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ANALYSIS OF BIOGAS PLANTS OPERATING MODES AND OPTIMAL MODE SELECTION

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АНАЛИЗ РЕЖИМОВ РАБОТЫ БИОГАЗОВЫХ УСТАНОВОК И ВЫБОР ОПТИМАЛЬНОГО РЕЖИМА

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Abstract. The present study is dedicated to a comparative analysis of operating modes of biogas plants (BGP), in which the biogas production process from anaerobic fermentation by bacteria obtained from plant and animal origin biomass (BM) and organic waste (OW). The stages of the anaerobic fermentation process and the mechanisms of their realization are described. An optimal mode has been shown for a specific case.

Аннотация. В настоящей работе проводится сравнительный анализ режимов работы биогазовых установок (БГУ), предназначенных для реализации процессов получения биогаза из биомассы (БМ) растительного и животного происхождения и органических отходов (ОО), путем анаэробного сбраживания (ферментации) их, посредством бактерии. Разъясняются этапы процесса анаэробного сбраживания и механизмы реализации этих этапов. Указывается, что какой из режимов является оптимальным, для конкретного случая.

Keywords: biomass, organic waste, sewage waste, biogas, biomethane, carbon dioxide, anaerobic fermentation, psychophilic, mesophilic, thermophilic, microorganisms, hydrolysis, acidification, methanation, temperature regime.

Ключевые слова: биомасса, органические отходы, отходы сточных вод, биогаз, биометан, диоксид углерода, анаэробное сбраживание, ферментация, психофильные, мезофильные и термофильные режимы, микроорганизмы, гидролиз, подкисление, метанирование, температурный режим.

Introduction

It's known that the "20-20-20" project has been developed for environmental protection in the European Union countries. The project aim is to reduce toxic gases released to the atmosphere by 20% and increase the share of renewable energy sources in total energy sources up to 20%. In this regard, creating both power plants and fuels used for various purposes have great importance. Numerous works are being done in this field in the world. In the 80s of the last century, in Brazil began biomethanol and bioethanol production by biothermal decomposition (fermentation) of the special productive specie of sugar beet and a few years later, ethanol began to be used as a 20% additive to automotive fuel. At present, the transport run entirely on bioethanol, which is also used for heating and

electricity generation. Moreover, Brazil exports bioethanol to a number of Far Eastern countries. However, later studies have shown that biogas production by anaerobic fermentation is more efficient than biochemical decomposition of methanol or ethanol from various types of BM, including plant origin BM and OW. So that, biogas production has the following advantages: 1) unlike ethanol, biogas can be transported via trunk pipelines, so it is both easy and inexpensive to deliver biogas to enterprises and residences in hard-to-reach areas, and there is no need for transportation costs; 2) Biogas can be produced from numerous types of BM, including animal origin OW, effluents from factories and plants, effluents from human activities, etc. raw materials, which are considered renewable raw materials; 3) it is possible to

more ecologically efficient dispose of environmentally harmful BM and OW, as well as industrial, construction and household (municipal) origin solid combustible waste during biogas production; 4) releasing of gases which generate heat effect such as CO_2 , CH_4 , N_2O etc into the environment from the agro-industrial sector are significantly prevent; 5) the quality of mineral residues obtained as a result of fermentation in BGP is better than unprocessed BM and OW, in particular manure, the intensity and alkalinity of unpleasant odors are reduced when applied to the soil as fertilizer and nutrients uptake by plants is significantly accelerated; 6) the possibility of the formations of pathogenic microbes, pests and weeds during the fermentation process goes down to a minimum; 7) in the use of toxic drugs and pesticides are significantly saving, mineral residues obtained at the end of the fermentation process in the BGP are considered to be better quality and more environmentally friendly substitute of conventional organic fertilizers; 8) the amount of energy produced from 1 Ha of arable land is 2-4 times more than the amount of energy from bioethanol and biodiesel produced from the same area of arable land when using energy-efficient hybrid corn as a raw material; 9) 6,6-35 tons of wet manure can be obtained from one cattle during per year, which give an opportunity to produce 257-1785 m^3 of biogas. This indicators are equivalent to 193-1339 m^3 of natural gas, 157-1089 kg of gasoline, 185-1285 kg of fuel oil and 380-2642 kg of firewood in terms of heat transfer capacity (HTC). This means 10 kW·h of energy production per day for a head of cow. Therefore, a well-designed, energy-efficient dwelling with biogas produced from the manure of 2-3 cows can be supplied with excess energy (heat and electricity). In this case, moreover, a high-quality organic fertilizer is obtained, which can be used both for the use of the peasant in their own fields and for the purpose of earning additional income by selling. In this case, moreover, a high-quality organic fertilizer is obtained, which can be used both for the use of the peasant in their sown areas and for the purpose of earning additional income by selling [1, 2].

