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Study of parameters for the design of a continuous flow laboratory biogas reactor

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Abstract.

This study aimed to determine the parameters needed to design a continuos flow bioreactor. Developing studies that expand the quantity and efficiency of biogas currently produced on an industrial anaerobic wastewater treatment in a food processing plant in the Brazilian State of Goiás. The procedures developed in this work we used nine sets of bioreactors in batch and followed the German Standard VDI 4630. A special workbench was developed for that purpose, alternative procedures for determining the volume of the produced biogas were tested. The biomass studied in this work is the resulting sludge of the wastewater treatment from an industrial plant. The daily production is about nine tons, currently, which is totally discarded. Through this batch tests, it was possible to calculate the volume of biogas production and the ideal biomass retention time of the biomass. Obtained data to project a laboratory continuous flow bioreactor. With this data was made a projection of the biogas production potential by the use of this feedstock in an industrial bioreactor constructed for this purpose.

Key words

Biogas, reactor, sludge, anaerobic biodigestion, continuous flow

1. Introduction

The industry produces large amounts of solid and liquid waste during the processes of various types of products. One type of waste is biomass. The biomass can be obtained from non-woody plants, woody plants, such as wood and its residues as well as organic waste, in which meet agricultural waste, municipal and industrial [1].

This biomass can be used as fuel in various processes such as power generation, boilers, furnaces and as a substrate in the process of anaerobic digestion to produce biogas. The biomass which is generated in the treatment of effluents from food industry can be used as an energy source. The treatment of these effluents can be realized by anaerobic fermentation that, plus the ability to cleanse, allows enhancing an energy product, biogas, and still get a fertilizer [2].

In the treatment of effluents of the food industry sludge is generated as waste. The sludge resulting from wastewater treatment process basically consist of organic materials (volatile solids), and minerals (fixed solids), beyond water [3]. In Brazil these wastes are usually disposed in landfills, without any type of use.

This biomass has a high energetic value and may be used for the production of biogas. Biogas is a byproduct of great potential for use as renewable fuel [4]. The production of biogas through anaerobic digestion generates a biofuel as well as fertilizer or soil conditioner. In the digestion, the organic matter is degraded by the consortium of bacteria forming biogas, a mixture of principally methane, carbon dioxide and some nitrogen, saturated with water and with possible traces of hydrogen sulfide and others.

The digestion is the process in which anaerobic bacteria in an environment without of oxygen (anaerobic digester), degrade the organic matter, obtained as byproducts biogas and biofertilizer [5].

The produced biogas can be converted into electrical and heat energy. The non-gaseous residues from anaerobic digestion can be applied in agriculture as fertilizer, because it contains still all inorganic nutrients.

The process of anaerobic digestion is carried out in four stages by a consortium of bacteria that work in the degradation of biomass. The microorganisms under anaerobic conditions act, converting complex organic matter into simpler substances. The first stage of the digestion is the hydrolysis, a phase able to perform a breakdown of complex molecules into substances such as fatty acids, sugars and amino acids. Those compounds are metabolized by other bacteria to even lower substrates, characterizing the phase of acidogenesis, producing carbonic acids and alcohols, as well as carbon dioxide and possibly hydrogen and ammonia. These intermediate substrates are converted into acetates, hydrogen and carbon dioxide, acidifying the medium. This step is called acetogenesis. The final step is called methanogens, where there methane as well as additional carbon dioxide is formed.

Because bacteria are susceptible to changes, the conditions of pH, temperature and organic load are factors that must be controlled, beside possible accumulation of inhibitors like hydrogen sulfide or ammonia The ideal temperature range for the production of biogas is 35-45 º C (mesophilic bacteria). It can also be obtained with biogas digesters operating in the range 50-60 ° C (thermophilic bacteria) [6].

The ideal pH for methanogenic bacteria is between 6.6 and 7.3 [7]. The sludge in the study, is a waste classified as Class II, not inert according to ABNT NBR-1004/2004 [8]. The slugde in not exploited after the process of wastewater treatment in the food industry located in the state of Goiás. There are discarded daily about ten tons (10t) of this sludge to the municipal landfill.

The system of the cited wastewater treatment plant counts with a system of an anaerobic bioreactor used to reduce the organic load of the effluents, which in the year 2011 had an average biogas production of 4740.42 m^3/day.

