Research of the Influence of the Combined Electromagnetic Field on Biogas Output

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***Abstract*.** The purpose of research is determining the conditions of stimulating effect of the combined influence of constant and variable electromagnetic fields on the substrate and microorganisms in the bioreactor. This goal is achieved by solving the following tasks: development of mathematical model, conducting numerical simulation to determine the distribution of magnetic field in active zones of the stator-bioreactor system; conducting experimental researches during the fermentation of pig's manure with litter from wheat straw in the mesophilic mode of fermentation. One category of bioreactors (control samples) was not exposed to influence of magnetic field, for the other, periodically were made treatment simultaneously with a low-frequency electromagnetic field and constant magnetic field synchronously with the process of mixing the substrate. The most significant results are: an experimental proof of effectiveness of the proposed method of intensification of the biogas output and increasing its quality, high accuracy of mathematical model of distribution the magnetic field in active zones of the stator-bioreactor system; assessment of the levels of consumption of nutrients by microorganisms from the substrate under the influence of the combined magnetic field and without influence of the magnetic field. The significance of obtained results lies in the fact that the proposed approach to intensification of the biogas output provides increase of the level production, the quality of biogas, and cumulative rate of methane output per unit of organic mass in the reactor.
***Keywords*:** biogas, combined electromagnetic field, microorganisms, mesophilic regime, methane, substrate, methanogenesis**.**

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Studiul influenței câmpului electromagnetic combinat asupra randamentului de biogaz

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***Abstract*.** Scopul studiului este de a determina condițiile pentru acțiunea stimulatoare al impactului combinat al câmpurilor electromagnetice constante și variabile asupra substratului și microorganismelor din bioreactor. Scopul se realizează prin rezolvarea următoarelor probleme: elaborarea unui model matematic, efectuarea simulării numerice pentru determinarea distribuției câmpului magnetic în zonele active ale sistemului stator - bioreactor; efectuarea studiilor experimentale în timpul fermentației gunoiului de porc cu așternut de paie de grâu în modul mezofil de fermentație. O categorie de bioreactoare (probe de control) nu a fost expusă unui câmp magnetic, în timp ce cealaltă categorie a fost tratată periodic simultan cu un câmp electromagnetic de joasă frecvență și un câmp magnetic constant sincron cu procesul de amestecare a substratului. Cele mai semnificative rezultate sunt: eficiența metodei propuse de intensificare a randamentului de biogaz și îmbunătățirea calității acestuia, precizia ridicată a modelului matematic de distribuție a câmpului magnetic în zonele active ale sistemului stator-bioreactor; evaluarea nivelurilor de consum a nutrienților de către microorganisme din substrat sub influența unui câmp magnetic combinat și fără influența unui câmp magnetic. Semnificația rezultatelor

obținute constă în faptul că abordarea propusă pentru intensificarea randamentului biogazului asigură o creștere a nivelului de producție, a calității biogazului și a ratei cumulate a randamentului de metan pe unitatea de masă organică din reactor.
Cuvinte-cheie: biogaz, câmp electromagnetic combinat, microorganisme, regim mezofil, metan, substrat, metanogeneză.

Исследование влияния комбинированного электромагнитного поля на выход биогаза

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Аннотация. Целью исследования является определение условий стимулирующего действия комбинированного воздействия постоянного и переменного электромагнитных полей на субстрат и микроорганизмы в биореакторе. Поставленная цель достигается путем решения следующих задач: разработки математической модели, проведения численного моделирования по определению распределения магнитного поля в активных зонах системы статор – биореактор; проведения экспериментальных исследований при ферментации навоза свиней с подстилкой из пшеничной соломы в мезофильном режиме сбраживания. Одна категория биореакторов (контрольные образцы) не подвергалась воздействию магнитного поля, для другой - периодически выполняли обработку одновременно низкочастотным электромагнитным полем и постоянным магнитным полем синхронно с процессом перемешивания субстрата. Наиболее существенными результатами являются: экспериментальное доказательство эффективности предложенного способа интенсификации выхода биогаза и повышения его качества, высокой точности математической модели распределения магнитного поля в активных зонах системы статор – биореактор; оценка уровней потребления микроорганизмами питательных веществ из субстрата при воздействии комбинированного магнитного поля и без влияния магнитного поля. Значимость полученных результатов состоит в том, что предложенный подход к интенсификации выхода биогаза обеспечивает повышение уровня производства, качества биогаза и кумулятивной скорости выхода метана на единицу органической массы в реакторе.
Ключевые-слова: биогаз, комбинированное электромагнитное поле, микроорганизмы, мезофильный режим, метан, субстрат, метаногенез.

INTRODUCTION

In connection with completeness of the Earth's minerals and pollution of the environment, humanity has been faced with the question of how to ensure energy production and improve ecology. The solution of this issue is in the use of non-traditional energy sources, in particular, obtaining energy from biomass. The production of biogas solves a multi-vector problem in the national and economic complex, namely: it improves the ecological situation, which allows the processing of waste from the food industry, agriculture, household and drain water treatment; possible production of heat, electricity and cold, as well as highly mineralized organic fertilizer that will allow to improve fertility of soils. The process of biogas production is based on the fermentation of biomass, that is, its decomposition by various groups of bacteria. On the vital activity of bacteria which take part in production of biogas, like most living organisms, significantly affects their environment. To increase the efficiency of biogas installations, the addition of special enzymes, maintenance of the appropriate thermal regime and mixing are used, but the last require significant energy consumption, which increases the cost of such production. Since the widely used methods of intensification of biomethanogenesis have practically exhausted themselves, the question of developing and improving new ones arises [1].

