Activated Anaerobic Digestion with a Membrane Filtration System

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ABSTRACT

A novel process, activated anaerobic digestion, has been successfully demonstrated in a full scale facility. The process includes an anaerobic digester working with a screw press and a UF membrane system, and produces biogas from agricultural and industrial feedstocks. The system was operated at two temperature zones; thermophilic , at 55 degrees C in 2010 and at a startup temperature of 45 degrees C in 2011 at a daily biogas(methane) generation rate of 0.34 m3/kg COD.

The feed materials included hog manure, corn silage, grains and other industrial organic material with high biogas potential. The membrane system is unique, with a vortex generator that resist fouling by physical and chemical components. The screw press cake separates non-active biosolids from active biomass, with the screw press cake shipped out as a nutrient rich fertilizer. The UF system captures and concentrates all microorganisms and returns them to the digester The UF membrane permeate is a high-quality water suitable for downstream treatment by reverse osmosis.

GPS-X modeling software was utilized with the Mantis2 model. A model was calibrated and validated with two sets of data from full scale operation. The models were run for both steady state and dynamic operations. The results showed the impact of key variables including temperature and influent flow rate on the stability of the system. The model was also used to demonstrate the effects of selected disturbances, such as feed disruptions and step increase in feed . Both the full scale data and model predictions successfully established the stability of the new process and benefits from membrane filtration.

KEYWORDS: Biogas, Dynamic Model, GPS-X Model, Anti-fouling filtration system, Biomass Recycle, Manure, Agricultural Feedstocks, Thermophilic, Mesophilic

INTRODUCTION

The conversion of waste organic materials to useful fuels has grown in importance in the past 20 years, accompanying concerns about use of fossil fuels and increases in greenhouse gas levels in the atmosphere. Major sources of waste organic material are farm operations producing manure. Many such facilities have sought to produce biogas (methane) from manure and other available industrial or agricultural waste materials using mesophilic anaerobic digestion. While such systems are effective, recent research (1) indicated that operating anaerobic digesters at higher temperatures to favor thermophiles can increase the production of biogas, with an associated reduction in solids requiring disposal. The difficulty with thermophilic operation is that systems can be more sensitive to upsets, and the solids, especially those from manure, are often more difficult to dewater by conventional separation techniques. Recent work with a novel ultrafiltration (UF) membrane system design has allowed for successful operation of a full-scale anaerobic digestion with cell recycle (2). The system uses an innovative vortex device to keep the biosolids from fouling the membrane, allowing recycling of live bacteria that enables a high organic loading rate in the digester. The recovery and recycling of cells allows the digester to operate similar to an activated sludge system. Activated sludge systems are known to have more stable operations than similar systems without recycle, due to the opportunity to decouple cell residence time from hydraulic residence time. In addition, the system provides a higher amount of gas generation compared to non-recycle systems.

The system has been in operation for over a year, with a 2011 re-start following a maintenance shutdown. The system feed includes several agricultural and industrial waste products as well as manure from hog operations. Data were collected in both 2010 and 2011 for modeling purposes. This paper presents results from both periods.

System Description

Anaerobic digestion converts organic waste into methane and carbon dioxide via complex metabolic processes. The resulting liquid effluent has high concentration of ammonia, relative to organic carbon, rendering common biological nitrogen removal process impossible. Membrane filtration is the only alternative for treating anaerobic digestate.

Although many articles and academic theses have dealt with digestate treatment using membrane filtration, it is hard to find a stable-operating biogas plant that uses membranes as a treatment method. The difficulty arises from the high solid content in the digestate, which is known to contribute significantly to fouling. Although fats, oils, and grease (FOG) offer enhanced biogas production from the digester, the elevated water viscosity serves to further inhibit the filtration process.

The system is depicted in Figures 1 and 2. Figure 1 shows that in 2010, feed other than manure, including corn, wheat, and other organic wastes, was sent directly to the anaerobic digester, with the manure blended with the digestate. Under the current model conditions in 2011 as shown in Figure 2, manure was also sent directly to digester. Solids from the digester were dewatered via a screw press to recover solids and nutrients in a form of a sludge cake. That cake was then used as a fertilizer. . The performance of screw press depends on the type of feed stock to the digester and the ratio of feed stock mixture. Thus, both feed stock characteristics and screw press performance may affect the membrane concentrate quality and quantity as a recycled feed to the digester.

The supernatant from the screw press was then fed to an FMX UF membrane filter unit (BKT Technologies, Anaheim, CA). The novel UF membrane system uses an anti-fouling vortex generator with flat membranes, which allows the membrane system to take TS in the range of up to 5%. Due to the design and material of construction, the system can also take high temperature up to 90 degree C. These characteristics are ideal for digestate treatment from thermophilic anaerobic digesters.

Retained solids, including microorganisms, from the UF unit were returned to the digester, while the permeate was treated through reverse osmosis (RO) then reused or discharged. The RO retentate was used as a liquid fertilizer.

