Upflow Anaerobic Sludge Blanket (UASB) Reactor Design

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Abstract

Upflow Anaerobic Sludge Blanket (UASB) Reactors are a conventional primary wastewater treatment technology. Improvements to UASB reactors are required for the development of affordable small-scale wastewater treatment systems. This semester, the feasibility of two design modifications to conventional UASB reactors were explored: (1) a submerged gas capture lid (SGCL) to increase gas capture capacity, and (2) plate settlers to improve solids (granules) retention. The results of SGCL prototype testing showed that the SGCL was gas-tight, which is not achieved in traditional UASB reactors. Additionally, granule settling tests demonstrated that plate settlers do not improve settling capacity for small-scale UASB reactors operating at slow upflow velocities. Based on these results, the SGCL is recommended for implementation in small-scale UASB reactors. In the immediate future, AguaClara should fabricate a full-scale UASB reactor that incorporates the SGCL design and other design modifications detailed in the January 2017 EPA P3 proposal. Eventually, AguaClara should explore post-treatment options to couple with this UASB reactor to develop a complete small-scale wastewater treatment system.

Introduction

The contamination of ground and surface water sources by wastewater has adverse environmental and health affects. First, the biological degradation of wastewater by aerobic microbes lowers the dissolved oxygen content in natural waterways, preventing aquatic life from thriving and potentially creating dead zones. Additionally, it increases waterborne fecal matter content and increases the risk of exposure to pathogens (Chong et al., 2012). The latter is of particular concern to individuals in the global south, as communities downstream of wastewater outfalls often have inadequate drinking water treatment.

Wastewater can also be an opportunity for energy recovery. According to recent estimates, the energy potential of wastewater and biosolids is more than ten times the energy needed for treatment (Ghoneim et al., 2016). Most wastewater treatment facilities in the US do not optimize the recovery of energy and resources from biosolids (Ghoneim et al., 2016). While it is important to develop wastewater treatment technology to optimize current wastewater treatment for all individuals, the focus of this research was on small communities in the global south. Such communities do not have widespread wastewater infrastructure, and therefore much of the wastewater is left untreated.

Currently in the United States, effective municipal wastewater treatment facilities have long retention times, require large land areas, and have a high fixed cost per capita (Chong et al., 2012). Due to economy of scales, small systems have even higher fixed costs per capita and these high fixed costs make conventional wastewater treatment systems inaccessible for small communities. Many cities in the global south forgo wastewater treatment altogether due to the high cost and instead discharge untreated wastewater to the environment (Chong et al., 2012). Research and development of small-scale and decentralized wastewater treatment methods should be prioritized in order to make wastewater treatment accessible for all communities.

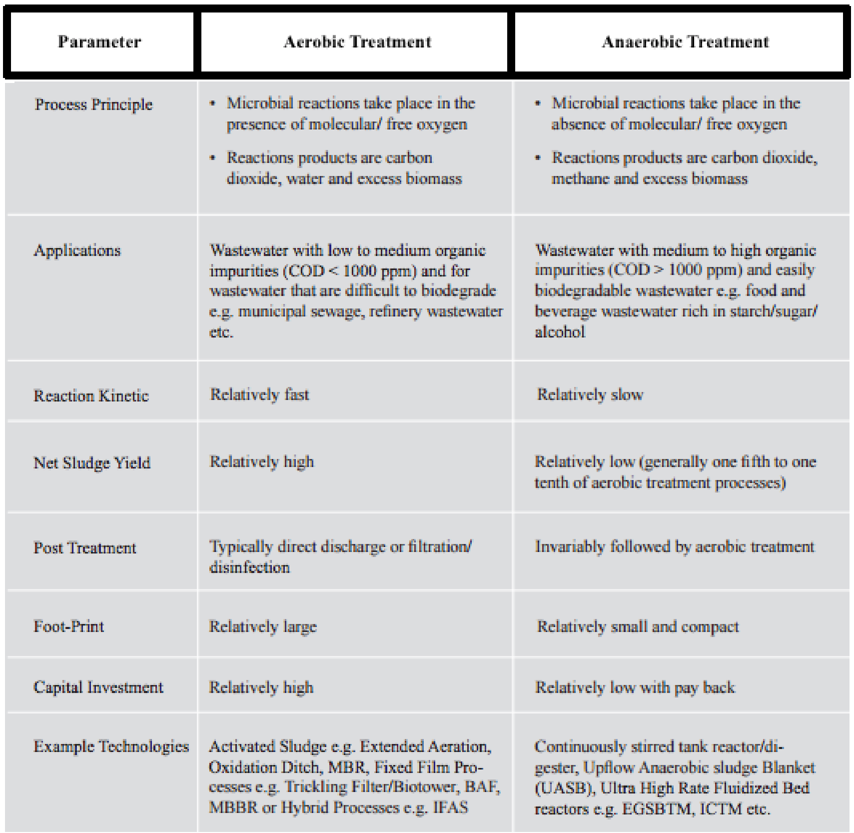
Upflow Anaerobic Sludge Blanket (UASB) reactors are conventionally used as a preliminary wastewater treatment process to clarify wastewater by removing suspended solids and reducing organic matter (Chong et al., 2012). UASB reactors rely on gravity to clarify wastewater, biological processes to remove organic matter and convert it to biogas, and are less energy intensive than other forms of preliminary wastewater treatment that use aerobic processes. A byproduct of the biological processes in UASB reactors is methane. Methane is a potent greenhouse gas, but if collected, can be used as a fuel or burned and safely released into the atmosphere.

In January 2017, a novel pilot scale UASB reactor design was created by AguaClara for the EPA People, Prosperity and the Planet (P3) Student Design Competition proposal. This reactor was designed to improve the accessibility of wastewater treatment for small communities. The proposed UASB reactor design identified five areas to improve conventional reactor design: (1) plate settlers, (2) submerged gas collection lid, (3) sludge weir, (4) submerged exit launder, and (5) fabrication methods. Of these design modifications, the Spring 2017 UASB Team researched and tested the impact of plate settlers and submerged gas collection lid on improving granule retention rate and gas collection capacity, respectively.

Literature Review

Conventional Wastewater Treatment Options

Municipal and industrial wastewater can be treated via biological, chemical oxidation, or thermal oxidation treatment processes. Biological treatment is commonly used because the latter two treatment options require higher capital investment and operational costs (Mittal, 2011). The two main types of biological treatment are the activated sludge process and anaerobic digestion. As shown in Figure 1, when compared to the activated sludge process, anaerobic digestion yields less sludge and reduces energy input (Mittal, 2011). Although there are some drawbacks to anaerobic digestion such as long solids retention time (SRT) and insufficient nutrient removal, the reduced energy input renders it the most feasible technology for communities in the global south (Chong et al., 2012).



Parameter	Aerobic Treatment	Anaerobic Treatment
Process Principle	• Microbial reactions take place in the presence of molecular/ free oxygen • Reactions products are carbon dioxide, water and excess biomass	• Microbial reactions take place in the absence of molecular/ free oxygen • Reactions products are carbon dioxide, methane and excess biomass
Applications	Wastewater with low to medium organic impurities (COD < 1000 ppm) and for wastewater that are difficult to biodegrade e.g. municipal sewage, refinery wastewater etc.	Wastewater with medium to high organic impurities (COD > 1000 ppm) and easily biodegradable wastewater e.g. food and beverage wastewater rich in starch/sugar/ alcohol
Reaction Kinetic	Relatively fast	Relatively slow
Net Sludge Yield	Relatively high	Relatively low (generally one fifth to one tenth of aerobic treatment processes)
Post Treatment	Typically direct discharge or filtration/ disinfection	Invariably followed by aerobic treatment
Foot-Print	Relatively large	Relatively small and compact
Capital Investment	Relatively high	Relatively low with pay back
Example Technologies	Activated Sludge e.g. Extended Aeration, Oxidation Ditch, MBR, Fixed Film Processes e.g. Trickling Filter/Biotower, BAF, MBBR or Hybrid Processes e.g. IFAS	Continuously stirred tank reactor/digester, Upflow Anaerobic sludge Blanket (UASB), Ultra High Rate Fluidized Bed reactors e.g. EGSBTM, ICTM etc.

Figure 1: Comparison of activated sludge (aerobic) and anaerobic treatment technologies for wastewater. (Chong et al., 2012)

Details of Anaerobic Digestion

After several weeks of anaerobic digestion, dense aggregates of anaerobic microorganisms, called granules, naturally form and perform methanogenesis (Abbasi and Abbasi, 2012; Rittmann and McCarty, 2013). Methanogenesis is the process by which organisms, known as methanogens, convert organic matter to methane (Rittmann and McCarty, 2013). Formation of granules is preferred since granules have a high settling capacity, promoting compact design, and high biomass concentration in reactors (Kreuk and Bruin, 2004).

Upflow anaerobic sludge blanket (UASB) reactors are one example of high-rate anaerobic digesters. UASBs are used as primary clarification of wastewater, and therefore require post-treatment options such as trickling filters and secondary clarifiers to achieve ideal reduction of chemical oxygen demand (COD), suspended solids (SS), and nutrients (Abbasi and Abbasi, 2012). High-rate anaerobic digesters, such as UASBs, are designed to operate at short hydraulic retention times (HRT) and long solids retention time (SRT) to increase loading capacity and improve sludge stabilization (Chong et al., 2012). Due to these advantages, UASB reactors were chosen as the basis for preliminary wastewater treatment design for communities in the global south.