ANALYSIS OF LATEST RESEARCHES AND PUBLICATIONS

Numerous biological researches show that microorganisms are sensitive to constant magnetic fields, electromagnetic and acoustic fields of various frequency ranges[2,3]. These fields, as shown by the results of experiments, can have an inhibitory, stimulating or destructive effect on biological objects. The work [1] shows the application of the magnetic field with the frequency of 50 Hz and an induction of 0.28-12 mT, which is created inductively connected by Helmholtz’s coils. Observations of S.Cerevisiae for 9 hours showed that their greatest growth by 17% occurs with magnetic induction of 0.5 mT. Researches [4] of impact of the combined electromagnetic field created by pair of Helmholtz's coils on samples of brew show that the level of stimulation can reach 30%. Conducted researches [5] of impact of the constant magnetic field on substrate at thermophilic and mesophilic temperature modes of operation showed that at the intensity of the last 15 mT it is possible to increase the amount of biogas mixture release by 12-14%, in comparing with experiment without using of such field. Conducted experiments of impact of the low-frequency electromagnetic field with an intensity of 3.5 mT on substrate made of pig's manure [6] show that the biogas output increases and its maximum value reaches on the 9-11th day of fermentation, and the pH value stabilizes at the neutral level. Also in [7-9] were studied the aspects of influence on microorganisms by the system with combination of constant and variable fields. It was established that the reaction of cells in this case depends from the spatial orientation of the last, and their perpendicularity provokes the greatest effect [9]. In addition, it was proved in [10] that there is a fundamental difference between the final effect from stimulation by impulse and constant magnetic field, and in some cases the direction of the total vector can have decisive importance for the flow of life processes, and therefore will be determine the intensity of biogas output and the efficiency of process in general.

Magnetic-field effects in the range of 2-10 mT, that are registered for all bacteria regardless of the magnesium-isotope enrichment of the environment, indicate about sensitivity of intracellular processes to weak magnetic fields.

Several physico-chemical mechanisms have been proposed to explain the effects of magnetism in biological systems [11–14]. One of the most likely is enzymatic spin-dependent ion-radical reactions [12–14]. They were for the first time described for enzymatic phosphorylation with the participation of the magnetic isotope ^{25}Mg [12,13]. The detected magnetic- isotope effect (MIE) during the enzymatic synthesis of ATP is explained by the magnetic interaction of the ^{25}Mg nucleus with the unpaired electron spin and induction of the singlet-triplet conversion of the ion-radical pair in the active site of the phosphorylating enzyme. When the probability of direct reaction of ATP synthesis increases, the output of product increases accordingly. Similar MIE were detected in the synthesis of ATP for the magnetic isotopes of zinc ^{67}Zn and calcium ^{43}Ca, as well as in the synthesis of DNA in vitro's experiments [12,13, 15,16].

The joint effect of the constant magnetic field and magnetic isotopes of magnesium and zinc allowed to change the growth and biochemical parameters of E. coli bacteria [17, 18]. Such effects open new opportunities for controlling enzymatic processes and, as a result, the main physiological properties of bacteria. One of such properties of particular interest is the formation of biofilms. Communities of microorganisms united in biofilms are a complex structure that consisting of the microbes themselves and the polymer matrix synthesized by them (proteins, polysaccharides, and nucleic acids). Biofilms protect bacteria from the influence of external physical and chemical factors: antibiotics, ultraviolet radiation, mechanical impact, etc. [19].

The theory of biological magnetosensitivity justifies the sensitivity of intracellular processes to the external magnetic field and to magnetic moments of atomic nuclei of isotopes [14]. The sequence of intracellular biochemical reactions, in which the process involving magnetic isotopes takes place, will lead to the physiological response of the organism available for experimental registration. Thus, the addition of the magnetic isotope of magnesium to the nutrient medium for the growth of E. coli bacteria contributed to increase in growth rate and colony-forming ability [14].

In 1975 R. Blackmore discovered strong natural intracellular nano-sized magnets (biogenic magnetic nanoparticles) in bacteria and their synthesis is carried out by the genetically programmed microorganisms themselves. Bacteria that synthesize chains of biogenic magnetic nanoparticles (BMN) were called magnetotaxis bacteria, of point of view on given possible functional appointment of such natural magnets — taxis, that is, orientation of bacterial movement in the direction of force lines of the geomagnetic field [20].

To date, BMN has been found in archaea [21], which include methanogenic bacteria.

At the same time, it is known that genes of the magnetosomal island of magnetotaxis bacteria are related with the metabolic ways of anaerobic respiration [22].

Own heterogeneity magnetic fields of BMN will significantly affect on the speed of biochemical reactions, the slowest stage of which is the transport of reactants or reaction of products (diffusion or mixed kinetics) [23, 24, 25].

For magnetotaxis bacteria, depending on the magnitude and duration of application of an external magnetic field, the effects of change in the shape of chain and location of BMN due to the purely mechanical movement of magnetic nanoparticles under the influence of the external magnetic field [26], as well as a significant increase in the number of BMN, change in their shape, size, and location were found as a result of increased expression genes of magnetosomal island during long-term cultivation of magnetotaxis bacteria in the external magnetic field [27]. The duration of application of external magnetic fields is an important parameter during studying their effect on living organisms due to impact on the process of biomineralization of BMN.

1, 2 – measuring tube of biogas output from bioreactors, 3 – teslameter, 4 – laid stators with a substrate, 5 – the substrate is laid, 6 – a moving platform for mixing the substrate of test samples, 7 – container with lime water.

Fig. 1. Experimental installation.

Therefore, the external magnetic field can improve microbial activity and promote biodegradation of organic matter. However, little researches has been conducted due to use of the combined magnetic field to stimulate biogas production in anaerobic fermentation systems.