The system processed 90 to 135 m^3/day (24,000 to 36,000 gal/day) of industrial waste, agricultural waste, and pig manure through five 3000 m^3 digesters. The biogas from this system is being used to generate 4-6 MW of electricity. The use of membranes for filtering even digested biosolids has been considered infeasible in the past because of fouling.

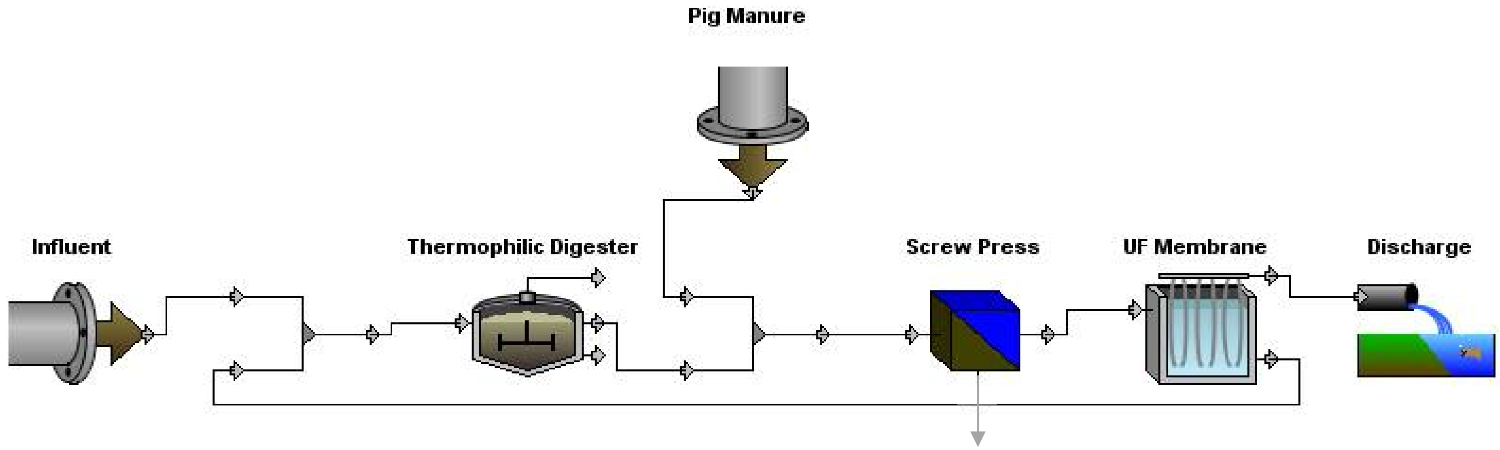

Figure 1: Process Layout for 2010

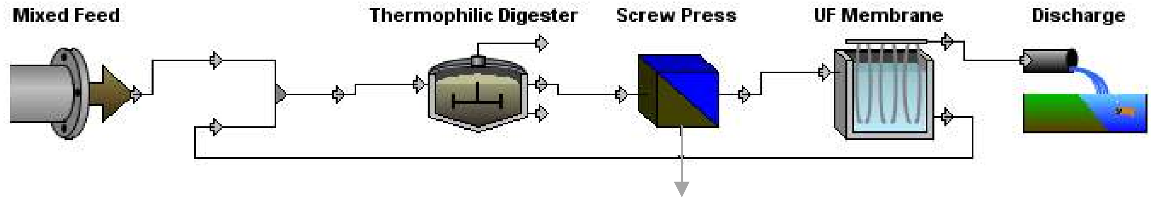

Figure 2: Process Layout for 2011

System Modeling

The thermophilic digestion system was modeled in the GPS-X WWTP simulation platform using the Mantis2 plant-wide biological model and the anaerobic digestion, sludge dewatering, and membrane filtration processes (see Figure 3 for the plant flowsheet as represented in GPS-X). An optional splitter is inserted into the recycle line so that the recycle sludge can be diverted to study its impact.

The Mantis2 model describes activated sludge, anaerobic digestion, and side-stream processes in one integrated model and includes the modeling of pH, gas transfer, and precipitation. The model is based in part on the UCTADM1 anaerobic digestion model (Sötemann et. al., 2005) and the inorganic precipitation model of Musvoto et al. (2000) and includes the modeling of organic and inorganic phosphorus-containing compounds.

