PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

CRIAÇÃO DO MODELO MATEMÁTICO DE COMPUTADOR DO PROCESSO BIOTECNOLÓGICO DO PROCESSAMENTO DE MATÉRIAS-PRIMAS

CREATION OF A COMPUTER-ASSISTED MATHEMATICAL MODEL FOR THE RAW MATERIALS BIOLOGICAL PROCESSING

СОЗДАНИЕ КОМПЬЮТЕРНОЙ МАТЕМАТИЧЕСКОЙ МОДЕЛИ БИОТЕХНОЛОГИЧЕСКОГО ПРОЦЕССА ОБРАБОТКИ СЫРЬЯ

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RESUMO

No processo de digestão anaeróbica, a alternância de substâncias líquidas e sólidas na composição do substrato faz com que as bactérias se adaptem às condições variáveis, o que reduz significativamente a emissão de biogás e a concentração de metano, bem como aumenta o tempo de presença do substrato no biorreator. A solução para esse problema ao usar a destruição de cavitação pode não apenas minimizar a heterogeneidade da temperatura, mas também resolver o problema da mesma carga na biocenose e na superfície de contato máxima das bactérias durante a digestão anaeróbica no biorreator. As pesquisas realizadas mostraram que a composição e quantidade de biogás não são constantes e dependem do tipo de substrato que está sendo processado e da tecnologia de produção de biogás. Para estabilizar a composição do biogás resultante e torná-lo em uma fonte de energia alternativa independente e de alta qualidade, é possível usar a destruição da membrana ou a moagem de matérias-primas orgânicas. O consumo de energia, o tempo de fermentação e a concentração de metano na produção final de biogás dependem do tratamento primário. No presente artigo, propõe-se um modelo matemático do processo de moagem, dispersão e homogeneização de resíduos de fazendas leiteiras e de engorda, que permite determinar e otimizar seus parâmetros operacionais, bem como promover a digestão anaeróbica eficaz do substrato no biorreator. Para determinar o modelo matemático do processo biotecnológico de processamento de matérias-primas com parâmetros teóricos ou experimentais conhecidos, foram utilizados os métodos numéricos, que são uma das poderosas ferramentas matemáticas para solucionar o problema. Os resultados dos parâmetros operacionais dos processos estudados foram obtidos no ambiente Mathcad e testados no pacote de software de controle e monitoramento automatizado SCADATraceMode 6.10.1.

Palavras-chave: *usina de biogás, destruição de cavitação, regressão hiperbólica.*

ABSTRACT

During anaerobic fermentation, the alternation of liquid and solid substances in the substrate makes the bacteria adapt to changing conditions, which significantly reduces the biogas yield, reduces the methane concentration in it, and increases the retention time of the substrate in the bioreactor. The solution to this problem when using cavitation destruction can not only minimize temperature nonuniformity but also solve the problem of the same load on the biocenosis and maximum contact surface of bacteria during anaerobic fermentation in the bioreactor. Studies have shown that the composition and quantity of biogas are not constant and depend on the type of substrate being processed and the biogas production technology. To stabilize the composition of the resulting biogas and bring it to a high-quality, independent alternative energy source, it is possible using membrane destruction or crushing of organic raw materials. The energy consumption, fermentation time, and methane concentration in the final biogas output depend on the primary treatment. This work proposes a

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mathematical model of the process of crushing, dispersing, and blending waste from dairy and fattening farms, which allows to determine and optimize its operating parameters, as well as to promote effective anaerobic fermentation of the substrate in the bioreactor. To determine the mathematical model for the raw materials biological processing with known theoretical or experimental parameters, numerical methods were used, which are one of the powerful mathematical tools for solving the problem. The results of the operational parameters of the studied processes were obtained using the Mathcad environment and tested in the SCADA Trace Mode 6.10.1 automated process control and monitoring software package.

Keywords: *biogas unit, cavitation destruction, hyperbolic regression.*

АННОТАЦИЯ

В процессе анаэробного сбраживания чередование жидких и твердых веществ в составе субстрата заставляют бактерии приспосабливаться к меняющимся условиям, что значительно сокращает выход биогаза, снижают концентрацию метана в нем и увеличивает срок пребывания субстрата в биореакторе. Решение данной проблемы при применении кавитационной деструкции позволяет не только свести к минимуму температурную неоднородность, но и решить вопрос одинаковой нагрузки на биоценоз и максимальную поверхность контакта бактерий во время анаэробного сбраживания в биореакторе. Проведенные исследования показали, что состав и количество биогаза не являются постоянными и зависят от вида перерабатываемого субстрата и технологии производства биогаза. Для стабилизации состава получаемого биогаза и доведение его до качественного, самостоятельного альтернативного источника энергии возможно при использовании мембранной деструкции или измельчении органического сырья. От первичной обработки зависят энергозатраты, время брожения и концентрация метана в конечном выходе биогаза. В статье предложена математическая модель процесса измельчения, диспергации и гомогонизации отходов молочно-товарных и откормочных ферм, позволяющая определить и оптимизировать его режимные параметры, а также способствовать эффективному анаэробному сбраживанию субстрата в биореакторе. Для определения математической модели процесса биотехнологического процесса обработки сырья при известных теоретических или экспериментальных параметрах использовали численные методы, которые являются одним из мощных математических средств решения задачи. Результаты режимных параметров исследуемых процессов были получены с использованием среды Mathcad и протестированы в программном комплексе автоматизированного управления и контроля за технологическими процессами SCADATraceMode 6.10.1.

