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Mathematical Research of the Accelerated Three-Stage Process of Substrate Fermentation in Bioreactors

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Abstract

Phased transition of methane fermentation substrate in bioreactors which is connected with the accelerated and efficient methane output in biogas installation is considered in the paper. The main advantages of the offered approach are the low cost of biogas installation, work with a trace amount of renewable raw materials from cattle excrement available to farmers and the accelerated, intensive substrate fermentation in bioreactors.

Parameters of three-stage methane fermentation substrate process are temperature, pH = 7.0 - 7.5, activity of enzymes, pressure, flow movement of components, the constant discharge and unloading of a substratum, humidity and refinement of cattle excrement which influence intensity of technological process and methane output. In this regard, we consider conducting mathematical research of methane fermentation's phased process of organic waste in the reactor, allowing to determine the connection of parameters in each step and in a single cycle; reasoning of design parameters stages on acceleration and efficiency criteria; developing a mathematical model describing the process of cavitation and heating of supplied biomass, saturation the bacteria with auxiliary heating in each process step and in a single cycle, as well as modeling and automation allowing to identify optimal performance characteristics to accelerate the digestion process and to get maximum biogas with a maximum concentration of methane, making the novelty of the proposed project.

Keywords: methane; methane fermentation, bioreactor, three-stage process, hydrolysis, acetogenesis, methanogenesis, bacteria, pH level.

1. INTRODUCTION

In all countries, the cattle is generally kept in commercial dairy farms in shelters and its wastage which pollutes environment by pathogenic bacteria, eggs of helminthes and weeds of earth localities which demand their utilization and processing in biofertilizer and energy source.

Researches of foreign scientists and experts are generally directed to creation of biogas units which are differentiated by a large amount of daily consumption of wastage and vegetable biomass which increases hauling and other charges for collecting, storage and preparation which are not affordable to each farmer. In addition, the high initial cost, the long process of fermentation in silage, complexity in monitoring and operation and the lengthy payback distinguish these installations [1-4].

In Russia, in Kazakhstan and the CIS countries due to the high initial cost of biogas units, their total does not exceed several hundred. In Kyrgyzstan, through the grants from UNDP "Increase in potential usage of biogas units in Kyrgyzstan" and state support, more than 50 biogas units are created, which are installed in villages Kyzyl-Charba, Karakol and Petrovka. Analysis of work results of these plants shows that significant design improvements are required throughout the chain process, providing easy control and access to the service of farmers [2].

The market is saturated by biogas units obtained by the fermentation of mesophilic bacteria in the silos for a long time with high cost of production.

The approach chosen by us is based on the acceleration and the maximal methane output from cattle excrement by continuous gradual methane fermentation of substrate in bioreactors (three-stage process). At the same time, important factors are: low cost of biogas units; work with a small amount of manure of cattle available to farmers; accelerated and efficient process of substrate fermentation in reactors.

The main process steps of biogas unit are the gradual digestion of the substrate in the reactor. Methane fermentation is a process of organic compounds decomposition to simple substances, in which the gas is released. Fats and proteins are mainly decomposed by high release of methane, and carbohydrates are by the release of carbon dioxide. A mixture of these gases is biogas. The decomposition process happens by the result of anaerobic microorganisms' activity [5,6].

In this paper, as a basis for the biogas unit, a three-stage fermentation process in the reactors is selected. The main reason of choosing this process is that bacteria metabolism of first fermentation stage is hundred times faster from bacteria metabolism of the last two stages. Besides, bacteria of the first stage are less susceptible to the spread of the raw material parameters. Therefore fast acidic cattle excrement is first placed in a hydrolysis reactor where its pH can be lowered or raised, without harming the acetogenic bacteria and methanogens (2 and 3 stages). From hydrolysis reactor, split and acidic substrate is transferred with small portions to other stages of fermentation. As portions are small, they do not change the overall pH in the reactor and have time to be absorbed by bacteria before entering the next portion. However, the effectiveness of the process in other two digestion stages is necessary to maintain a high concentration of mesophilic and thermophilic bacteria in the reactor and prevent their substantial leaching out [7-11].

Each phase is described by a set of chemical equations. There are simultaneously several different reactions in each phase. The quantitative ratio of these

reactions depends on the type of feedstock and the bacteria types which involved in this phase and many other factors. Binding factors in this case are: anaerobic conditions, humidity, temperature, period of fermentation, the pH level, uniform feeding of the substrate, the supply of nutrients, particles' size, mixing, and process stability [12,13].

2. METHOD

In particular, following tasks are supposed to be accomplished:

- To develop software product, allowing young scientists and researchers to join the scientific environment and to learn new knowledge on methane fermentation of organic waste, on the basis of experimental data, computer simulation, and the recommendations contained in the database;
- To develop model of compact biogas unit, which is affordable in price, effective in speed of methane production, which in its commercialization will allow farmers to dispose waste in the field of production; to obtain energy resources from local renewable raw materials; to get cheap non-polluting organic fertilizer and to restore soil fertility.

