AC 2008-2166: THE DESIGN OF AN EXPERIMENTAL ANAEROBIC DIGESTOR FOR ORGANIC WASTE PROCESSING

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Abstract:
Biogas is produced when organic matter is degraded in the absence of oxygen. The process, from degradation to gas production is called anaerobic digestion. This anaerobic digestion occurs naturally in wetland, Lake Bottom and deep landfills. An experimental digestor was built that converts cow manure and agricultural waste into methane-rich biogas that can be used as alternate energy resources to generate electricity or thermal energy. The research in this study focuses on the feasibility of the design of an operational digestor, the monitoring and control of the different biodegradation process variables and experiments to boost or maximize the gas production; and the analysis of the biogas produced, using a Gas Chromatograph (CG), with Flame Ionization Detector (FID), to separate the methane from carbon dioxide.
The biogas produced contains Methane CH_4, with very small percentage of Carbon dioxide CO_2, and some traces of Nitrogen N_2, Hydrogen H_2, and Hydrogen Sulfide H_2SO_4. The economic viability of this technology, advantages, and the production cost compared to other renewable energy resources are also compared. This technology will be used to power the heating unit in a Zero Energy Home (ZEH) currently under construction.

Introduction:

The first phase of the Anaerobic digestor design project takes students through the engineering design process, i.e., the conceptual design and analysis, and design feasibility study. The second phase was to build the experimental digestor system, the pro engineer drawing, and construction of an operational digestor.

The Design Process:

The design process is a decision making process in which several steps are taken to reach a desired goal, objective or final design so as to satisfy a definite goal or stated objective. The fundamental elements of such design processes are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. Like any other engineering design the Anaerobic Digestor design follows these fundamental processes. The desire or need of finding a suitable heating system for a Zero Energy Home (ZEH) that is efficient, cost effective and uses a form of renewable energy, led to the option of the Anaerobic Digestor. Research was done on other types of residential heating systems that relied on renewable energy and the Anaerobic Digestor suited our need considering our limitations.

The selected option was then assessed for its feasibility, design requirements, and cost. A preliminary design or prototype system was built tested, and evaluated to observe if the desired goal has been effectively met. A system of engineering drawings was then developed for a final production of the operational Anaerobic Digestor heating system that will effectively heat the Zero Energy Home.

Conceptual Design and Analysis:

Renewable energy

Renewable Energy is a type of energy whose sources naturally replenish itself, i.e. its sources such as the wind and sun can never be exhausted. They cause fewer emissions and are locally available. Their use can to a large extent cut or reduce chemical, radioactive and thermal pollution. They are a viable source for clean and limitless energy. Renewable energy technologies are sometimes criticized for being unreliable or unsightly, yet the market is rapidly growing for many forms of renewable energy that include solar, geothermal, wind, biofuel, biomass, ocean/hydro, and biogas energies [1,2,4].

Anaerobic Digestor **(**Methane Digester**):**

Anaerobic digestion is a process in which microorganisms break down biodegradable material in the absence of oxygen. The process is widely used to treat wastewater sludge's and organic wastes because it provides volume and mass reduction of the input material. As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere. Anaerobic digestion is a renewable energy source because the process produces a methane and carbon dioxide rich biogas suitable for energy production helping replace fossil fuels. Also, the nutrient-rich solids left after digestion can be used as fertilizers. The digestion process begins with bacterial hydrolysis of the input materials in order to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. Acetogenic bacteria then convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. Methanogenic bacteria finally are able to convert these products to methane and carbon dioxide.

Careful control of the digestion temperature, pH, and loading rates is crucial to obtaining efficient breakdown of the material, and disturbances to a digest can lead to process failure. Ensuring that the quality of input materials to the digestors is maintained and that the process effectively monitored is essential for ensuring that a digestor's performance is reliable.

Our objective is to produce methane gas that is going to be pumped into a 1000 sq ft Zero Energy Home through pipes that will then be connected to the cooker and gas furnace to heat the house.