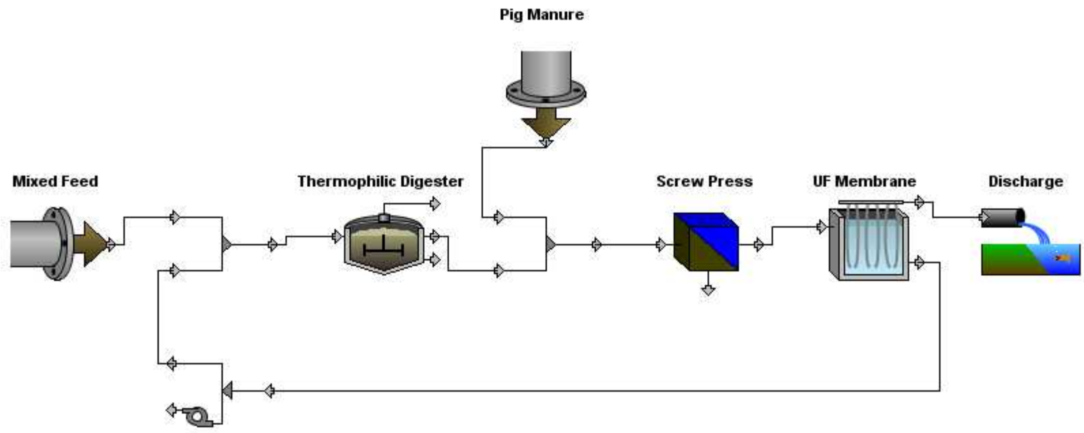

Figure 3: Plant Flowsheet as Represented in GPS-X

For the current project, it is important to use an integrated plant-wide model so that the anaerobic biomass can be tracked outside the digester in the UF membrane concentrate stream. This is especially important as it is assumed that the screw press preferentially removes inert materials and allows more active biomass to be concentrated in the recycle stream.

The kinetic model parameter values for the anaerobic biomass in Mantis2 are based on mesophilic conditions. For the current project, the kinetic parameter values were adjusted, as shown in Table 1, using temperature correlations given by Buhr and Andrews (1977) for temperatures of 45 ^oC of 55 ^oC. The Buhr and Andrews (1977) temperature expressions were implemented in GPS-X. The temperature correlations were applied to the rates of hydrolysis and all of the anaerobic biomass growth and decay processes. These correlations will be studied as part of future investigations of the thermophilic digester system being studied.

Table 1: Kinetic Parameter Values used in Mantis2 for Current Project

KINETIC COEFFICIENT	MESOPHILIC VALUE (35^{o}C)	45^{o}C	THERMOPHILIC VALUE (55^{o}C)
MAX FERMENTATION RATE	3	5.5	10
DECAY RATE FOR FERMENTIVE BIOMASS	0.04	0.2	0.7
MAX GROWTH RATE OF ACETOGENS	0.35	0.64	1.2
DECAY RATE FOR ACETOGENS	0.02	0.08	0.3
MAX GROWTH RATE OF HYDROGENOTROPHIC METHANOGENS	0.368	0.67	1.22
DECAY RATE OF HYDROGENOTROPHIC METHANOGENS	0.01	0.04	0.2
MAX GROWTH RATE OF ACETATE UTILIZING BACTERIA	0.15	0.27	0.50
DECAY RATE FOR ACETOCLASTIC METHANOGENS	0.02	0.08	0.3
HYDROLYSIS RATE CONSTANT	3	5.5	10

Model Calibration and Validation

The GPS-X model was calibrated as best as possible to averaged plant operating data from 2010, which is provided in Table 2. More detailed data will be collected in a future study. During the calibration data collection period, pig manure was fed to the screw press and a mixed waste stream containing components such as glycerol and corn waste were fed to the digester after being mixed with a UF concentrate recycle stream. As shown in Table 2, not all required measurements were available and these measurements have been estimated using total solids (TS) and volatile (VS) measurements, chemical oxygen demand (COD) mass balances around the digester and entire plant, and typical COD/VS ratios for biomass. The entire measurement set was then reconciled as best as possible to be consistent with mass balances and typical ratios.

The input parameters used in the model are given in Table 3. The influent characteristics for the pig manure stream were assumed based on an examination of literature data. The mixed influent COD fractionation and volatile suspended solids to total suspended solids (VSS:TSS) ratio were adjusted as shown in Table 3 to match the digester COD, VSS, TSS and gas production given in Table 2. The screw press TSS removal efficiency was adjusted to match the data in Table 2. The UF membrane TSS removal efficiency was assumed to be 100%.

Table 2: Reconciled Data Used for Model Calibration – 2010 Normal Operating Data

Characteristic	Mixed Influent	Pig Manure	Digester Effluent	Screw Press Effluent	Screw Press Cake	UF Permeate	UF Concentrate
Flow (m^3/d)	75	60	105	105	60	75	30
Soluble COD (mg/L)	---	---	12,000[5]	12,000[5]	12,000[5]	12,000	12,000[5]
COD (mg/L)	500,000[1]	150,000	88,800[4]	41,440[4]	296,000[4]	12,000	91,760[4]
COD (kg/d)	35,620	9,000	9,320	4,350	17,760	900	2,750
TS (mg/L)	---	120,000	100,000	40,000	300,000	22,000	85,000
VS (mg/L	---	90,000	60,000	28,000	200,000	14,000	62,000
TSS, mg/L	---	---	78,000[3]	18,000[3]	278,000[3]	0	63,000[3]
VSS, mg/L	---	---	46,000[2]	14,000[2]	186,000[2]	0	48,000[2]
TN, mg N/L	---	8,000	---	---	---	3,500	---
TP, mg P/L	---	1,200	---	---	---	200	---
Gas Flow (m^3/d)	---	---	21,000	---	---	---	---
Methane Gas Flow (m^3/d)	---	---	12,180	---	---	---	---
Gas COD (kg/d)	---	---	29,880	---	---	---	---
Gas Composition, CH_4, %	---	---	58	---	---	---	---
Gas Composition, CO_2, %	---	---	42	---	---	---	---
Temperature, °C	---	---	55	---	---	---	---

