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Macromodelling of Fermentation Process of Municipal Solid Organic Waste at Biogas Plants on the Acidogenesis Stage

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Abstract. *In this work the task of modeling processes of anaerobic microbiological fermentation with keeping the balance on the stages of hydrolysis and acidogenesis was considered. It was proposed and justified to build the model at the stage of acidogenesis in the form of interval difference operator (IDO). The structure identification method of IDO on the principles of honey bee colony functioning in the food search process, which provides the possibility of obtaining simple IDO structures with specified prognostic properties relative to existing methods, was substantiated.*

Keywords: *biogas, municipal solid organic waste, biogas plants, structure identification, interval difference operator, artificial bee colony algorithm..*

1. Introduction

The amount of waste is growing permanently together with growth of urban population and number of industrial enterprises. Municipal waste are formed and accumulated not only in residential premises, but also in offices, administrative buildings, cinemas and theaters, shops, cafes and restaurants, kindergartens, schools, institutions, hospitals, hotels, train stations, markets or simply in the streets. Industrial and municipal waste creates many ecological problems [1].

If we do not carry out recycling of waste, and keep all waste at landfills, related environmental problems appear, that is: leaching of nutrients and pollution of inland waters; methane formation, which leads to the greenhouse effect; soil subsidence etc [2]. Accordingly, accumulation of municipal solid organic waste (MSOW) is one of today's environmental problems. For its solving we should utilize MSOW by using biogas plants (BGP), which give opportunity together with solving ecological problem to receive highly organic fertilizers and energy in the form of biogas [3].

From 30-50% (Western Europe) till 60-75% (USA, Japan) of solid municipal waste is recycled in developed countries, in developing countries, - 7-10% [4]. Therefore the task of solving the problem of MSOW recycling in big cities and improvement of renewable energy systems development in Ukraine is actual.

Complex heat and mass exchange processes at different stages of methane fermentation take place in the main elements of BGP. Such processes were defined and described in many works [5, 6], however we have often the problems of technological requirements nonobservance at BGP, at which the balance is not kept.

Scientific schools of such Ukrainian and foreign scientists, as Griffin, McMahon, Mackie, Raskin, Holub, Kozlovets, obtained the most significant results at study of the problems of MSOW recycling through anaerobic microbiological fermentation.

Nowadays the processes of anaerobic microbiological fermentation are also described in the number of works at the level of macro models of type «input-output» [7, 8]. However, such models are not suitable for solving management tasks, because they do not reflect products balance at different stages, providing opportunities for effective organization of the process at BGP. Consequently, at best, we'll have low biogas output, and at worst – reaction fading because of death of mesophilic bacteria. That is why the purpose of this work is development of macro models of anaerobic microbiological fermentation process for some stages. In particular, macro modelling task for acidogenesis stage was considered.

2. Statement of problem

Let's consider the process of biogas formation by means of anaerobic microbiological fermentation of solid household organic waste.

The process of biogas formation is called methane fermentation. Its essence is in anaerobic fermentation, which takes place due to microorganisms vital activity and is accompanied with number of biochemical reactions [9]. Several species of microorganisms take part in general reactions, which include the following stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [10]. Anaerobic fermentation requires balanced activity of microbial associations for substrates oxidation and removal of inhibiting acids and hydrogen for methane formation. General diagram of methane fermentation is shown on Fig. 1.

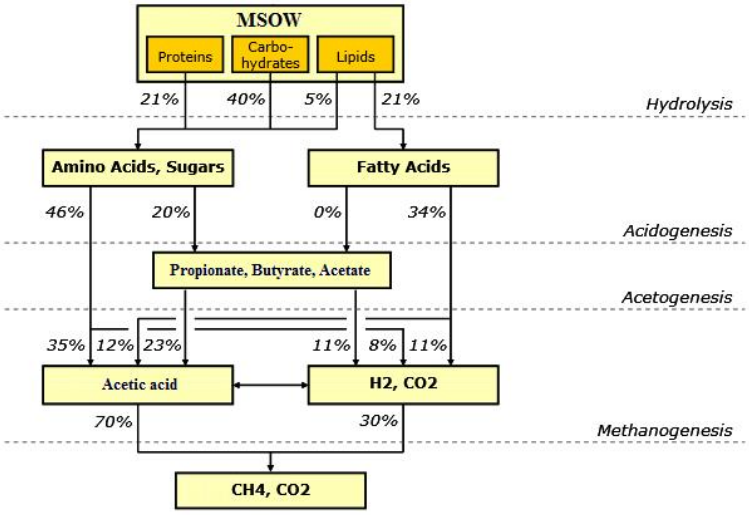

Figure 1: Anaerobic microbiological fermentation diagram of MSOW

On the stage of hydrolysis decomposition of macromolecular compounds (carbohydrates, fats and proteins) into micro molecular organic compounds takes place. Their anaerobic ability to biological decomposition depends on the relative amount of each component. Almost all carbohydrates decompose easily, and proteins, fats and cellulose require longer time for hydrolysis.