Availability/Cost

The majority of the anaerobic digestors that are in use are either incorporated as a massive plant or either made simply from a polymer such as a plastic container with release valves. Other types include the covered lagoons which can cost anywhere from $95,000 to $300,000+ [3]: Covered lagoons: A pool of liquid manure topped by a pontoon or other floating cover. Seal plates extend down the sides of the pontoon into the liquid to prevent exposure of the accumulated gas to the atmosphere. Designed to use manure with two percent or less solid content, this type of digestor requires high throughput in order for the bacteria to work on enough solids to produce gas. Most frequently used in warmer southern regions, where the atmospheric heat can help maintain digestor temperatures, this is the least expensive of all designs to install and operate. About 18 percent of all digestors presently in use in the U.S. are covered lagoon systems. Covered lagoon system cost can be as low as $25,000 for 150 animals (swine) and as high as $1.3 million for 5,000 animals (dairy). Plug flow digesters range from $200,000 for 100 dairy cows, to $1.8 million for 7,000 dairy cows.

Technical Considerations for Anaerobic Digestion

Key considerations in the design of an anaerobic digestor include the amount of water and inorganic solids that mix with waste during collection and handling. The anaerobic digestor itself is an engineered containment vessel designed to exclude air and promote the growth of methanogenic bacteria. The three digester types most suitable are ambient-temperature covered-lagoon, complete-mix, and plug-flow digesters.

(a) Collection and Use of Biogas

Biogas formed in the anaerobic digestor bubbles to the surface where it is captured. Sometimes the biogas is scrubbed to reduce the hydrogen sulfide content. Depending on the application, biogas may be stored either before or after processing, at low pressures. More often recovered biogas is fed directly into an internal combustion engine to generate electricity and heat, or it can be used only for heating. If the biogas is upgraded to biomethane, additional uses are possible.

(b) Upgrading Biogas to Biomethane and Other Fuels

By removing hydrogen sulfide, moisture, and carbon dioxide, biogas can be upgraded to biomethane, a product equivalent to natural gas, which typically contains more than 95% methane. The process can be controlled to produce biomethane that meets a pre-determined standard of quality. Biomethane can be used interchangeably with natural gas, whether for electrical generation, heating, cooling, pumping, or as a vehicle fuel. Biomethane can also be pumped into the natural gas supply pipeline. High pressures can be used to store and transport biomethane as compressed biomethane (CBM), which is analogous to compressed natural gas (CNG), or very low temperatures can be used to produce liquefied biomethane (LBM), which is analogous to liquefied natural gas (LNG).

Technologies for Upgrading Biogas to Biomethane:

There are three steps to upgrading biogas to biomethane [3]. They are: (1) removal of hydrogen sulfide, (2) removal of moisture, and (3) removal of carbon dioxide. The simplest way to remove moisture is through refrigeration. H2S can be removed by a variety of processes:

I. Air injected into the digester biogas holder
II. Iron chloride added to the digester influent

III. Reaction with iron oxide or hydroxide (iron sponge)

IV. Use of activated-carbon sieve

V. Water scrubbing

VI. Sodium hydroxide or lime scrubbing

VII. Biological removal on a filter bed

The following processes can be considered for CO2 removal from dairy manure biogas. Some of them will also remove H2S. The processes are presented roughly in the order of their current availability for and applicability to waste biogas upgrading:

I. Water scrubbing

II. Pressure swing adsorption

III. Chemical scrubbing with amines

IV. Chemical scrubbing with glycols (such as SelexolT)

V. Membrane separation

VI. Cryogenic separation

VII. Other processes

Some technologies are more suitable for dairy farm operations than others, typically because of cost considerations, ease of operation, and other concerns such as possible environmental effects. A possible design for a small dairy biogas upgrading plant might consist of the following:

I. Iron sponge unit to remove hydrogen sulfide

II. Compressors and storage units

III. Water scrubber with one or two columns to remove carbon dioxide

IV. Refrigeration unit to remove water

V. Final compressor for producing CBM, if desired

Operation and maintenance of this system would be relatively simple, which is one reason it is recommended over other, possibly more efficient, processes. Electricity for the compressors could be produced from an on-site generator using biogas, which could also generate power for other on-site uses, or from purchased power. If purchased power were used, the major operating costs for this process would be for power for gas compression.