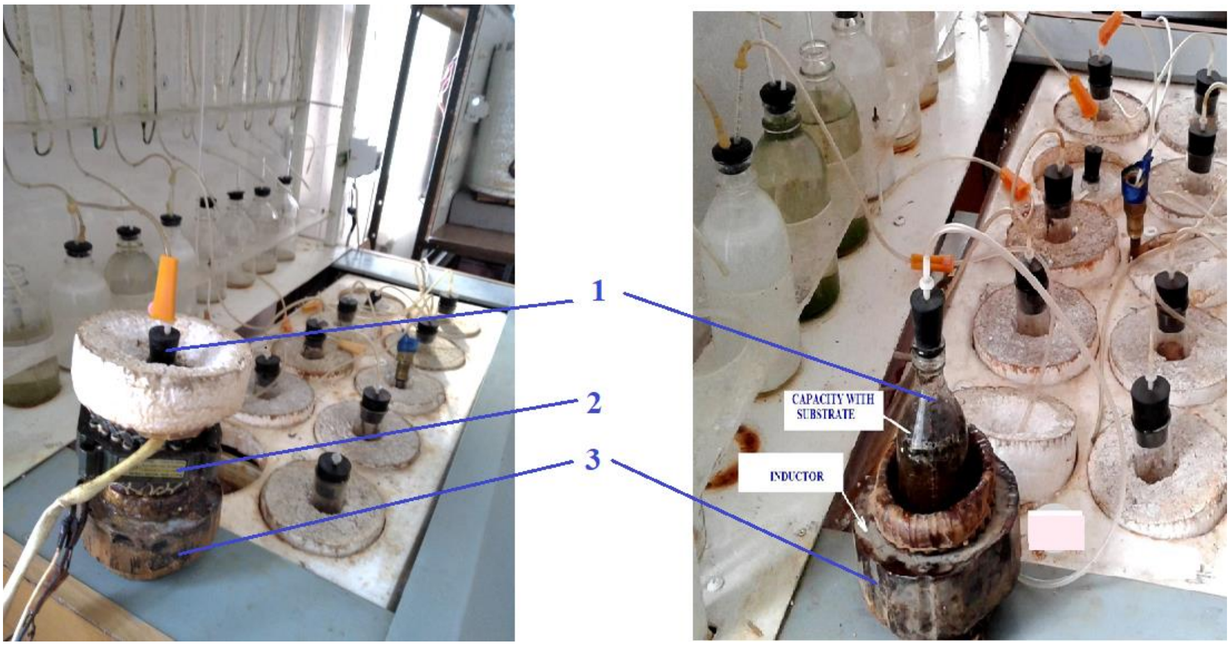
The purpose of research is experimental determine the stimulating action of the combined impact of constant and variable low-frequency electromagnetic fields on substrate and microorganisms to increase the output of biogas and methane.

RESEARCH METHODS

Determination of the intensity of biogas and biomethane output during liquid anaerobic fermentation (L-AD) of pig's manure mixed with wheat straw under influence of the variable and constant electromagnetic field was carried out on specially designed installation (Fig. 1). For conducting the experiment, containers (mini bioreactors) were taken, which were filled with 200 ml of seeding from the operating bioreactor and 25 g of pig's manure was added together with the litter made of lignocellulosic raw material, namely wheat straw. Pigs from the private sector were fed with dry food. Three samples of bioreactors were exposed to impact of the low-frequency variable electromagnetic field with the magnetic induction of 3.5 mT and the constant one - 4.5 mT, and the other three similar samples of bioreactors were controls. To create magnetic fields, stators of single-phase electric engines were used, one of which was connected to the variable current source of industrial frequency of reduced voltage of 29 V, and the second one was powered by constant current with voltage of 12 V (Fig. 2). A 43205/1 teslameter was used to measure electromagnetic fields. The operating mode of bioreactors is mesophilic (t=38-40ºC). Before laying, the pH of substrate was measured with a pH 301 device, the initial value pH = 7.6. The fermentation process took place for 21 days, while stirring and treating of three samples with the combined electromagnetic field were carried out periodically (three times a day). The output of biogas was measured by amount of displaced water from the measuring tubes (Fig. 1). For measuring the amount of produced methane , the output from the bioreactors is connected to containers which are filled with lime water (450 ml) for removing carbon dioxide from the formed biogas. At the same time, a corresponding chemical reaction occurs:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 \downarrow + H_2O \qquad (1)$$

Containers with lime water are connected with measuring tubes, filled with water, and by amount of displaced water was determined the output of biomethane.



1 – bioreactor, 2- the stator of an electric engine that is powered by a constant current source, 3 – the stator of the electric engine, which is powered by variable current of industrial frequency.

Fig. 2. Bioreactor with devices of electromagnetic influence.

The installation was turned on for creating the combined electromagnetic field (Fig. 2) three times a day for 20 minutes. and at the same time mixing of substrate was carried out.

To determine the consumption of nutrients by microorganisms from the substrate under the influence of the combined magnetic field and without influence, the following experiment was conducted. Digestate was taken from two mini bioreactors, which were used in experiments with and without influence of the combined magnetic field, dried, and then the same weights were burned to determine the inorganic residue according to the standard method.

RELATIONSHIP OF MAGNETIC AND ELECTRICAL PARAMETERS OF DEVICES THAT CREATE ELECTROMAGNETIC FIELDS

The equation that relating the magnetic induction B and the vector magnetic potential A for constant current is described by the expression:

$$B = \nabla A = \begin{pmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{pmatrix} = = i\left(\frac{\partial}{\partial y}A_z - \frac{\partial}{\partial z}A_y\right) - - j\left(\frac{\partial}{\partial x}A_z - \frac{\partial}{\partial z}A_x\right) + + k\left(\frac{\partial}{\partial x}A_y - \frac{\partial}{\partial y}A_x\right), \quad (2)$$

The equation that connecting the magnetic field strength H and the current density vector J is described by the expression:

$$\nabla H = \begin{pmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{pmatrix} = = i\left(\frac{\partial}{\partial y}H_z - \frac{\partial}{\partial z}H_y\right) - -j\left(\frac{\partial}{\partial x}H_z - \frac{\partial}{\partial z}H_x\right) + +k\left(\frac{\partial}{\partial x}H_y - \frac{\partial}{\partial y}H_x\right), \quad (3)$$

Combining expressions (2) and (3), we obtain the Poisson's equation for the vector potential A due to the current density J:

$$\Delta A = \frac{\partial^2}{\partial x^2}A + \frac{\partial^2}{\partial y^2}A + \frac{\partial^2}{\partial z^2}A = J, \quad (4)$$

For variable current, after solving the Helmholtz's equation according to expression (2), we obtain the following formula:

$$\left(j\omega\rho - \omega^2\varepsilon\varepsilon_0\right)A + \nabla H = j, \quad (5)$$

where, ω -is the angular frequency; ρ – specific electrical conductivity of the conductor; ε – dielectric permeability of the substance;

ε_0 – dielectric permeability in vacuum.

Let's transform expression (5) into a compact form of notation that connecting the current density J and the vector magnetic potential A:

$$\left(j\omega\rho - \omega^2\varepsilon\varepsilon_0\right)A + \mu\Delta A = j, \quad (6)$$

where μ -is the magnetic permeability.