Ключевые слова: *биогазовая установка, кавитационная деструкция, гиперболическая регрессия*.

1. INTRODUCTION

There are works of domestic and foreign scientists, as well as specialists in the field of intensification of anaerobic fermentation of cattle excrement in biogas units, their degree of automation, and control: S. D. Durdybaev, Yu. N. Sidyganov, V. Baader, B. Eder, E.S. Pantskhava, V. P. Druzianova, V. I. Marchenko, E. Hashimoto, A. G. Kudryashova, L. I. Ruzhinskaya, I. A. Trakhunova, E. K. Vachagina, V. A. Ivanov (Akhnazarova and Kafarov, 1985; Druzyanova, 2008; Eder and Schulz, 2011; Kudryashova, 2011; Ivanov and Gasparyan, 2013; Ruzhinskaya and Fomenkova, 2014; Tlebayev *et al*., 2017; Butova *et al*., 2018). These authors noted that during anaerobic fermentation, the alternation of liquid and solid substances in the substrate makes the bacteria adapt to changing conditions, which significantly reduces the biogas yield, reduces the methane concentration in it, and increases the retention time of the substrate in the bioreactor (Biogas manual…, 2010; Dong *et al*., 2018; Kusuma *et al*., 2019).

In animal waste, there are various solid particles, such as sand, clay, *et al*., which cause the formation of sediment, while light materials like straw and others rise to the surface of the bioreactor and form a crust, which leads to a decrease in gas formation (Koller *et al*., 2017; Zagorulko *et al*., 2018; Sokolova *et al*., 2018; Iskakov *et al*., 2019; Kudrin *et al*., 2019; Popov *et al*., 2019). Therefore, plant residues (straw, scraps and others) must be crushed before loading into the reactor, and it is necessary to strive for the absence of solids in the raw materials (Sidyganov *et al*., 2008; Golubtsova, 2017). To eliminate the problem, Figure 1 presents a developed primary treatment system for cavitation destruction of cattle excrement and anaerobic fermentation in a psychrophilic (are extremophilic organisms that are capable of growth and reproduction in low temperatures) mode (Dotsenko *et al*., 2017; Kulbjakina and Dolotovskij, 2018; Chandra *et al*., 2019).

The main goal of the raw materials processing unit mathematical modeling is to determine the optimal conditions for the process, to control it on the basis of a mathematical model, and transfer the results to a real object in the Birlik-Tuimekent SEC.

Liquid raw materials (cattle manure) 2 weighing 600 liters, humidity 80-85% enters tank 1, where it mixes with water at room temperature, in a ratio of 1:1, to a moisture content of 92%. From the tank 1, the raw material enters through the pipe 3, with the help of the pump 4, into the spiral separator 5, where large particles of the raw material are crushed. Next, the pre-crushed biomass enters the tank 6. Entering the macerator 9, solid particles are crushed, and heavy impurities are simultaneously separated. Further, the gerotor type pump 10 breaks the long fibrous inclusions present in the biomass, pumping the substrate into the dispersing agent 11, which exposes the composition of the substrate to destruction and creates a homogeneous mixture. While the biomass is in the tank 6, an automatic mixer 7 periodically mixes it. During crushing of the biomass in the tank 6, biogas enriched in $CO_2$is released and removed through the pipe 13. When the required size of crushing is reached, the lower valve 12 is closed, and the upper valve 12 is opened, where the crushed substrate pumped into the bioreactor of the second stage of the biogas unit.

The biogas unit (BGU) effectiveness is greatly influenced by the preliminary preparation of the initial substrate. The smaller the particle sizes of the organic feedstock components, the greater their specific surface area and, accordingly, the fermentation processes occur more intensively. When analyzing literary sources, as articles by I. V. Meshcheryakov, “Development and research of a multistage hydro-percussion and cavitation device for fine crushing of complex ores” and A.T. Zhumagazhinov, N.K. Algazinov “Methods of intensification of the anaerobic fermentation processes” (Meshcheryakov, 2014; Kiss et al., 2015; Vachagina and Karaeva, 2009; Zhumagazhinov and Algazinov, 2014; Trakhunova, 2014), a table of the relationship between the destruction efficiency and performance was compiled (Table 1).