Storing, Distributing, and Using Biogas and Biomethane

Biomethane, which was upgraded from biogas by removing the hydrogen sulfide, moisture, and carbon dioxide, has a heating value of about 1,000 Btu/scf [4]. Because of this high energy content, biomethane can be used as a vehicular fuel. It could also be sold for off-farm applications to industrial or commercial users or for injection into a natural gas pipeline.

Storage of Biogas and Biomethane

The least expensive and easiest to use storage systems for on-farm applications are low-pressure systems; these systems are commonly used for on-site, intermediate storage of biogas. Floating gas holders on the digestor form a low-pressure storage option for biogas systems. The energy, safety, and scrubbing requirements of medium- and high-pressure storage systems make them costly and high-maintenance options for biogas. They can be best justified for biomethane, which is a more valuable fuel than biogas.

Biomethane can be stored as CBM to save space or for transport to a CNG vehicle refueling station. High-pressure storage facilities must be adequately fitted with safety devices such as rupture disks and pressure relief valves. Typically, a low-pressure storage tank is used as a buffer for the output from the biogas upgrading equipment and would likely have sufficient storage capacity for around one to two days worth of biogas production.

Biomethane can also be liquefied to LBM. Two advantages of LBM are that it can be transported relatively easily and it can be dispensed to either LNG vehicles or CNG vehicles.

Estimated Costs for Building a Biogas Fueled Electric Plant or Biomethane Upgrading Plant A waste anaerobic digestor that will be used to create biogas for electrical generation has two major components. The first is the system to generate and collect the biogas. The second component is the system to generate the electricity. A waste anaerobic digester whose ultimate purpose is to produce biomethane uses the same sort of digester to generate and collect biogas. The biogas is then upgraded to biomethane by removing the hydrogen sulfide, moisture, and carbon dioxide. Finally, the biomethane is compressed or liquefied, stored, and/or transported to a location where it can be used.

Estimated Costs for Anaerobic Digestors for Electricity Generation, the average cost for building the anaerobic digestor systems for electrical generation was about $4,500 per average kilowatt generated. Of course costs for specific projects vary considerably from these averages based on local conditions. At the lower average cost of $4,500 per average kilowatt generated, the capital costs for a digester-generator with a capacity of about 100-kW would be about $450,000 (without NOx controls). At 28% efficiency, with operating costs included and with the plant fully amortized over 20 years at 8%, this plant would have a levelized cost of electricity of $0.067/kWh.

Estimated Costs for Storage and Transport of Biomethane

In addition to the costs of generating biogas and upgrading it to biomethane, a biomethane producer must add the costs of storing and transporting the biomethane. If the biomethane could be put into a pipeline, there would be no storage expense. If the biomethane were purchased by the pipeline owner, there would be no transportation expense. Otherwise these expenses must be paid by the producer or the buyer.

Storage costs vary considerably with the length of time for which the gas must be stored. For example, enough storage capacity to store a day's worth of CBM produced from a plant that produces 45,000 ft3 of biomethane per day would add $100,000 to $225,000 to the cost of the facility ($0.60 to $1.40 per thousand ft3 of gas) to the cost of the biomethane production [4].

Summary of Experimental Work:

Project Description

- Anaerobic digestion is the degradation of organic matter in the absence of oxygen

- There are two kinds of anaerobic digestion:
  - Mesophilic realized between 30-38 degree Celsius (85-100 degree F)
  - Thermophilic at 50 to 60 degree Celsius (122 to 140 degree F)

Purpose:

The main purpose of the anaerobic digestion experiment is to obtain methane gas CH4, also known as biogas

The remaining part which is called digestate is used for soil conditioning or compost.