When working with expression (6), you can use the following form of the equation:

$$\left(j\omega\rho - \omega^2\varepsilon\varepsilon_0\right)A + V(\mu^{-1}VA) = \frac{\rho V}{2\pi r}, \quad (7)$$

where, V -is the voltage, that applied to the coil.

Magnetic energy is calculated according to the expression:

$$W = 2\pi\oint Ardr, \quad (8)$$

For creating an electromagnetic field, stators of the single-phase asynchronous engine were introduced, in the middle of which the container with substrate was placed (Fig. 2). The electromagnetic field at each point of the considered region is determined by the vectors of magnetic induction $\vec{B}$, magnetic field strength $\vec{H}$, electric displacement $\vec{D}$ and electric field strength $\vec{E}$. The mathematical model of a nonlinear magnetic system with distribution of current densities is the system of Maxwell's equations for electromagnetic field vectors in all areas of the engine, which contains: full current law

$$rot\vec{H} = \vec{j}, \quad (9)$$

the law of electromagnetic induction

$$rot\vec{E} = -\frac{d\vec{B}}{dt}, \quad (10)$$

the equation of the continuity of the magnetic field

$$div\vec{B} = 0, \quad (11)$$

A quasi-stationary field is considered. Displacement currents are neglected.

The system of equations (1) – (11) is supplemented by the equation of the connection between the vectors of induction and magnetic field intensity

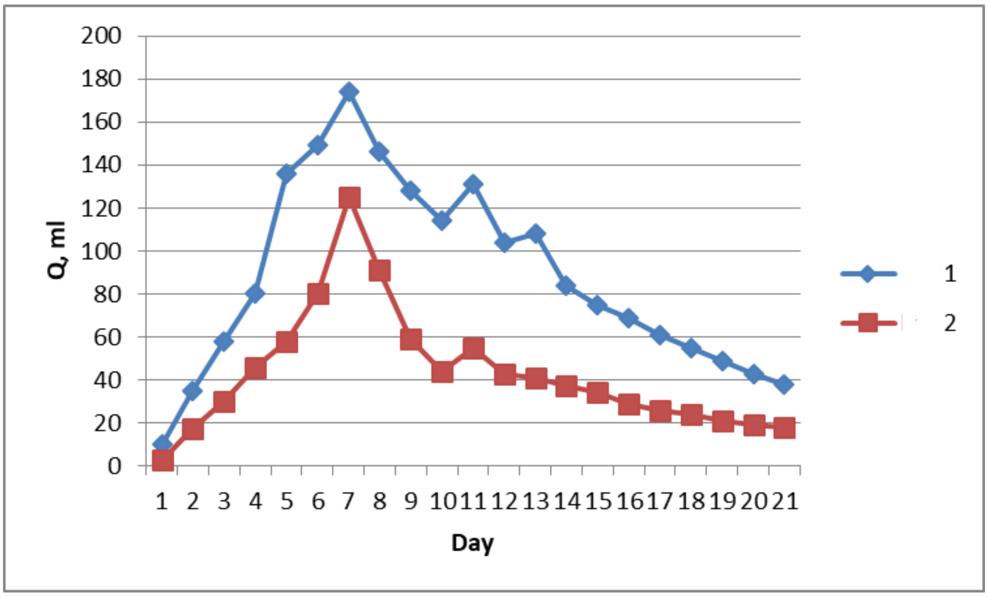
$$\vec{B} = \mu\vec{H}, \quad (12)$$

Where $\mu = \mu_0 + \mu_\upsilon$ is the absolute magnetic permeability of the substrate; μ_0 - magnetic permeability of vacuum; μ_{υ} - relative magnetic permeability of the substrate.

Using the proposed mathematical model, numerical simulation was carried out in the computer program COMSOL Multiphysics using the finite element method.

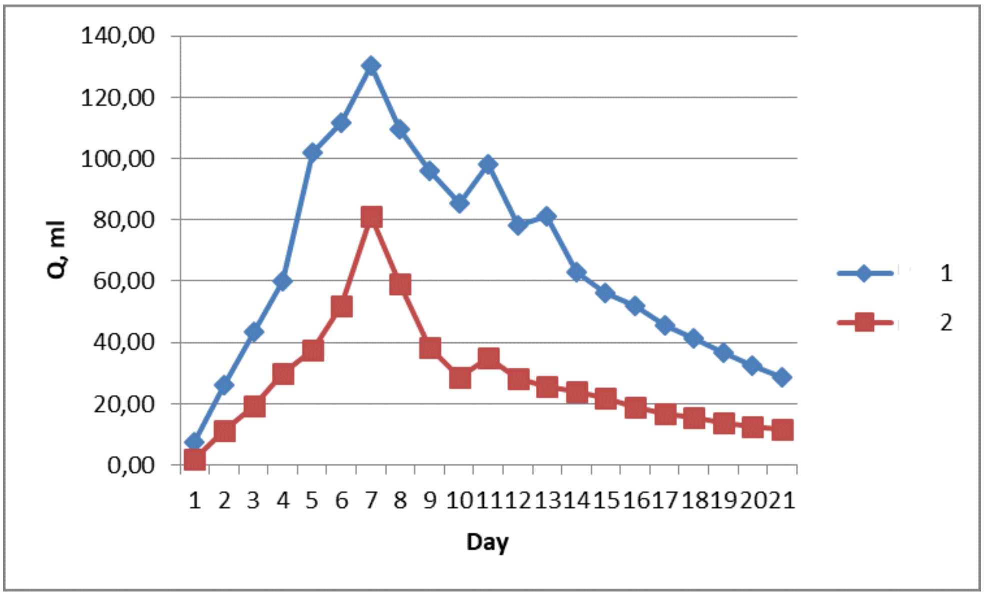
RESEARCH RESULTS AND THEIR DISCUSSION

In Fig. 3 and Fig. 4 are shown graphical dependences of the volumes of produced biogas and methane for each day during 21 days of anaerobic fermentation in the mesophilic mode, respectively. The research results show that the output of biogas and methane under the influence of the combined electromagnetic field increases in comparing to the control samples.



1– when the substrate is exposed by the combined magnetic field, 2-without exposure.

Fig. 3. Biogas output.



1– when the substrate is exposed by the combined magnetic field, 2– without exposure

Fig. 4. Output of methane.