Conventional UASB Reactor Design

A conventional UASB reactor is shown in the Figure 2 below. The major components of a UASB reactor are the inlet system, sludge blanket, gas-liquid-solid separator system (GLSS), and exit weir.

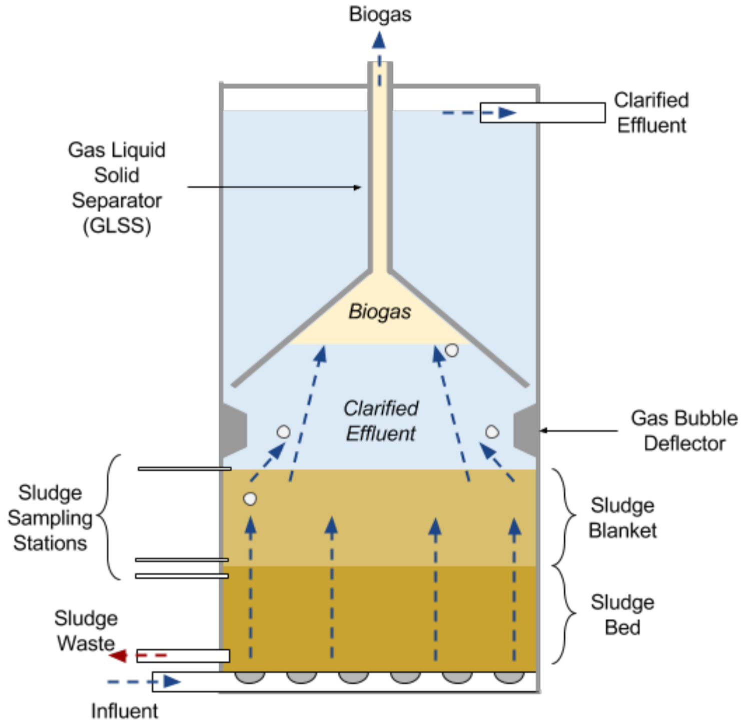


Figure 2: Schematic of a conventional UASB reactor. Important components of the reactor are labeled.

Problems with Conventional Reactor Design

Conventional UASB reactors utilize GLSS to collect biogas (carbon dioxide and methane) that is produced during anaerobic digestion (Narnoli and Mehrotra, 1997). Since methane is a potent greenhouse gas, the biogas should be captured to reduce negative environmental impacts (Chong et al., 2012). GLSS are submerged funnels that function as a three-phase separator, where biogas is deflected to the funnel and either harvested for energy or burned before it is emitted into the atmosphere (Chong et al., 2012). Conventional UASB reactors are not gas-tight systems because the free-surface of water is open to the atmosphere.

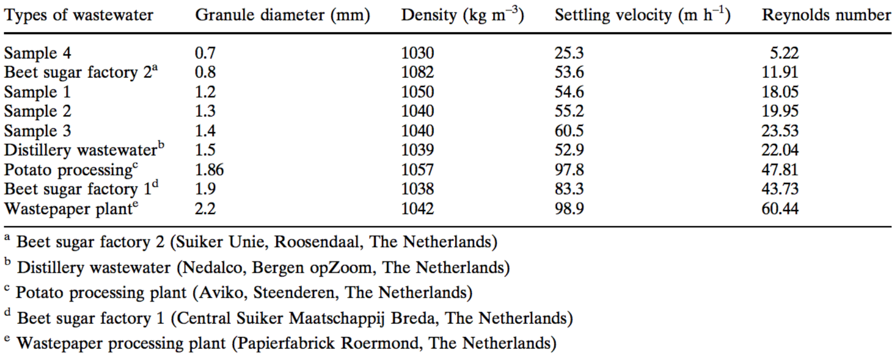
When sludge escapes the sludge blanket and accumulates at the water surface open to the atmosphere, it forms a filamentous layer of bacteria (Lettinga and Holshoff Pol, 1991). This is problematic because the exit weir skims the water surface. In traditional UASB design, the effluent outlet is located at this gas-water interface, allowing for bacteria and other solids carried up by gas bubbles to escape untreated.

Sludge Blanket

Anaerobic bacteria are crucial to the functionality of UASB technology. However, due to the size of the bacteria, an efficient upflow velocity would easily washout free-floating bacteria. To successfully process organic waste, UASB reactors heavily rely on the accumulation, concentration, and conglomeration of a large population of these bacteria in order to form diverse microbial community known as granules. Proper granulation and retention of these granules in a reactor is imperative to maximize the removal of COD and BOD and increase the overall effectiveness of UASB technologies (Subramanyam, 2013).

To maintain a specified sludge bed height, granule retention in the sludge bed is important. Granule retention and settling in the sludge bed is the result of the density difference between granules and water. Compared to the density of water, $1000\frac{kg}{m^3}$, granule densities are slightly higher, within the range of $1000\frac{kg}{m^3}$ to $1050\frac{kg}{m^3}$ (Liu et al., 2006). According to Liu et al., higher density granules have large diameters which has a positive correlation with settling velocity (Liu et al., 2006). This average of granule densities from multiple wastewater treatment UASB reactors with associated settling velocities is shown below in Table 1.

Table 1: Densities and settling velocities observed by Liu et al. (2006)



Types of wastewater	Granule diameter (mm)	Density (kg m^{-3})	Settling velocity (m h^{-1})	Reynolds number
Sample 4	0.7	1030	25.3	5.22
Beet sugar factory 2[a]	0.8	1082	53.6	11.91
Sample 1	1.2	1050	54.6	18.05
Sample 2	1.3	1040	55.2	19.95
Sample 3	1.4	1040	60.5	23.53
Distillery wastewater[b]	1.5	1039	52.9	22.04
Potato processing[c]	1.86	1057	97.8	47.81
Beet sugar factory 1[d]	1.9	1038	83.3	43.73
Wastepaper plant[e]	2.2	1042	98.9	60.44

[a] Beet sugar factory 2 (Suiker Unie, Roosendaal, The Netherlands)

[b] Distillery wastewater (Nedalco, Bergen opZoom, The Netherlands)

[c] Potato processing plant (Aviko, Steenderen, The Netherlands)

[d] Beet sugar factory 1 (Central Suiker Maatschappij Breda, The Netherlands)

[e] Wastepaper processing plant (Papierfabrick Roermond, The Netherlands)

The mathematical settling model created by Liu et al. simply assumes that the granules are perfectly spherical and constant average density of the granules in determining settling velocity (Liu et al., 2006). It does not account for instances of biogas formation on the surface of granules, thus altering density properties. This is a topic that needs to be further explored as granules can rise along with biogas as it is formed.

Previous Work

Plate Settlers

For treatment processes that utilize anaerobic digestion, one long-term problem is that long retention times increase the required volume for the reactor due to the slow growth rate of the microorganisms used in the process(Von Sperling and de Lemos Chernicharo, 2005). If the Spring 2017 UASB team is able to maintain higher levels of biomass, which is the total mass of microbes, and guarantee sufficient contact time between microbes and organic matter in the reactor, the drawbacks of low growth rate of anaerobic microbes can be offset and accordingly, the reactor tank volume reduced.

One proposal is to incorporate plate settlers between the exit launder and the sludge blanket to encourage the settling of solids. By capturing and redirecting solids back to the sludge blanket, the reactor produces a cleaner effluent. Plate settlers can also function as a separator for solids that are encompassed by gas bubbles, similar to the function of GLSS.

Plate settlers have been successfully applied in AguaClara's full scale and 1 L/s drinking water treatment plant to prevent flocs from escaping (Herrara et al., 2016). In terms of drinking water treatment, plate settlers make use of reactor parameters, such as upflow velocity and capture velocity, and settler geometry, such as spacing between plates and plate angle, to enhance settling of flocs (Weber-Shirk, 2016).

Submerged Gas Capture Lid

One of the byproducts created by anaerobic digestion is methane, a potent greenhouse gas. Each molecule of methane contribute 25 times more to global climate change than each molecule of carbon dioxide (Forster et al., 2007). While it is harmful in the atmosphere, methane gas produced in anaerobic digestion can be collected and utilized as an energy source. For these reasons, efficient capture of methane is an important goal of this project, as it can minimize greenhouse gases discharge and maximize potential energy resources.

Maximizing biogas capture will result in an efficient UASB reactor. Therefore, the proposed design change to be implemented was to replace the GLSS funnel with a removable submerges gas capture lid. This lid will employ a water-tight seal to eliminate potential gas leakage and will lead to easier reactor cleaning and maintenance.

Other Design Modifications

Besides the introduction of plate settlers and the gas capture lid, other notable design changes come in the form of a sludge weir, submerged exit launder, and fabrication methods. The sludge weir automatically sets the sludge blanket height. The submerged exit launder prevents any instance of solid escape. The specifications of these modifications are mentioned in detail in the January 2017 EPA P3 proposal.

Methods

In order to figure out the validity and efficiency of the two innovative modifications, plate settlers and submerged gas collection lid, two experiments were conducted during this semester. In the first experiment, the granule settling test, plate settlers were implemented to promote granule capture. For the second experiment, the submerged gas capture lid test, a submerged lid was fabricated and tested to determine whether or not it was gas-tight. The results of these experiments will inform the appropriate design modifications to conventional UASB reactors.