Product and Micro Organism:

Several products are used for the anaerobic digestion

- Organic waste, cow manure, etc
- Feed stock
- Bacteria, used for digestion
  - Methane forming bacteria (Halophilic bacteria, Coenzyme M, Nickel containing coenzyme)

Stages of Anaerobic Digestion:

- Hydrolysis stage (simple sugar, amino acid, fatty acids)
- Acidogegenesis (Volatile fatty acids, Acetic, propionic, NH4)
- Acetogenesis (Co2, H2O, Acetic Acid)
- Methanogenesis (CH4, CO2, H2O)

- Acetate -→ $CH_4 + CO_2$
- $H_2 + CO_2$ -→ CH_4
- Methanol -→ $CH_4 + H_2O$

Factors Controlling the Conversion of Waste to Gas:

The rate and efficiency of the anaerobic digestion process is controlled by:

- The type of waste digested
- It's concentration
- It's temperature
- The presence of toxic materials
- The PH and Alkalinity
- The HRT (Hydraulic Retention Time) time available to convert waste to gas

HRT = V/Q   Q = volume of tank

V = daily flow of gas

- The SRT (Solid Retention Time) time required to convert the solid to gas (10-15 days) for low rate digestion and (20-30 days) for high rate digestion

Costs Estimation:

The $ amount of the anaerobic digestor can be estimated according to:

- The size of the digestor
- Material (vinyl, steel, etc..)

- The shape (cylinder, square, rectangular, flat, and cone bottom)
- Number of tanks on the digestor, the number of feeders and features
- The purpose of use (biogas, pharmacy, laboratory, etc)
- The time required to run an operational digester from the beginning to the end

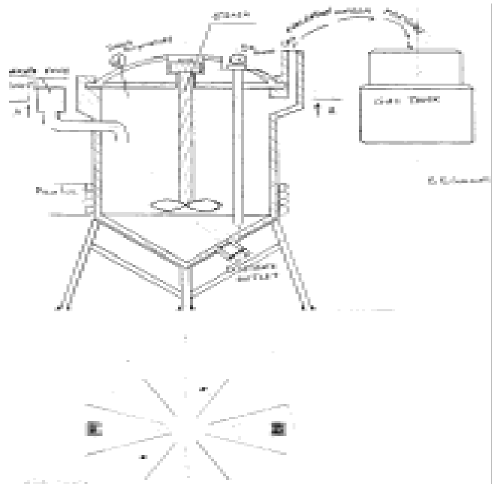
Our custom made digestors ranged from ($200.00 plastic bucket – estimated $20,000.00, 55-gallon factory made steel digestor) each, all features included.

Energy Requirements calculations:

- Average household that is 800 sq ft uses approximately 8.25×10^5 BTU, whereas 2000 sq ft household uses 20.625×10^5 BTU per month. The heating value obtained from research is 23,214 BTU for every lb of methane (CH^4). Hence, a 2000 sq ft household will require 20.625×10^5 BTU x (1 lb CH^4 / 23,214 BTU) = 88.84 lbs of methane gas per month. From references on Biogas production [3], approximately 90,000 BTU can be produced from 600 pigs and 50 cow manures. A 1400lb cow produces daily 12.5 gallons of waste. This is equivalent to 27,800 BTU in one day. A 2000 sq ft household will require 31.31 gallons per day or 219.17 gallons per week, which is equal to 1829 lbs per week of waste consumption from a total of 4 pigs and 3 cow manures.