2.1 Three-Stage Process Of Methane Fermentation

Three-stage process of methane fermentation of organic waste in the reactors, determining the speed and the production of biogas, comprises:

1. On the first stage, the aerobic bacteria rearrang macromolecular organic substance (protein, carbohydrate, fat, cellulose) using enzymes to lower molecular weight compounds such as monosaccharide, amino acids, fatty acids and water. Enzymes, secreted by hydrolytic bacteria, decompose organic substrate components into small water-soluble molecules. The polymers are converted into monomers (single molecule). This process is called hydrolysis [1]. The chemical reaction equation of formation of glucose, ethanol, propionic and oil acids is given below [12]:

$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2$ *(1)*

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ *(2)*

$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH \rightarrow 2H_2O$ *(3)*

2. On the second stage, acidifying bacteria is involved with digesting. Individual molecules penetrate into the bacterial cell and further transformation is undergone. In this process anaerobic bacteria partially participate, using the remnants of oxygen and thus form anaerobic conditions required for methane bacteria. At this stage: acids (acetic, formic, butyric, prop ionic, caproic and milk), ketones and alcohols (methanol, ethanol, propanol, butanol, glycerol, and acetone), the gases (carbon dioxide, carbon, hydrogen sulfide and ammonia) are produced.

The equation of chemical reaction of acetic acid formation from propionic and oil acids is given below [12]:

$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$ *(4)*

$2C_6H_{12}O_6 + 4H_2 \rightarrow 4CH_3CH_2COOH + 4H_2O$ *(5)*

After that acid-forming bacteria create initial products from organic acids for methane formation, namely: acetic acid, carbon dioxide and hydrogen.

$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3 + 3H_2$ *(6)*

$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$ *(7)*

Keeping of a stable optimum temperature condition is very important for activity of these bacteria which absorb hydrogen.

3. On the third stage, methane, carbon dioxide and water are formed. 90% of all methane is developed at this stage, from which 70% comes from acetic acid. Thus, acetic acid formation on the 2nd stage splitting is the factor defining a methane generation speed on the third stage.

In the third stage of acetogene splitting of complex organic substances with methane formation is made by methanogenic bacteria. As a result, acetate with separation of hydrogen and carbon dioxide are formed by means of the first group of bacteria [12].

$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2$ *(8)*

$CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2$ *(9)*

$2CH_3CH_2OH + CO_2 \leftrightarrow 2CH_3COOH + CH_4$ *(10)*

$4H_2 + 2CO_2 \rightarrow CH_3COOH + 2H_2O$ *(11)*

At this stage, methanogenic bacteria transform an acetic acid into methane and carbon dioxide, and bacteria using hydrogen process transform hydrogen and carbonic acid into methane and water [12].

$CH_3COOH \rightarrow CH_4 + CO_2$ *(12)*

$CO_2 + H_2 \rightarrow CH_4 + H_2O$ *(13)*

2.2 The Efficiency Of Process Methane Fermentation

Investigations which are delivered by scientists on major factors of intensity and operating speed of biogas units show [7,11-13] that in the process of methane fermentation the methane bacteria participating in procreation are less active than acid-forming. At formation of large amount of organic substances it is possible to excess mass output of volatile acid. It leads to decrease of methane bacteria activity when unit pH decreases lower than 6.5. Eliminating the decrease of large amount of acids formation we select CO_2 on the first stage and we give it for sparging on the third stage.

At sparging a gas bubble, rising up through a layer in the bioreactor, lug away shoulder bed of substrate liquid, which leads to formation of its upward flow in the central area and substrate degassing, which promotes methane increase [7,9,10,30].

At crushing of cattle excrement the complex links of organic matters fibers are torn on a molecular scale (lignine, cellulose) from cell-like and subcellular materials, natural enzymes are more intensively released, which are considered as biological catalysts of methane fermentation substrate. In this case, all bacteria strains which are involved in biogas formation, at all its levels, it becomes easier to decompose biogenic materials as their homogeneous structure is destroyed and respectively the area of bacteria covering of cattle excrement increases. Biological processes are significantly stabilized, which leads to lack of foam and floating crust in a bioreactor. All the useful volume of the bioreactor is effectively used [14, 15].

The efficiency of anaerobic digestion is largely determined by regeneration of the circulating substrate of psychrophilic (temperature from 15 to 25 ºC), mesophilic (temperature from 37 to 40 ºC) and thermophilic bacteria (temperature from 55 to 59 ºC) in each step, allowing to intensify and optimize the process of methane fermentation reactors, to increase its efficiency and ability to adapt to the real production conditions [14].

To make the fermentation process in the reactor unproblematic, it is necessary to maintain it by constant conditions such as:

- PH = 7.0 -7.5;
- The content of fatty acids, volatile 3-8 mg.ekv / l;
- The content of alkali-content 70-76 mg.ekv / l;
- The content of ammonium salts of nitrogen 600-800 mg. / l.

Feed and discharge of sludge in the reactor during the day is recommended to be done uniformly (straight-flow diagram of operation), as well as to maintain the desired heating temperature possibly by steaming. Operation mode of such scheme is possible in continuous state and stopped only for repair and checking procedure

Of course, there are other factors influencing the effect of fermentation:

1. The presence of heavy metals (cobalt, copper and nickel), and chromium and sulfur compounds have an inhibitory effect on the anaerobic digestion process.
2. Stirring the reactor charge is made to prevent the formation of dead zones of bundle precipitate, crust formation, deposition of sand as well as to make effective use of all reactors' capacity, equalization of temperature and concentration of metabolites (intermediate substrate).

The high degree of disintegration and homogenization of raw material, as a consequence of increasing the number of particles on the surface as well as the regeneration of working substrate can increase and intensify biogas production up to 30-50%. The result of reducing of the fermentation period is the possibility to build reactors of small volumes and sizes, which leads to significant cost savings on capital structure [16].