A second anaerobic reactor was implemented in July 2012, raising the average biogas production to 10423.87 m^3/day, with an average concentration of 54.6% of methane. A research and development project in early stage aims to produce electricity from biogas produced in the wastewater treatment plant, therefore will be investigated a possible process optimization to produce more biogas with a possible higher methane content.

The optimization processes of methane should be performed at first in batch experiments, in order to define a curve to define the retention time of biomass. At this stage it is important to check how long it takes for the occurrence of maximum production of biogas. During this stage, the inoculum should also be tested to verify the adaptation to that the biomass.

The batch tests are crucial to define which parameters should be used in continuous flow anaerobic digestion. The best types of materials that can be used in the process and the best method to capture and store biogas have to be tested. With a maximum production of biogas, the next tests will be directly linked to optimization of methane concentration.

2. Biogas production

The laboratory batch tests performed were prepared following the recommendations of the German Standard VDI 4630/2006 [9]. The Standard of the German association of engineers (VDI) recommends for these tests of biogas potential a ratio of 1:0.4 of organic dry mass of substrate sample and inoculum.

A. Analysis of the studied biomass

The moisture content of the sludge (figure 1) determined in a loss on drying technique with a Halogen Moisture Analyzer (Marte, ID50). To determine the organic (ODM) and inorganic dry mass (IDM) the samples were heated in the furnace for a period of one hour to 550 °C, remaining there for additional four hours at the same temperature.

Fig. 1. Sludge

After determining the moisture and the ODM of inoculum and substrate, the calculations of the proportions of sludge could be performed, followed by reactor installation and start of the digestion tests.

Some parameters were monitored and studied to improve process performance. The biological treatment occurs in controlled and balanced, rapid changes in some process parameters, like as organic load, pH, temperature or concentration of a toxic element may hinder the treatment, leading to decreased metabolism and death of bacterias [10]. Digestion may be carried out between pH 6.6 and 7.6 [11].

B. *Mounting the test bench*

Figure 2 illustrates one piece of the workbench designed and mounted for the anaerobic fermentation tests. This workbench was composed by the following components:

1) *Kitasato flasks or Büchner flasks with a total capacity of 500 mL were used as reactors to perform the anaerobic fermentation, the substrate occupied a volume of 350 mL.*
2) *The temperature was controlled by a electronically controlled water bath ("Bain Marie") at a range between 36 and 38 °C.*
3) *The produced gas was captured in water filled glass recipients, connected by gas tubes and valves.*
4) *Electronic balance performed the measuring of the water displacement, which indicates – after all necessary corrections - the quantity of the produced biogas.*

Fig. 2. General view of the batch reactors

Samples were placed in the reactors after pH corrections of the acid pH by adding sodium bicarbonate ($NaHCO_3$) to the recommended values of 6.8.

After preparation of the samples from the reactor, it was placed immersed in water bath at 37 ºC, containing a thermostat temperature control with external sensors [12]. The biogas produced in the bioreactor, by the anaerobic digestion process, was connected to a collection vessel containing water, a gasometer.

The biogas formed in the digestion was directed into the container filled with water. The biogas displaced the water out of the collection vessel. This mass of the displaced water was measured with an electronic scale, which was adapted to avoid problems with power loss and recalculation of Tara in the process of rebooting. The mass values obtained on the scales indicated the volume of gas produced in the process. To convert from mass to volume value was used the density of water at the respective temperature, as well as the gas volume was converted to standard volume using the actual temperature and air pressure during the measurement. Figure 2 illustrates how the process works with nine units constituting the test bench.

For purposes of validation of the assays were performed in triplicate, containing the following mixtures in the digesters: i) inoculum, ii) sludge plus inoculum and iii) microcrystalline cellulose (standard) plus inoculum. These mixtures formed a total of nine samples were mounted and under the same conditions to be able to compare the production of biogas.

The monitoring of biogas production was carried out at intervals of four hours, within the first 48 hours, the period of increased biogas production, and then every 24 hours to fifteen days, when the production turned to be insignificant, following the recommendations of VDI 4630/2006 [9].

Figure 3 illustrates the detailed operation of the process for each of nine units constituting the test bench.