Notes:

1. Calculated to allow reasonable closure of COD balances around the plant and the digester.
2. Estimated as difference between VS and UF permeate VS.
3. Estimated as difference between TS and UF permeate TS.
4. Calculated as VS multiplied by assumed COD to VS ratio of 1.48.
5. Assumed to be the same as UF permeate COD.

Table 3: Conditions Used for Model Calibration and Validation

Parameter	Calibration Period	Validation Period
Mixed Feed Influent		
Flow rate (m^3/d)	75	93
Particulate inert fraction of total COD (%)	17	6
Soluble inert fraction of total COD (%)	2.6	2.6
VSS:TSS ratio (%)	88	73.5
Pig Manure Influent to Screw Press		
Flow rate (m^3/d)	60	0
Particulate inert fraction of total COD (%)	10	---
Soluble inert fraction of total COD (%)	5	---
VSS:TSS ratio (%)	80	---
Digester		
Volume (m^3)	15,000	10,000
Temperature (^oC)	55	45
Screw Press		
Cake Flow (m^3/d)	60	20
TSS Removal Efficiency (%)	78	59
UF Membranes		
Concentrate Flow (m^3/d)	30	50
TSS Removal efficiency (%)	100	100

As shown in Table 4, the modeled values, determined using a steady state simulation, match the measured values within 10% in most cases, with the exception of the UF permeate total phosphorus (TP).

The model was validated to averaged operating data from 2011, which are provided in Table 5. During this period a mixed waste stream consisting of pig manure and agricultural feedstocks was fed to the digester. The plant was being started up again after a period of inactivity. This start-up period was considered long enough that averaged data could be used. As shown in Table 5, not all required measurements were available and these measurements have been estimated using TS, VS, and COD measurements, COD mass balances around the digester and entire plant, TSS and VSS mass balances around the screw press and UF membranes, and using typical COD/VSS ratios for biomass. The entire measurement set was then reconciled as best as possible to be consistent with mass balances and typical ratios. The input parameters used in the model are given in Table 3. The mixed influent COD fractionation and VSS:TSS ratio were adjusted as shown in Table 3 to match the digester COD, VSS, TSS and gas production given in Table 5. The screw press TSS removal efficiency was adjusted to match the data in Table 5. The UF membrane TSS removal efficiency was assumed to 100%.

As shown in Table 6, the modeled values, determined using a steady state simulation, match the measured values within 10% in most cases with the exception of the digester methane gas flow rate and the UF permeate TN and TP (see shaded values). The influent TN and TP in the model were estimated in order to match the digester TN and TP values and will be measured in a future study. The plant COD mass balance does not close, indicating that some discrepancy between the modeled and measured methane gas flow rate is expected.

Overall, the model matches the calibration and validation data reasonably well. In both cases the influent characterization had to be adjusted, which is expected given that different waste streams were treated.

Table 4: Simulation Results for the Calibration Period – 2010 Normal Operating Data

Parameters	Measured	Model Predictions	Percent Difference (%)
Digester			
TSS (mg/L)	78,000	76,160	2
VSS (mg/L)	46,000	45,530	1
COD (mg/L)	88,800	92,520	4
Total Gas Flow (m^3/d)	21,000	21,490	2
Methane Gas Flow (m^3/d)	12,180	12,800	5
Gas Composition			
Methane (%)	58	60	3
Carbon Dioxide (%)	42	40	5
SRT (days)	---	95	---
Screw Press			
Screw Press Effluent TSS (mg/L)	18,000	18,670	4
Screw Press Effluent VSS (mg/L)	14,000	12,780	9
UF Membranes			
Permeate TSS (mg/L)	0	0	0
Permeate COD (m^3/d)	12,000	12,200	2
Permeate TN (mg N/L)	3,500	3,510	<1
Permeate TP (mg P/L)	200	335	68
Concentrate TSS (mg/L)	63,000	65,340	4
Concentrate VSS (mg/L)	48,000	44,730	7