The highest value of the achieved current rate of CH_4 production (average for repetitions) was: for bioreactors with influence of the combined magnetic field – 1.67 ml/kg/day; for reactors without exposure – 0.93 ml/kg/day. Therefore, the impact of the combined magnetic field increases the current production rate of CH_4 by almost in 1.8 times.

The cumulative specific rate of release of CH_4 from a unit mass of the experimental mixture in the reactor over the entire period of observation for bioreactors under the influence of the combined magnetic field was 2.11 ml/kg/day; for bioreactors without exposure – 0.92 ml/kg/day. The added mass of dry organic matter of the experimental mixture, including the inoculant, was used for calculations.

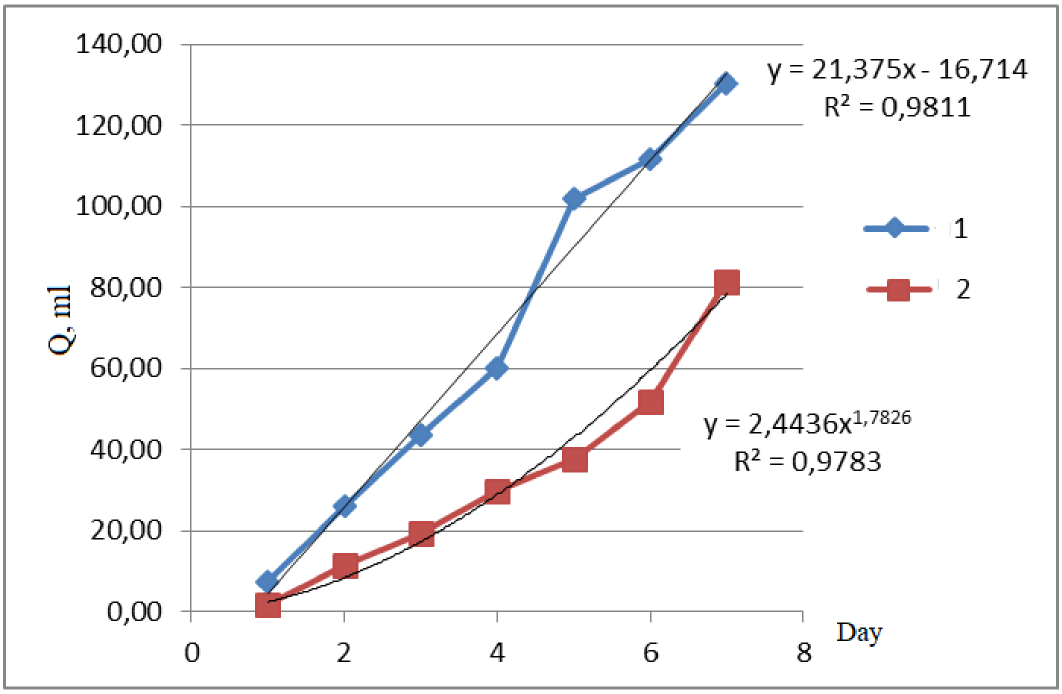
The average concentration of CH_4 in biogas based on research results is presented in Table 1. Under the influence of the combined magnetic field, is observed the significant (by 10%) increases in the concentration of CH_4 in biogas

Table 1

Average concentration of CH_4 in biogas

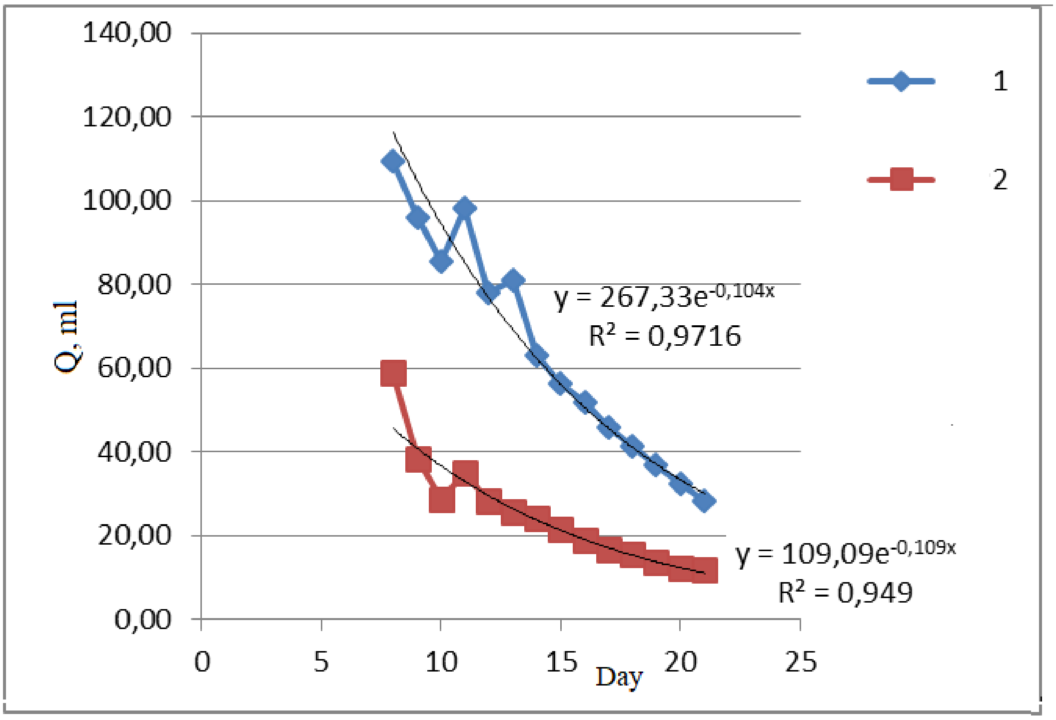
Conditions of anaerobic fermentation	Average concentration of CH_4 in biogas , %			
	5 day	7 day	10 day	21 day
Without influence of the magnetic field	66.1	64	64.4	65
Under the influence of the combined magnetic field	76,1	74	74	75

The kinetics of biogas and methane production, which is shown in Fig. 3 and Fig. 4, was modeled using linear[28] and exponential equations[29]. The kinetic researches was divided into two rate periods, namely the increasing period and the decreasing period of the methanogenesis rate. In Fig. 5 and Fig. 6 are shown the results of the approximation of methane production rate graphs, respectively, for periods of growth and decline in the rate of methanogenesis.