3. RESULTS

3.1 Results Of Methane Fermentation Investigation

In the world literature there are many scientific and research works on the results of methane fermentation investigation developing from simplest to complex [11-16]. The complete model of anaerobic fermentation among complex models is ADM1 which includes several stages of biochemical, physical and chemical processes description (8 groups of bacteria and 11 reactions, mortality of microorganisms, their disintegration, and also pH influence, ionic and interphase equilibrium). In practice, the projection of anaerobic fermentation currently is used in empirical process models based on equations and the theory of microbial kinetics and the theory [13-16]. Chen-Hashimoto model which is a modified model of Konto [13] is of the greatest interest to engineering calculations [13]. In the CIS countries a small amount of works are devoted to mathematical model processes of hydrodynamics and heat exchange in a methane digester by authors A.A. Kudryashov, A. G. Dugout, A. A.Chernyshov, Yu. N. Sidyganov, E. M. Onuchin [17-20]. Kudryashova A. G. [11] developed mathematical model of three-stage process of substrate fermentation in biogas unit. Various ways of bioreactor heating of anaerobic fermentation of organic wastage are presented in the works of T. I. Espolov, Yu. N. Sidyganova, E. M. Onuchin, A. A. Medyakov [8, 17-20]. The model of float biomass fluctuation belongs to A. A. Chernyshov [17]. E. K. Vachagina [21] created a mathematical model of two-phase gas-liquid substance fluctuation in a cylindrical methane digester with a mechanical intermixing. O. V. Naumova and I. V. Reshetnikova created energy saving technologies of organic wastage fermentation [22, 23]. Numerical process model of heat exchange at jet mix of sewage sludge in methane digester with an inner circulation pipe is presented in the works of R. G. Shayakhmetov and V.G.Isakova [24].

3.2 Mathematical Model Of Anaerobic Fermentation Process

The analysis of considered mathematical models of anaerobic fermentation process shows that the accounting of hydrodynamic characteristics of process is a necessary condition for the complete description of methane fermentation processes in the bioreactor [25-27].

We consider following data for mathematical description of model:

1. In each bioreactor the quantity of stream arrives and mixes up with all weight and so much decreases, i.e. in the limit of the first, second and third steps where the stream quantity remains equal to 1, 440 ton;
2. The residence time of particles in 1st bioreactor is τ=11 days, in the 2nd bioreactor is τ=9 days, in the 3rd bioreactor is τ=8 days, in all biogas unit is 28 days.
3. As in each bioreactor we accept that the stream is in ideal mixture condition, the mathematical description has the following appearance [28]:

$$\frac{dC_i}{dt} = \frac{1}{\tau_1}(C_{i-1} - C_i) \quad (13)$$

where i=1,2,3

4. We find residence time in the separate device, which is divided this time for number which is sequentially switched-on in bioreactors, believing that the overall residence time τ is evenly distributed on three bioreactors:

$$\tau_1 = \frac{\tau}{3}$$

At the same time equality (1) has appearance:

$$\frac{1}{3} \cdot \frac{dC_i}{dt} = \frac{1}{\tau}(C_{i-1} - C_i) \quad (14)$$

where i=1,2,3.

Taking into account the chemical transformation the dynamic model of the ideal mixture reactor of continuous action has the following appearance:

$$\frac{dC_i}{dt} = \frac{1}{\tau}(C_{\text{вх}} - C_{\text{вых}}) \pm W_i \quad (15)$$

Where C_i is concentration of substance i, kmol/m^3;

W_i is speed of reactions on substance i, kmol/m^3;

Konto's model applied for mathematical description of anaerobic fermentation process of organic wastage is of considerable interest to engineering calculations. And for speed determination of biogas output we accept Chen and Hashimoto's equation, modified model of Konto [29]:

$$v = \frac{B_0 \cdot S}{\tau} \cdot \left(1 - \frac{K}{\mu_m \cdot \tau - 1 + K}\right) \quad (16)$$

here, v is biogas output speed; B_0 is limited biogas output; S is substrate concentration; τ is substrate fermentation duration; K - kinetic parameter; μ_m is maximal specific speed of biomass increment.

The maximal specific speed of biomass μ_m depends on temperature of substrate fermentation and is calculated by the following formula [12]:

$$\mu_m = 0.013 \cdot t - 0.129\ day^{-1} \quad (17)$$

here, t is the fermentation temperature, ^{0}C. Three modes of fermentation are accepted for our biogas unit: psychrophilic within 18-25^{0}C; mesophilic within 25-40^{0}C; thermophilic within 40-55^{0}C.

The calculated values of maximal specific speed of biomass for different temperature schedules are given in Table1:

Table 1. Values of maximal specific speed of biomass

Temperature, t	Maximal specific speed of biomass, μ_m
18-25^{0}C	0.586
25-40^{0}C	0.391
40-55^{0}C	0.196

We will determine kinetic parameter (K) from an empirical equation offered by Hashimito and coauthors [29]:

$$K = 0.6 + 0.0206e^{(0.051 \cdot S)} \quad (18)$$

Substrate concentration (S) is necessary for determination of kinetic parameter. Substrate concentration depends on manure composition and is estimated by the content of dry organic matter in biomass:

$$S = \rho(100 - W)(100 - A)10^{-4} \quad (19)$$

here, A is content of dry cattle wastes, %; W is biomass humidity in the bioreactor, %; ρ is biomass density.

Biomass density is defined by ratio [29]:

$$\rho = W\rho_w + (1 - W)\rho_{ss} \quad (20)$$

here, ρ_w =1000 kg/m^3 is water density, ρ_{ss} =1400 kg/m^3 - density of dry (solid) substance of manure, W=88% - biomass humidity. Optimum parameters of weight for an anaerobic fermentation are taken from methodical recommendations on technological projection systems of removal and preparation for manure and dung usage [30].