2. MATERIALS AND METHODS

To determine the mathematical model for the raw materials biological processing with known theoretical or experimental parameters, numerical methods were used, which are one of the powerful mathematical tools for solving the problem.

To find the Equation 4, the approximation method was used in the work. Approximation allows us to study the numerical characteristics and qualitative properties of an object, reducing the problem to the study of simpler or more convenient objects (for example, characteristics of which are easily calculated or whose properties are already known).

To find the function in work, the approximation approach was used. At the initial stage, it was compiled a table of auxiliary quantities (Table 2).

To verify the found function was used, a computer experiment method implemented through the Scada Trace Mode automated process control and monitoring system. At the same time, to implement the full software package, all possible programming methods were used—namely, the creation of modules in different programming languages of the International Electrotechnical Commission 6-1131/3 standard. Firstly, as the fundamental programming languages of this standard, the Tehno Structured Text (a high-level programming language similar to Pascal) and the Tehno Instruction List (the simplest mnemonic instruction language that looks like assembly), as well as the Tehno Function Block Diagram visual languages (is a diagram consisting of a set of functional blocks interconnected via inputs and outputs), Techno Sequential Function Chart (a tool for structuring complex algorithms), Techno Ladder Diagram (ladder logic diagrams).

3. RESULTS AND DISCUSSION:

In domestic and foreign practices are increasingly being used energy supply systems for agricultural enterprises using an alternative energy source - biogas. Biogas is formed as a result of anaerobic fermentation of organic substances when waste is processed, and highly effective biofertilizers are obtained. It also solves the environmental and agrobiological problems of agricultural enterprises. For the production of biogas, bioreactors are widely used. In most countries of the world, biogas technologies have become the standard for the processing of biowaste in order to obtain additional raw materials and energy resources. The need to increase the energy efficiency of a biogas plant is due to the large energy consumption for the technological needs of the equipment. According to the classification presented in the article, the main instruments in the technological scheme of the processing of organic raw materials are a mixing tank, a macerator, a gerotor pump, a cavitation destructor, which largely determines the effectiveness of the technology as a whole. A promising measure to increase the energy efficiency of methane fermentation technology is the availability of primary processing of raw materials.

The data from Table 1 point that after the 6th cycle, the values of the change in the size of the initial particles are minimal, less than 10 microns; it was considered the 6th cycle to be inappropriate.

It was calculated the a and b coefficients for the hyperbolic regression equation (Equation1). According to the well-known equations (Equations 2-3) (Akhnazarova and Kafarov, 1985). In sum, the desired regression equation has the form (Equation 4). Where x is the number of passes, and y is the particle size of the crushed mixture after the x-th pass.

Let’s analyze the graph of the regression equation using the Mathcad program (Figure 2). In this connection, the index of correlation (Equation 5). And the determination index: $R^2 = 0.9725^2 \approx 0.9457$. Analyzing the graph, it could be concluded that equation (4) describes the crushing process only up to x <= 4 or before crushing at 14 microns. With large crushing, the error of approximation increases, and the data becomes incorrect.

To find the function that describes the crushing process after about 14 microns, the Trendline function in Excel was used (Figure 3). The average error of approximation (Equation 6). Moreover, the average approximation error is 17.89%, which indicates a good “fit” of the obtained function to the parameters under study. It was simulated this function in Mathcad (Figure 4).

Further, the organic raw materials processing (crushing) can be described by the system of equations (Equation 7). This equation describes the grinding process, where x is the number of passes of the processing of organic raw materials, f(x) is the size of the particles of the crushed mixture after the x pass, while the first equation is applicable for large grinding, and the second describes the grinding process after about 14 microns.

Find the intersection point of the graphs to determine the conditions of the system (Figure 5). Figure 5 shows that the graphs intersect at x = 3.7282, y = 18.184. Rounding off the values to integers, a system of equations with limitations was obtained (Equation 8).

To display the general equation of the processing of the raw materials through the preferred parameters (processing time and loading volume), the equation for the processing time was derived, so the number of cycles necessary to complete in one pass is defined as (Equation 9). Where V_{vol} is the volume of loaded raw material (l), the parameter V_{pip} is the total volume of the system pipes (V_{vol}=4.69).

Processing time in one pass is calculated as (Equation 10). Where $T_ц$ is the total execution time of one cycle (T_{cycl}=9.61). Further, the total runtime of the processing of the raw materials can be represented in the form (Equations 11-12).

Using the static parameters of the system was obtained (Equations 13-14). It was substituted the obtained value of X into the system of equations, general expression (Equation 15). For a given system (Equation 16), having simplified was obtained (Equation 17).