The main advantages of the using of BGP are: a large amount of conventional fuels such as oil, gas, coal, fuel oil, electricity, etc. and energy carriers are being saved, the ecological condition of the areas near livestock farms and poultry factories is improving, the discharge of wastewater into the environment, as well as sewage and other harmful wastes, is prevented due to the use of BGP.

All these mentioned above confirms once again the importance of obtaining biogas from various types of BM and OW. The existing methods to the production of biogas by BM and OW fermentation, the required temperature regimes in BGP and other requirements are discussed below.

BC and OW fermentation methods and comparative analysis of BGP operating modes

Biogas is a waste product of the metabolic processes of specific bacteria (microorganisms) and is obtained by fermentation of any type of substrate of biological origin (BM or animal origin OW crushed and mixed with hot water) under anaerobic conditions

(oxygen-free environment). In this regard, this process is called methanation fermentation and obtained BG is contained from 50-87% of CH_4 , 13-50% of CO_2 and a small part of H_2 and H_2S . The biomethane which an analogue of natural gas is obtained after purification of BG from CO_2 . Therefore, the main gas component that affects the energy performance of the obtained biogas is methane.

Biogas obtaining process (biomethanogenesis) by BM and OW fermentation methods usually consists of three stages (when using cellulose-containing OW) as well as four stages in some cases:

1) **Hydrolysis stage.** In this stage, the stable complex chemical compositions (*proteins, fats, hydrocarbons, etc.*) are decomposed into simpler substances (*amino acids, fatty acids, glucose, etc.*) as a result of the hydrolysis with acetogenic aerobic bacteria (e.g. *Syntrophobacter wolinii*);

2) **Acidification (Acidogenesis)** (conversion of hydrolyzed substrate to acids) **stage.** In this stage, the mixed constituents obtained during the initial stage are decomposed into other organic substances (*acetic and propionic acids, alcohols and aldehydes*), as well as a number of inorganic substances (H_2 , CO_2 , N_2 , H_2S) by acid-forming bacteria (*acidogenic type bacteria*). This stage lasts until the growth of bacteria is slowed down under the influence of the formed acids;

3) **Acetogenesis stage.** The acids formed in the previous stage are converted into acetic acid by *acetogenic bacteria* in this stage;

4) **Methanation (Methanogenesis) stage.** The transformation process of acetic acid, formed in stage 3 to methane, carbon dioxide and water occurs by *methanogenic anaerobic bacteria*. Simultaneously, carbon dioxide and hydrogen formed in the previous (second) stage are transformed into methane and water.

Numerous microorganisms types (up to several hundred species of bacteria) are participating to occurs all these complex chemical transformation processes. Most numerous of them are hydrolyzing, fermenting, syntrophic and methanizing bacteria. The quantitative and qualitative composition of bacteria strongly depends on the content of the fermented BM or OW. On the other hand, the provided condition in the bioreactor is also strongly influence to these indicators. All above mentioned transformations processes (reactions) occurs in simultaneously and in this case, more stringent requirements are imposed on the ability of methanogenic bacteria to function.

However, according to the mechanism provided by Barker, it is claimed that the methane fermentation process of BM and OW occurs in the two-phase scheme. In this case, the above mentioned 3 stages together form the first phase and methanation stage forms the second phase separately. According to this scheme, in the first phase, the complex organic substances (*proteins, hydrocarbons, fats*) are decomposed to a number of acids (*vinegar, antacid, milk (lactate)*), fatty (*butyric and propionic acids*), alcohols (*ethyl, propyl, butyl etc.*), gases (*carbon dioxide, hydrogen, hydrogen sulfide, ammonia*), amino acids and glycerin with the presence of water through acid bacteria. In the second phase, the intermediate

products formed as a result of the vital activity of acid bacteria in the first phase are decomposed by *methanogenic bacteria* and as a result, methane, carbon dioxide, nitrogen and hydrogen contain biogas is formed.