Carbohydrates decomposition. Hydrolysis of carbohydrates — decomposition

of starch polysaccharides with addition of water. The final products of starch hydrolysis in biogas plants are glucose and fructose.

At rapid heating starch is decomposed into dextrins of formula $|C_6H_{10}O_5|_n$, where n — number of glucose residues.

$$|C_6H_{10}O_5|_n + nH_2O = nC_6H_{12}O_6. \quad (1)$$

Lipids decomposition. Animal and vegetable lipids or oils are prevailing fats in waste, causing pollution problems in anaerobic fermentation.

In the process of hydrolysis lipids are decomposed into glycerol and long chain fatty acids (Fig. 2). Inhibitory effect of lipids is usually attributed to higher fatty acids. They remain on the surface between lipids and water and, therefore, affect the activity of lipases, ferments, catalyzing hydrolysis of insoluble substrates, helping to decompose lipids, and may cause damage of transport channels of bacterial cells. Under ferment lipase affect the lipids are hydrolyzed into glycerol and carboxylic acids.

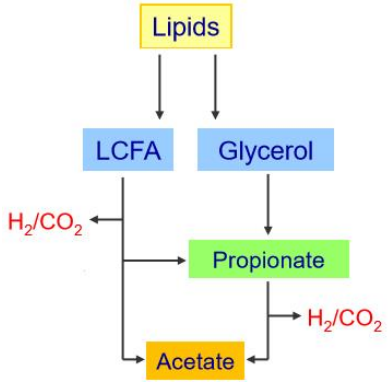

Figure 2: Lipids decomposition diagram

Proteins decomposition. Proteins are main nitrogenous waste in solid municipal waste, manure and sewage slag. These molecules have a relatively large surface area and are not soluble in water and do not precipitate. Proteins serve as a source of carbon and energy for bacterial growth in anaerobic reactors, and as a source of nitrogen from ammonia, which is released at hydrolysis.

Proteins hydrolyzed into amino acids with various extracellular proteases, ferments, which decompose peptide connection between amino acids in proteins. Proteins hydrolysis depends on solubility of protein and pH (Fig. 3).

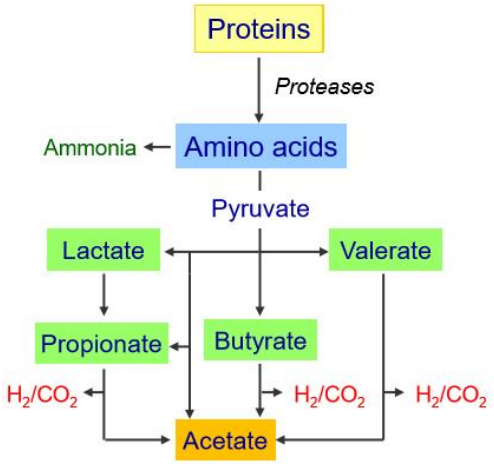

Figure 3: Proteins decomposition diagram

At fermentation of sugars, higher fatty acids and amino acids at the stage of acidogenesis an important intermediate element is acetate, which with participation of acid-forming bacteria at the stage of acetogenesis further decomposition with formation of organic acids and their salts, as well as alcohols and aldehydes takes place. These acids are oxidized and acetic acid is formed.

At this stage the types of acid-forming bacteria Acetobacter aceti and artificially bred Clostridium thermoaceticum are involved in enzyme production. To feed these bacteria they use sugar-containing raw material - glucose, which is formed during the first stage – hydrolysis.

$$C_6H_{12}O_6 + 2H_2O = 2CH_3COOH + 2CO_2. \quad (2)$$

At the last stage – methanogenesis, by using methane forming bacteria, methanogenic fermentation, which is the final bacterial transformation of organic substances with formation of methane and water, takes place. Methane creating bacteria are more sensitive to environmental conditions, than acid creating bacteria, they need a complete absence of oxygen.

$$CH_3COOH = CH_4 + CO_2; 4H_2 + CO_2 = CH_4 + 2H_2O. \quad (3)$$

These reactions occur simultaneously, moreover existence conditions of methane creating bacteria are much higher, than of acid creating bacteria. Speed and extent

of anaerobic fermentation of methane creating bacteria depend on their metabolic activity.

However existing chemical transformations do not allow to simulate the whole fermentation process and to determine in dynamics optimal conditions of its provision. And existing macro models, which are used for biogas modeling, describing substrate dependence in the form of MSOW, do not make it possible to manage this process.