The time required to crush a given value (micron) can be calculated by a function in a general form (Equation 18). For a given system for organic raw materials processing (Equation 19), where V is the volume of the loaded raw material (l), L is the desired output size (microns), $T_{об}$ which is the required time to complete the process (sec).

For finer crushing, you should use the second function of the system, in general, the function of finding the processing time will have a form (Equation 20). Where: V_{vol} is the volume of loaded raw material (l); T_{cycl}– the total execution time of one cycle ($T_ц$=9.61); L is the desired output size (microns);V_{pip}– the volume of the pipe system; $\mathrm{T}_{об}$ – the required time to complete the process (sec).

Substituting the parameter values was obtained (Equation 21). Thus, the system of equations for finding the processing time in a general form can be represented as (Equation 22) for the studied processing system as (Equation 23). It was constructed the resulting system of equations in Mathcad (Figure 6).

The increase in the degree of decomposition is proportional to the increase in the active surface of the organic substance involved in the process of methane formation and has a substantially nonlinear character, which makes it possible to use this effect to intensify gas escape in biogas technologies.

The use of cavitation destructors can significantly reduce the time of raw materials pretreatment, due to the effect of the destruction of the membrane of raw materials particles. Cavitation destructor allows us to use the destructive effect of cavitation to give the feedstock a homogeneous mass. Under the influence of directed and controlled cavitation in the biological raw materials, complex bonds of the fibers of organic substances at the molecular level (lignin, cellulose) are breaking. As a consequence of this process, the dispersion of biological raw materials is significantly increased, and its particles are reduced in size to 0.1 - 8 microns. Thus, it becomes easier for all bacterial strains involved in the biogas formation at all its stages to decompose biogenic materials, because their homogeneous structure is destroyed and, accordingly, the area covered by bacteria of biological raw materials increases. (Obolensky and Kraynov, 2012). All these factors contribute to improving energy efficiency and reducing equipment wearing.

Of course, even the most complex models are not yet able to describe all the existing relationships, reflect the whole variety of behavior of complex agrobiological systems in various situations. However, the obtained equations are able to describe the process of crushing dispersion and homogenization of the substrate for an optimal control system, the regime of periodic loading of a new portion of raw materials, and the temperature regime of the fermentation in the capacity of the psychrophilic regime, while saving energy (Yudaev *et al*., 2019; Barisa *et al*., 2020).

To analyze the resulting mathematical model, a computer experiment was conducted in the Scada Trace Mode. Trace Mode consists of an instrumental system and a set of executive modules (runtimes). Using the Trace Mode executive modules, the project of the automated control system is launched for execution in real-time at the workplace by dispatcher or operator. If we need to organize communication between Trace Mode and Arduino, we can use the modbus-rtu protocol and connect the converter to RS – 485 or RS-232.

An automated system for controlling the technological processes of organic raw material recycling is a form divided into four logical zones (Figure 7):

1. A graphical representation of the raw materials processing unit structural elements.

2. Parameters and schedule for raw materials crushing.

3. Calculation of indicators for heating raw materials at a psychrophilic mode.

4. Calculation of the CO_2 concentration at the outlet.

As a reference plan for the experiment, a matrix of initial and final parameter values will be created (Zhumagazhinov and Algazinov, 2014). To identify the relationship between the particle size at the outlet and the concentration of biogas, it was assumed that (Table 3):

– the volume of loaded raw materials;

– the volume of the pipes of the raw materials processing unit;

– the initial temperature of raw materials;

– the desired temperature of the raw material, there are constant values, and only the desired particle size at the outlet changes.

Thus, when entering the initial parameters, the system calculates the outlet parameters (Figure 8). Similarly, all other experiments will be conducted. After conducting the experiments, the data obtained was analyzed (Table 4).

As can be seen from the graph (Figure 9), with a decrease in particles, methane yield (CH_4) increases, and the percentage of carbon dioxide (CO_2) decreases. However, it can be seen that after particle crushing by less than 10 microns, the methane increase is insignificant, but the processing time of the raw materials increases and, consequently, the financial costs and equipment wear increase (Figure 10).

Thus, particles of a fraction of 10 μm will be the main ones for biogas production and will have a high level of flotation; smaller particles make a small contribution to the formation of methane and are prone to precipitation. This confirms the previously obtained assumption, based on the values of Table 1, about the inappropriateness of processing raw materials of more than 10 microns.

In a production environment, in addition to the main set of factors studied using a computer experiment, process indicators are influenced by many factors that are difficult or impossible to control. This leads to the fact that the optimal conditions found through a computer experiment are often not reproduced in industry. In this regard, it is necessary to periodically conduct an experiment directly at an industrial facility to refine and control the initial parameters.

