Anaerobic Wastewater Treatment

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Abstract

As AguaClara has grown, it has become increasingly important to not only improve methods for the treatment of drinking water, but also to treat community wastewater in a sustainable manner. The long term goals of this research are to develop a a gravity driven system for wastewater treatment and to characterize the general mechanism for anaerobic waste treatment. This team will operate under the principles of reducing human impact on the environment by effectively treating domestic wastewater before reintroduction to natural bodies of water and treating waste as a source of energy rather than a sink.

Literature Review

1 Energy Potential in Wastewater Treatment

Water reuse is already widely practiced where water is in limited supply, but this often increases the energy needed for treatment because of increased water quality requirements for reuse [1]. There are three energy forms that we mainly use from the wastewater. First of all, wastewater N and P can be used for fertilizer instead of manufactured fertilizers. Secondly, potential energy might be gained from the thermal heat contained in water. And the third one which is most direct and common exploited is the energy contained in wastewater organics [2].

With conventional approaches involving aerobic treatment a quarter to half of a plants energy needs might be satisfied by using the CH4 biogas produced during anaerobic digestion, and other plant modifications might further reduce energy needs considerably. That is to say, if we could capture more of the potential energy in wastewater or reduce energy for wastewater treatment, then we might make the wastewater treatment become a net energy producer. And according to Perry L. McCarty's paper, complete anaerobic treatment has the potential to achieve net energy production while meeting stringent effluent standards [3]. Apart from the potential energy, the CH4 is also a kind of powerful greenhouse gas and thus cannot be allowed to escape to the atmosphere but should be collected and reused.

2 Different Technologies within Anaerobic Wastewater Treatment

Knowing the various advantages anaerobic waste water treatment has over aerobic waste water treatment, considerable effort has been put into developing different types of reactors in order to optimize the use of this technology. Each type of reactor has its unique feature which eventually serves to reach the common goal of producing clean water and to increase efficiency by using the energy produced in the process, to run the reactor.

UASB - Uplfow Anaerobic Sludge Blanket

Within the anaerobic treatment sphere, Upflow Anaerobic Sludge Bed (UASB) reactors are some of the most compact in design and have the ability to treat the highest loading rates. These have been selected for initial investigation and adaptation for effective implementation in developing nations. Aiyuk, et al. review the structure and operation of a UASB, the competing biocatalyzed reactions that occur in the reactor, and the challenges that come up during operation, such as ensuring sludge granulation during start-up and inhibiting disintegration over time [4]. The UASB reactor initially inoculated with sludge, often in granular form though it may be in a flocculent form, and operated with liquid flowing upward from the bottom of the reactor. The Upflow operation of the system causes the wastewater to flow by the dense sludge in the bottom of the reactor and fluidize the less dense sludge blanket above. Treatment occurs throughout the reactor, but we hope to characterize the level of treatment carried out in the different zones of the reactor due to the varying sludge formations. The microbes within the inoculum grow throughout the life of the reactor and may evolve sludge of varying qualities; flocculent inoculum may even form granules by itself. Sludge evolution is believed to depend on the Organic Loading Rate (OLR) and Sludge Loading Rate (SLR) during startup, though it has been shown the presence of cations may also play an important role in granule formation [6], [5]. Granules ideally prevent the need for support materials in UASBs, though we plan to investigate the effect of support materials in granule formation.

In a well operating reactor, gas is produced, containing primarily methane and carbon dioxide. The gas serves to further fluidize the reactor, assists in mixing, and the methane within the biogas may serve as an energy source if effectively captured [6]. This depends greatly upon the design of the Gas/Liquid/Solid (GLS) separator, stereotypically a funnel type design to capture as much gas as possible, allow liquids to flow out of the reactor, and direct solids downward back to the body of the reactor. It is believed the sharp angles of the GLS separator assist in the redirection of the solids, though there is little evidence to support this conclusion. We propose a GLS design to more effectively capture the solids of the reactor and improve effluent quality. This will also serve to further increase the independence of the Hydraulic Residence Time (HRT) and Solids

Residence Time (SRT) of the reactor, an innate advantage of the UASB design. Since the COD produced is converted to methane, it is important to check how this can be carried out efficiently. Here, the influent COD concentration, hydraulic retention time and temperature play an important role. The focus must be placed on the conversion of COD to biogas and not only on the COD removal (T. Elmitwalli) to ensure stable performance of the reactor, because the removal of COD varies with the hydraulic retention time and temperature.[11]