According to formula (20) biomass density is ρ=1048kg/m^3.

According to formula (19) we find substrate concentration: S=106.896. By means of substrate concentration we will determine the kinetic parameter K=5.402957129, by formula (18).

Values of biogas output speed at three temperature regimes which depends on fermentation duration are given in Table 2:

The diagram of the biogas output speed which is made according to Table 2, calculated by formula (16) is provided on the Figure 1:

Table 2. Values of biogas output speed at three temperature regimes

Methane output speed at 55^{0}C	Methane output speed at 40^{0}C	Methane output speed at 25^{0}C
-381.4349458	-583,9196047	-803,5753342
70,90662741	-96,62983502	-291,4196049
188,5079515	47,53738988	-126,480051
228,9081401	108,6165752	-47,85320291
241,9569318	138,0847386	-3.415615536
243,4004095	152,7872275	24,16786594
239,4978034	159,7482408	42,29860506
233,0887032	162,3533937	54,65681313
225,5709151	162,3988989	63,27174756
217,6675377	160,9041918	69,34931024
209,7620259	158,4769141	73,64788284
202,0577237	155,4925909	76,66599182
194,6589033	152,1895315	78,74317175
187,6140257	148,7218179	80,11746105
180,9397381	145,1902486	80,95979284
174,6345812	141,6610865	81,39540755
168,686992	138,1777712	81,51764483
163,0800437	134,7684257	81,39708875
157,7942747	131,4507739	81.08778614

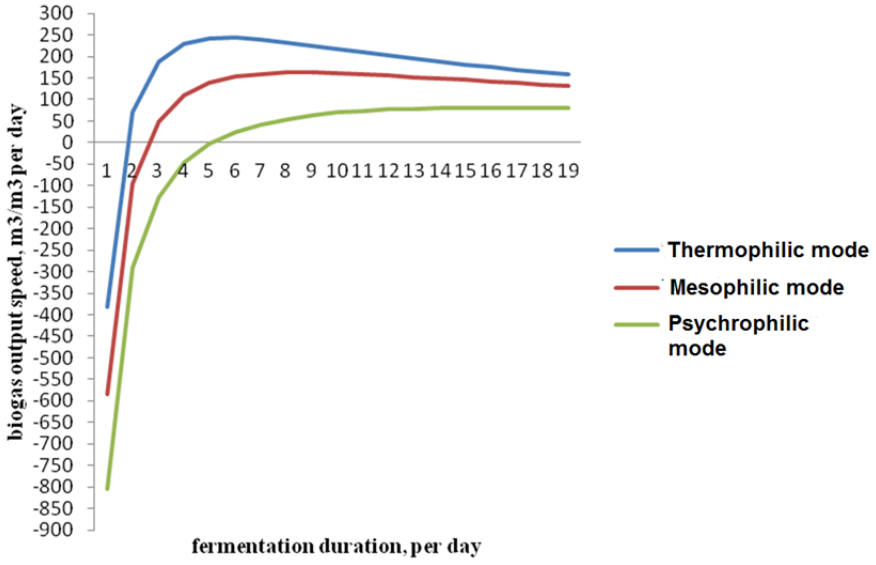

Figure 1: Diagram of biogas output speed

At the thermopiles mode the diagram of biogas output accelerates on the second day, at the mesophilic mode on the third day, and at the psychrophilic mode schedule of biogas output is carried out only after the fifth day.

Crucial importance of defining the methane concentration values, the expense of selected stream and the temperature at all steps of technological process of cattle excrement methane fermentation has constructive solutions of biogas unit projection.

3.3 Calculation Of A Biogas Plant

Our biogas unit projection is calculated for 40 cattle.

First of all we determine the total weight of animal wastes taken from 40 cows within a day. Daily intake of biomass is calculated by the following formula [3]:

$m_{bm} = \sum N_{qj} \cdot m_{sj}$=40 cattle·36 kg/day=1440 kg/day (21)

where N qj is cattle quantity of j type, cattle;

m sj is daily excrement output from j type of animal, kg/days.

We will take 36 kg cattle excrement output per day [1].

The share of organic matters in excrement of nonvolatile solid makes about 75 — 85%. Cattle manure contains carbon and nitrogen corresponding 15-16. Animal urine contains about 50% of nitrogen which is emitted together with excrement.

Determining the capacity for substrate preparation from excrement and water which represents a parallelepiped, its volume is calculated by formula [3]:

$$V = a \cdot b \cdot h \qquad (22)$$

To get the necessary volume, we will take width b = 1.25m, length = 1.25m and height h = 2 m. Thus we get volume:

$$V = 1{,}25 \cdot 1{,}25 \cdot 2 = 3{,}1 \text{ m}^3$$

Determination of bioreactor volume – first stage where the substrate is fermented and a large amount of CO_2[3] is allocated:

$$V_{1st.} = \frac{(0{,}7\ldots0{,}9)\cdot m_{bm}\cdot t_{bm}}{\rho_{bm}} = \frac{(0{,}8\cdot 1440\cdot 11)}{1048} = 12.09 \text{ m}^3 \quad (23)$$

where $t_{bm}$is fermentation duration, per day;

ρ_{bm}- fermentable biomass density, kg/m^3. Manure density is equal to 1048 kg/m^3.