Granule Settling Test

Purpose of Experiment

The granule settling test was designed to simulate the impact of plate settlers on solid retention rate and the potential of granule escape. One simplified way of doing this is to extract one single settling zone out instead of fabricating the whole plate settlers as shown in Figure 3 below.

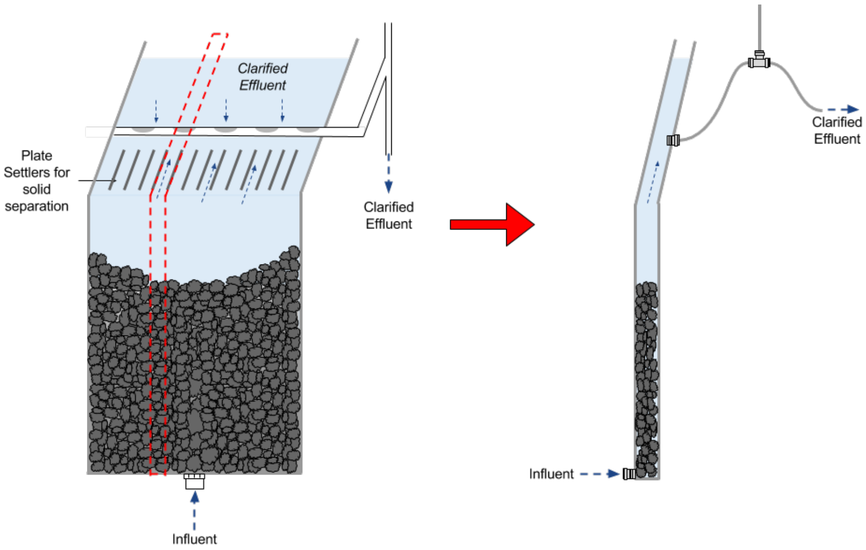


Figure 3: A single settling zone (shown within the dashed lines) of the full scale UASB reactor on the left. The modeled lab scale alternative reactor is shown on the right. The plate settlers were simplified and modeled as a single tube settler.

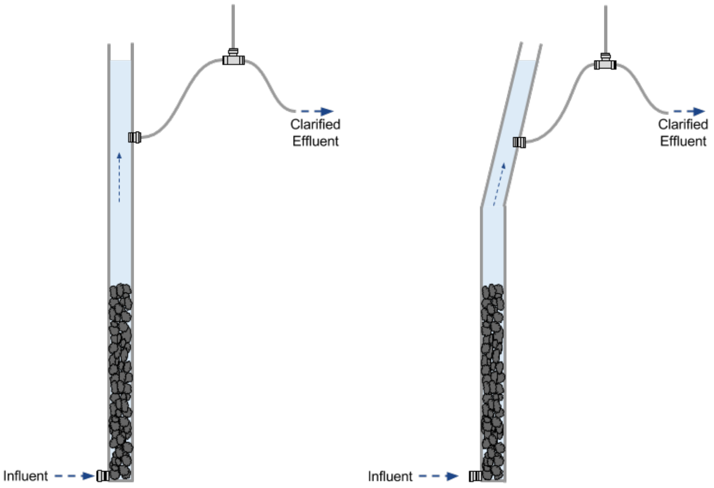


Figure 4: The tube reactor on the left is conventional reactor and the tube reactor on the right is the Alternative Reactor. As previously mentioned, the conventional reactor was a section of the full scale UASB reactor. The alternative reactor was a section of the full scale UASB reactor with the addition of plate settlers.

Between the two reactor designs, as shown in Figure 4 above, the reactor with fewer granules leaving as effluent should be used to design a full scale UASB reactor. This is because the reactor with fewer granules had a higher SRT and was expected to enhance organic matter removal.

Apparatus Design

The process of growing granules is long, and may take several weeks to months (Grimshaw et al., 2013). Due to this extended time frame, the team used the two reactors from the Spring 2016 UASB Team's setup and modified them to fit the needs of the granule settling testing. The experiment apparatus was set as shown in Figure 5. For detailed instructions, refer to the Fabrication Manual.

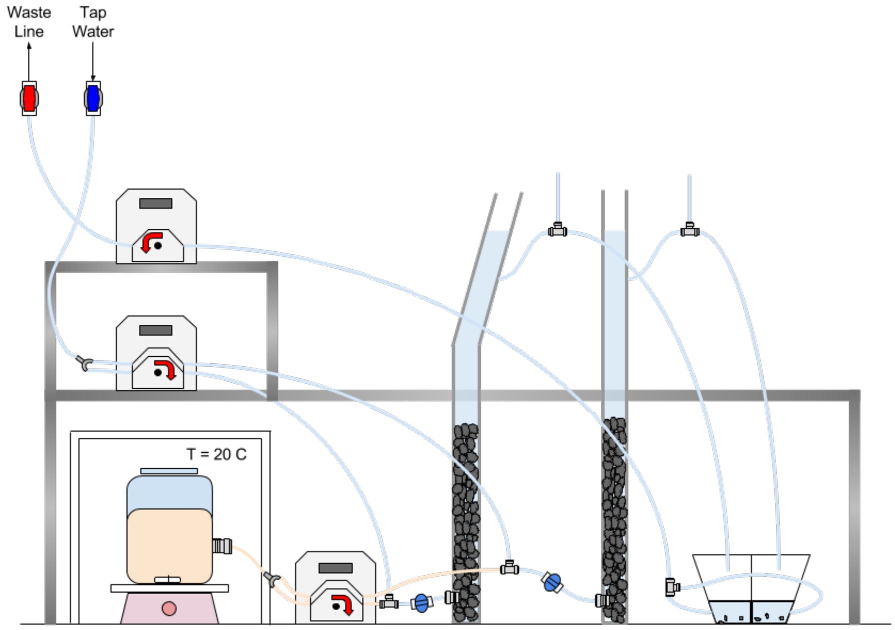


Figure 5: The experimental apparatus schematic for the granule settling test. The synthetic wastewater stock, which was refrigerated, was pumped and combined with tap water to dilute the influent. Submerged effluent lines empty effluent into a waste bucket. This effluent was then pumped to the waste line.

Constantly mixed synthetic wastewater was refrigerated and pumped into the two tube reactors together with water. The synthetic wastewater stock was pumped at 1.0 RPM and the water was pumped at 3.4 RPM. These influent supply rates simulated 4 hours HRT and 3 g COD/(L-d) for a full-scale UASB reactor. The effluent flow rate was determined by setting wastewater pump flow rate to 5.0 RPM (determined by the Reactor Parameters Google Sheet).

The effluent was submerged under the water level, which is consistent with full-scale design in order to avoid scum and methane escaping as effluent. The water level was set by a weir created by the push-to-connect tee connection. In order to have an accurate visual inspection for the number of escaping granules, this experiment used an equally divided effluent bucket that separately collected the effluent from two reactors.

Experiment Procedure

1. A hydraulic test was conducted to ensure the system was not leaking. Fixed all loose connections and proceeded to test with synthetic wastewater.

2. Ran the system for two weeks and observed the granule accumulation in the waste bucket and the top of the reactor. Reported all results.

Submerged Gas Capture Lid (SGCL) Test

Purpose of Experiment

The goal of the submerged gas capture lid (SGCL) test was to examine the gas capture capacity of a SGCL that used a water seal rather than a traditional gas-tight, pressurized seal. A simplified lab-scale UASB reactor with the prototype SGCL design was fabricated to simulate the functionality of the full-scale reactor. Air was injected into the lab-scale reactor full of water. The SGCL was connected to a bottle of water, referred to as the Gas Collection Bottle. If bubbles were observed in the the Gas Collection Bottle while no bubbles were observed on the sides of the SGCL, the design of the SGCL should be recommended for the full scale reactor.

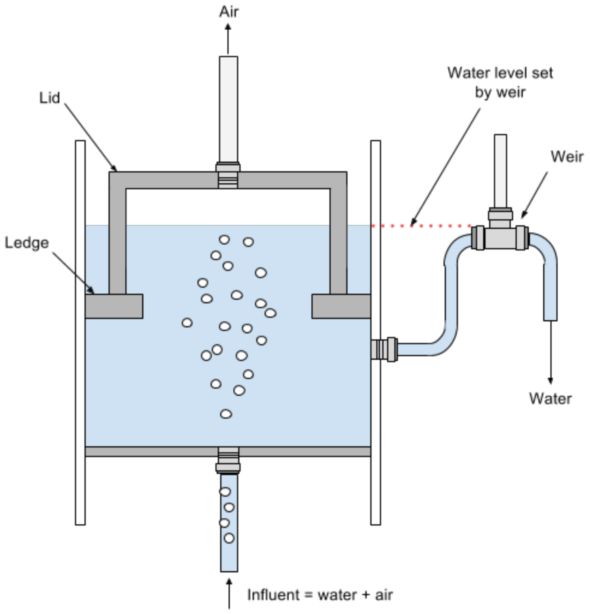


Figure 6: Schematic illustration of the removable lid for improved biogas capture

Apparatus Design

The SGCL test was setup as shown in Figure 7.