If wastewater treatment has any chance of being a net energy producer, methane capture must be extremely efficient. Though COD removal rates and CH4 production rates are historically high for UASBs, Lobato et al. has demonstrated discrepancies between COD rates and CH4 rates, indicating methane within the system[7]. These losses are often unaccounted for, likely due to the absence of methane use for energy in many reactors, especially those constructed in the early days of the technology used for industrial wastewater treatment[8]. The UASB reactor designs have changed and improved since the invention of the technology; however, post treatment is still widely believed to be necessary to meet effluent standards before discharge into the natural environment. Chong et al discuss many possible options. The technologies deemed most appropriate for exploration are constructed wetlands, downward hanging sponges, and pond systems[6]. These systems improve COD, nutrient, and pathogen removal, though other very different strategies have been proposed to improve independence of treatment efficiency from ambient temperature as well as to increase nutrient removal. One simple strategy would be to source separation of nutrients by urine diversion, though this would lead to a very different wastewater.

AFBR - Anaerobic Fluidized Bed Reactor

In the Anaerobic Fluidized Bed Reactor, the biofilm attaches itself to an inert media and grows around it. When liquid of increasing flow is passed through these bio granules (bi film plus carrier inert material) , the bed of bio granules expands and gets suspended in the liquid , thus creating a fluidized state . The shear stress of the biofilm must be at least great enough to balance the net negative buoyancy of the media and cause fluidization. Bio-film is more homogenous and smooth under conditions of high liquid velocity (high shear) than under low shear. The bed fluidization model by Nicolella et al., 2002 emphasizes on the importance of the fluidization characteristics like terminal velocity and the size of the particles that allow efficient performance.[9] We are also focusing on obtaining the right media for this reactor as the kind of media /carrier material plays an important role in the performance of the AFBR .According to Fan et al, 1984, the fluidization of the bio granules occurs smoothly in a homogenous expansion i.e., when the particles are of uniform size. When the particles are not uniform, then there is a high tendency that segregation of particles will occur because of heterogeneous expansion. The other physical characteristics that will contribute to using the right media is density, hardness, roughness of the media particles and the chemical characteristics are chemical adsorption and inertia.[10]Schreyer and Coughlin (1999) found that the disadvantage of this process is the possibility of an increase in thickness of the biofilm. This happens as the biofilm is continuously growing .Thickness in biofilm results in decrease in the particle's overall density and increase in its buoyancy, which causes biofilm detachment from the media particle and subsequently gives rise to wash out problems. Hence, efforts will be made to prevent stratification and to maintain the particle size , by removing the excess biofilm .[9]

AFMBR - Anaerobic Fluidized Membrane Bioreactor

Jeonghwan Kim et al used a two-stage system to evaluate the performance of AFMBR. A 120-d continuous-feed evaluation was conducted using this two-stage anaerobic treatment system operated at 35 °C and fed a synthetic wastewater with chemical oxygen demand (COD) averaging 513 mg/L [3]. The first-stage was a similar fluidized-bed bioreactor without membranes (AFBR), operated at 2.0-2.8 h hydraulic retention time (HRT), and was followed by the above AFMBR, operating at 2.2 h HRT [3].

It was found that AFMBR requires only a small fraction of energy that AFBR needs, therefore the potential energy advantage of the AFMBR is apparent. And AFMBR can reduce the effluent TCOD of AFBR and thus increase the overall COD removal for the two-stage system to 99% [3]. AFMBR also can remove the effluent TSS and VSS of AFBR to near zero. In summary, the AFMBR used for post-treatment of effluent from an AFBR produced an excellent polished effluent.

Introduction

Wastewater treatment is the process of treating the sewage water that leaves homes before the wastewater gets reintroduced to the environment. In a typical wastewater treatment process, solid waste is separated out of the water stream, organic matter in the waste stream is treated and disinfected, and particulates are settled out. The difference between wastewater treatment and drinking water treatment processes has to do with the robustness of the treatment and the standards that the effluent water needs to reach. Understandably, wastewater contains more contaminants in its stream that need to be treated. At the end of the wastewater process, water is treated to the standard of environmental quality of raw water in natural sources. Drinking water treatment processes treat an influent stream of the raw water to a quality suitable for human consumption. Additionally, wastewater treatment processes often contain a unit operation for organic matter digestion, i.e. breaking down solid organic biomass using microbes and converting it into biogas, typically carbon dioxide and methane, and treatable liquid effluent [12]. The AguaClara wastewater treatment division plans to use anaerobic digestion, microbial decomposition of organic matter in the absence of oxygen, in its treatment process.