As a rule, bioreactors have cylindrical form, height relation to its caliber is equal to h/d = 0.9 … 1.3. We accept h/d = 1. As,

$$V_{BR} = \frac{\pi d_в^2}{4} \cdot h = \frac{\pi d_в^2}{4} \cdot d_в \quad (24),$$

so

$$d_в = \sqrt[3]{\frac{4V_{BR}}{\pi}} = \sqrt[3]{\frac{4 \cdot 12.09}{3{,}14}} \approx 2{,}5 m.$$

$$V = S_{окр} \cdot H = \pi R^2 H \quad (25)$$

here we calculate the bioreactor height of first stage:

$$H = \frac{V}{\pi R^2} \qquad (26),$$

so,

$$H = \frac{12.09}{3{,}14\cdot 1.25^2} = 2{,}47 \text{ m}.$$

Considering that the total amount of substrate has to be less than 2/3 volumes of capacity it is possible to calculate new volume by formula:

$$V_{f1st.} = 3/2 \cdot V_{1st.} = 12.09 \cdot 3/2 = 18.2 \text{ m}^3 \quad (27)$$

Then proceeding from the fact that we increased volume, the final height of this bioreactor will be calculated by formula (26):

$$H = \frac{18.2}{3{,}14\cdot 1{,}25^2} = 3.7 \text{ m}.$$

Internal volume calculation (third stage) of bioreactor. We calculate volume by formula (23):

$$V_{3st.} = \frac{(0{,}7\ldots0{,}9)\cdot m_{bm}\cdot t_{bm}}{\rho_{bm}} = \frac{(0{,}8\cdot 1440\cdot 8)}{1048} = 8.8 \text{ m}^3$$

We calculate diameter by formula (24):

$$d_в = \sqrt[3]{\frac{4V_{BR}}{\pi}} = \sqrt[3]{\frac{4 \cdot 8.8}{3{,}14}} \approx 2{,}25 m.$$

from this we calculate bioreactor height of third stage by formula (26):

$$H = \frac{8.8}{3{,}14\cdot 1.12^2} = 2{,}25\text{m}.$$

Considering that the total amount of substrate should be less than 2/3 volumes of capacity it is possible to calculate new volume by formula:

$$V_{f3st.} = 3/2 \cdot V_{1st.} = 8.8 \cdot 3/2 = 13.2 \text{ m}^3$$

On the basis of fact that we increased volume, the final height of this bioreactor will be calculated by formula (26):

$$H = \frac{13.2}{3{,}14\cdot 1{,}12^2} = 3.4 \text{ m}.$$

We will calculate the volume of 2nd stage of the bioreactor by formula (23):

$$V_{3st.} = \frac{(0{,}7\ldots0{,}9)\cdot m_{bm}\cdot t_{bm}}{\rho_{bm}} = \frac{(0{,}8\cdot 1440\cdot 9)}{1048} = 9.9\text{m}^3$$

We will calculate the diameter by formula (24):

$$d_в = \sqrt[3]{\frac{4V_{BR}}{\pi}} = \sqrt[3]{\frac{4 \cdot 9.9}{3{,}14}} \approx 2{,}32 m.$$

here we calculate bioreactor height of the third stage by formula (26):

$$H = \frac{9.9}{3{,}14\cdot 1.16^2} = 2{,}35\text{m}.$$

Considering that the total amount of substrate has to be less than 2/3 volume of capacity, it is possible to calculate new volume by formula:

$$V_{f2st.} = 3/2 \cdot V_{1st.} = 9.9 \cdot 3/2 = 14.8 \text{ m}^3$$

Proceeding from the fact that we increased the volume, the final height of bioreactor will be calculated by formula (26):

$$H = \frac{14.8}{3{,}14\cdot 1{,}16^2} = 3.5 \text{ m}.$$

The total bioreactor height of 2nd and 3rd stages of biogas unit is equal to 3.58 m.

Biogas output determination at complete manure decomposition, m^3:

$$V_{full} = n \cdot m \qquad (28)$$

where n is biogas output from 1 kg of various starting material, m^3/kg. In our example, for cows' wastes the biogas output weight is equal to 0,315 m^3/kg.

Biogas output = 0,315 m^3/kg x 1440 kg = 453.6 m^3

Further calculation of biogas unit equipment comes down to determination of unit volume and a form, determination of flow diagram, calculation of pumps, mixers and other accessory equipment of biogas unit.

Biogas unit was designed on results of calculation data. The process flow diagram of receiving a methane product is presented in Figure 2.

Distinctiveness of this biogas unit is:

- the separation of ballast carbon dioxide from the volume of biogas, division of an anaerobic fermentation of substrate into two parts - the hydrolyzing and enzymatic, realized in different containers.
- the barbotage of carbon dioxide leading to separation of small gas bubbles from methane microorganisms which facilitates their contact with nutritious substrate and increases potential feed stock,
- the excrement preparation, its refinement at cavitational processing.