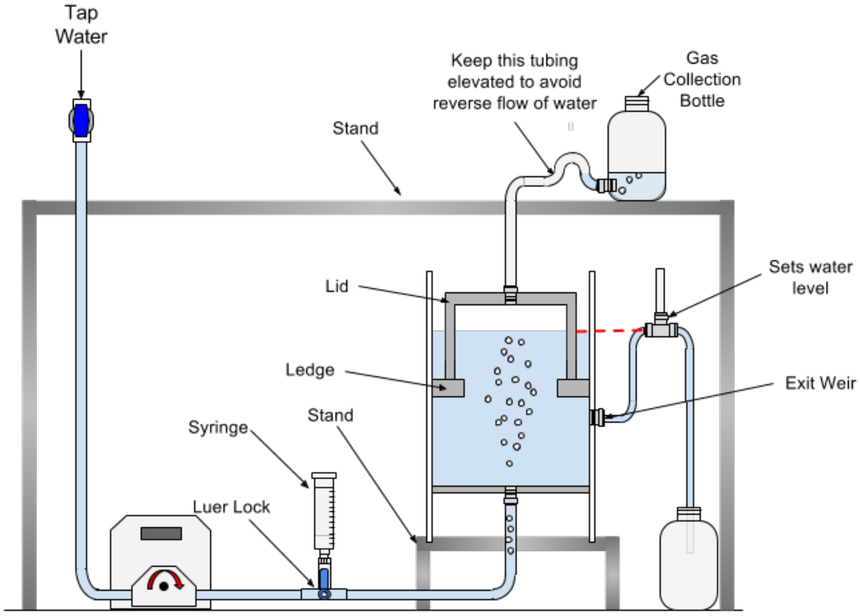


Figure 7: Experiment apparatus for SGCL Test. Details of apparatus setup can be found in the Fabrication Manual

A hydraulic test was conducted after completing the fabrication for the reactor body, effluent collection system, and gas collection system to avoid any leaks during the experiment. The SGCL was designed to be submerged to create a gas-tight collection system, thus the water level was was set to an appropriate position below the ledge and the lid by a weir created by a push-to-connect tee connection as shown in Figure 6 above. A total of two SGCLs were fabricated for two trials of experimentation. The first SGCL had a height of 2 in. height and the second SGCL had a height of 10 in. For further explanation of fabrication and experimental procedure, refer to Appendix Section.

To test the gas collection capacity of the reactor with the removable SGCL, the team injected different volumes of air from the influent tube of the reactor by a glass syringe (borosilicate glass syringe provided by Prof. Matt Reid). The threshold pressure accumulation in the head space of the SGCL is a function of the back pressure created by the column of water surrounding the SGCL and the head loss that must be exceeded for gas to escape the SGCL. A qualitative analysis was achieved by observing if there was gas bubble coming out from the side of the SGCL or from the gas collection bottle (See Figure 7).

An alternative way to analyze this experiment would be to measure the exact volume of gas captured by attaching a syringe to the gas collection bottle. This would not be a practical analysis because data regarding the gas capture efficiency of GLSS is not available to offer a comparison.

The volume of air collected in the gas collection bottle can be compared to the volume of air injected into the system to determine the threshold pressure accumulation in the head space of SGCL. However, due to the uncertainties in head loss considerations, this volume comparison will not reveal accurate parameter estimates when this technology is scaled up.

Experiment Procedure

A total of two trials were conducted using the same procedure. The first trial used an SGCL with a height of 2 inches. The second trial used an SGCL with a height of 10 inches. The results from both trials were compared for further analysis.

1. Set up reactor to water level shown in Figure 7
2. Stopped the pump
3. Opened the Luer Lock on influent supplying tube
4. Gradually injected 30ml amount of air into the luer lock using syringe
5. Closed the Luer Lock
6. Ran the pump
7. Observed the gas bubble behavior on the side of the lid and from the gas collection system

Results and Analysis

Results

Granule Settling Test

From visual inspection of the effluent collection tank, it was observed that there were no granules collected in the tank or visible in the effluent lines coming from either reactors as shown in Figure 8.

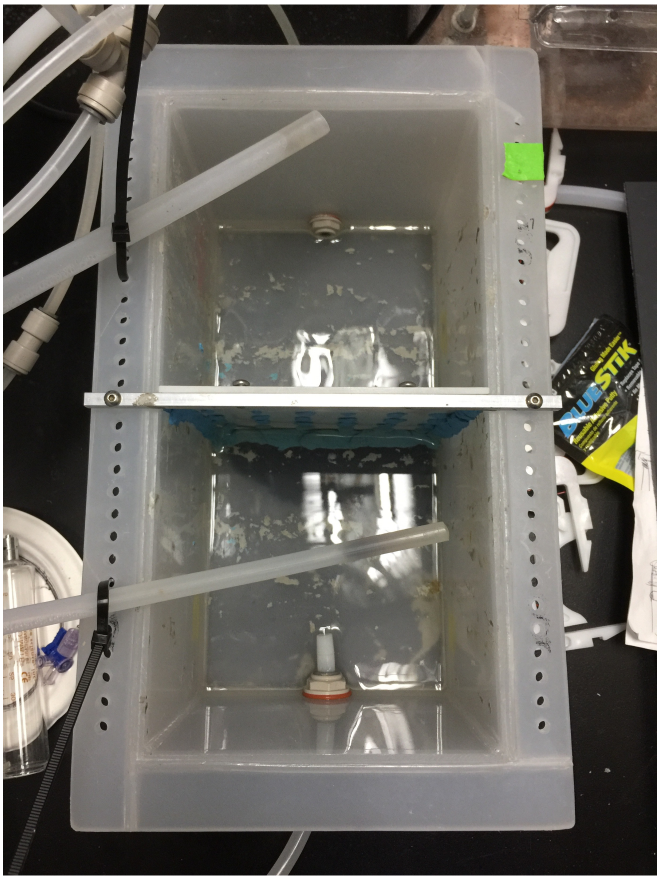


Figure 8: Effluent collection tank of the Granule Settling Test for the Conventional Reactor (lower compartment) and the Alternative Reactor (upper compartment). By visual inspection, there was no granules collected in the collection tank or trapped in the effluent tubes

SGCL Test

Back pressure is an important parameter to consider when designing a gas-tight capture system. Back pressure refers to pressure upstream the system exceeding the downstream pressure to create reverse flow. Therefore, the bigger the pressure buildup, the larger the probability that gas will escape from the SGCL.

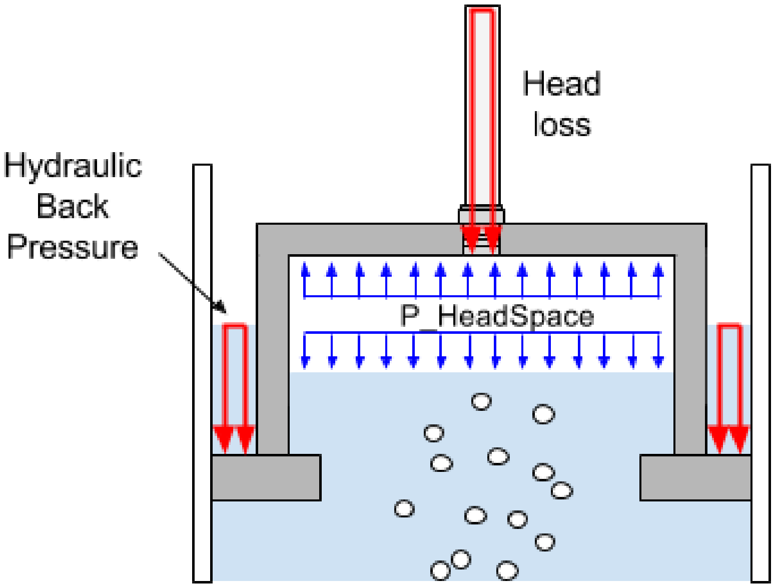


Figure 9: The pressure in the head space of the SGCL must exceed the head loss to leave the cap without exceeding the hydraulic back pressure.

In terms of an energy analysis of the SGCL, the energy inside the head space provided by gas accumulation must exceed the energy loss in the exit of the SGCL, but it must also be less than the potential energy of the water surrounding the SGCL. To avoid gas leakage from the sides of the SGCL, the height of the the water surrounding the SGCL should be monitored and adjusted.

The first trial for the SGCL test failed because the SGCL was not tall enough to allow enough hydraulic pressure to build up on the outside of the SGCL. Without sufficient back pressure to counteract the pressure accumulation in the head space of the SGCL, the free surface in the SGCL dropped below the ledge, allowing air bubbles to escape through the sides of the SGCL.

In the second trial, the height of the SGCL was extended to 10 inches. The same test was performed and gas bubbles were only observed in the gas collection bottle which is connected to the SGCL. No bubbles were observed on the sides of the SGCL. It took approximately 100 mL gas (complete experimental records shown in Appendix Section 0.1) to pressurize the head space before gas bubbles were observed in the gas collection bottle.

Analysis

Granule Settling Test

Based on the results of the Granule Settling Test, plate settlers were not proven to significantly improve SRT. However, there are two main factors that may make the results of this experiment inconclusive.