TECHNOLOGY AND DESIGN

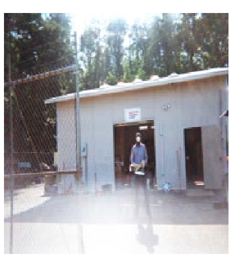
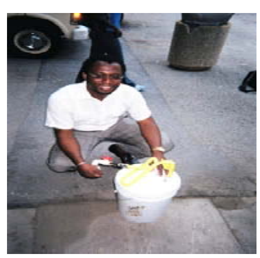
- Example of our cone bottom anaerobic digester.
- Material: polyethylene
- Volume 60 gallons
- Mixers
- PH probe
- Temperature control
- Band heater
- Gas separator
- Gas collector



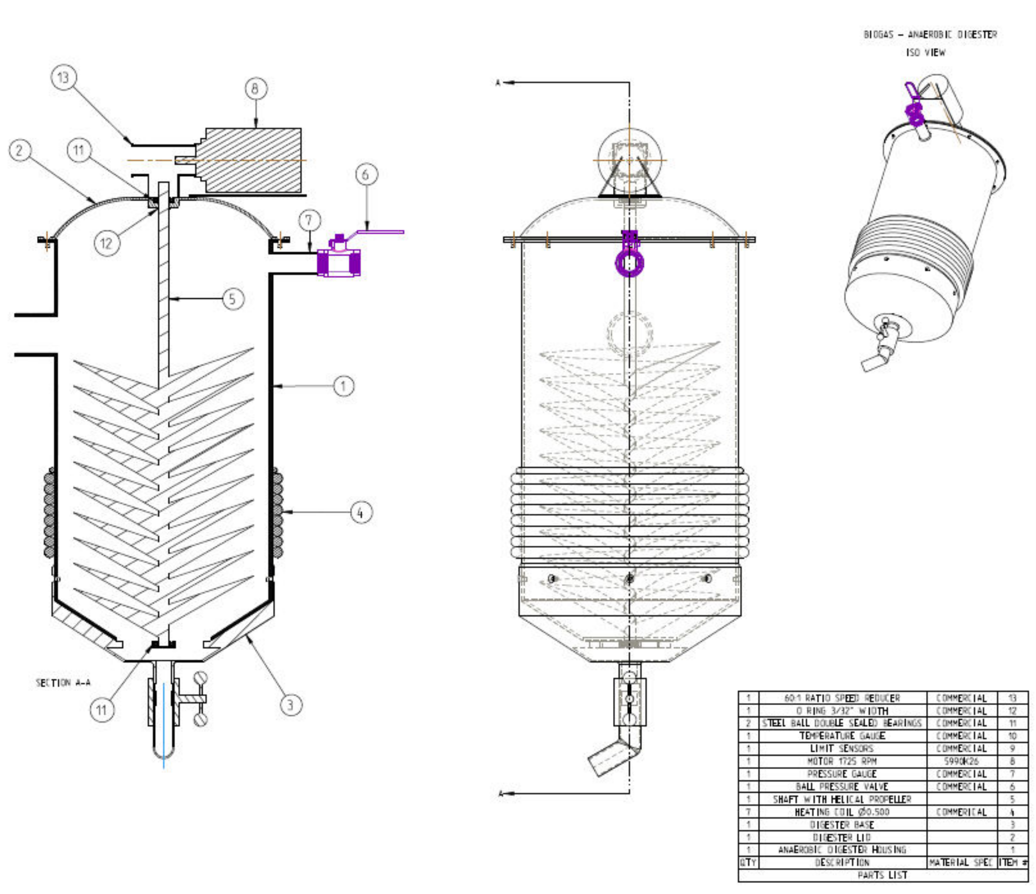
EXPERIMENT

Our experiment is first realized with basic digester (bucket) on which a pipe is being connected and the balloon at the other end to collect the gas produced.

- Cow manure 20 gallons (methane forming bacteria) Fresh
- Glucose+4H_2O ---> 2 Acetate
- Estimated proportion of 60% CH_4 And 40% CO_2
- Digestion Time 8 to 10 days