The mathematical modeling of the process of animal waste crushing using cavitation destruction consists of three interrelated stages:

– compilation of a mathematical description of the raw materials processing unit;

– the choice of a solution method of the system of equations of mathematical description and its implementation in the form of a modeling program;

– establishing conformity (adequacy) of the raw materials processing unit model of pilot industrial biogas technology at the facility in the Birlik – Tuimekent SEC;

– at the stage of compiling the mathematical description, the main factors and parameters in the raw materials processing unit are identified, and then the relationships between them are established. Further, for each selected parameter and factor, a system of equations reflecting its functioning and the equations of connection between them was wrote;

– at the stage of choosing a solution method and developing a modeling program. The system of nonlinear equations was solved in the Mathcad environment, which was distinguished by the speed of obtaining and accuracy of the solution and its implementation first in the form of a solution algorithm, and then in the form of a program suitable for computer calculation;

– at the stage of testing the mathematical model, a computer experiment was conducted in the TRACE MODE tool system;

– the raw materials processing unit model built on the basis of physical concepts qualitatively and quantitatively describes the properties of the simulated process and is adequate to the real object in the Birlik – Tuimekent SEC;

– at the stage of checking the adequacy of the mathematical model for the real process, the results of measurements at the Birlik – Tuimekent SEC were compared with the calculation results obtained from the mathematical model and mathematical modeling.

In this article:

1. The physical and chemical foundations of the process of biogas production during anaerobic solid waste fermentation were considered;

2. The component parts of the organic raw materials processing unit were examined;

3. Literary sources were analyzed using numerical methods of data processing, and a mathematical model was obtained for the process of organic raw materials primary procession.

4. A visual model of the biomass grinding process was built;

5. The parameters of heating the substrate to the parameters of the psychrophilic temperature regime were considered;

6. The equation for determining the percentage of biogas concentration was calculated;

7. The optimal time of biomass processing to the required size was calculated with the modified parameters of the modernized system;

8. An automated process control system was developed based on the received data;

9. A computer experiment was conducted to identify the optimal working parameters of the biogas plant.

4. CONCLUSIONS:

The greening of all production processes today is quite relevant. Therefore, in the article, a computer-assisted mathematical model for the raw materials biological processing was created. To analyse the resulting mathematical model, a computer experiment was conducted in the Scada Trace Mode system.

It was established that particles of the 10 μm fraction will be key for biogas production, since they have a high level of flotation, smaller particles make a small contribution to the formation of methane and are prone to precipitation.

It has been demonstrated that the use of cavitation destruction can significantly reduce the volume of natural organic raw materials and destroy intercellular membranes, thereby use plant fibers most efficiently, significantly increase the speed and depth of extraction of raw materials, as well as its subsequent period of fermentation. And the use of modern automation systems for production processes, such as ScadaTraceMode and others, allows us to save time and technological resources, to avoid equipment deterioration during the experiment.

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$$y = a + \frac{b}{x} \quad \text{(Eq. 1)}$$

$$b = \frac{n\sum \frac{y_i}{x_i} - \sum \frac{1}{x_i} \sum y_i}{n\sum \frac{1}{x_i^2} - \left(\sum \frac{1}{x_i}\right)^2} = \frac{6 \cdot 234.721 - 2.45 \cdot 295.71}{6 \cdot 1.49138889 - 2.45^2} \approx 232.1369 \quad \text{(Eq. 2)}$$

$$a = \frac{1}{n}\sum y_i - \frac{b}{n}\sum \frac{1}{x_i} = \frac{1}{6} \cdot 295.71 - \frac{232.1369}{6} \cdot 2.45 \approx -45.5042 \quad \text{(Eq. 3)}$$

$$y = -45.5042 + \frac{232.1369}{x} \quad \text{(Eq. 4)}$$

$$R = \sqrt{1 - \frac{\sum (y_i - y_i)^2}{\sum (y_i - \bar{y}_i)^2}} = \sqrt{1 - \frac{1519.4042}{27976.6806}} \approx 0.9725 \quad \text{(Eq. 5)}$$

$$\overline{A} = \frac{1}{n}\sum \left| \frac{y_i - y_i}{y_i} \right| \cdot 100\% = \frac{4.033}{6} \cdot 100\% \approx 67.2172\% \quad \text{(Eq. 6)}$$

$$\begin{cases} f(x) = -45.5042 + \dfrac{232.1369}{x} \\ f(x) = 161.11x^{-1.705} \end{cases} \quad \text{(Eq. 7)}$$

$$\begin{cases} f(x) = -45.5042 + \dfrac{232.1369}{x}, x < 4(f(x) \geq 18) \\ f(x) = 161.11x^{-1.705}, x > 3(f(x) < 18) \end{cases} \quad \text{(Eq. 8)}$$

$$N = \frac{V_{vol}}{V_{pip}} \quad \text{(Eq. 9)}$$

$$T_{vol} = N \cdot T_{cycl} \quad \text{(Eq. 10)}$$

$$T_{cycl} = \frac{V_{vol}}{V_{pip}} \cdot T_{cycl} \cdot x \quad \text{(Eq. 11)}$$