Table 5: Reconciled Data Used for Model Validation – 2011 Re-Start of Plant

Characteristic	Influent	Digester Effluent	Screw Press Effluent	Screw Press Cake	UF Permeate	UF Concentrate
Flow (m^3/d)	93	143	123	20	50	10,000
Soluble COD (mg/L)	---	9,400	9,400	9,400	9,400	9,400
COD (mg/L)	360,000	40,200	21,750	---	9,400	38,800
COD (kg/d)	28,830	5,750	2,675	3,073	686	1,940
TS (mg/L)	277,000	110,000	30,000	---	24,000	41,000
VS (mg/L	255,000	32,000	17,300	--	---	---
TSS, mg/L	---	86,000[1]	34,480[3]	402,820[4]	0[6]	84,833[5]
VSS, mg/L	---	20,810[2]	8,345[2]	97,480[4]	0[6]	19,860[5]
TN, mg N/L	---	5,100	4,050	---	3,050	---
TP, mg P/L	---	527	136	---	110	---
Gas Flow (m^3/d)	---	17,935	---	---	---	---
Methane Gas Flow (m^3/d)	---	10,044	---	---	---	---
Gas COD (kg/d)	---	24,640	---	---	---	---
Gas Composition, CH_4, %	---	56	---	---	---	---
Gas Composition, CO_2, %	---	44	---	---	---	---
Temperature, ° C	---	45	---	---	---	---
pH	---	8.1	---	---	---	---

Notes:

1. **Estimated using measured TS in digester and measured TS in UF permeate.**
2. **Estimated using particulate COD and assumed particulate COD to VSS ratio of 1.48.**
3. **Estimated using digester TSS to particulate COD ratio and particulate COD in screw press effluent.**
4. **Estimated using TSS and VSS mass balances around screw press.**
5. **Estimated using TSS or VSS mass balances around UF membrane.**
6. **Assume all suspended solids removed by membrane.**

Table 6: Simulation Results for the Validation Period – 2011 Re-Start of Plant

Parameters	Measured	Model Predictions	Percent Difference (%)
Digester			
TSS (mg/L)	86,000	85,040	1
VSS (mg/L)	20,800	20,000	4
COD (mg/L)	40,200	41,520	3
TN (mg N/L)	5,100	5,030	1
TP (mg P/L)	527	532	1
Total Gas Flow (m^3/d)	17,935	19,880	11
Methane Gas Flow (m^3/d)	10,044	12,060	20
Gas Composition			
Methane (%)	56	61	9
Carbon Dioxide (%)	44	39	11
pH	8.1	7.7	5
SRT (days)	---	108	---
Screw Press			
Screw Press Effluent TSS (mg/L)	34,480	34,870	1
Screw Press Effluent VSS (mg/L)	8,345	7,830	6
UF Membranes			
Permeate TSS (mg/L)	0	0	0
Permeate COD (m^3/d)	9,400	9,370	< 1
Permeate TN (mg N/L)	3,050	4,310	41
Permeate TP (mg P/L)	110	280	155
Concentrate TSS (mg/L)	84,830	85,770	1
Concentrate VSS (mg/L)	19,860	19,260	3

Results and Discussion

Activated Anaerobic Digestion. In the original development of the Activated Sludge process, it was found that one of the advantages of cell recycle was that it provided "absolute and independent control of solids retention time (SRT) and hydraulic retention time (HRT)" (4,5). Without cell recycle, the SRT is tied to the HRT, which can lead to overly large reactors, high probability of cell washout, and other control challenges. The advantages of cell recycle for aerobic systems also apply to anaerobic systems such as an anaerobic digester. In this case, the recycle of cells allows an increase in SRT compared to the conventional "one-pass" anaerobic digester without cell recycle. This independent control of SRT thus ensures that the system can be operated with higher stability.

Recycled cells seeding effect. Another advantage of recycling cells in anaerobic digestion is that they are already acclimated to the waste, and so make a better seed than fresh microorganisms. In studies with a commercial inoculum designed to enhance gas production, it was found that a seed from an active digester provided superior performance (6).

System Performance

The system operated with long SRTs ranging between 95 and 108 days in both 2010 and 2011. The temperature averaged 55 C in 2010, which was in the ideal range for thermophilic bacteria, while in 2011 it was in the 45 C range but was being increased toward the thermophilic range.

The COD feed to the system decreased from 35,000 kg/d in 2010 to 28.900 kg/d in 2011, for an 18% decrease. However, gas production increased from 12,000 m^3/day in 2010 to 18,000 m^3/day in 2011, a 50% increase. The methane composition decreased slightly from 58 % in 2010 to 56% in 2011.

It should be noted that the feed point of pig manure had moved from the screw press to the digester in 2011. This had the effect of increasing the loading rate to the digester. With that, the VSS in the screw press effluent decreased from 14,000 mg/l to 8000 mg/l This lead to a decrease in VSS in the UF concentrate from 48,000 mg/l in 2010 to 19,000 mg/l in 2011. The COD in the UF permeate also decreased, from 12,000 mg/l in 2010 to 9,400 mg/l in 2011.

Overall, the new feed plan resulted in an increased biogas production and stable operation, even during this long startup period in 2011.