Wastewater treatment is a necessary and beneficial process for developed and developing countries. Wastewater from homes in underdeveloped areas of the world is often left untreated before getting reintroduced to natural water sources. This disregard for water quality diminishes the already short supply of clean fresh water and increases the demand for more water treatment. With the addition of a wastewater system, water gets treated for contaminants before it reenters the environment. The risks of waterborne diseases like typhoid or cholera are lessened for people who collect raw water from public water sources for personal consumption [13].

The benefits of wastewater treatment can be seen through the utilization of biogas. Methane produced as a byproduct of anaerobic digestion can be utilized as a source of energy for powering the building, heating the digester, or driving machinery if enough biogas is harvested [14].

AguaClara has a strong background in creating sustainable, energy-efficient, and cost-efficient drinking water treatment technologies in developing nations. One of its newest challenges is developing the same level of efficiency for wastewater treatment technology. The AguaClara Wastewater Division, newly established in early 2013, aims to adapt the drinking water treatment innovations to the wastewater environment. The division's first project is the development of an anaerobic digestion bioreactor. The team wishes to expand upon research conducted over summer 2013 in finding ideal reactor specifications to maximize the rate and extent of anaerobic digestion. Additionally, the team seeks to discover methods of maximizing methane production and minimizing oxygen levels in the system.

Methods

COD

The influent and effluent water running through the reactor are tested for chemical oxygen demand daily. The water samples are stored in the freezer between sampling and the COD test to ensure the COD remains the same as when sampled. The COD is measured using prepackaged vials from CHEMetrics. The wastewater COD reduced dichromate in the test vials over a two hour period, then the decrease in dichromate concentration is measured colorimetrically by the use of a Hewlett Packard Diode Array Spectrophotometer. By creating a standard curve from samples of known COD concentration, the concentration of the wastewater samples can be determined from the transmittance readings of the spectrophotometer.

Chemical oxygen demand is a way to measure the organic matter in a sample in terms of the amount of oxygen needed to fully oxidize the organic compounds. The most basic objective of wastewater treatment is to decrease the chemical oxygen demand to a low enough level to be introduced into the environment without causing negative effects.

Gas Chromatography

Gas chromatography is the chosen method to quantify the methane production in the reactor. Each day, a 100 µL sample of biogas is taken from the gas chamber. This sample is injected into the Hewlett Packard Gas Chromatograph and the chromatography is performed usign a carrier gas of He. The elution times and peak areas are recorded, and the peak areas are used to calculate the methane partial pressure through a standard curve procedure similar to that referenced in the COD method. The methane production is measured to determine the possible energy that could be produced by the reactor. The group hypothesizes the methane partial pressure should directly correlate with the COD destruction in the reactor.

Process Controller

The Process Controller file used for the operation of the reactor has three states that rotate only based upon time. These time steps control the tap water and stock valves so that the stock is only pumped for 4.5 seconds of every minute and the tap water is pumped for the remaining time time to dilute the stock to an influent COD of 500 mg/L. The states control the tap and stock valves as well as the stir plate to mix the concentrated stock solution within the refrigerator. During operation, the tap valve is open for 35 seconds while the stir plate is off. The tap valve remains open for another 20.5 seconds while the stir plate is on and then the stir plate remains on while the tap valve closes and the stock valve opens.

The pressure within the gas chamber is recorded by a pressure sensor as indicated in Figure 1. As gas is produced and fills the chamber, the differential pressure between the two ports decreases. When the water level in the chamber reaches two cm above the lower port, the gas valve opens, releasing gas until the water level rises to seven cm above the lower port, at which point the gas valve closes and the chamber begins to once again collect gas. The pressure measured by the pressure sensor is recorded in a Microsoft Excel file every 30 seconds. This pressure data is then graphed and the number of off-gas events is visually determined in order to calculate the daily gas production within the reactor.

Synthetic Wastewater Preparation

The synthetic wastewater used in the experiments was modeled after the synthetic wastewater used by Aiyuk et al. The constituents of the wastewater and appropriate concentrations are shown in Table 1. As indicated above, the synthetic wastewater is diluted by a factor of 13.3 when pumped into the reactor to achieve an influent COD of 500 mg/L. After preparation, the wastewater is sterlized in the autoclave before use.