Macro model of biogas production, based on measurements of the residual mass capacity, was considered in the work [11]. This model is recorded in the form of IDO [11]:

$$[\hat{v}_k^-; \hat{v}_k^+] = [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] - \frac{h \cdot [\hat{g}_1^-; \hat{g}_1^+] \cdot [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] \cdot (1 + h \cdot ([\hat{g}_2^-; \hat{g}_2^+][\hat{v}_{k-2}^-; \hat{v}_{k-2}^+] - [\hat{g}_3^-; \hat{g}_3^+]))}{[\hat{g}_4^-; \hat{g}_4^+] + [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+]}, \quad (4)$$

$$k=1,...,K,$$

where $[\hat{v}_k^-; \hat{v}_k^+]$ – valuation of guaranteed interval of the residual mass capacity of organic waste at k-moment of time; $[\hat{g}_i^-; \hat{g}_i^+]$ – interval estimation of parameters at i=1,. . . ,4.

It should be noted, that macro model in the form of (4) has several advantages, that is – it's not necessary to measure physical parameters of the substrate and to consider its inhomogeneity at BGP for its identification. Disadvantage of this model is that it does not describe biochemical processes balance at all stages. As a result – using this model does not allow organizing the process of anaerobic microbiological fermentation at BGP in a way, providing maximum biogas output. The way out of this situation can be the approach, at which for each stage of anaerobic microbiological fermentation of MSOW they build some macro models and on their basis provide a balance of products for each stage in a way to ensure maximum biogas output in general.

In view of the aforesaid, a macro model of initial stages of anaerobic microbiological fermentation – acidogenesis, the product of which is acetate, which accordingly is used by acid forming bacteria at the next fermentation stage, is considered in this work.

Let us consider mathematical formulation of this task.

Imagine, that for some fermentation process at the stage of acidogenesis at a given level of medium acidity pH the time parameters of acetate concentration at

biogas plant are known:

$$[\vec{V}^{-}; \vec{V}^{+}] = \begin{cases} [v_1^{-}; v_1^{+}]; \\ \vdots \\ [v_k^{-}; v_k^{+}]; \\ \vdots \\ [v_N^{-}; v_N^{+}], \end{cases} \tag{5}$$

where $[v_1^{-}; v_1^{+}]$ – lower and upper value of measured acetate concentration on k-time discrete.

It is necessary to build a mathematical model in the form of difference operator:

$$v_k = \vec{f}^{T}(v_0, ..., v_{k-1}) \cdot \vec{g}, \; k = p, ..., K, \tag{6}$$

where $\vec{f}^{T}(\bullet)$ - vector of unknown basis functions (known class), which defines the structure of difference operator; symbol $(\bullet)$ means a set of basic functions in the equation (6); v_k – acetate concentration in time discrete $k = p, ..., K$;
$\vec{g} = (g_1, ..., g_i)^T$ – vector of unknown parameters of difference operator.

It should be mentioned, that general view of difference operator (6) we will receive on the basis of experimental data analysis, presented in the interval form and received for limited number of time discrete under conditions of preset acidity of pH medium. Here with the valuation vector $\hat{\vec{g}}$ of parameters $\vec{g}$ and the vector of basic functions $\vec{f}^{T}(\bullet)$ in difference operator (6) we will receive from terms of ensuring the specified model accuracy:

$$[\hat{v}_k^{-}; \hat{v}_k^{+}] \subseteq [v_k^{-}; v_k^{+}], \forall k = 1, ..., K, \tag{7}$$

where $[\hat{v}_k^{-}; \hat{v}_k^{+}]$ - in formula (4) now and henceforth we will assume as interval valuations of foreseen acetate concentration in the substrate.

So, mathematical task of model parameters identification we write in the task form of interval system of nonlinear algebraic equations (ISNAE) solving [12]:

$$\begin{cases} [\hat{v}_0^{-}; \hat{v}_0^{+}] \subseteq [v_0^{-}; v_0^{+}], [\hat{v}_1^{-}; \hat{v}_1^{+}] \subseteq [v_1^{-}; v_1^{+}], ..., [\hat{v}_p^{-}; \hat{v}_p^{+}] \subseteq [v_p^{-}; v_p^{+}]; \\ [\hat{v}_k] = [\hat{v}_k^{-}; \hat{v}_k^{+}] = \vec{f}^{T}([\hat{v}_0^{-}; \hat{v}_0^{+}], ..., [\hat{v}_{k-1}^{-}; \hat{v}_{k-1}^{+}]) \cdot \hat{\vec{g}}; \\ v_k^{-} \le \vec{f}^{T}([\hat{v}_0^{-}; \hat{v}_0^{+}], ..., [\hat{v}_{k-1}^{-}; \hat{v}_{k-1}^{+}]) \cdot \hat{\vec{g}} \le v_k^{+}, k = p, ..., K, \end{cases} \tag{8}$$

where $[\hat{v}_0^{-}; \hat{v}_0^{+}]$, $[\hat{v}_p^{-}; \hat{v}_p^{+}]$ – interval valuations of acetate concentration in time discrete $k = 0$ and $k = p$ accordingly.