System Modeling

To better understand the thermophilic digester system, a number of steady-state and dynamic simulation studies were conducted using the process model. These include studying the impact of the recycle stream, the fraction of particulate inert COD in the influent, the digester temperature, and the influent flow rate. Dynamic simulations were conducted to study the impact of influent flow disturbances on digester performance. Table 7 provides the operating conditions used for these simulations which were based on anticipated future operating conditions.

Steady State Model.

Figure 4 shows a series of steady-state simulations run at different digester temperatures. As shown, the VSS drops with temperature as the observed yield drops. The methane gas production increases as the extra COD no longer used for cell synthesis due to the reduced yield is available to be converted to methane.

Figure 5 shows a series of steady-state simulations run at different influent flow rates. As expected, the digester VSS concentration and methane gas production both increase as more substrate becomes available for cell synthesis and gas production. As expected, Figure 6 shows that more digester gas is produced when the influent particulate inert COD fraction is reduced.

Table 7: Conditions Used for Model Sensitivity Studies and Dynamic Simulations

Parameter	Value
Influent	
Flow Rate (m^3/d)	100
COD (mg/L)	360,000
Inert particulate fraction of total COD	6%
Digester	
Volume (m^3)	5,000
Temperature (^oC)	55 (45 for recycle sensitivity)
Screw Press	
Cake Flow (m^3/d)	20
TSS Removal Efficiency (%)	60
UF Membranes	
Concentrate Flow (m^3/d)	50
TSS Removal Efficiency (%)	100

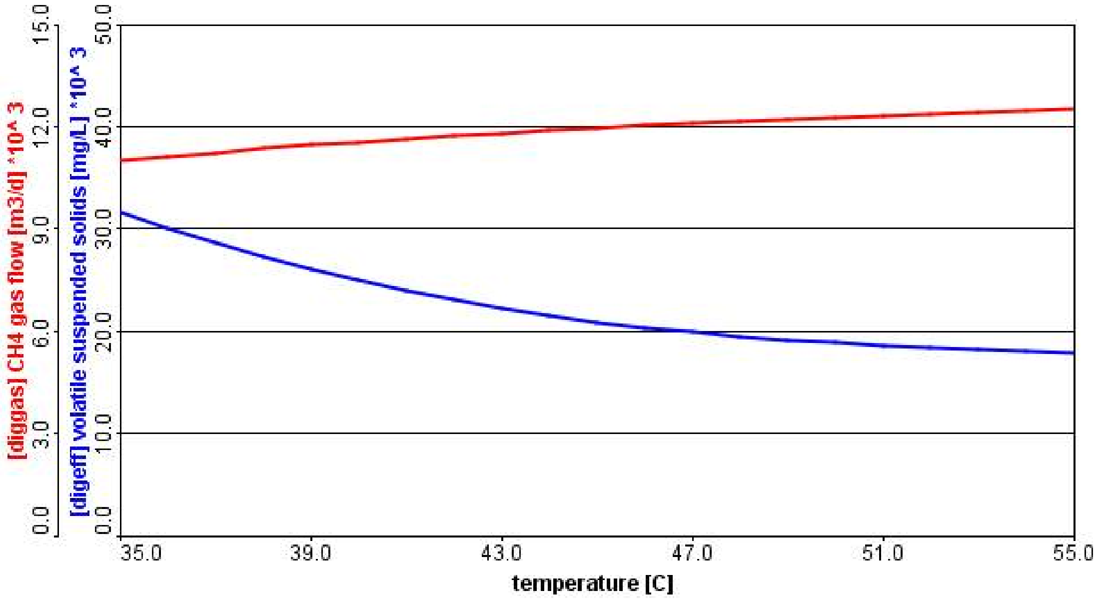

Figure 4: Effect of Digester Temperature on Methane Gas Production and VSS Concentration