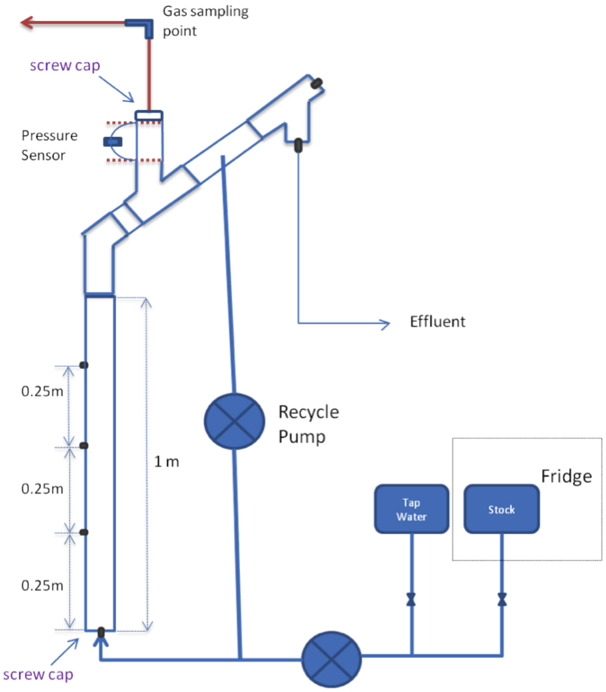

Figure 1: Diagram of Future Reactor Design

Urea	1600 mg/L
NH4Cl	200 mg/L
Na-acetate	1357 mg/L
Peptone	300 mg/L
MgHPO4-3H2O	500 mg/L
K2HPO4	305 mg/L
FeSO4.7H2O	100 mg/L
CaCl2-2H2O	120 mg/L
Starch	2100 mg/L
Milk Powder	2000 mg/L
Yeast Extract	900 mg/L
Vegetable Oil	500 mg/L
CuCl2.2H2O	10 mg/L
MnSO4.H2O	2 mg/L
NiSO4.6H2O	5 mg/L
ZnCl2	5 mg/L

Table 1: Concentrated Synthetic Wastewater Recipe

Results and Analysis

There have been no quantitative results yet obtained this semester. However, it has been noticed that the gas production within the reactor is far below the level seen while the reactor was in the basement and operated in a semi-batch fashion. Though the reactor is now being fed approximately ten times the COD per day as during the batch operation, the gas production is neglible when compared to the previous production levels.

Conclusions

None yet.

Future Work

Reactor Construction

In the coming weeks, the group will complete construction of five reactors in addition to the reactor currently in operation. The clear PVC for the construction was just ordered, so the construction should be complete by Friday, October 4th. Each of the reactors will have a similar design to Reactor 2.1 currently in operation in that they will each have tube settlers as the GLS separators. The reactor design is shown in Figure 1. The reactors will operate with a flow rate of 7 mL/min leading to an upflow velocity of .102 mm/s for the $1\,\frac{1}{2}$ inch pipes used for these reactors. Once the reactors are constructed, each will need to be rigorously tested for liquid and gas leaks. The main area that will need to be made watertight will be the screw cap at the bottom of the reactor. Gas capture will be optimized if all gas leaks in the vertical gas collection part of the reactor are sealed. All connections must be sealed tightly and will be tested for gas leaks by pumping air through the completed gas collection apparatus and placing the tubes and connections beneath water and looking for the production of bubbles. The system will be deemed airtight if the gas chamber is filled with air and the pressure sensors measure the same pressure overnight with all valves closed.

Model Development

During construction and testing of the reactors, the group will also be focusing on model development for three different aspects of reactor operation. The first model will focus on fluidization and sedimentation velocities, modifying and adding to the model created during the summer. This model relies on the following equation for fluidization velocity:

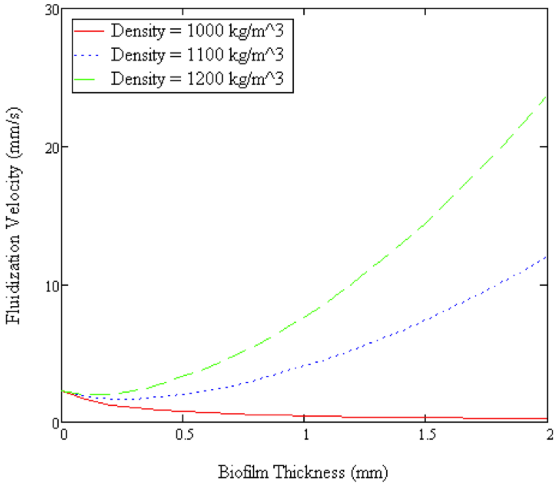

Figure 2: Fluidization Velocity Model

$$V_{MinFluidization} = \frac{\varepsilon_{FiSand}^{3} g D_{60}^{2}}{36kv(1-\varepsilon_{FiSand})}\left(\frac{\rho_{Sand}}{\rho_{Water}}-1\right) \tag{1}$$

The density of sand in the equation is replaced in this instance with the density of the support material with an attached biofilm. Figure 2 shows the beginnings of the model created during the summer and the minimum fluidization velocity of a sand grain with an attached biofilm of varying density. Future models will show how the fluidization velocity changes as the biofilm develops and with support materials of varying size and density. This will assist in the identification of an ideal support material and can be tested in the reactors.