$$X = \frac{T_{vol} \cdot V_{pip}}{V_{vol} \cdot T_{cycl}} \quad \text{(Eq. 12)}$$

$$T_{vol} = \frac{V_{vol}}{4.69} \cdot 9.61 \cdot x = 2.049 \cdot V \cdot x \quad \text{(Eq. 13)}$$

$$= \frac{T_{vol}}{2.049 \cdot V} = 0.49 \cdot \frac{T_{vol}}{V_{vol}} \quad \text{(Eq. 14)}$$

$$\begin{cases} f(x) = -45.5042 + \dfrac{232.1369 \cdot V_{vol} \cdot T_{cycl}}{V_{pip} \cdot T_{vol}}, x \leq 4(x \geq 18\, microns) \\ f(x) = 161.11 \cdot \left(\dfrac{V_{pip} \cdot T_{vol}}{V_{vol} \cdot T_{cycl}}\right), x > 4(x < 18\, microns) \end{cases} \quad \text{(Eq. 15)}$$

$$\begin{cases} f(x) = -45.5042 + \dfrac{232.1369 \cdot V}{0.49 \cdot T_{vol}}, x \leq 4(x \geq 18\, microns) \\ f(x) = 161.11 \cdot \left(\dfrac{2.04 \cdot V_{vol}}{T_{vol}}\right), x > 4(x < 18\, microns) \end{cases} \quad \text{(Eq. 16)}$$

$$\begin{cases} f(x) = -45.5042 + 475 \cdot \dfrac{V}{T_{vol}}, x \leq 4(x \geq 18\, microns) \\ f(x) = 543 \cdot \left(\dfrac{V_{vol}}{T_{vol}}\right)^{1.705}, x > 4(x < 18\, microns) \end{cases} \quad \text{(Eq. 17)}$$

$$T_{vol} = \frac{233.1369 \cdot V_{vol} \cdot T_{cycl}}{L + 45.5042} \quad \text{(Eq. 18)}$$

$$T_{vol} = \frac{475 \cdot V}{L + 45.5042} \quad \text{(Eq. 19)}$$

$$T_{vol} = \left(\frac{161.11 \cdot V_{vol}^{-1.705} \cdot T_{cycl}^{1.705}}{L \cdot V_{pip}^{1.705}}\right)^{0.59} \quad \text{(Eq. 20)}$$

$$T_{vol} = \left(\frac{543.67 \cdot V_{vol}^{-1.705}}{L}\right)^{0.59} \quad \text{(Eq. 21)}$$

$$\begin{cases} T_{vol} = \dfrac{233.1369 \cdot V_{vol} \cdot T_{cycl}}{L + 45.5042}, x \leq 4(x \geq 18\, microns) \\ T_{vol} = \left(\dfrac{161.11 \cdot V_{vol}^{1.705} \cdot T_{cycl}^{1.705}}{L \cdot V_{pip}^{1.705}}\right)^{0.59}, x > 4(x < 18\, microns) \end{cases} \quad \text{(Eq. 22)}$$

$$\begin{cases} T_{vol} = \frac{475 \cdot V}{L+45.5042}, x \leq 4 (x \geq 18\ microns) \\ T_{vol} = \left(\frac{543.67 \cdot V_{vol}^{1.705} {}_{*} \cdot T_{cycl}^{1.705}}{L} \right)^{0.59}, x > 4 (x < 18\ microns) \end{cases} \quad \text{(Eq. 23)}$$

Table 1. *The relationship between destruction efficiency* and *performance*

Cycle No.	I (destruction efficiency)	D(destruction size) micron	Q(dispersing agent performance) m^3/h
1	-	200	8.547
2	4.74	42.19	9.048
3	2.17	19.44	9.426
4	1.47	13.22	10.148
5	1.21	10.93	11.687
6	1.1	9.93	12.348

Table 2. *Auxiliary quantities*

I	x_i	y_i	$\frac{1}{x_i}$	$\frac{1}{x_{2i}}$	$\frac{y_i}{x_i}$
1	1	200	1	1	200
2	2	42.19	0.5	0.25	21.095
3	3	19.44	0.33333333	0.11111111	6.48
4	4	13.22	0.25	0.0625	3.305
5	5	10.93	0.2	0.04	2.186
6	6	9.93	0.16666667	0.02777778	1.655
∑∑	21	295.71	2.45	1.49138889	234.721

Table 3. *The matrix of initial values of the experiment*

Parameter	Experiment number N							
	1	2	3	4	5	6	7	8
volume of loaded raw materials	600	600	600	600	600	600	600	600
desired particle size at the outlet	2000	1000	200	100	50	20	10	5
the volume of the pipes of the raw materials processing unit	5	5	5	5	5	5	5	5
heating element power	50	50	50	50	50	50	50	50
initial temperature of raw materials	10	10	10	10	10	10	10	10
desired temperature of the raw material	25	25	25	25	25	25	25	25