Thus, the bacteria that are realizing each subsequent stage during the fermentation of BM and OW are fed by the vital activity products of the previous bacteria. All these bacteria exist in the cattle organism. Not only methanation bacteria, but all three types of bacteria work together in biogas production. It should be noted that, the cattle and other domesticated animals including poultry manure, alcohol production pulp from cereals and sugar beet, organic waste generated during beer production, beet pulp, human activity waste (feces, etc), organic waste production from fisheries and butcheries (blood, fat, intestine, stomach etc), grass plants, organic household and industrial waste, dairy plant waste (salted and raw milk whey), biodiesel fuel production wastes (technical glycerin produced during the production of biodiesel fuel from rapeseed), fruits, berries, juice production pulp from vegetables and grapes, aquatic plants, starch production wastes, unsweetened kernels and puree, syrup, potato production waste, as well as grapes and cotton swabs, sunflower, tobacco and corn stalks, corn kernels and husks, crown part of sunflower, white and red elderberry and crown parts of them, etc and OWs refers to raw materials. Currently, a number of artificially grown energy raw materials (corn silage, mollusk-eating insects, various types of aquatic plants etc) also widely used in order to biogas production of which it is possible to produce 300 m³ biogas from each ton. The maximum amount of biogas is 1300 m³/t produce from fat.

It is important that methanizing bacteria are active under the following conditions: 1) adherence to the temperature regime (average temperature, optimal temperature and allowable temperature change interval); 2) selection of fermentation mode; 3) nutrients supply; 4) selection of fermentation time; 5) ensuring uninterrupted operation of the bioreactor in one session; 6) determination of daily loading of raw materials; 7) determination of processing time of raw materials; 8) alkaline-acid balance (pH indicator) control; 9) carbon:nitrogen:phosphorus ratio control; 10) ensuring optimal moisture content of raw material (substrate); 11) grinding solid and dry parts of raw

materials to the nominal level; 12) periodic mixing of the substrate; 13) provision of the fermentation process by inhibitors [4].

First of all, it should be noted that since the anaerobic fermentation process occurs in the oxygen-free environment, the hermeticity of the bioreactor must be ensured and always monitored. Most species of methane bacteria die at temperatures above 700 °C with the exception of several strains. Therefore, three temperature regimes are used to optimize the processing of BM and OW resulting in the production of biogas and mineral fertilizers:

- psychrophilic mode - temperature varies in the range of 20-25 °C (optimal temperature is 25 °C)
- mesophilic regime - the temperature varies in the range of 25-40 °C (optimal temperature is 37 °C);
- thermophilic regime - the temperature is above 40 °C (optimal temperature is 55 °C).

The rate of methane production by bacteria increase with increasing of temperature. However, the amount of the ammonia also increases with increasing temperature which cause to slows down the fermentation process. When using bioreactors operating in psychrophilic mode that are not heated by an external source, sufficient biogas production is possible only when the average annual temperature is above 20 °C. The only advantage of this mode is that the process occurs in natural conditions, i.e. an additional heating system is not used. However, this regime does not allow to obtain mineral residues used for fertilization. So that, the insect eggs, weed seeds and other harmful substances for agriculture remain as in the raw material, which significantly reduces the quality of the mineral residue.

The selecting of the optimal temperature mode strongly depends on the composition of the initial substrate. So that, the optimal temperature regime for the mesophilic regime is 34-37 °C, and for the thermophilic regime is 52-54 °C when using mixed raw materials (a mixture of cattle, pork and poultry manure). Biogas production process occurs more intense in the psychrophilic mode at 23 °C temperature.

There are special requirements for the temperature change interval inside the bioreactor in the BGP. Thus, for the psychrophilic regime, the temperature is allowed to change within ± 20 °C per hour, and for the mesophilic and thermophilic regimes, it is allowed to change to ± 10 °C and ± 0.50 °C per hour, respectively.

Figure 1. Temperature dependence of biogas yield producing from BGP for mesophilic and thermophilic modes: curves 1 and 2, for thermophilic and mesophilic modes, respectively

The main advantages of the thermophilic regime in comparison with the mesophilic regime are that, firstly, the rate of decomposition of raw materials and consequently, the production of biogas increases, and secondly, the complete destruction of pathogenic bacteria, eggs of insects and weed seeds. The disadvantage is the need to use an additional energy source to maintain the required temperature mode and in most cases, a large part of the biogas (up to 50%) is used for this purpose. This, in general, leads to an adequate reduction in the efficiency of the BGP.