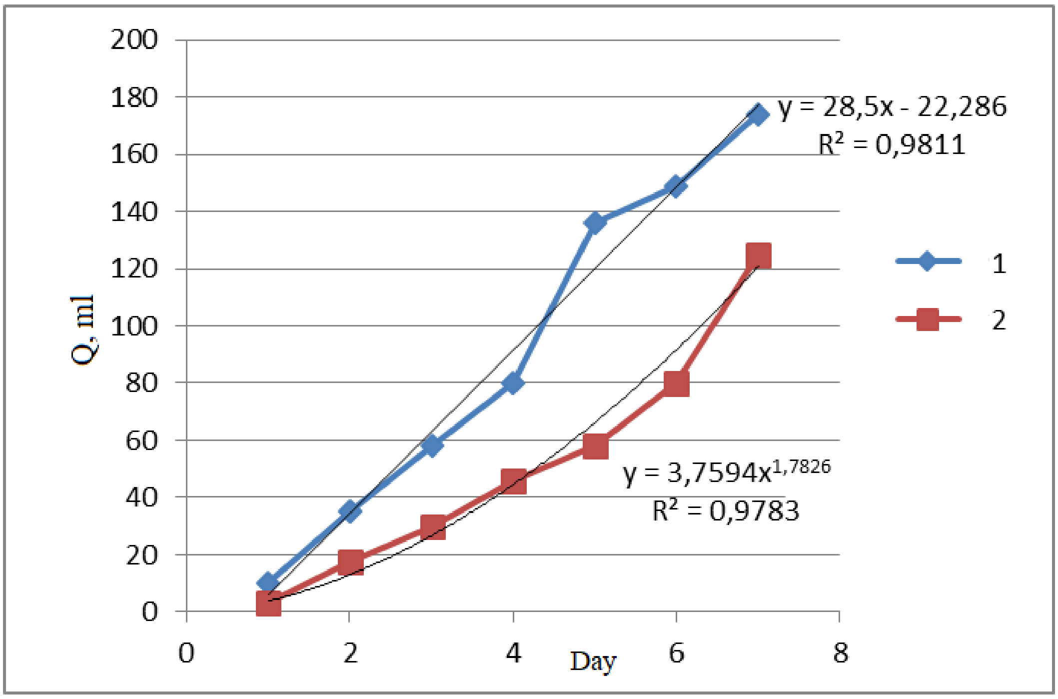
1– when the substrate is exposed by the combined magnetic field, 2– without exposure.

Fig. 5. Approximation equations of periods of growth in the rate of methane production.



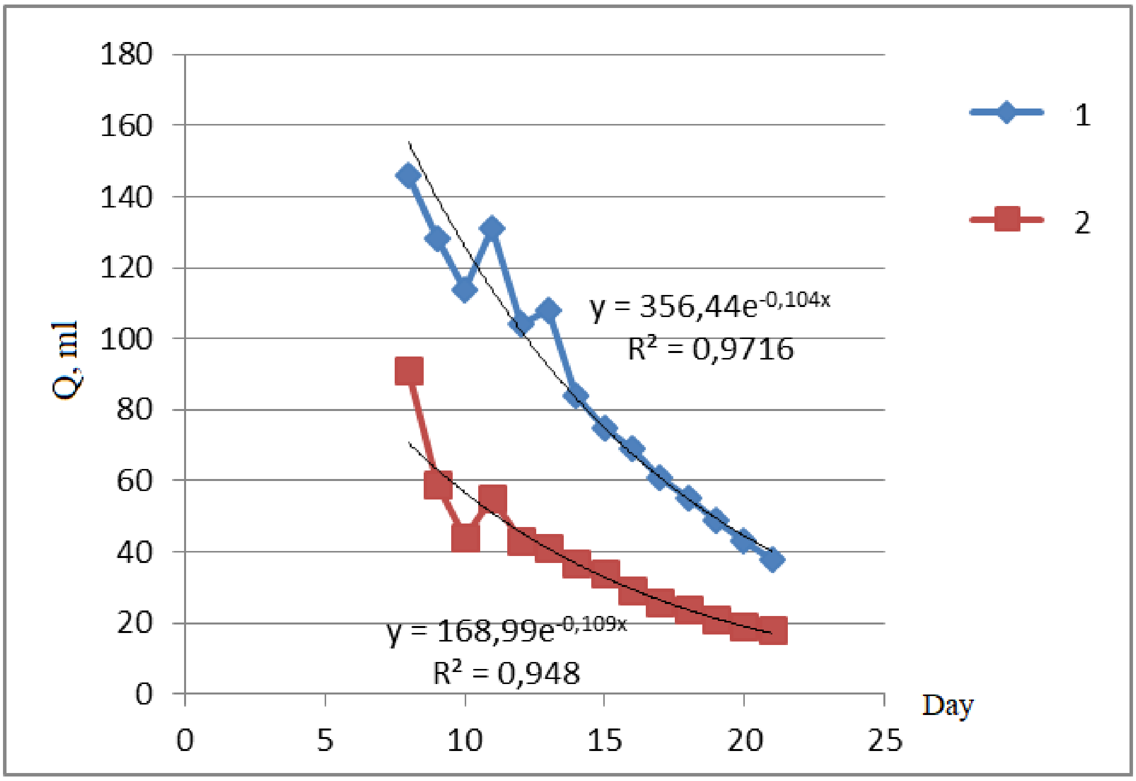
1– when the substrate is exposed by the combined magnetic field, 2– without exposure.

Fig. 6. Approximate equations of the periods of decline in the rate of methane production.



1– when the substrate is exposed by the combined magnetic field, 2– without exposure.

Fig. 7. Approximation equations of periods of growth in rate of biogas production.



1– when the substrate is exposed by the combined magnetic field, 2– without exposure.

Fig. 8. Approximation equations of periods of decline in rate of biogas production.

With sufficiently high regression coefficient R^2= 0.9783, the generation of biogas and methane during the absence of influence of the combined magnetic field on substrate occurs according to an exponential dependence both during the period of growth and during the period of decrease in the rate of methane production. At the same time, a short lag- phase is observed at the initial stage. This agrees with results obtained in work [30] during recearch of methane production during liquid anaerobic digestion (L-AD) of the mixture of lignocellulosic biomass (wheat straw) with an inoculant. Methane production in this case can be explained by a simple first-order kinetic model.