So, the task of IDO parameters identification for dynamics macro model of acetate concentration is a task of ISNAE solving (8). However, in general case, basic functions $\vec{f}^{T}(\bullet)$ are unknown, which leads to set structural IDO identification. The meaning of this task is in forming of sequences of IDO structures, which provide building of ISNAE in the form of (8). One of ISNAE (8) in sequence will be compatible, which means completion of IDO building procedure as follows:

$$[\hat{v}_k] = [\hat{v}_k^-; \hat{v}_k^+] = \vec{f}^{T}([\hat{v}_0^-; \hat{v}_0^+], ..., [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+]) \cdot \hat{\vec{g}}. \quad (9)$$

3. Dynamics model of acetate concentration of MSOW

Let us consider the process of biogas production on the first two stages (hydrolysis and acidogenesis) of anaerobic microbiological fermentation. The main output product of these stages is acetate, thanks to it continuation of fermentation process on the next stage – acetogenesis, and further on methanogenesis takes place.

In the example, provided in the work [13], the processes of anaerobic fermentation of MSOW are considered. All the experimental data were received by the authors under conditions of use of 5-liter reactor with periodic loads with initial capacity of substrate 3 dm^3. Speed of mixing was 400-600 rotations per minute.

They load in bioreactor MSOW, which have been collected from different factions of paper (Community Recycling Center, Champaign, IL) and food waste from several local restaurants and grocery stores, and combining of these components in the proportion 4 : 1. Wastepaper and paper packaging were crushed by using the industrial paper shredder (model AZ-15, ShredPax Corp., Chicago, IL), and food waste are mixed in a blender (model 91-215, Woring, New Hartford, CT). $NaHCO_3$ (3 g) and $NaOH$ (2 ml) were also added to the reactor, for control and increase of pH medium up to 7.2, since at substrate loading pH level was insufficient for the process of anaerobic fermentation. Seeds material for brewing pot consists of 500 ml of anaerobic sludge mix (75%) (Urbana & Champaign Sanitary District Sewage Treatment Plant) and cattle manure (25%) (Department of Agriculture, University of Illinois at Urbana–Champaign). Also 150 ml of distilled water was added. As result, working volume of the substrate was 3 l.

The fermentation process was studied from the beginning of downloading of MSOW during 50 days at temperature $[T_0^-; T_0^+] = [35; 37]\ ^oC$. Acetate concentration $[v_k^-; v_k^+]$ was measured daily. It's known, that instruments for concentration

measuring have precision of 5% . Therefore in the process of identification model it is necessary to realize terms, that interval valuations of projected acetate concentration value were within the limits of this error. Measurement results of acetate concentration for given technological factors (fermentation process temperature and medium acidity) are shown in the Table 1.

Table 1: Experimental data of acetate concentration dynamics during 50 days in the interval form

k	τ, day	$v_k^-, g/l$	$v_k^+, g/l$	**k**	τ, day	$v_k^-, g/l$	$v_k^+, g/l$
0	1	0.285	0.315	25	26	0.266	0.294
1	2	0.665	0.735	26	27	0.247	0.273
2	3	0.903	0.997	27	28	0.228	0.252
3	4	1.425	1.575	28	29	0.209	0.231
4	5	1.473	1.627	29	30	0.19	0.21
5	6	1.9	2.1	30	31	0.18	0.2
6	7	2.28	2.52	31	32	0.171	0.189
7	8	2.66	2.94	32	33	0.162	0.178
8	9	2.945	3.255	33	34	0.152	0.168
9	10	3.325	3.675	34	35	0.143	0.157
10	11	3.705	4.095	35	36	0.133	0.147
11	12	3.99	4.41	36	37	0.124	0.136
12	13	4.275	4.725	37	38	0.114	0.126
13	14	4.56	5.04	38	39	0.105	0.115
14	15	4.75	5.25	39	40	0.095	0.105
15	16	4.18	4.62	40	41	0.095	0.105
16	17	3.61	3.99	41	42	0.095	0.105
17	18	3.04	3.36	42	43	0.095	0.105
18	19	2.47	2.73	43	44	0.095	0.105
19	20	1.9	2.1	44	45	0.095	0.105
20	21	1.425	1.575	45	46	0.095	0.105
21	22	0.95	1.05	46	47	0.095	0.105
22	23	0.38	0.42	47	48	0.095	0.105
23	24	0.427	0.473	48	49	0.095	0.105
24	25	0.285	0.315	49	50	0.095	0.105

For synthesis of mathematical model of the process, first of all, it is necessary

to form a model structure - the stage of structure identification, then carry out the procedure of its parameters setup - the stage of parametric identification [14].