First, the granules used in this experiment were dormant, kept at room temperature without food, for several months until the start of this experiment. After being dormant, reactors typically require about six months to achieve steady state, but this experiment was only run for about two weeks. Therefore, the two weeks of the experiment were likely a part of the lag phase when microbial activity and biogas production is relatively low. The results of this experiment would have been more valuable had the reactors been operating at steady state with stable COD removal and biogas production rate.

Second, in drinking water treatment, plate settlers redirect the vertical flow of water through a reactor and lower the effective upflow velocity of water. Flocs are captured when the capture velocity of flocs exceeds this reduced upflow velocity of water. The results of the Granule Settling Test suggest that the upflow velocity in small-scale UASB reactors is slow enough that plate settlers are not needed for the capture velocity of granules to exceed the upflow velocity of water. However, this ignores the effect of biogas bubbles carrying granules towards the top of the reactor. If enough biogas was produced in this experiment, the effect of plate settlers on granules coated in biogas may have been observed. Unfortunately as previously mentioned, little biogas was produced to observe any effects.

The combined effect of low gas production and low upflow velocity lead to the result that plate settlers may not be effective in improving solid retention. There is uncertainty of whether or not the result from this test are representative of conclusions drawn from full-scale testing. To better understand the effects of plate settlers on granule settling, more experiments, detailed in the Future Works section, need to be explored.

SGCL Test

The results from the two trials of SGCL test suggest that there are a lot of factors that determine the characteristics of the SGCL. Failure from the first trial and success from the second trial suggested that there must be a minimum height of the water seal that ensures that gas is captured in the appropriate place. It is suspected that the failure from the first trial was because of an insufficient water seal and the buildup of back pressure on the SGCL due to increased head loss from all of the subsequent connections. This buildup led to gas escaping from the sides of the SGCL as opposed to collecting at the top of the reactor.

Conclusions and Recommendations

From the Granule Settling Test, it was concluded that plate settlers would not significantly improve SRT in a full-scale UASB reactor. The flow rate of the reactor is slow enough that the shear force of up-flow water does not cause the granules in the granule bed to re-suspend. Additionally, according to the results of the Granule Settling Test, biogas production rate in anaerobic digestion is not high enough to cause massive amounts of granules to float beyond the tube settler. However, it should be noted that granules used in this experiment were not running for a few months until mid April 2017. Therefore, during the span of the experiment, it is possible that the maximum biogas production rate was not observed.

From the SGCL Test, it was concluded that the back pressure produced by the connections after the SGCL determines the height of water above the ledge required to establish a gas-tight seal. If the biogas is flamed, the hydraulic pressure from the water above the SGCL must overcome the back pressure from the springs in the check valve. If the biogas is harnessed in a gas tank, the hydraulic pressure from the water above the SGCL must overcome the back pressure from the springs in the check valve and the pressure build up in the gas tank.

An important feature of the new SGCL design will be a check valve, as shown in Figures 10 and 11. A check valve will allow for continuous collection into a gas tank without any gas loss or reverse flow.

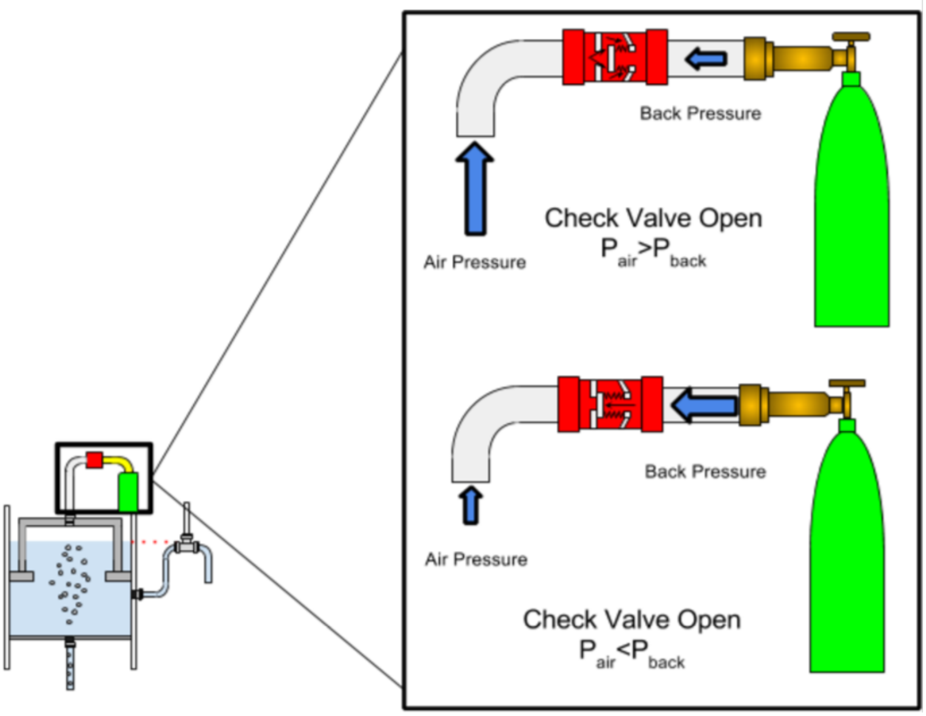


Figure 10: Possible design for a biogas capture system beyond the SGCL. The system would use a check valve to allow for continuous collection into a gas tank without loss.

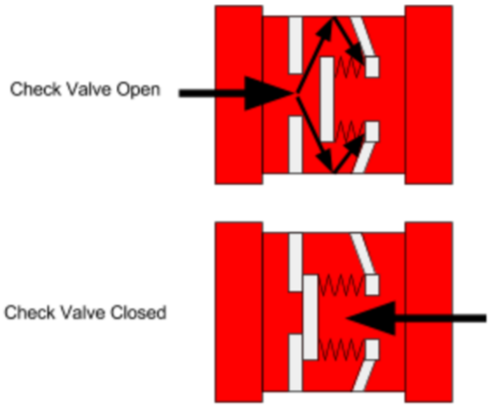


Figure 11: Enlarged image of a check valve. When the air pressure is higher than the back pressure, the valve opens (above). When the back pressure is higher than the air pressure, the valve closes. Before the back pressure builds up, the pressure required to open the valve is dependent on the spring constant behind the valve.

This seems to suggest that the most optimal design will be a gas capture system that is burned before releasing to the atmosphere. However, it is uncertain to determine if there will be a steady production of gas to sustain a constant flame. For this reason, a combined capturing-burning system will be suggested. Directly after the gas is captured, it will be collected in a chamber. This chamber will have a gas release valve that can be opened to burn the collected gas. This recommendation will need to be evaluated to determine if it is a feasible and safe solution.

$^{AK:}$ [Again, I'm not sure if this level of detail is necessary for the analysis. I would like to see a more in depth analysis of your actual results. Maybe a discussion on this back pressure would be appropriate if you guys were testing how much air you pumped in before seeing the gas lid fail? In your analysis you justify a reason for this check valve because of the failure of the first trial. Wasn't the second trial more successful? Could we mention a discussion of the results - that we only have a qualitative estimate and what the implications are? How could we go about getting a more quantitative and certain idea that our system is gas-tight? What we can conclude is that our system is promising, but that's not the end of the story. - MAKE BACK PRESSURE EXPLANATION CLEARER]

Future Work

Future teams should explore the appropriate fate of gas after preliminary wastewater treatment. The two possible options are to harness the gas for energy purposes or to burn the gas for reduced impact on the environment. Teams can calculate the hydraulic pressure from the water above the ledge and the back pressure form the springs in the check valve (if burning the gas) and the back pressure from both the springs in the check valve and the pressure buildup in the gas tank (if harnessing the gas). These calculations can better inform the design of the modified UASB reactor.

To reach a conclusion regarding the effect of plate settlers on overall performance, teams should conduct COD tests on both sides of effluent collection tank. These tests might reveal a more accurate indication of the performance of plate settlers that cannot be achieved by visual inspection.

Another design modification to consider is sloping the effluent of the reactor to mimic a tube settler. In the event that granules settle in the effluent line, having the submerged exit launder at an angle will prevent granules from escaping the reactor.

Finally, future UASB teams should design and build the full-scale UASB reactor, based on the design conclusions. In addition to the SGCL, a sludge weir and submerged exit launder should be included. After testing, the team should determine if this design is easy to maintain and operate.

Beyond design of a full scale UASB, future wastewater teams should begin to test the post treatment options within the limits of AguaClara technologies. Post treatment options include, but is not limited to: further organic matter removal, nutrient recovery, and pathogen inactivation.

AK: [Also try to include some of the other stuff I mentioned in comments earlier]

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Appendix

.1 Table from SGCL Test

Table 2: The amount of air that was pumped into the reactor before gas was collected in the Gas Collection Bottle

Trials	Without Outliers (mL)
1	118
2	88
3	84
4	87
5	85
6	110
7	108
8	111
9	84
10	86
Average (mL)	Standard Deviation (mL)
96.1	13.8

If the outlier of 175 mL of air were included in this analysis, the average of these entries would have been 103.3 mL with a standard deviation of 27.1 mL.