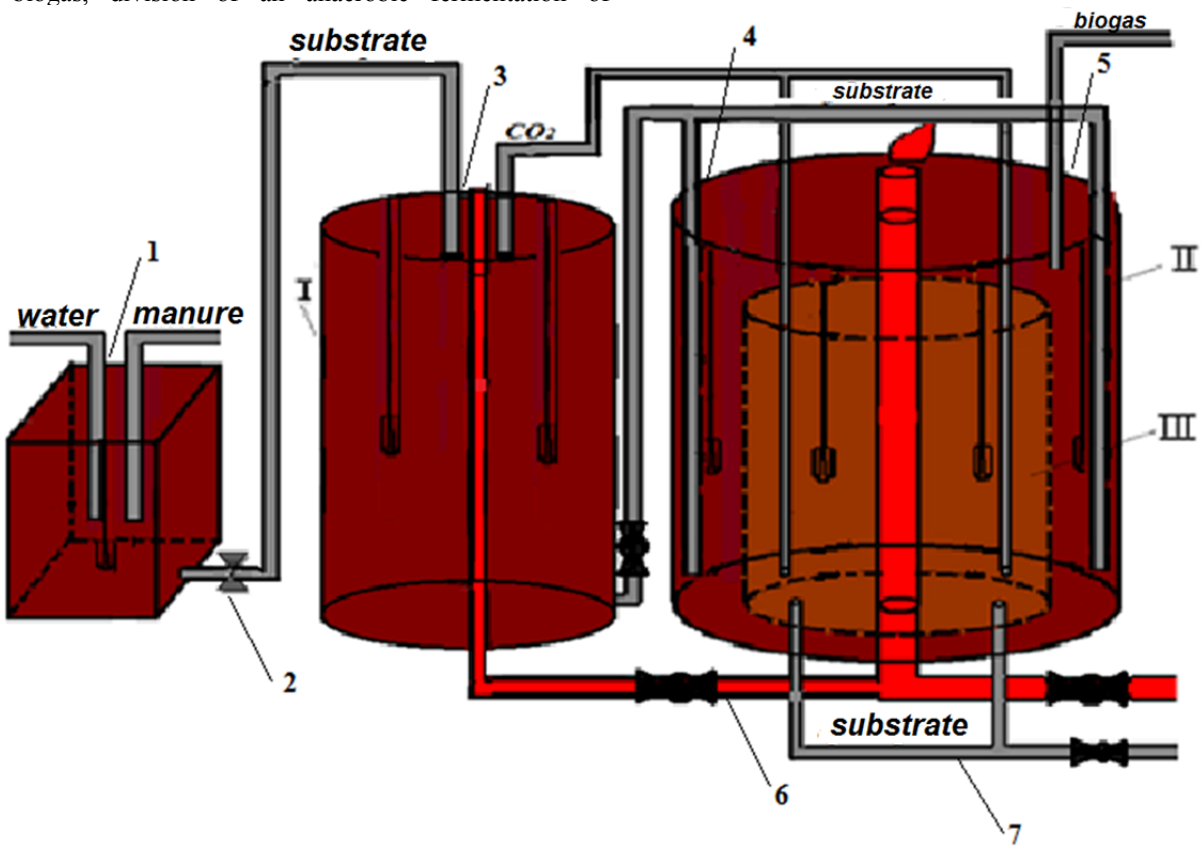

Figure 2: The modernized biogas unit with substrate cavitation and CO_2 separation on the first stage

1-manure tank; 2-transporting pump of substrate; 3- bioreactor; 4- two-stage methane digester (anaerobic bioreactor); 5-compressor of biogas pumping; 6-gas heater; 7- exhaust substrate disposal pump.

The presented process flow diagram of methane fermentation will allow organizing three-stage process of methane fermentation, substrate heating at the expense of received biogas and high-speed substrate transformation into methane product.

4. Discussion

4.1 The Sequential Decision Algorithm Of Methane

The sequential decision algorithm of methane fermentation in the above presented modernized biogas unit consists of the following stages:

1. Preparation. At this stage raw materials preparation happens in the capacity-1, it is filled by excrement and water. With the help of relay the substrate humidity in capacity is defined. The liquid indicator calculates the necessary liquid amount to be added to receive necessary substrate humidity. Raw materials humidity is equal to 92%. The amount of water necessary for addition is calculated by the following formula [12]:

$$PC = M_{bm} * (B2 - B1) / (100 - B2) \quad (29)$$

here, M_{bm} is loaded excrement mass, kg;

B1 is excrement humidity registered by relay, %;

B2 is humidity which we need, %;

RS is liquid amount which needs to be added, l.

2. Cavitation. At this stage, excrement mixed with water crushed with the help of cavitator. Solids have to be crushed to particular sizes beforehand. Minimum size achievement of the solids gives the chance of more fast bacteria intermixing in substrate, therefore biogas output is higher.

3. 1st stage (hydrolysis). At this stage, after collecting and cavitation of substrate of 1.4tn. quantity through loading pump – 2, it is pumped through pipe into container - 3 into psychrophilic camera. During fermentation process in

container - 3 floating scum can be formed on a surface. For its prevention we need to mix periodically substrate with mixers. In consequence of intermixing by mixers, it is possible to distribute evenly substrate nutrients. Intermixing is carried out once a day at an interval of 10 minutes and with a rotation speed of 24-33 rpm. Substrate heating is carried out by the gas heater with the help of gas received from biogas unit. Temperature in capacity - 3 should be within 18-25 degrees [14]. In psychrophilic camera the carbon dioxide is selected and moves on sparging to the thermophilic camera by means of the compressor [30].

4**. 2nd stage (acidogenesis).** At this stage on the expiry of 7 days in the psychrophilic camera – 3, 1.4 ton of substrate is poured via transporting pump into capacity - 4 then into mesophilic fermentation camera where the second stage of fermentation is carried out. Substrate heating is carried out by gas heater with the help of gas received in biogas unit. Temperature in mesophilic camera - 4 has to be within 25-40 degrees [29]. Intermixing should be carried out once every 2 hours at 10 minutes and with rotation speed of 42-51 rpm.

5. 3rd stage (methane produce). At this stage on the expiry of 7 days, 1.4 ton of substrate is poured into the thermophilic fermentation camera where third stage of fermentation is carried out.

