets formed in the shaft of the reactors. Another problem with the current reactor setup is the large amount of daily maintenance required to keep the reactors operating. The influent water needed to be replaced and effluent needed to be emptied approximately every 18 hours. The team also used two programmable peristaltic pumps and one other constant RPM pump to keep the reactors operating. In addition, two more pumps would be needed for the methane sensing. With the short supply of programmable pumps and the small size of the lab space, the large number of pumps required was problematic. Tubing was easily tangled and making repairs or changes to the tubing was very difficult due to the crowded nature of the lab space.

Conclusions and Future Work

To fix the problems the team discovered in the few weeks the reactors were operational, a number of steps will be taken. To solve the issue of gas becoming trapped in the densely packed bed of granules, obstructions can be placed in the shaft of the reactor to facilitate the breakup of large plugs of granules. These obstructions can be placed on one side of the reactor, spaced according to the size of the granules, and protrude about one third the way into the reactor. More calculations will be needed for the exact design of these obstructions, but if designed properly, they can provide additional downward forces on the granules to offset the forces of drag and surface tension that cause the granules to rise. If rising plugs of granules continue to cause issues in future semesters, these obstructions will be designed and installed. Another step that can be taken to fix the issues the team encountered is to redesign the influent feeding and effluent collection. Pumping the effluent up to the waste outlet tube hanging from the lab ceiling will eliminate the need to empty the effluent containers daily and it would reduce the chance of spills. Cutting back on the number of pumps the team is using and increasing the efficient use of space will be another step the team will take in future semesters. Extending the pumps to drive up to 4 head units will cut the number of pumps in half. Using head units that hold 4 tubes instead of 1 tube can also greatly increase the efficiency of the pumps and reduce clutter in the lab space.

After May 25th, the reactors will be taken over by Andrew Kim for the summer. He will be trained to operate the the week before he takes over to ensure the smooth transition. Zoe Maisel, who is very familiar with UASB operation, will also be in Ithaca and can assist Andrew should he run into any issues. During the summer, testing will be conducted on the UASBs ability to treat high strength blackwater and the reactors resilience to oxygen stress will also be investigated. Following the summer of testing, more research will be conducted on the reactors under the supervision of the new UASB team in the Fall of 2016.

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