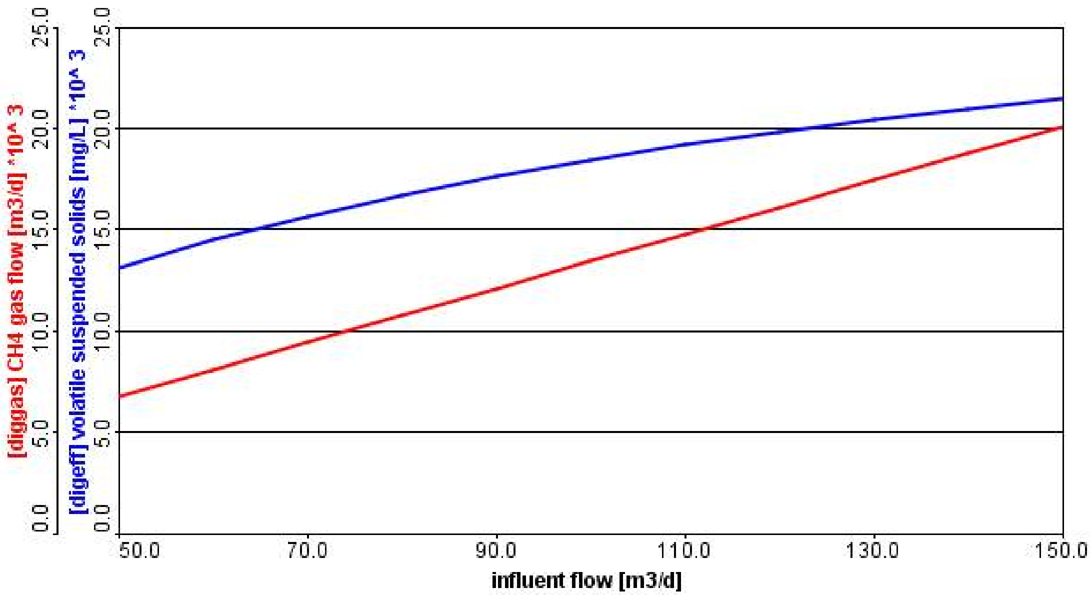

Figure 5: Effect of Influent Flow Rate on Digester Methane Gas Production and VSS Concentration

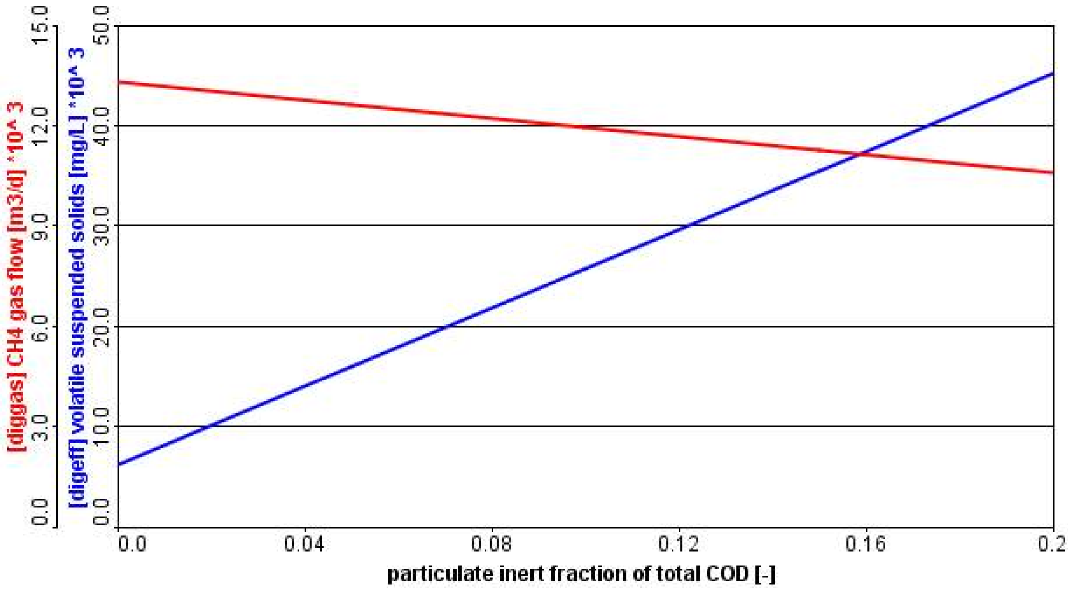

Figure 6: Effect of Influent Particulate Inert COD Fraction on Methane Gas Production and VSS Concentration

Dynamic Modeling

Figure 7 shows a dynamic simulation where the digester feed was stopped for 1 day followed by feeding for 5 days and then stopped again for 2 days. When the feed is stopped, the fermenting biomass quickly decays at the high temperature and the gas production quickly drops within ¾ of a day. The system can quickly respond and produce gas again after the feed is re-started but it takes longer to return to pre-stoppage gas production after longer stoppages.

Figure 8 shows the impact of a step change in influent flow rate. The gas production quickly responds and eventually settles at a new gas production rate within 3 days of the disturbance. The VSS response is slower and has still not levelled off after 13 days.
As demonstrated, the process model is a valuable tool for better understanding the system, quantifying the impact of operational changes, and optimizing performance.