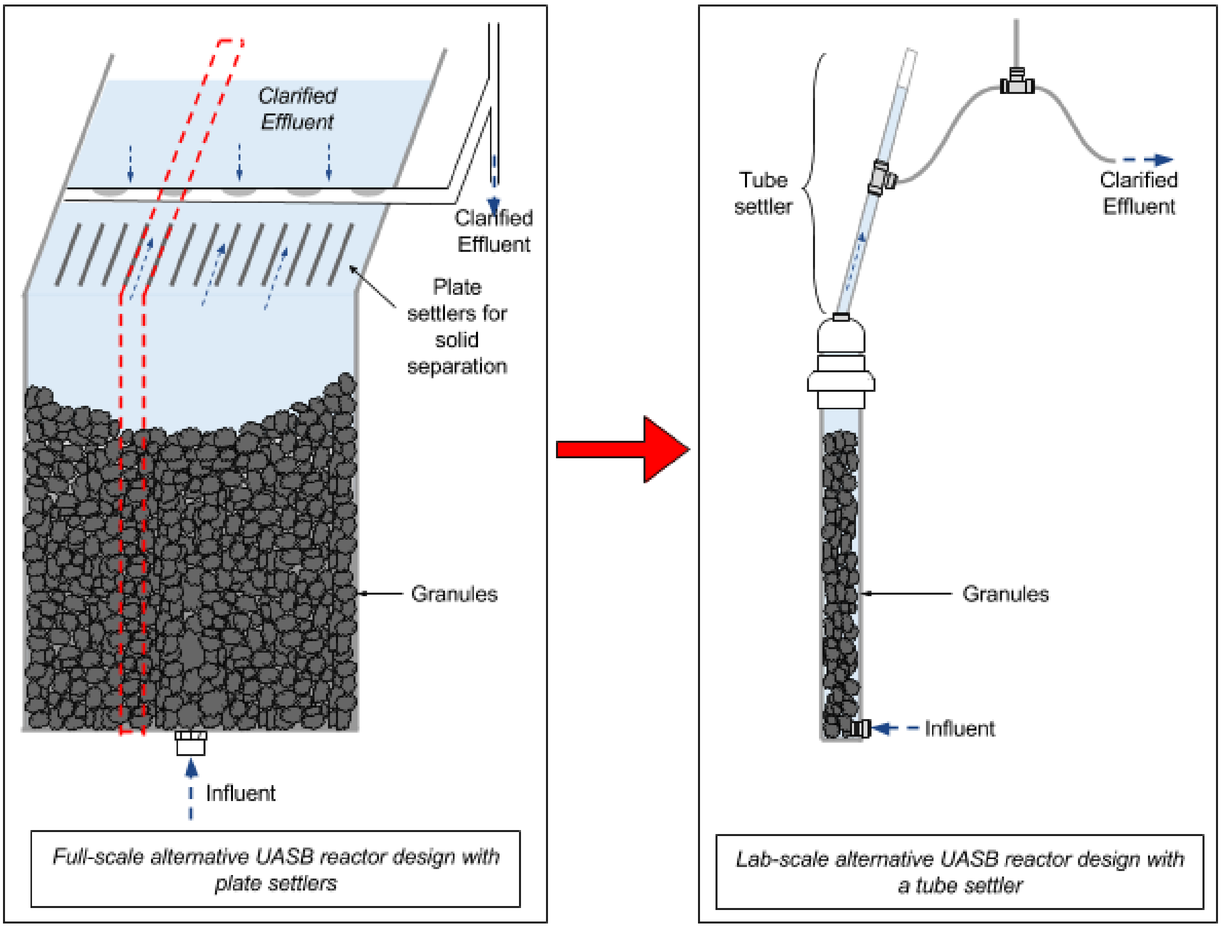
UASB Manual Spring 2017

Experiment: Granule Settling Test

- I. Purpose/Concept
- II. Materials/Equipment
  - A. Modified UASB reactor
  - B. Apparatus? (idk what to call the rest of the experimental apparatus)
  - C. Synthetic wastewater stock
  - D. Granules
- III. Safety precautions
- IV. Experiment preparation
  - A. Fabrication of modified UASB reactor
  - B. Apparatus set-up
  - C. Preparation of synthetic wastewater stock solution
  - D. Establishment? Management?Preparation? Of granules
- V. Experimental procedure
- VI. Granule retention analysis

I. Purpose

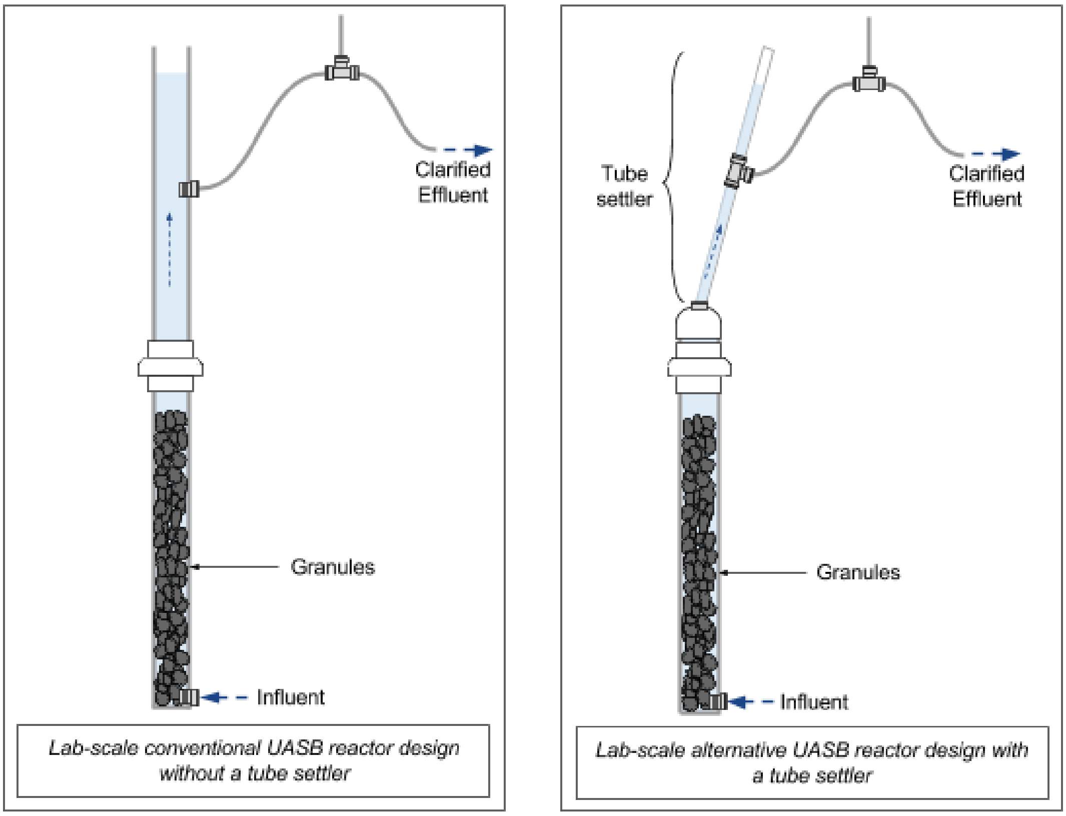
The purpose of this experiment is to observe the impact of plate settlers on the solid retention rate of UASB reactors. Two simplified UASB reactors built by the Spring 2016 UASB team containing granules were modified and operated: (1) with a tube settler and (2) without a tube settler (see Image 2). These testing reactors essentially represent a section of a full scale UASB reactor (see Image 1) . After operating the two reactors with synthetic wastewater, the reactor with fewer granules leaving as effluent should be used to design a full scale UASB reactor since it has a higher solid retention rate.



Full-scale alternative UASB reactor design with plate settlers

Lab-scale alternative UASB reactor design with a tube settler

Figure 1: A segment (shown within the dashed lines) of the full scale UASB reactor on the left was modeled as the lab scale reactor on the right. The plate settlers were simplified and modeled as a single tube settler.



Lab-scale conventional UASB reactor design without a tube settler

Lab-scale alternative UASB reactor design with a tube settler

Figure 2: The conventional reactor is shown on the left and the alternative reactor which aims to improve solid capture capacity by using a tube settler is shown on the right.

II. Materials/Equipment

A. Modified UASB Reactor

There are 2 ways to obtain anaerobic microbial granules for wastewater treatment. The first method is to grow the granules from scratch. To do so, a reactor should be inoculated with bacterial biomass. Over time, the bacteria eventually undergo a process known as granulation. Granulation can take months and occurs in three main steps: absorption, adhesion, and multiplication.

The alternative to facilitating the time consuming inoculation and granulation processes is to find a reactor that already has granules in it. For example, the Spring 2017 Granule Settling Test modified 2 of AguaClara's UASB reactors fabricated in Spring 2016 and inoculated in Summer 2016. These reactors were designed to have a removable top half such that different reactor designs and configurations could be tested without having to inoculate bacterial biomass for each new reactor.