Table 4. *The dependence of the selected parameters*

Parameter	Experiment number N							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
desired particle size at the outlet	2000	1000	200	100	50	20	10	5
time of raw materials crushing	10 min	21 min	1.31	2.33	3.54	5.42	6.43	7.23
methane content	22.92	32.92	53.36	61.1	68.26	76.91	82.17	84.43
carbon dioxide content	77.07	67.07	46.63	38.9	31.74	23.08	17.10	15.57

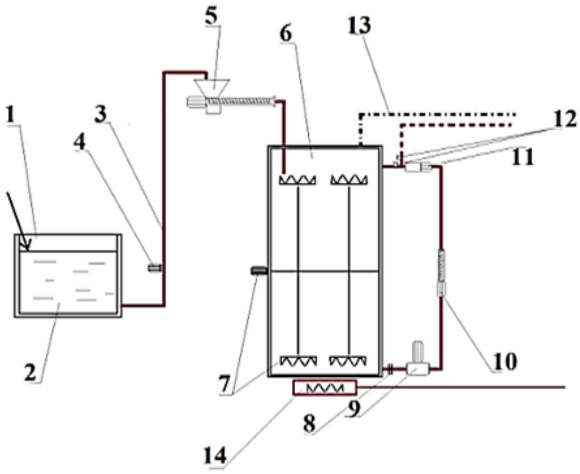

Figure 1. *Processing line of nodes for cavitation destruction of animal waste* and *anaerobic fermentation in a psychrophilic mode: 1 – a tank for mixing cattle manure with water; 2 – liquid manure; 3 – 57 mm pipe; 4 – pump for transferring liquid manure into the inducer; 5 – spiral separator; 6 – facility for temporary storage, crushing* and *fermentation of biomass; 7 – automatic mixer; 8 – coupling; 9 – macerator; 10 – gerotor type pump; 11 – dispersing agent; 12 – valves that regulate the direction of the substrate; 13 – biogas outlet pipe; 14 – boiler for heating the tank (6)*