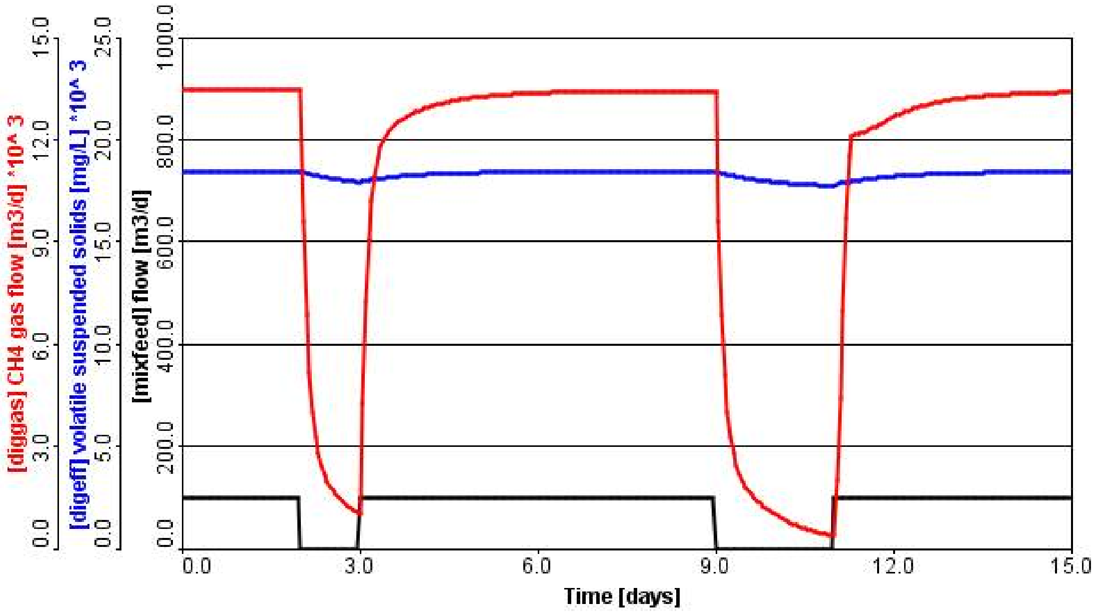

Figure 7: Dynamic Simulation of Impact of Feed Stoppages of One, Two, and Three Days on Digester Gas Production and VSS Concentration

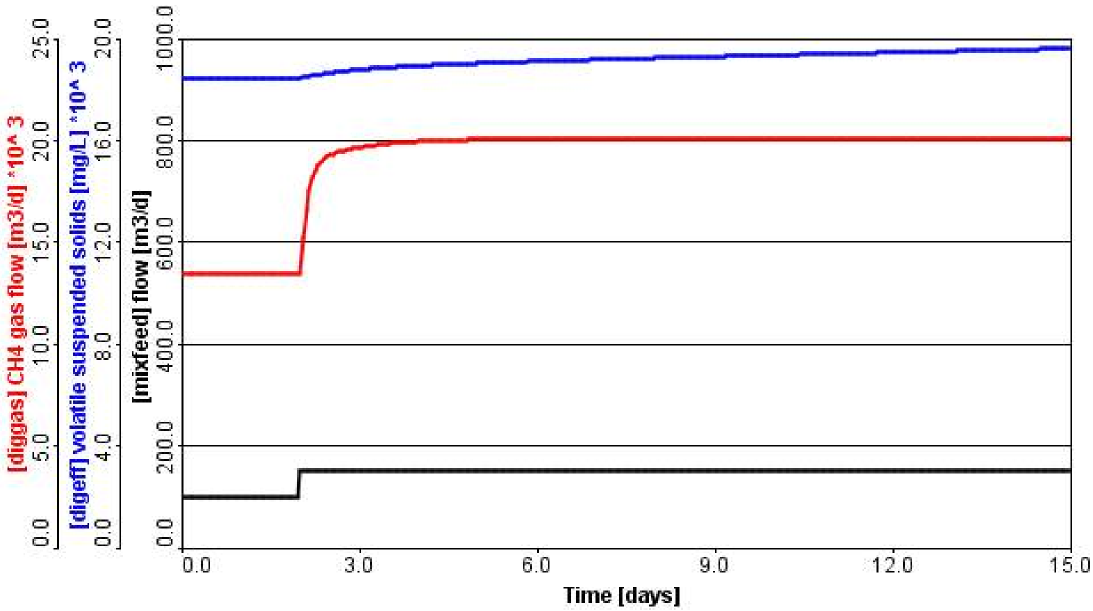

Figure 8: Dynamic Simulation of a Step Change in Influent Flow Rate on Digester Gas Production and VSS Concentration

Conclusion and Recommendations

A novel activated anaerobic digester (AAD) with membrane filter system has been demonstrated to effectively reduce waste volume and generate usable methane. The enhancements attributed to the use of a UF membrane system with a vortex generator include:

- demonstrated good performance by minimizing membrane fouling

-production of high quality effluent for downstream treatment

- creation of a recycle stream with live biomass using a novel anti-fouling membrane for increased gas generation and

-more stable operation compared to "single pass" for lower sludge residence times.

A model for the system created using GPS-X was calibrated and validated. It was demonstrated that GPS-X model Mantis 2 was a versatile tool to model this new process in the same way as an activated sludge process, for both steady state and the dynamic modes.

Our recommendations include :

Operation and data collection should continue into the future, with an eye toward evaluating:

a. Development of new methods for determining the active, living biomass recirculated to the digester due to the screw press/FMX system, compared to the amount of non-living VSS recirculated.

b. Determination of the degradable and non-degradable volatile fractions and degradation rates for each of the feedstocks to the digester. Each possible feedstock presents differing levels of degradable and non-degradable solids, as well as presenting differing challenges to biodegradation.

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