<u>Spring 2016 UASB reactor dimensions:</u>

Note: Both reactors had the same dimensions

Reactor pipe ID (Inner Diameter), 1”
Height of bottom half of reactor, 24”
Height of granule bed, 12 ½”
PVC pipe union, 1.325” ID

Equipment:
Bandsaw
Drill press
½” Diameter drill bit
PVC Cement

B. Apparatus

Materials:
80/20 Aluminum framing
Rectangular bucket from Hollister Hall Teaching Lab
Divider, 1
Putty, 1 packet
Pump tubing
3 - Stop pump tubing, yellow-blue
Rigid tubing
Push-to-connect reducers
Push-to-connect tees
Male threaded push-to-connect fittings
Zip-ties
PVC pipe caps
PVC pipes
Rigid tubing valves
PVC Sheet

Equipment:
3 peristaltic pumps
Bandsaw
Drill press

C. Synthetic Wastewater Stock

Ingredients:
Water, 4 L
Urea, 6.4 g
NH_4CL, 0.800 g
Peptone, 1.2 g

$MgSO_4$, 1.58 g
KH_2PO_4, 1.22 g
$FeSO_4$-$7H_2O$, 0.080 g
$CaCl_2$-$2H_2O$, 0.48 g
Glucose, 16.4 g
Yeast extract, 3.6 g
Vegetable oil, 2 g
$CuCl_2$-$2H_2O$, 0.040 g
$MnSO_4$-H_2O, 0.008 g
NiSO4-$6H_2O$, 0.020 g
$ZnCl_2$, 0.02 g

Equipment:
Stir bar
Stir plate
200 g balance
Spatula
Graduated cylinder
Refrigerator

III. Safety Precautions

When in the lab, safety goggles must be worn at all times. This is especially important when handling the drill press, bandsaw, and any other mechanical equipment. When operating such equipment, be sure to work with at least one other person.

When preparing and/or handling the synthetic wastewater stock, safety goggles and gloves must be worn to prevent direct contact with potentially hazardous chemicals.

IV. Experiment Preparation

1. **Fabrication of modified UASB reactor**

   Reactor 1:

   Same diameter as reactor
   Height = 58”
   Water level = 48”

   1. Find a clear PVC pipe that is the same ID
   2. Using the bandsaw, cut a PVC pipe that is the same ID as the previously fabricated reactor bottom into appropriate length as described above

   Reactor 2:

   Diameter = ⅜”
   Height = 60”
   Water Height = 48”
   3. Drill a hole, diameter = ⅜”, height = 58”

4. Glue the connections with PVC primer and cement.
5. Connect to correctly to pumps and stock.
6. The effluent tubing for the plate settler test was mounted to the 80/20 frame on the left side of the reactor to make sure that water are not getting on any electronics on our station or other stations. (see Figure 3)
7. The effluent collection bucket is placed on the lab bench and covered with PVC plate to avoid smell??
8. Do hydraulic testing to check if there's any leaking.

2. Apparatus set-up

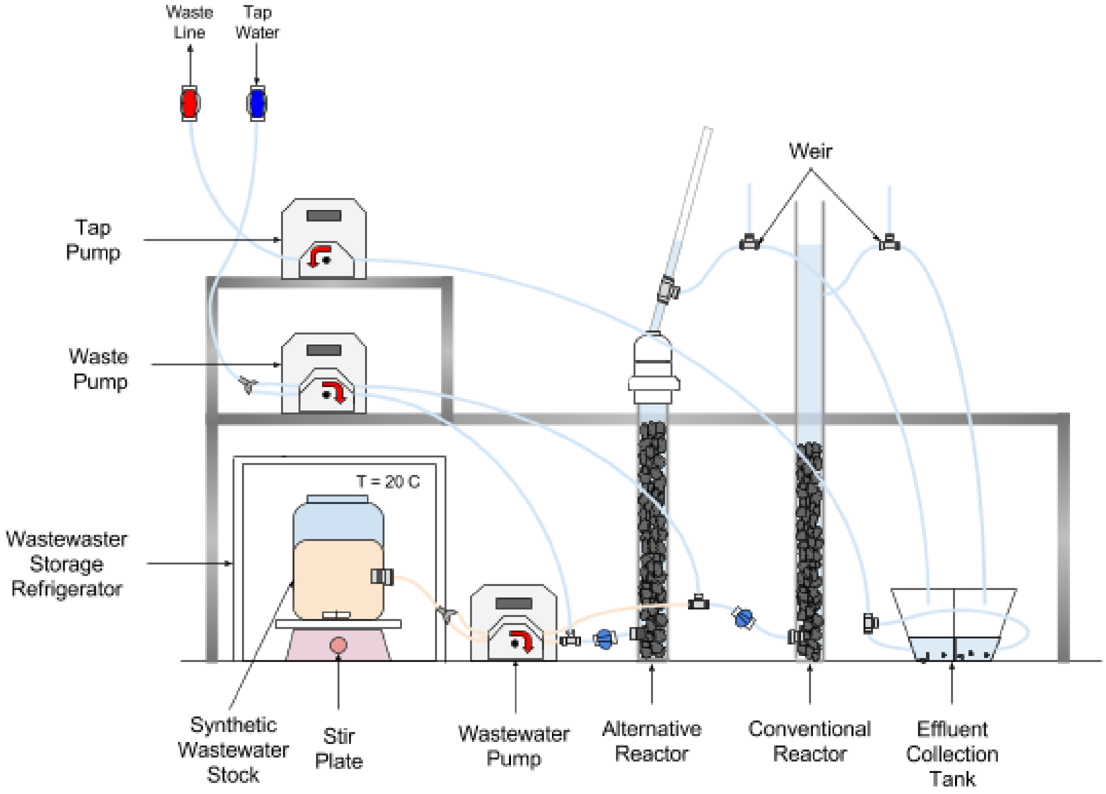


Figure 3: Benchtop setup of the granule settling experiment. The reactors were set up away from any electronics

3. Preparation of synthetic wastewater stock solution

The following synthetic wastewater recipe was developed by previous AguaClara wastewater teams. The recipe can also be found taped to the cabinet containing all the materials, across from the lab table and and sink. The recipe yields 4 liters of synthetic wastewater stock.

Synthetic wastewater stock per 4 Liter Solution:

1. Place a stir bar in a stock tank. Put the stock tank on a stir plate and mix at medium speed
2. Using a graduated cylinder, measure out 1 L of water and place into the stock tank
3. Measure out, using a 200 g balance and spatula, 6.4 g of urea
4. Measure out, using a 200 g balance and spatula, 0.8 g of formate
5. Measure out, using a 200 g balance and spatula, 1.2 g of Peptone
6. Measure out, using a 200 g balance and spatula, 1.58 g of $MgSO_4$
7. Measure out, using a 200 g balance and spatula, 1.22 g of KH_2PO_4
8. Measure out, using a 200 g balance and spatula, 0.08 g of $FeSO_4$-$7H_2O$
9. Measure out, using a 200 g balance and spatula, 0.48 g of $CaCl_2$-$2H_2O$
10. Measure out, using a 200 g balance and spatula, 16.4 g of glucose
11. Measure out, using a 200 g balance and spatula, 3.6 g of Yeast extract
12. Measure out, using a 200 g balance and spatula, 2 g of Vegetable oil
13. Measure out, using a 200 g balance and spatula, 0.04 g of $CuCl_2$-$2H_2O$
14. Measure out, using a 200 g balance and spatula, 0.008 g of $MnSO_4$-H_2O
15. Measure out, using a 200 g balance and spatula, 0.02 g of NiSO4-$6H_2O$
16. Measure out, using a 200 g balance and spatula, 0.02 g of $ZnCl_2$
17. Measure out, using a 200 g balance and spatula,
18. Using a graduated cylinder, measure out 3 L of water and add to the stock tank

V. Experimental Procedure

1. Set up reactor as described above.
2. Open the water line ball valve.
3. Turn on the wastewater pump and set flow rate to 1 rpm (determined by the Reactor Parameters Google Sheet in the Spring 2017 UASB Google Drive).
4. Turn on water pump and set flow rate to 3.4 rpm (determined by the Reactor Parameters Google Sheet in the Spring 2017 UASB Google Drive).
5. Turn on the waste pump and set flow rate to 5 rpm (determined by the Reactor Parameters Google Sheet in the Spring 2017 UASB Google Drive).
6. Open the inlet ball valves for the two reactors.
7. Let the system run for at least 1 week and note any granule accumulation in the waste bucket or the top of the reactor. Replenish wastewater stock solution as needed.

IV. Granule Settling Analysis

The reactor design that leads to the lowest amount of granule collection in the waste buck should be used for a large scale reactor.

Experiment: Gas Tight Lid Test

VII. Purpose

VIII. Materials/Equipment

   A. Modified UASB reactor

   B. Apparatus? (idk what to call the rest of the experimental apparatus)

IX. Safety precautions

X. Experiment preparation

   A. Fabrication of modified UASB reactor

   B. Apparatus set-up

XI. Experimental procedure

XII. Gas capture analysis

V. Purpose

Test the gas capture ability of lid that uses a water seal rather than a traditional gas tight, pressurized seal. A modified UASB reactor tank with proposed lid design was built. Clear water was used to simulate condition in the tank while gas was bubbled in and the lid was connected to a bottle of water. If gas travels from the lid and bubbles through the bottle of water, the lid design for the full scale reactor will use a water seal.

VI. Materials/Experiment

A. Materials

PVC sheets
PVC Pipe: For reactor body Diameter = 6’’
For lid Diameter = 5”
PVC Pipe cap: 5”

PVC tee
PVC reducer
PVC primer & cement

Luer lock (From Reid’s lab)
Glass syringe (From Reid’s lab)
Transparent bottle
Effluent collection tank
80/20 frame

Welding rod

B. Equipment

PVC welder
1 peristaltic pumps

Bandsaw
Drill press

VII. Safety Precautions

For this fabrication, clean up the working space before starting, be especially cautious and make sure wearing gloves and goggles when using weldler.