It is necessary to pay attention to the difference in the nature of the approximation equations of periods of growth in the rate of biogas (methane) production under the influence of the combined magnetic field on substrate and without influence of the magnetic field.

The influence of different magnetic fields on the activity of anaerobic sludge was studied in laboratory reactors that containing two predominant strains - Bacillus sp. and Brevibacillus sp.[31]. A linear dependence of variation of the accumulated volume of methane with the reaction time during the growth period was observed for reactors with action of the magnetic heterogeneous field and, on the contrary, an exponential dependence for reactors without the impact of the magnetic field. The results showed that magnatic heterogeneous field of 0–4 mT most effectively improved the activity of this sludge, and the peak methane generation rate increased by 20.6%. But in our research, significantly higher results were obtained both as for the achieved current and cumulative specific rates of CH_4 production, so and of the level of methane concentration in biogas.

The average concentration of CH_4 in biogas based on research results is presented in Table 1. Under the influence of the combined magnetic field, there is the significant (by 10%) increase in the concentration of CH_4 in biogas.

Table 2

Average concentration of CH_4 in biogas.

Conditions of anaerobic fermentation	Average concentration CH_4 in biogas, %			
	5 day	7 day	10 day	21 day
Without influence of the magnetic field	66.1	64	64.4	65
Under influence of the combined magnetic field	76,1	74	74	75

The effect of increasing the concentration of CH_4 in biogas under the influence of the combined electromagnetic field was also observed in researches [32], in which a solenoid created the magnetic and an electric field at the same time. The average level of magnetic induction (4.1-6.2) mT, which has a positive effect on the process of anaerobic digestion, is also confirmed. According to research [32], the electromagnetic system, such as solenoid, generates both the electric field and the magnetic field, which form significant Lorentz forces in substrate. Therefore, increasing the intensity of the magnetic field above the level of 6.2 mT leads to decrease in productivity of the bioreactor. The effect of the electromagnetic field strengthens the clustering of colloidal particles of substrate and bacterial activity, but duration of this impact also has certain limits, if it is exceeded, depression of the bacterial community can be observed. In our researches, the impact of the combined magnetic field was carried out periodically synchronously with mixing, which ensured mass exchange of the volumes of substrate exposed to the magnetic field and the total exposure time of 60 min/day.

Obviously, there is an optimal exposure time for different substrates. For example, during anaerobic fermentation of municipal drain sludge, the extended time (432 min/day) significantly reduced the output of CH_4, as well as the population of methanogenic bacteria. At the same time, the highest content of methane in biogas (66.1% ± 1.9%) was found in the variant with the influence of the magnetic field of 144 min/day [33].

Since the two bioreactors have the same composition of substrate, as well as the fermenters are in the same temperature regime and mixing regime, the explanation of different rate of the fermentation process and biogas output should be sought in the mechanisms of influence of the magnetic field. According to research [6], the schemes of interaction between molecular and ionic structures of substrate during methane generation during two different processes of processing substrate fractions with methanogenic bacteria can be represented by the following equations:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$
$$\Delta G^o = -135 kJ / mol.methane, \qquad (13)$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$
$$\Delta G^o = -31 kJ / mol.methane, \qquad (14)$$

Specified processes are carried out by two different types of methanogenic bacteria. Mandatory components of community are primary anaerobes of hydrolytic microflora (hydrolyze biopolymers), fermentative microflora (ferment monomer molecules), acetogenic microflora (transform various fermentation products into methanogenesis substrates) and secondary anaerobes - methane-forming archaea. The mechanism of interaction of charged particles (ions), polar molecules and the possibility of the influence of the magnetic field on the kinetics of chemical reactions in substrate is proposed in [6]. . The speed of chemical reactions in substrates and the interaction of charged particles (ions), polar molecules under the influence of the magnetic field increases and is determined by the square of the magnetic induction and the speed of movement of ions [6].

The growth of bacterial mass in the process of methane fermentation is relatively low and, according to [34], less than 5% of the carbon mass is converted into bacterial mass. When evaluating the degree of decomposition of the organic matter of substrate, according to the German standard [35], the total increase in the cell mass of the bacterial consortium at the level of 7% of the mass DOM of t substrate is taken into account. It is obviously that the existing norms should be specified during applying additional stimulating conditions regarding the bacterial consortium.

During conducting the experiment to determine the consumption of nutrients by microorganisms from substrate, the dry digestate was weighed on an electronic scale WPS

110/C/1 (RAGWAG) with 3.692 g of each sample. After incineration, the inorganic residue of each sample was weighed according to the standard method. The sample that was exposed to influence of the combined electromagnetic field weighed 1.221 g, and the sample that was not treated by the magnetic field weighed 0.856 g (Fig. 9).

1–with the influence of the magnetic field, 2– without the influence of the magnetic field

Fig. 9. The process of weighing digestate samples from bioreactors.

During biomass destruction, occurs the decrease of particle’s size, which in turn leads to increase in the reaction of surface area. According to simple model of collisions, a chemical reaction between two starting substances can occur only in result of collision of the molecules of these substances. But not every collision leads to the chemical reaction. It is necessary to overcome the certain energy barrier so that the molecules start to react with each other. That is, molecules must have certain minimum activation energy to overcome this barrier

It can be concluded that microorganisms under the influence of the combined electromagnetic field processed more organic material and, accordingly, produced more biogas.

The obtained data regarding output of biogas and methane (Fig. 3 and Fig. 4) show that the maximum output of biogas and methane is observed on the 6-8th day of fermentation. But from the bioreactor, which contained substrate treated with electromagnetic fields, more biogas is released (curve 1) than from the control sample of the bioreactor (curve 2). This can be explained by the fact that under the influence of electromagnetic fields, the metabolism of microorganisms improves, the availability of microorganisms to food and, accordingly, the increase of their colonies. In substrate that is fermented, there is wheat straw, in which, in recalculation on dry matter, the concentration of Fe (with the content DM of 10%) will be 2360 mg/kg [36].The magnetized state of Fe, a food component, as well as the magnetization of biogenic magnetic nanoparticles [20] created conditions for the dynamic direction of microorganisms to nutrients. At the same time, the output of biogas increased by 35%.