The second model will address shear on the individual particles in the reactor. The literature will be investigated to identify the maximum shear at which microbial growth can still take place on a support material. Additionally, the model must take into account the flow patterns within the reactor, as the flow velocity and thus shear are not uniform throughout the reactor. It is likely the moment of greatest shear will occur where there is the greatest upflow velocity. The model will indicate at what level this shear must be maintained to allow proper biofilm development.

The last model will deal more directly with the microbial communities present in the reactor with the overall goal of determining what limits the rate of COD destruction in the reactor. It is assumed now that mass transfer from the bulk fluid to the surface of the biofilm or surface of the granules is the rate limiting step within the reactor. The model will elucidate at what rate the substrate enters the microbial community and may serve to identify a relationship between the organic loading rate of the reactor and the necessary surface area of microbes to effectively degrade the substrate. Further model development will model the growth of different microbial species in the reactor as well as concentrations of the substrates for these communities, ie complex carbohydrates, simple carbohydrates, acetate, and methane as a product.

References

[1] B Burton, Franklin, et al. "Water reuse: issues, technologies, and applications." (2007): 392.

[2] McCarty, Perry L., Jaeho Bae, and Jeonghwan Kim. "Domestic wastewater treatment as a net energy producer–Can this be achieved?." Environmental science & technology 45.17 (2011): 7100-7106.

[3] Kim, Jeonghwan, et al. "Anaerobic fluidized bed membrane bioreactor for wastewater treatment." Environmental science & technology 45.2 (2010): 576-581.

[4] S. Aiyuk, I. Forrez, D. K. Lieven, A. van Haandel, and W. Verstraete, "Anaerobic and complementary treatment of domestic sewage in regions with hot climates–a review," Bioresour. Technol., vol. 97, no. 17, pp. 2225–2241, Nov. 2006.

[5] M. M. Ghangrekar, S. R. Asolekar, and S. G. Joshi, "Characteristics of sludge developed under different loading conditions during UASB reactor startup and granulation," Water Research, vol. 39, no. 6, pp. 1123–1133, Mar. 2005.

[6] S. Chong, T. K. Sen, A. Kayaalp, and H. M. Ang, "The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment–a state-of-the-art review," Water Res., vol. 46, no. 11, pp. 3434–3470, Jul. 2012.

[7] L. C. S. Lobato, C. A. L. Chernicharo, and C. L. Souza, "Estimates of methane loss and energy recovery potential in anaerobic reactors treating domestic wastewater," Water Sci. Technol., vol. 66, no. 12, pp. 2745–2753, 2012.

[8] G. Lettinga and L. W. H. Pol, "UASB-Process Design for Various Types ofWastewaters," 10-Mar-2011. [Online]. Available: http://www.iwaponline.com/wst/02408/wst024080087.htm [Accessed: 13-Jun-2013].

[9] Sarvananan and Sreekrishnan paper from 2006 in Journal of Environmental Management. "Modelling anaerobic biofilm reactors—A review"

[10] Iza, J. "Fluidized bed reactors for anaerobic wastewater treatment." Water Science & Technology 24.8 (1991): 109-132.

[11] Elmitwalli, Tarek, et al. "Anaerobic biodegradability and treatment of Egyptian domestic sewage." Journal of Environmental Science and Health, Part A 38.10 (2003): 2043-2055.

[12] "Water Vs. Wastewater." Water Vs. Wastewater. Huntsville Water Pollution Control, 2001. <http://www.huntsvillewpc.org/oldsite/differences.htm>.

[13] "Wastewater and Public Health." On-Site Wastewater Disposal and Public Health. Purdue University, n.d. <https://engineering.purdue.edu/~frankenb/NU-

prowd/disease.htm>. From Pipeline, Summer 1996, Vol.7, No.3

[14] Lono-Batura, Maile, Yinan Qi, and Ned Beecher. "Biogas Production And Potential From U.S. Wastewater Treatment." <http://www.biocycle.net/2012/12/18/biogas-production-and-potential-from-u-s-wastewater-treatment/> BioCycle. N.p., Dec. 2012. Vol. 53, No. 12, p. 46