When welding a base for the inside of the reactor, always weld the closest edge to the body. Point the welder towards you so the hot air is deflected the other direction. Make sure not to rest the reactor against any part of the body.

VIII. Experiment Preparation

A. Fabrication for modified reactor

1. Cut the 6” PVC tube into 16 ½ ” long section

2. Cut a 2” inner diameter and 6” outer diameter donut shaped PVC sheet and weld it to the wall of the reactor approximately 9” from the top of the reactor

3. Cut PVC sheet into a 6” diameter circle with ⅜” inches diameter hole, weld it as the bottom of the reactor leaving room for the height of a connection
4. Drill a ⅜” hole at 6” height of the reactor as effluent outlet
5. Check if the reactor is water tight
6. Cut a 4” diameter PVC pipe into a 9” length
7. Drill a ⅜” inches hole on a 4” diameter pipe cap
8. Make the water tight lid by glueing pipe tube and pipe cap together
9. Connect to pumps and effluent collection buckets


Figure 4: Appearance of the donut when placed inside the reactor

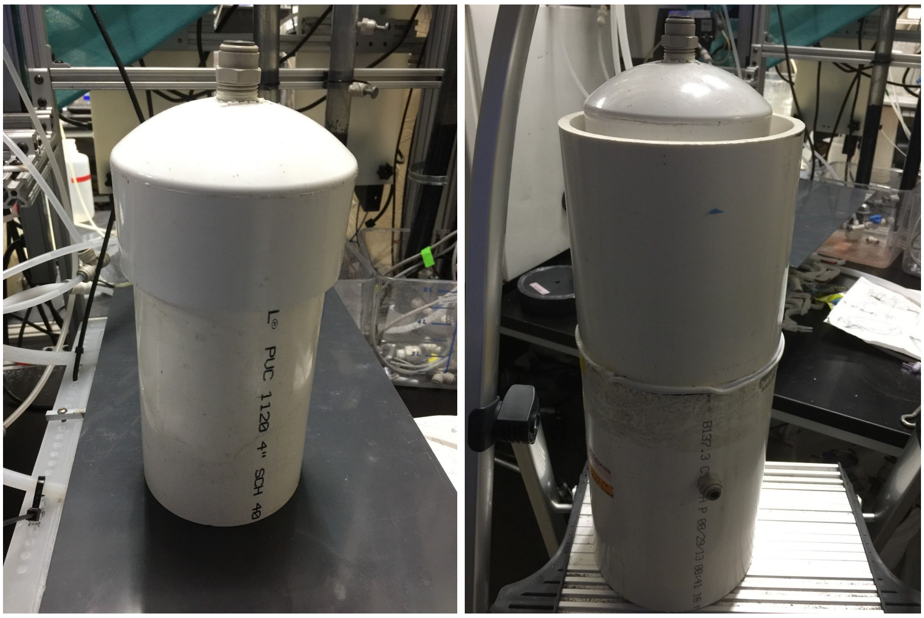


Figure 5: Finished lid made from 5” pipe and pipe cap (left). Lid apparatus placed inside the reactor (right). The length of the lid should span the height from the ledge to the top of the reactor

B. Apparatus set-up

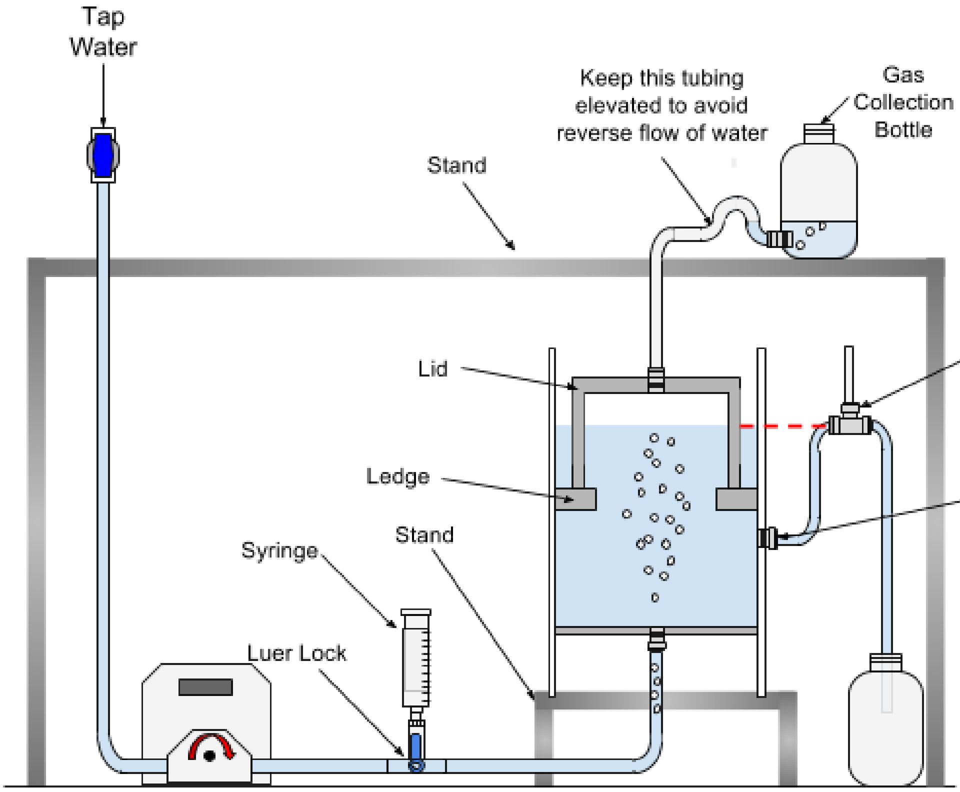


Figure 6: Benchtop step up of the lid test

IX. Experimental Procedure

A. Set up reactor as described above.
B. Stop the pump
C. Open the Luer Lock on influent supplying tube.
D. Gradually inject 30ml amount of air into the luer lock using syringe
E. Close the Luer Lock
F. Run the pump
G. Observe the gas bubble behavior on the side of the lid and from the gas collection system

X. Gas Capture Analysis

We observed that a certain amount of gas should be injected in reactor before gas can be seen in the outlet, thus it may be helpful if calculate the volume of gas that has been pumped in.

Part I

Semester Schedule

Task Map

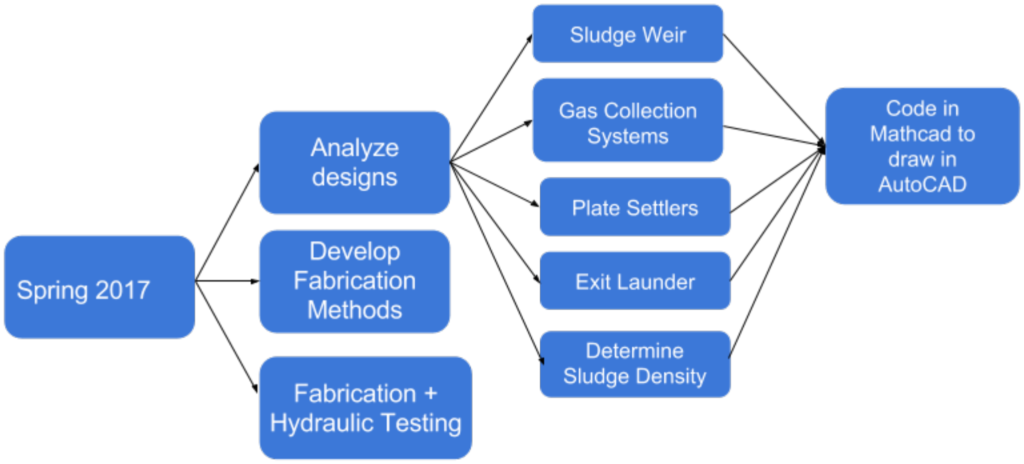


Figure 12: Example Task Map

.2 Task List

You should keep and update your detailed task list from the first assignment in each of your reports. Denote completed tasks and modify your deadlines to reflect your most recently completed progress and any delays.

1. Determine sludge density/March 3 - Everyone - Read literature to determine the appropriate density of the sludge blanket. Code in Mathcad to draw in AutoCAD. Develop fabrication methods.

2. Analyze sludge weir/March 10 - Everyone - Based on the sludge density, design a sludge weir using the existing design equations for AguaClara floc hoppers. Code in Mathcad to draw in AutoCAD. Develop fabrication methods.
3. Analyze plate settlers/March 17 - Everyone - Based on the sludge density, design plate settlers using the existing design equations for AguaClara plate settlers. Code in Mathcad to draw in AutoCAD. Develop fabrication methods.
4. Analyze gas collection system/April 14 - Everyone - Evaluate existing GLSS systems for UASB technology and explore new designs for gas capture. Code in Mathcad to draw in AutoCAD. Develop fabrication methods.
5. Analyze exit launder/April 28 - Everyone - Determine placement and design. Code in Mathcad to draw in AutoCAD. Develop fabrication methods.
6. Fabricate/test lab scale model/May 10 - Everyone - Based on the chosen methods, begin fabrication and hydraulic testing.

.3 Team Roles

Team Coordinator - Linping Materials Coordinator - Subhani Data Coordinator - Zac Design Coordinator - Serena