Another disadvantage of the thermophilic regime is the lower quality of the mineral residue (mineral fertilizers) obtained during this method under the more stringent conditions against temperature changes.

Although high amino acids are retained in the mineral residue during the mesophilic regime, it is not possible to completely neutralize the toxins in the raw material. Another disadvantage of the thermophilic process is that the amount of methane in the obtained biogas can be reduced by the percentage, which in turn causes to reduce the heat capacity of the single volume of biogas (1 m³) compared to other methods. Although there is not much difference between thermophilic and mesophilic methods in the amount of biogas produced per day, in the following days there is a significant increase in the amount of biogas produced per day in BGP, operating with thermophilic mode. This difference is obviously seen from the graphical dependence presented in Figure 1. In many countries around the world, mesophilic regimes have been more preferred as a result of research and experiments on the

BGPs operating in different modes and currently, most of the high-power and high-productivity BGPs used for biogas production operate at mesophilic temperature regime.

The nutrient-rich nature of the raw materials used in the production of biogas is also an important condition for increasing the activity of methanizing bacteria. It is important to have microelements such as nitrogen, sulfur, phosphorus, potassium, calcium and magnesium, as well as small amounts of iron, manganese, molybdenum, zinc, cobalt, selenium, tungsten, nickel, etc. in the initial raw material in order to be active of these bacteria. The cattle manure is very rich with each of these chemical elements.

The optimal fermentation time of BM and OW depends on the loading dose of the bioreactor and the selected temperature regime, i.e. the fermentation method. If the fermentation time is excessively reduced due to the application of a high temperature regime, the useful methanizing bacteria can be removed along with the removal of the residues from the bioreactor. The total surface area of raw material particles is one of the decisive factors in biogas production. Thus, the smaller the particle size of the raw material (substrate), the higher the decomposition rate of BC. Moreover, the smaller the particles of the substrate, the easier it is to mix, which allows the use of lower power electric motors to automate the mixing process. Consequently, the additional energy consumption is reduced, the total coefficient of performance (c.o.p.) of BGP and the efficiency of its work increases significantly.

Amount of water to be added,

Figure 2. The amount of water to be added depending on the initial moisture of the substrate:
 1- to reach 85% moisture of the substrate;
 2- to reach 92% moisture of the substrate

Other physical parameters that affect the fermentation process in BGP are: pressure in the BGP, hydraulic regime, humidity of the environment, total surface area of raw material particles (grinding degree), transfer and mixing periods to the bioreactor of the substrate, stimulating additives. Figure 2 shows graphical dependencies to the determination of the amount water should be added to a given mass (100 kg) of the substrate at values starting at 60% of the initial moisture content to reach 85% and 92%, respectively. The curves 1 and 2 in Figure 2 are showing how much water must be added to the substrate at different values, starting from 60% of the initial moisture, to reach 85% and 92% of moisture content of the substrate, respectively. It is clearly seen that both curves change linearly. Since in the first case the value of the maximum moisture content is 85%, and in the second case it is 92%, the graphs intersect with the abscissa at these values of moisture. The selected maximum moisture values in Figure 2 are justified by the fact that the moisture content of the substrate loaded into the bioreactor for the winter season should not be less than 85% and for the summer season not less than 92%. The amount of hot water that must be added to the manure to obtain the required moisture is determined using the following formula [4]:

$$M = P \cdot \frac{N_2 - N_1}{100 - N_2}$$

where M - is the amount of hot water to be added, l; P - amount of manure loaded into the bioreactor, kg; N₁ - initial moisture of manure, %; N₂ - required moisture of the substrate, %.

Experiments show that 36 kg of manure with 65% moisture can be obtained from a head of cattle during per day. However, the daily amount of a mixture of manure, urine and straw (excrement), which is more productive in terms of the amount of produced biogas is much higher, 55 kg with 85% moisture, which does

not require additional water for the winter season and only 7% extra water can be added for the summer season.

A two-stage technological process should be used to ferment a number of mono-composite (pure) raw materials. For instance, poultry manure, alcohol production pulp, etc. raw materials cannot be fermented in conventional single-stage bioreactors. An additional hydrolysis reactor must be used for this purpose. These types of reactors allow to control the acidity level, which eliminates the possibility of the destruction of irritating bacteria due to excess acidity or alkalinity. It is also possible to process above mentioned and other types of raw materials by the single-stage technology, but in this case they include other types of raw materials, such as manure, straw, silage, etc. should be added [5].