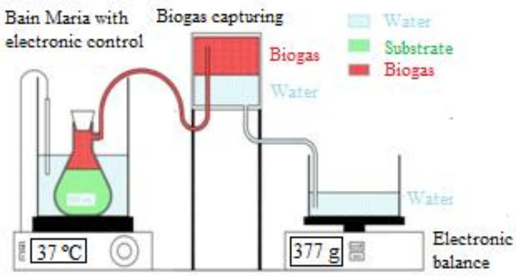

Fig. 3. Batch reactor with gas capturing system (gasometer) and volume control by weighing displaced water

C. Analysis of results

The data collected in the batch are shown in Figure 4, normalized according to the NTP (Standard conditions for temperature and pressure)[14], for the performance evaluation of this biomass in the production of biogas.

Figure 4 shows the cumulative gas production of samples: (i) inoculum plus sludge (ii) standard plus inoculum and (iii) the inoculum. The period considered for the sampling of values was twenty days. From fifteen days on the biogas production became negligible.

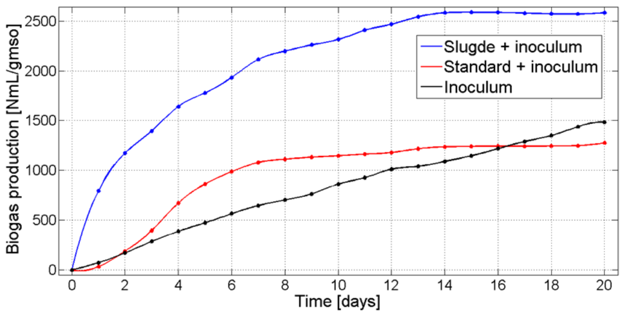

Fig. 4. Accumulated biogas production of samples

Biogas production was observed in all reactors. In reactors containing only the inoculum, gas production was small throughout the process. In reactors that have been assembled with inoculum plus sludge, had a gas production well above the container containing only the inoculum. Reactors with standard plus inoculum the production was despicable in the first 48 hours and accelerated after the initial 48 hours until the sixth day and then decreased again.

The production of biogas in the reactor was very high in the first and second day after the gas production had a significant drop in hours.

Figure 5 shows the normalized net daily production of sludge (NNDPS). The net production of sludge is obtained by subtracting the production of the inoculum NPDI from the total biogas production NPDS as shown in equation 1.

$$NNDPS = NDPS - NDPI \quad (1)$$

NNDPS = Normalized net daily biogas production from sludge (NmL/g_{ODM})

NDPS = Normalized daily biogas production from sludge (NmL/g_{ODM})
NDPI = Normalized daily biogas production from inoculum (NmL/g_{ODM})

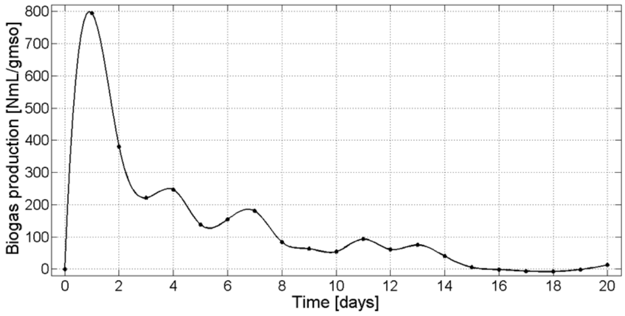

Fig. 5. Daily production of biogas

Figure 6 shows the percentual values of the daily acumulated normalized biogas production from the sludge.. The daily percentual values in relation to total production, is shownin equation 2.

$$NNDPS(\%) = \left(\frac{NDPS-NDPI}{\sum NDPS-NDPI}\right)x100 \qquad (2)$$

Where:
$\sum NDPS - NDPI$ = Sum of the differences between the daily production of sludge and daily production of inoculum for the considered evaluation period. (NmL/g_{ODM}).

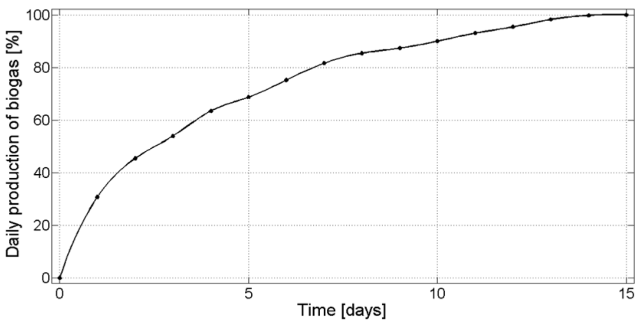

Fig. 6. Daily acumulated normalized biogas production as percentage of total production

The evaluation period was considered fifteen days. The period was defined taking into account that from day fifteen on the biogas production of sludge become lower than 1%.