Let's solve a task of structure identification of dynamics macro model of acetate concentration at BGP on the stage of anaerobic fermentation process in the form of IDO, using these measurement results.

For solving this problem of IDO structure identification, a bee colony algorithm was offered in the work [15]. The bee colony algorithm models honey bees behavior in the search of nectar sources [14]. The idea of activity of algorithm of the bee colony is in optimization of some objective function, depending on the selected set of structure elements.

Let us consider the example of formation of objective function for given set of structure elements. First, we introduce a number of signs, necessary for disclosure of formal setting a task.

Let's mark current IDO structure as λ_s:

$$\lambda_s = \{f_1^s(\bullet) \cdot g_1^s; f_2^s(\bullet) \cdot g_2^s, ..., f_{m_s}^s(\bullet) \cdot g_{m_s}^s\} \subset \Lambda, \tag{10}$$

where $\vec{f^s} = \{f_1^s(\bullet), f_2^s(\bullet), ..., f_{m_s}^s(\bullet) \subset F\}$ is a set of structural elements, giving the current -structure of IDO.

Then let's introduce the following symbols: $m_s \in [I_{min}; I_{max}]$ – number of elements in the current structure λ_s; F – set of all structure elements,$F = \{f_1(\vec{v}_{k-1}), ..., f_L(\vec{v}_{k-1})\}$, where $|F| = L$ (set power F); $\vec{g}^s = \{g_s^1, g_s^2, ..., g_{m_s}^s\}$ – vector of unknown parameter's values, which for the current IDO structure will be valuated, basing on the methods of parametric identification, which are based on the procedures for random search [16]; Λ – set of all possible IDO structures.

The task of structure identification is in search of the structure λ_0 IDO in the form (10), formed on its basis of IDO:

$$[v_k^-; v_k^+] = [f_1^0(\bullet)] \cdot \hat{g}_1^0 + f_2^0(\bullet)] \cdot \hat{g}_2^0 + ... + f_{m_0}^0(\bullet)] \cdot \hat{g}_{m_0}^0, \tag{11}$$

would satisfy the conditions (7), that is provided appropriateness of interval valuations of projected value of modeled specifications to intervals of acceptable values of modeled specifications on the set of all discrete.

It should be noted, that parametric identification in this case is a stage of structure identification. As we know, in case, when parameters are set in the interval form, this stage means creation of some vector of basic functions (current structure λ_s of IDO) and finding valuations of IDO parameters by means of ISNAE solving [12]. However, instead of ISNAE solving (highly sophisticated calculating

task) they search some its approach to solution, which sets quality of current IDO structure λ_s. In this case the task of ISNAE solving takes the form of optimization task.

Thus, the quality of the current IDO structure shall be estimated by the value of objective function $\delta(\lambda_s)$, which quantitatively determines closeness of current structure to satisfactory one in the sense of providing conditions (7). Value objective function $\delta(\lambda_s)$ will be calculated by using the expression, received in the work [12], the form of which for fixed structure is as follows:

$$\delta(\lambda_s) = \max_{k=1,...,K}\{|mid(\vec{f}^{Ts}([\hat{v}_0],...,[\hat{v}_{k-1}])\hat{\vec{g}}^s) - mid([v_k])|\}; \tag{12}$$

$$\text{if } [\hat{v}_k] \cap [v_k] = \varnothing, \exists k = 1,...K,$$

$$\delta(\lambda_s) = \max_{k=1,...,K}\{|mid(\vec{f}^{Ts}([\hat{v}_0],...,[\hat{v}_{k-1}]) \cdot \hat{\vec{g}}^s) - wid(\vec{f}^{Ts}([\hat{v}_0],...,[\hat{v}_{k-1}]) \cdot \hat{\vec{g}}^s) \cap [v_k]|\}; \tag{13}$$

$$\text{if } [\hat{v}_k] \cap [v_k] = \varnothing, \forall k = 1,...K,$$

where $mid(\bullet)$, $wid(\bullet)$ - operations of determination of intervals center and width, accordingly.

Expression (11) describes «closeness» of current structure to satisfactory on the initial iterations, while the expression (12) in the case of $\delta(\lambda_s) = 0$ provides the condition implementation (10).

We should mention that objective function $\delta(\lambda_s)$ is discrete from $s = 1,...,S$ and has no representation in analytical form, and its value can be calculated only with numerical methods. Formulas (12) and (13) for calculation of objective function value, as «mismatch» between the corridors of interval valuations of foreseen specifications, based on IDO, and experimental valuations of these specifications on all discretes on l- iteration of search of the IDO parameters for fixed structure λ_s, is illustrated on Fig. 4.