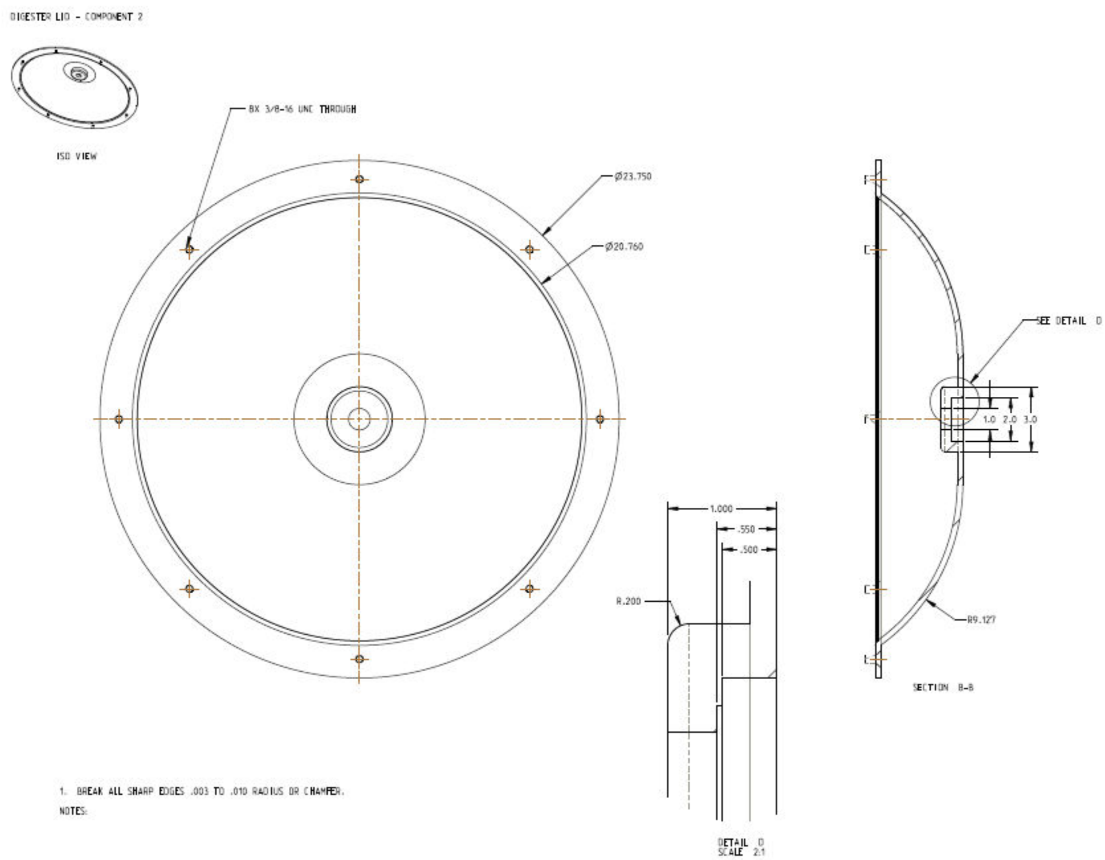



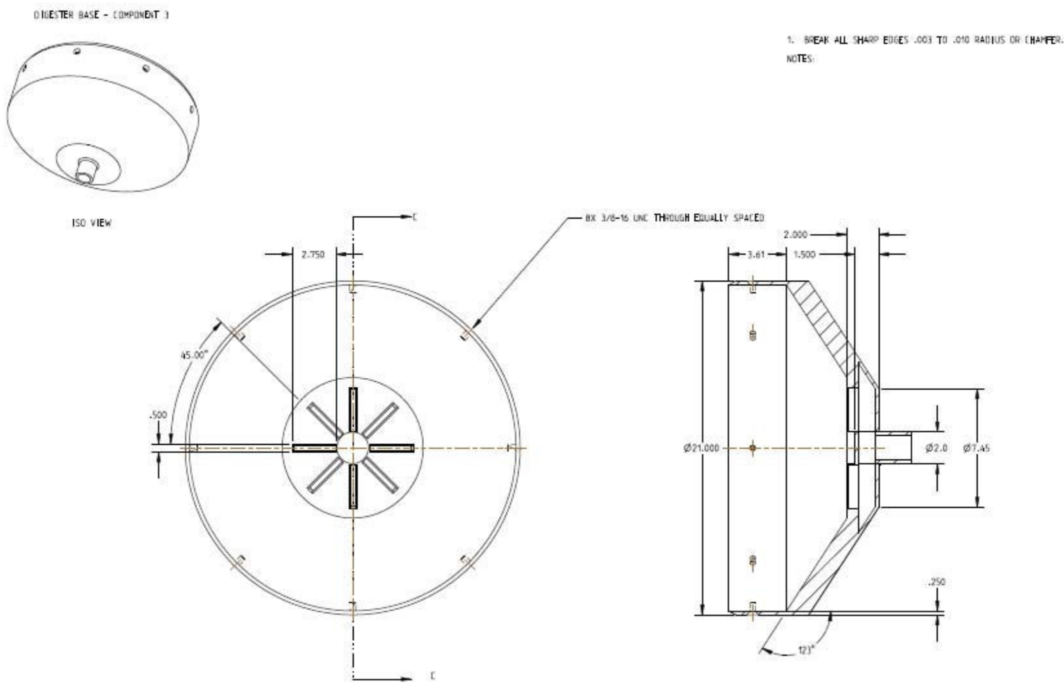

Work is currently in progress for the engineering design and fabrication of a 55-gallon custom made digestor. The Proengineer drawings and part lists are as shown below:



QTY	DESCRIPTION	MATERIAL SPEC	ITEM #
1	60:1 RATIO SPEED REDUCER	COMMERCIAL	13
1	O RING 3/32" WIDTH	COMMERCIAL	12
2	STEEL BALL DOUBLE SEALED BEARINGS	COMMERCIAL	11
1	TEMPERATURE GAUGE	COMMERCIAL	10
1	LIMIT SENSORS	COMMERCIAL	9
1	MOTOR 1725 RPM	5990K26	8
1	PRESSURE GAUGE	COMMERCIAL	7
1	BALL PRESSURE VALVE	COMMERCIAL	6
1	SHAFT WITH HELICAL PROPELLER		5
7	HEATING COIL Ø0.500	COMMERICAL	4
1	DIGESTER BASE		3
1	DIGESTER LID		2
1	ANAEROBIC DIGESTER HOUSING		1

PARTS LIST


DIGESTER LID - COMPONENT 2
ISO VIEW
8X 3/8-16 UNC THROUGH
Ø23.750
Ø20.760
SEE DETAIL D
1.0
2.0
3.0
R9.127
SECTION B-B
1.000
.550
.500
R.200
DETAIL D
SCALE 2:1
1. BREAK ALL SHARP EDGES .003 TO .010 RADIUS OR CHAMFER.
NOTES:



Conclusion:

The design of an anaerobic biogas digestor highly depends on the factors that lead to higher gas production per feed. To achieve the desired result we should try to make the environment inside the digester comfortable for the bacteria. Anaerobic bacteria are known best to survive at 35 degree centigrade (95 degree Fahrenheit); therefore, the temperature of the digestor should be around this temperature. The higher the temperature the more chance that the bacterias will die thus, results in less gas production. If the temperature is too low the bacteria will become dormant and less gas production.

HRT is the measure of the amount of time the digester liquid will remain in the digester. If 10 liter of a 200 liter reactor is added and removed each day, it would take 20 days to completely replace the reactor content. This is very important because if feed does not stay in the reactor long enough for the entire digestion process to take place, biogas will not be produced. The best gas production in the digester also depends on the acidity and alkalinity of the digester. Acid forming bacteria produce acid and lower the PH, while the methanogeous bacteria increase the PH, forming a basic environment. The best PH for both of the bacteria is between 6.5 to 8.0. There are two stages in gas production; one is acidification and the other one is gas production. If the amount of acid in the digester is too high that means there are a greater number of acid forming bacteria (acidifiers) than methane forming bacteria's (methanoginious).

References

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3. FPL Energy (http://www.fplenergy.com/news/contents/090706.shtml), September 2006.

4. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (http://www1.eere.energy.gov/windandhydro/wind_how.html#sizes), May 2007.