Substrate heating is carried out by the gas heater by means of the gas received in biogas unit. Temperature in the thermophilic fermentation camera has to be within 40-55 degrees [29]. Intermixing should be carried out once every hour at 10 minutes and with rotation speed 51-60 rpm [14]. Before dumping of 1.4 ton substrate into the thermophilic fermentation camera 6, the same quantity of a ready organo-mineral fertilizer is taken away from it with the help of unloading pump - 7. The biogas with the maximal methane concentration is removed from mesophilic and thermophilic cameras of fermentation with the help of compressor – 5.

Methane fermentation algorithm in the flowchart form is presented in the Figure 3:

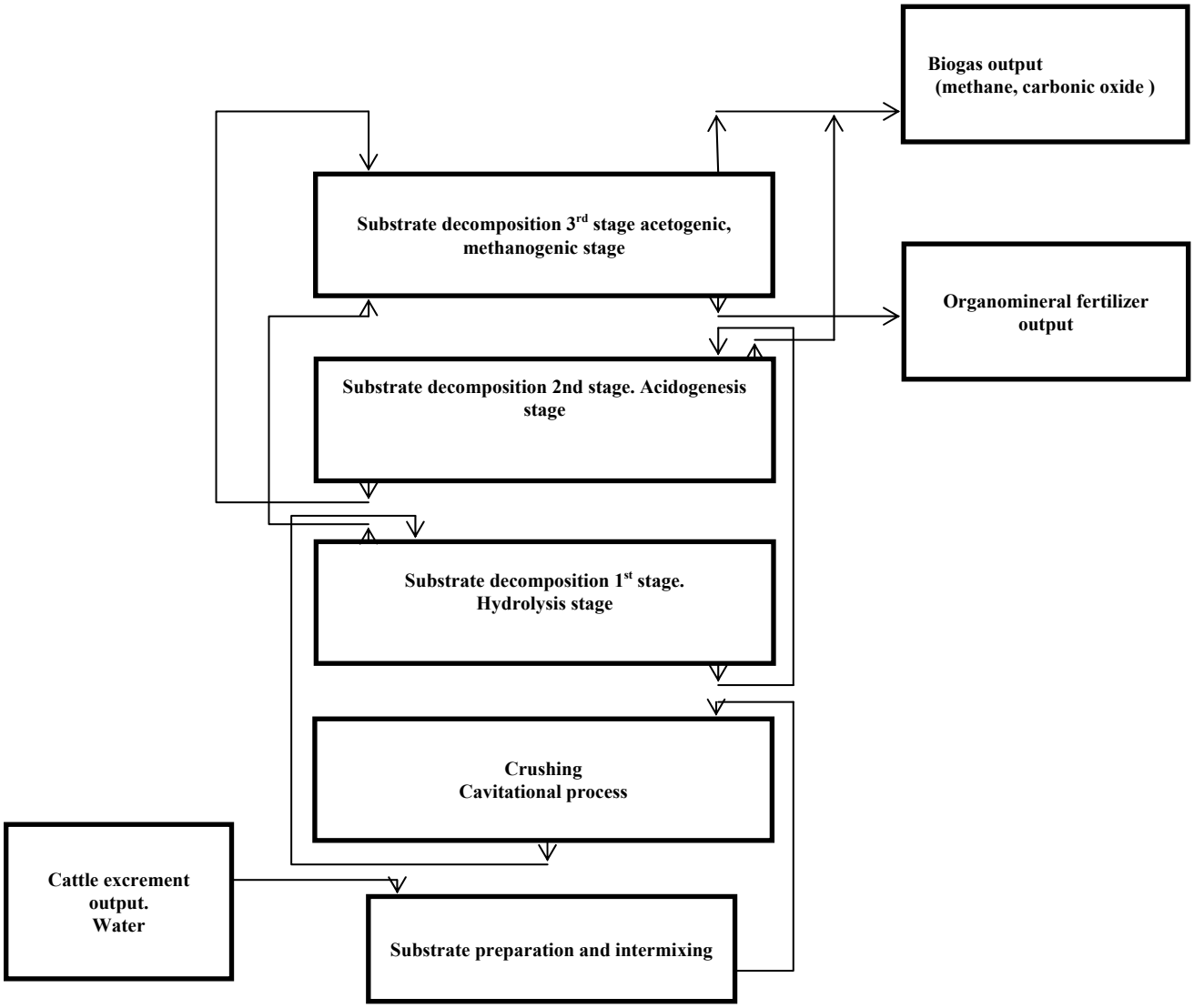

Figure 3: Flowchart of successive solution of methane fermentation of cattle excrement in biogas unit.

The conducted researches showed that methane output depends on products output of anaerobic fermentation at temperature activity stages of microorganisms: psychrophilic (from 10 to 25 °C), mesophilic – (from 25 to 40 °C), thermophilic – (from 40 to 55 °C). For each fermentation mode the optimum temperature schedule is defined, and barbotage period during a day connected with loaded mass of substratum and unloading from biogas unit. Stage of methane production is related to substratum intermixing in bioreactors in all three stages. First intermixing is carried out at interval of 10 minutes and with rotation speed of 25-35 rpm once a day, the second one is carried out once every 2 hours at interval of 10 minutes with rotation speed of 40-50 rpm and the third intermixing is carried out once in an hour at interval of 10 minutes and with rotation speed of 50-60 rpm [31].