As we see from the Fig.4 (a), in the first case (calculation by the formula (12)) interval valuations of foreseen specifications and those obtained from the experiment for discrete values k significantly deviate from each other. Besides, we see the largest deviation between intervals centers $[\hat{v}^-_{k=2}(l); \hat{v}^+_{k=2}(l)]$ and $[v^-_k; v^+_k]$ for discrete $k = 2$. This deviation module is the objective function value. As we see, one can suggest, that in this case of interval valuations of projected value of acetate concentration were received at inaccurate valuations of the parameters IDO (9).

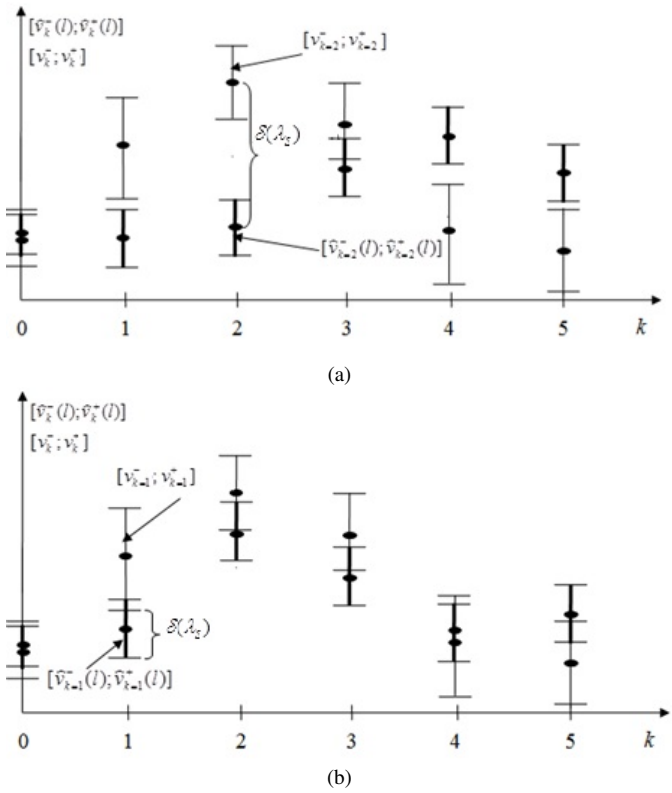

Figure 4: Illustration to objective function calculation: (*a*) by the formula (12) in case of valuation inaccurate approach of IDO parameters; (*b*) by the formula (13) in case of valuations rectification of IDO parameters

As we see from Fig.4 (*a*), interval valuations parameters IDO (9) in the process of random search procedure are specified, intersections of interval valuations of projected interval and intervals of these specifications, obtained from the experiment for each discrete become not empty multiplicities, as shown on the Fig.4 (*b*), then objective function is calculation by the formula (13).

From Fig.4 (*b*), the largest deviation (difference) is observed between the intervals $[\hat{v}^{-}_{k=1}(l); \hat{v}^{+}_{k=1}(l)]$ and $[v^{-}_{k}; v^{+}_{k}]$ and $[v^{-}_{k}; v^{+}_{k}]$ for discrete $k = 1$. This very difference, calculated by the formula (13), determines the value of objective function.

Now the task of structure identification IDO will be written formally in the

form of task of the minimum function finding $\delta(\lambda_s)$:

$$\delta(\lambda_s) \xrightarrow{\hat{\vec{g}}^s, \vec{f}^s(\bullet)} min, m_s \in [I_{min}; I_{max}], \vec{f}^s(\bullet) \in F. \quad (14)$$

From the expressions (12) and (13) we see, that for calculated value of objective function $\delta(\lambda_s)$ for fixed structure λ_s IDO under any circumstances in equation $\delta(\lambda_s) \geq 0$ will be right. So, we can state, that objective function $\delta(\lambda_s)$ has global extreme only in those points, for which the following equation is actual: $\delta(\lambda_s) = 0$. Based on the theory of the plurality of models [17], we can state, that in the space of task solutions search of structural identification of IDO function $\delta(\lambda_s)$ has many global minimums.

The lower value $\delta(\lambda_s)$ is, the «better» current IDO structure we have. If $\delta(\lambda_s) = 0$, then current IDO structure enables building of adequate model, for which interval valuations of foreseen specifications belong to intervals of possible values of modeled specifications.

Now we'll transfer to practical implementation of task of structure identification of dynamics macro model of acetate concentration at BGP.

First, basing on known features of acidogenesis process we'll generate a set of structure elements of macro model in the form of IDO. The results of this procedure are shown on the Table 2.