The use of rapidly decomposing raw materials, such as sugar beet, food waste, etc leads to fast oxidation of the bioreactor, and therefore these raw materials are considered unsuitable for pure fermentation. Therefore, these types of raw materials are mixed with other types of raw materials for safe fermentation. For this purpose, silage, various types of grasses, corn, bitter beans, grain wastes, etc are used in most BGPs. For the Azerbaijan, the tobacco sprouts, fern sprouts and leaves, white and red elderberry sprouts, leaves and crown parts, achillea (yarrow), etc can be successfully used as raw materials, which are very rich in most mountainous and foothill regions of the country. These types of BM are usually used as an additive to wet or dry manure that is not used cleanly. The resulting gas yield shows that it is more efficient to use these raw materials by mixing them before fermentation. It has been proved that While the biogas yield is 0.380 m³/kg per kg of raw material when using cattle manure alone, the use of cattle manure mixed with poultry manure increases this value up to 0.528 m³.

Following biological elements are included biogas production process: 1) composition of fermented raw materials (amount of proteins, fats, carbohydrates and lignin); 2) composition of microflora (types and quantity of microorganisms realizing decomposition stages); 3) existing conditions for the operating of microorganisms (presence or absence of harmful compounds).

The presence of any inhibitors (antibiotics, organic solvents, etc.) in the initial raw material has a very negative impact on the vital activity of microorganisms. A number of inorganic compounds also have a negative effect on the activity of microorganisms. For example, it is absolutely unacceptable to use synthetic detergents rich hot water removed from the washing machine for this purpose when mixing grinded initial raw materials with hot water [3-5]. The decomposition degree of the BM or OW depends directly on the composition of the raw material and it is represented in the amount of produced biogas. This indicator usually varies between 30-70%. The decomposition rate can be up to 80% in the BGP working with renewable raw materials. However, currently it is possible to increase biogas yield from 60% to 95% in the simplest BGPs with using various enzymes and enhancers (e.g. ultrasonic and liquid shredders) to degrade the initial raw material.

The full completion time of the fermentation process after loading the BGP reactor also depends on the operating mode of the device. Thus, this period is 30-40 days and more for psychrophilic regime, as well as, 10-20 days and 5-10 days for mesophilic and thermophilic regimes, respectively. However, if the fermentation time is excessively short, then as mentioned above, most of the bacteria are washed out of the reactor without being able to multiply when the fermented BM is discharged from the reactor. Consequently, after a while, the fermentation process can stop completely. It is not efficient the gasification process proceed excessively slow as in psychrophilic

mode. Thus, the amount of biogas produced in this case may not meet consumer demand.

The daily loading dose of the bioreactor depends on its cycle time and increases in proportion to the increase in temperature. The daily loading dose of the reactor is assumed to be 1/10 of its turnover for continuously operating BGP.

The selecting of fermentation time also depends on the type of processed raw material. So that, if the BGP operates in the mesophilic mode, then the fermentation time is 10-15 days for separate wet manure, and 40-80 days for manure mixed with plant origin BM species.

The alkaline-acid balance in the substrate should be maintained so that the pH varies between 6,5-8,5. Better results are obtained when the C/N ratio varies between 10-20 [5].

In conclusion, it can be summarized that the producing of biogas and mineral fertilizers by BM and OW processing is of particular importance. It is more expedient to carry out the fermentation process at mesophilic temperature regime. Since Azerbaijan is rich in both plant and animal origin raw materials, the use of BGP is very efficient in our country.

REFERENCES

1. А.К.Курманов. Совершенствование технологии производства биогаза. Ежеквартальный научный журнал. Вестник ВНИИМЖ, № 3, 2014, с. 170-176.
2. <https://bio.ukr.bio/ru/articles/3374/>.
3. А.С Добышев, А.А Острейко. Подпор и подготовка животноводческого сырья для биогазовых установок. Актуальные проблемы интенсивного развития животноводства. № 16(1), 2013, с. 394-401.
4. http://www.fluid-biogas.com/?pege_id=127.
5. Барбара Эдер, Хайнц Шульц. Биогазовые установки. Практическое пособие. Издательство Компания Zorg Bioqas, 2011, 268 с.