Substrate fermentation process happens more intensively on all bioreactors volumes, due to the instantaneous entered substrate stream heating of the following stage and due to optimum temperature stabilization of all bioreactors biomass volume. Substrate stabilization temperature in bioreactors is reached within several hours due to small portion inflow into bioreactors. At thermophilic mode, the biogas output schedule accelerates on the second day, at the mesophilic mode, on the third day, and at psychrophilic mode biogas output is carried out only after the fifth day. Therefore, in biorector 1 the volume and quantity of substratum portions increase up to 11, in the bioreactor 2, up to 9 and in bioreactor 3, up to 8.

The mathematical model method of ideal replacement of chemical reaction flow regularities in reactor constitutes:

- the change of methane concentration in bioreactors according to contact time and temperature;
- the stage of substrate transformation into bacteria in the intermediate products at each stage during contact;
- the temperature stabilization at all stages of technological process.

4.2 Automatic Control Visualization System Of Anaerobic Fermentation

The key optimization feature at each stage and general optimization of biogas unit consisted of automation and adoption of optimum regime characteristics, through mathematical calculation.

Automatic control visualization system of anaerobic fermentation process is presented in the stand assembled at the M.Kh.Dulaty Taraz State University which is given in Figure 4.

PLK100 forms control signals on actuation mechanism (pumps, gas heater) due to received signals from sensors. Temperature is measured by temperature sensor DTS055. Level sensors are presented as discrete sensors worked when needed level is achieved [17, p.118].

With the help of gas heaters the substrate heating is carried to the desired temperature. Pumps provide transporting of substrate from the preparation tank to the reactor, as well as the constant stirring of the substrate.

In order to avoid overflow of reactor, sensor-controlling stake is installed, controlling the maximum level at which signal is triggered in case of emergency.

GSM-modem is a remote control makes operation of biogas plant and alerts personnel in case of emergency situations and contingencies. All devices are linked via RS-485 interface.

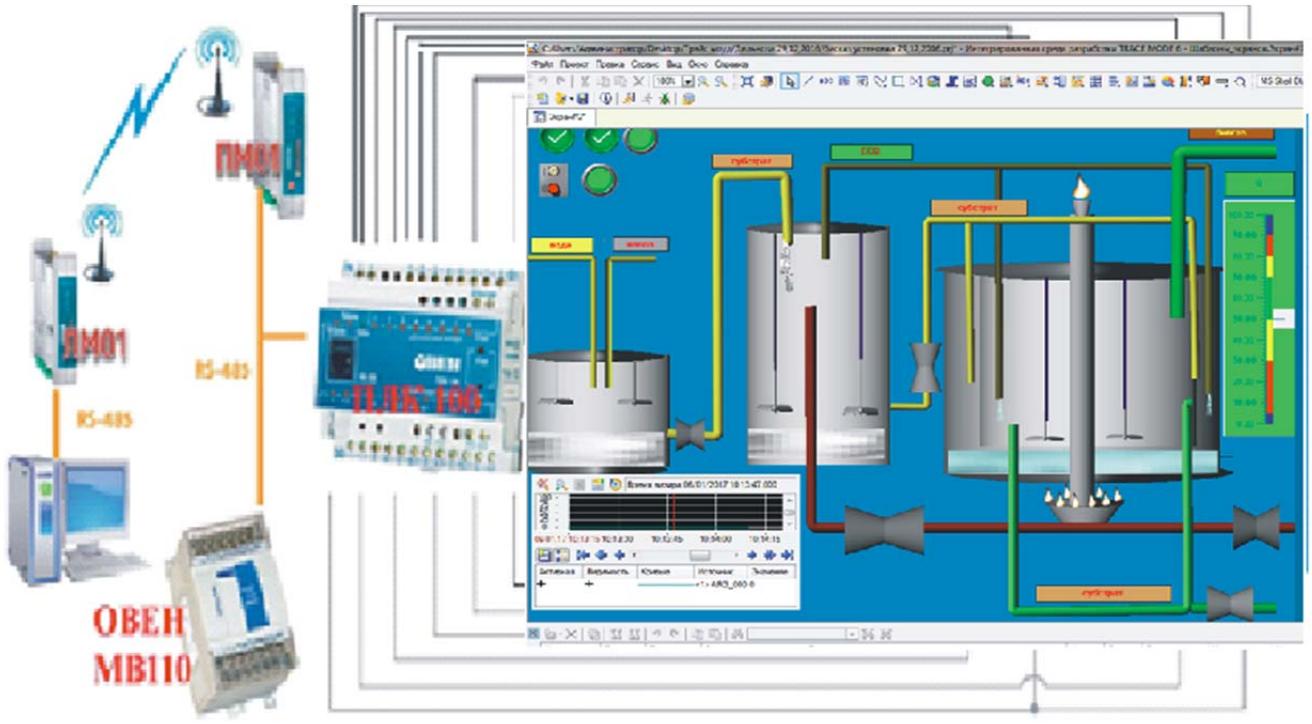

Figure 4: The functional chart of experimental biogas unit

CONCLUSION

In conclusion, by results of references analysis a mathematical model of three-stage biogas unit functioning was formulated, which includes the mathematical description of the following processes: process of organic substance transformation (each stage of methane fermentation model is chosen), substrate movement process at each stage (in bioreactors), CO_2 separation from the first stage and its sending to barbotage in the third fermentation stage, heat distribution in bioreactors. The research of methane fermentation regularities of cattle excrement in bioreactors by mathematical model method allowed determining the biogas output, methane concentration, substrate fermentation time and temperature at all stages of technological process of the modernized biogas unit.

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