D. Calculation of the parameters of the bioreactor of continuous cycle

Starting from a biomass with known characteristics and following the recommendation of the German Standard VDI 4630/2006 [9], the retention period was determined according to the daily net production of gas in the batch tests by the total amount of gas produced in the considered period.

From analysis of Figure 6, observe that on the sixth day the biogas production was 75.2% of the total production of the considered fifteen day period Based on this result the ideal retention time for the continuous flow experiments was determined as six days.

The retention time is a parameter that directly influences the efficiency of the anaerobic system and on the other hand will represent investment costs for constructing the bioreactor. The longer the retention time the greater the volume of the bioreactor. An evaluation of the cost-benefit ratio may indicate the best retention time to be used. With these data it is possible to design a streaming batch reactor. For the design of a small and economical laboratory reactor with continuous flow, a volume of 5 liters would be a sufficient.

With the aim to scale a laboratory bioreactor so that the sum of the volumes of inoculum and sludge is 5 liters, the flow of the stream input or output of the sludge will be 0.83 liters per day, according to Equation 3. Where *Q* means output, *V* means volume and *T* means retention time.

$$Q = V/T \qquad (3)$$

To set the retention period, the regime of mass balance was considered the same, i.e., the inflow is equal to the outflow.

The total reactor volume is 6.67 liter of this 75% is occupied by the sum of the volumes of inoculum and sludge, and 25% corresponding to the spatial volume for gas expansion, approximately 1.67 liters. [13].

E. Projection of the industrial bioreactor for the biogas production from sludge

The daily volume of sludge produced in the wastewater treatment plant corresponds to approximately 10 tons per day, then the approximate value of the organic dry matter is 1801710.7 g.

With the batch test has been found that 1g ODM of the sludge produces about 1.9 NL of biogas. One can then project that the biogas production capacity of the whole sludge will be daily 3423250.3 NL or 3423.3 Nm^3 per day.

3. Further Information

The continuous flow reactor will be built and supplied according to the data obtained from the batch test. With this reactor it will be possible to determine which parameters can be changed to increase the production of methane in the biogas.

Taking into account the relatively low amount of water in the sludge, 56.8% water and 43.2% dry matter, not wishing to provide a substantial dilution of this biomass by adding more water, a possible arrangement for the laboratory bioreactor continuous cycle is indicated in figure 7.

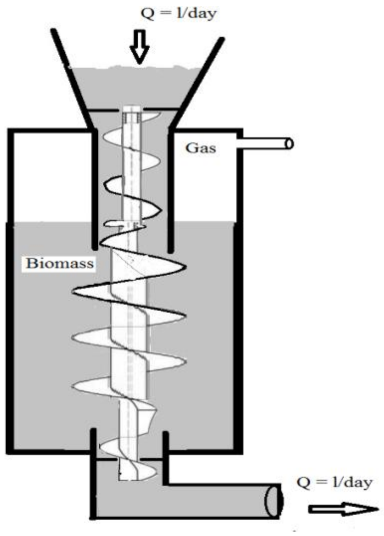

Fig. 7. Bioreactor of continuous cycle

The gas production from the sludge treatment plant in the food industry, was satisfactory in the digestion. The amount of organic matter present in the sludge during the harvest period June to October, between 42% and 55%, shows that its degradation may occur through anaerobic digestion to produce biogas as a byproduct even in not ideal conditions without agitation and dilution of the sludge.

The amount of biogas in the batch process quantified served as a support for defining a continuous flow reactor. Thereby identifying a flow reactor should be designed for a total volume of 6.7 liter with 5 liters to the sum of the volumes of sludge inoculum more and 1.7 liters for the volume expansion of the gas.

The expected daily production in this work, is 3423.3 m^3/day. This production represents about one third of the production of biogas from sewage treatment plant already installed. Studies have estimated that for the current production of biogas, which is around 10423.87 m^3/day, can produce an average power output in electric power of 830 kW. Based on these studies we conclude that could increase to 272 kW more power in continuous operation, if it is decided for the thermoelectric recovery of biogas from the sludge.

Further studies aimed at the utilization of sludge from wastewater treatment processes of the food industry in question as biomass for gas production and its use as fuel for thermoelectric generators are still needed, especially studies for the design and construction of a laboratory bioreactor of continuous cycle, guiding the studies and evaluations of technical and economic feasibility for the project and an industrial bioreactor for this purpose.

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