Table 2: The ranked set F of structure elements

N	Structure elements
1	v_{k-1}
2	v_{k-2}
3	$v_{k-1} \cdot v_{k-2}$
4	v_{k-1}^2
5	v_{k-2}^2
6	$v_{k-1}^2 \cdot v_{k-2}$
7	$v_{k-2}^2 \cdot v_{k-1}$
8	v_{k-1}^3
9	v_{k-1}^3

For synthesis of the structure IDO (9) by using the method of structure identification a multiplicity of structure elements F with capacity L=520 was generated. Multiplicity of structure elements includes polynomial functions, no higher than

the third degree. So, we'll search for IDO not higher than third order.

To implement the method of structure identification of IDO on algorithm basis of bee colony we set the following value [14]:

- MCN – maximum number of algorithm iterations;
- LIMIT – maximum possible number of iterations of structure «invariability», namely if the structure IDO did not give improvement for already LIMIT times, it is considered to be «exhaustive»;
- S – initial number of IDO structures;
- $[I_{min}; I_{max}]$ – interval, the limits of which set respectively minimum I_{min} and maximum I_{max} value of the potential quantity of structure elements in the structure of IDO λ_s;
- F – multiplicity of structure elements.

We set value parameters of the algorithm: MCN, LIMIT, S, $[I_{min}; I_{max}]$ and multiplicity of structure elements F. Then, we have formation of primary multiplicity of IDO structures Λ_0 (S capacity).

Based on the algorithm procedures of bee colony we shall consistently form new elements from the set of structure elements, building each time objective function and solving the task of minimization for the given set [15].

Considering given initial set of structure elements (Table 2) at each iteration with use of algorithm operators of bee colony (operator $P_b(\Lambda_{mcn}, F)$ means converting each structure λ_s^1 from the structures multiplicity Λ_{mcn}^1, of the first line of formation of generated on iteration of the algorithm *mcn*, in multiplicity of IDO structures $\Lambda_s^{'}$ (where $s = 1, ..., S$) in a way of random replace n_s of elements of each structure Λ_s^1, with the elements from multiplicity of structure elements F; operator $D_2(\lambda_s, \Lambda_s^{'})$ realizes the process of synthesis of multiplicity of IDO structures Λ_{mcn}^2 from the current multiplicities Λ_{mcn}^1 and $\Lambda_{mcn}^{''}$, in the manner of selection of IDO structures λ_s^2 due to quality parameters; operator $P_N(F, I_{min}, I_{max})$ means random generating of structure λ_s^2 from the multiplicity of all structure elements F, where number of structure elements – $m_s \in [I_{min}; I_{max}]$, we obtain sequence of structures, which at the end ensure compliance with the conditions (7) for all discrete values.

As a result of use of the algorithm of bee colony to solving a task (14) after 15 iterations of modifications ISNAE (8) we obtained IDO, which defines dynamics

of acetate concentration at BGP:

$$[\hat{v}_k^-; \hat{v}_k^+] = [0.53825; 0.54185] - [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] \cdot [0.036; 0.041] + [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] \times$$
$$\times [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] \cdot [1.01023; 1.02716] - [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] \cdot [\hat{v}_{k-1}^-; \hat{v}_{k-1}^+] \times \quad (15)$$
$$\times [\hat{v}_{k-2}^-; \hat{v}_{k-2}^+] \cdot [0.3096; 0.3218] \subset [v_k^-; v_k^+].$$

The obtained structure of difference operator and parameters adequately reflect the process of acidogenesis.

The forecasting results compared with experimental data of dynamics of acetate concentration of MSOW at $pH = 7.2$ is shown on the Fig. 5.

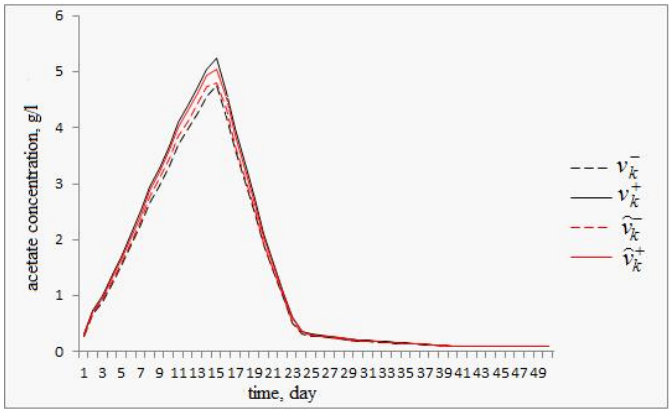

Figure 5: Dynamics corridor of acetate concentration of MSOW at $pH = 7.2$

From the Fig. 5, we can see the dynamics corridor of acetate concentration of MSOW is within the limits of experimental data corridor, providing adequate mathematical model.