The output of methane in the treated substrate increased by 56% in comparing to the untreated sample, that is, it can be assumed that the methane-forming bacteria are magnetotaxis archaea and the electromagnetic field has a stimulating effect. The decrease in the output of biogas and methane after the maximum on the 9th day of fermentation (Fig. 3, Fig. 4) can be explained by the gradual decrease of the food, and the fluctuations on the 10th - 12th days of fermentation - by the decrease of the food and periods of "rest-immobilization".

The results of modeling to determine the distribution of the magnetic field in the active zones of the stator - bioreactor system are presented in Fig. 10 and Fig. 11.

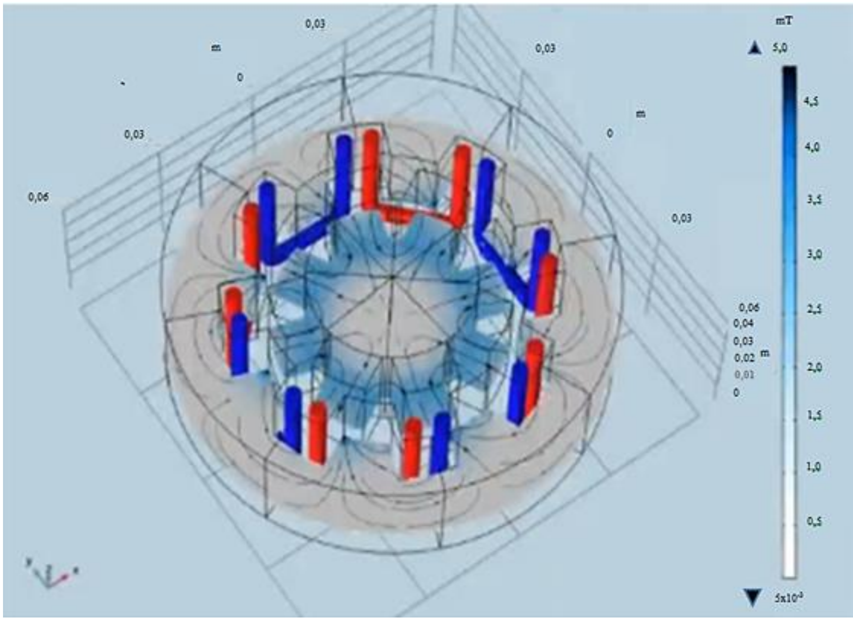


Fig. 10. Magnetic field in the cross-section of the stator of variable current electric engine.

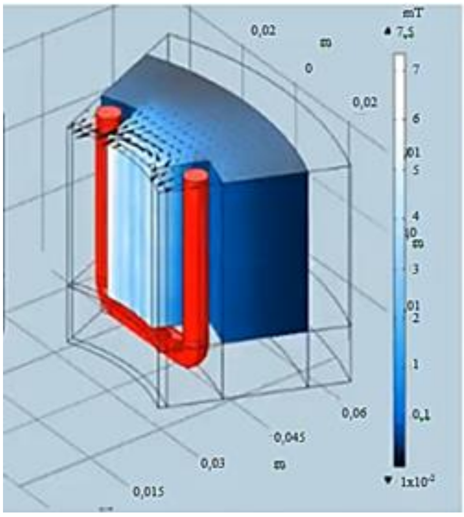


Fig. 11. The magnetic field in the pole zone of the stator fed by direct current.

Since the bioreactor was located in the inner cavity of the stators, the intensity of the magnetic fields throughout the volume of the bioreactor was different, i.e., a heterogeneous magnetic field was created not only in space, but also in time. The level of magnetic induction of the constant magnetic field in substrate near the

0.5 mT. The difference between the average values of the magnetic induction in substrate, which were measured experimentally and obtained by simulation results, does not exceed 11.5%, which confirms the adequacy of the walls of the bioreactor, directly tangential to the field source, is 5.5 mT, and in the middle, near the center, it is 0.4 mT. The level of magnetic induction of the low-frequency variable electromagnetic field in substrate near the walls of the bioreactor is 3.6 mT, and in the medium, near the center, it mathematical model of the stator-bioreactor system.

In comparison with [6], the level of magnetic induction was reduced through the combined impact of constant and variable low-frequency electromagnetic fields during maintaining the achieved effect of increasing productivity and increasing the concentration of methane in biogas. The stimulatory action of impact of combined electromagnetic field, which reached 30% in researches of brew samples, was confirmed [4]. But in this research, this method was used to stimulate biogas production in anaerobic fermentation systems.

CONCLUSIONS

According to the research results, it was established that the combined impact of constant and variable magnetic fields on methanogenesis not only increases the output of biogas, but also improves its quality, and also allows to reduce the duration of methanogenesis and increase the productivity of the biogas installation.

The highest value of the achieved current rate of CH_4 production (average for repetitions) was: for bioreactors with the influence of the combined magnetic field – 1.67 nl/kg/day; for reactors without influence – 0.93 nl/kg/day. Therefore, the impact of the combined magnetic field increases the current production rate of CH_4 by almost in 1.8 times.

The cumulative specific rate of release of CH_4 from a unit mass of the experimental mixture in the reactor over the entire period of observation for bioreactors under the influence of the combined magnetic field was 2.11 nl/kg/day; for bioreactors without influence – 0.92 nl/kg/day.

The difference in the character of the approximation equations of periods of growth of the rate of biogas (methane) production under the influence of the combined magnetic field on substrate and without the influence of the magnetic field has been established.

According to the results of the experiment with digestate samples, the levels of consumption of nutrients by microorganisms from substrate under the influence of the combined magnetic field and without influence were determined. Microorganisms under the influence of the combined electromagnetic field processed more organic material and, accordingly, produced more biogas.

In this work, for the first time, the real distribution of the combined magnetic field in the working zones of anaerobic fermentation was determined. Using the proposed mathematical model by the finite elements method in the computer program COMSOL Multiphysics, numerical simulation was carried out to determine the level of induction of the magnetic field and its distribution in the system of the source of the magnetic field - the bioreactor . By volume of the bioreactor a non-uniform magnetic field is created not only in space but also in time with an intensity of no more than 5.5 mT.

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