Obtained model makes it possible to predict dynamics corridor of acetate concentration of MSOW at the stage of acidogenesis, which includes such influence factors as: environment temperature $[T^-; T^+] = [35; 37]\ ^oC$ and medium acidity $pH = 7.2$. So, using the model, we can provide at this stage optimal dynamics of acetate concentration, which, in its turn, will determine the optimum development of micro organisms population, that is acid-forming bacteria on the next stage of anaerobic microbiological fermentation. To use the obtained macro model, with the purpose to predict dynamics of acetate concentration in the substrate at change of medium acidity of fermentation, it's enough to set just the initial parameters for these conditions.

Test parameters of acetate concentration dynamics to test the adequacy of the proposed macro model were obtained from the work [18] for such values of medium acidity of fermentation: $pH_1 = 6.9$ and $pH_2 = 7.5$. The results of the comparison are shown on the Fig. 6 and Fig. 7 respectively.

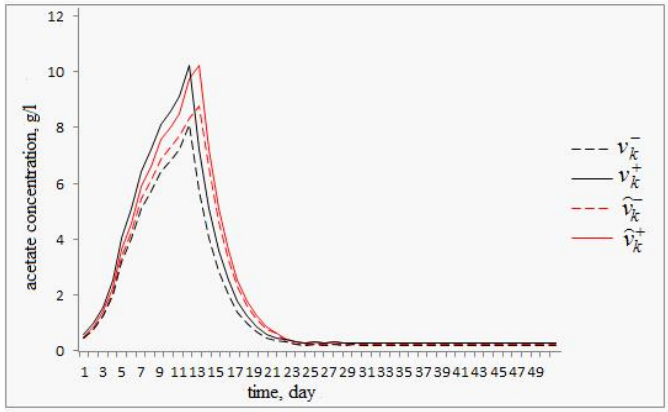

Figure 6: Dynamics corridor of acetate concentration of MSOW at $pH = 6.9$

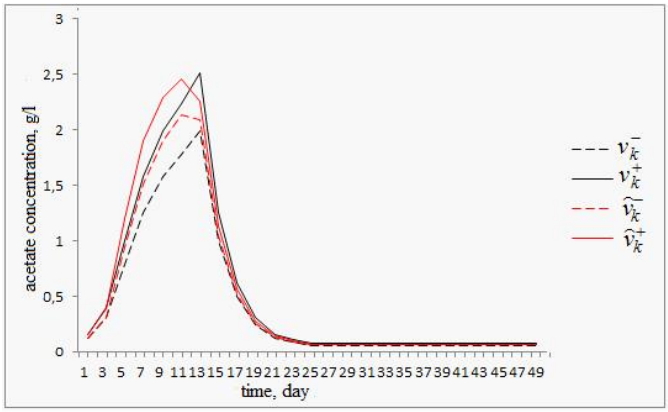

Figure 7: Dynamics corridor of acetate concentration of MSOW at $pH = 7.5$

As we can see, obtained macro model of acetate concentration dynamics at BGP is adequate, since the acidogenesis processes are shown on Fig. 6 and Fig. 7 match qualitatively due to test and predicted results.

Small differences in dynamics of projected and test process can be compensated in the manner of transition from non-autonomous to autonomous model of acetate concentration dynamics in the substrate by introducing additional factor in this model – medium acidity of anaerobic microbiological fermentation, which is the subject of further research.

4. Conclusions

1. In this work the task of modeling processes of anaerobic microbiological fermentation with keeping the balance on the stages of hydrolysis and acidogenesis was considered. It was proposed and justified to build the model at the stage of acidogenesis in the form of interval difference operator.

2. The structure identification method of IDO on the principles of honey bee colony functioning in the food search process, which provides the possibility of obtaining simple IDO structures with specified prognostic properties relative to existing methods, was substantiated. Efficiency of use of the proposed method and its computing scheme was illustrated on the example of building a model of the process of anaerobic microbiological fermentation of MSOW at BGP with the capacity 5 dm^3 at the stage of acidogenesis.

3. The macro model of fermentation process at the stage of acidogenesis (9) based on IDO, providing guaranteed prognostic properties for different conditions of anaerobic microbiological fermentation, by changing of medium acidity, was received for the first time.

4. It was shown, that received model qualitatively and adequately describes dynamics of acetate concentration at change of medium acidity of anaerobic microbiological fermentation. The maximum difference between prediction corridors and test corridors amounts about 5% . Small differences between dynamics of foreseen acetate concentration at BGP and test data can be compensated through transition from autonomous macro model in the form of IDO (15) to non-autonomous one with controlled «medium acidity» factor of anaerobic microbiological fermentation, which is the subject of further research.

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