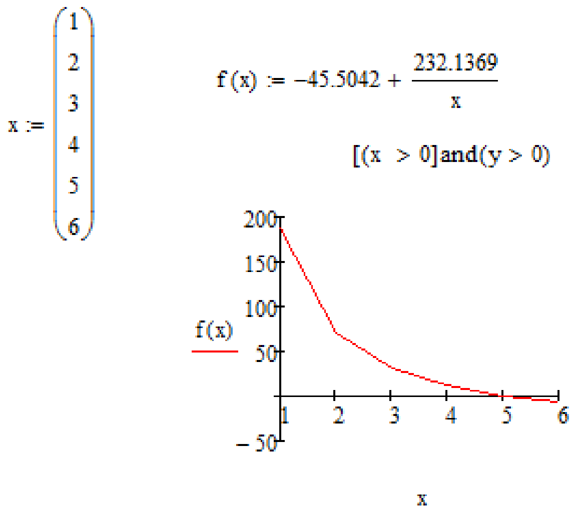

Figure 2. *The graph of the regression equation*

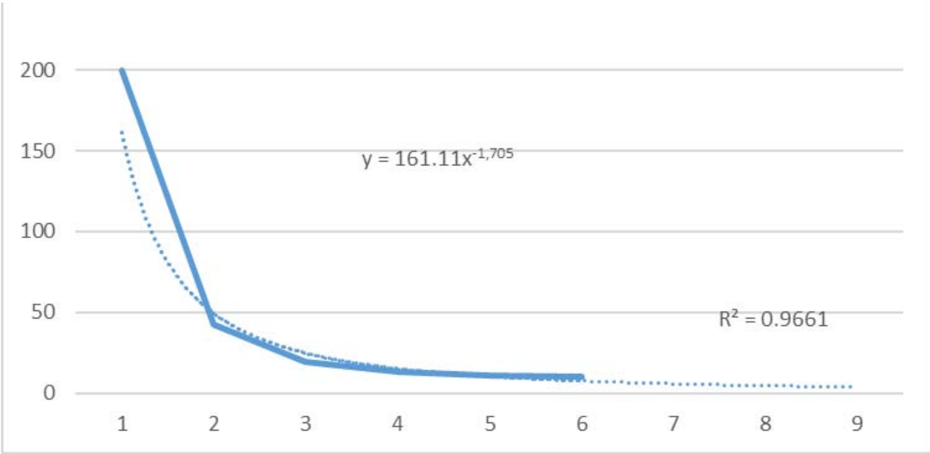

Figure 3. *The Trendline function*

$$f(x) := 161.11 \cdot x^{-1.705}$$

$$x := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{pmatrix}$$

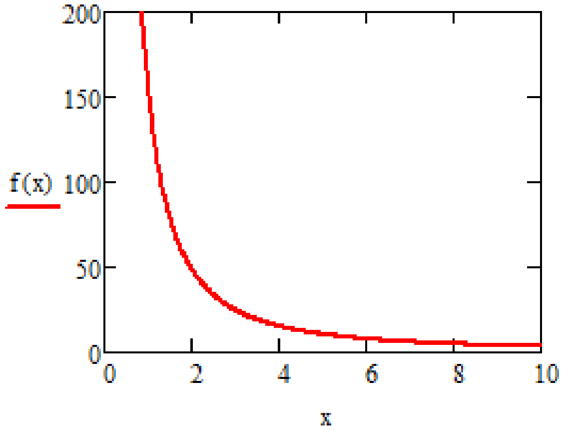

Figure 4. *Power function implementation in Mathcad*

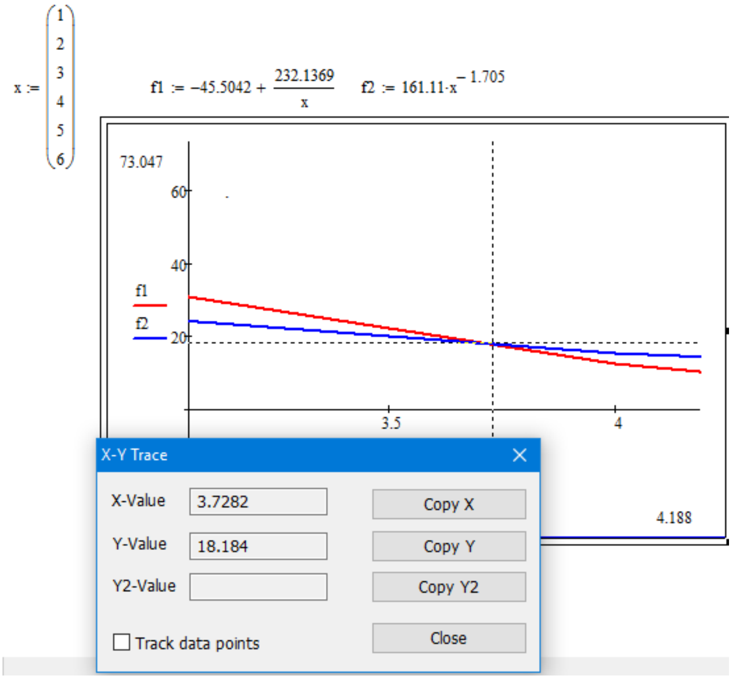

Figure 5. *Definitions of system limitations*

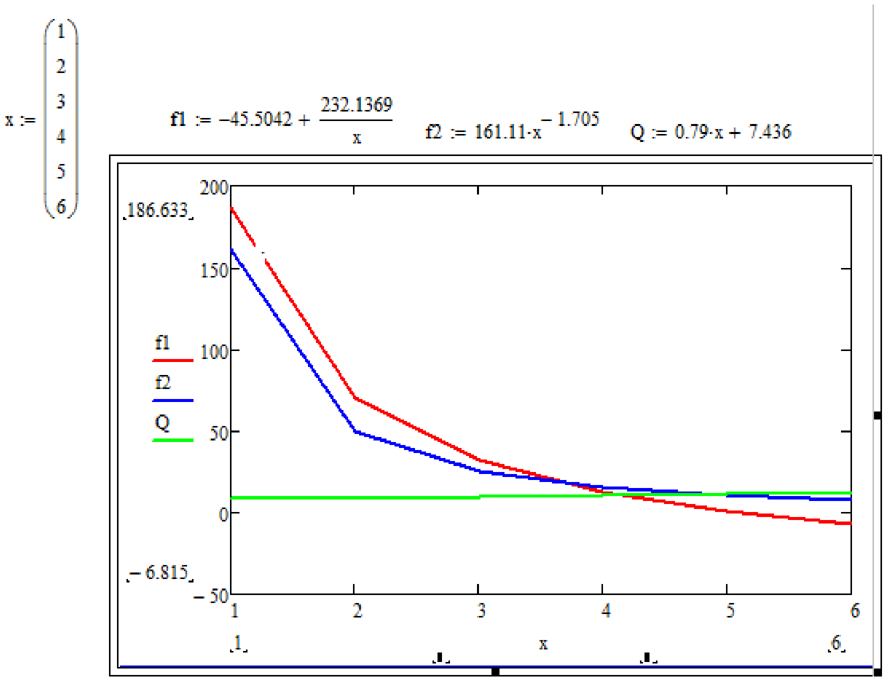

Figure 6. *The system of equations*

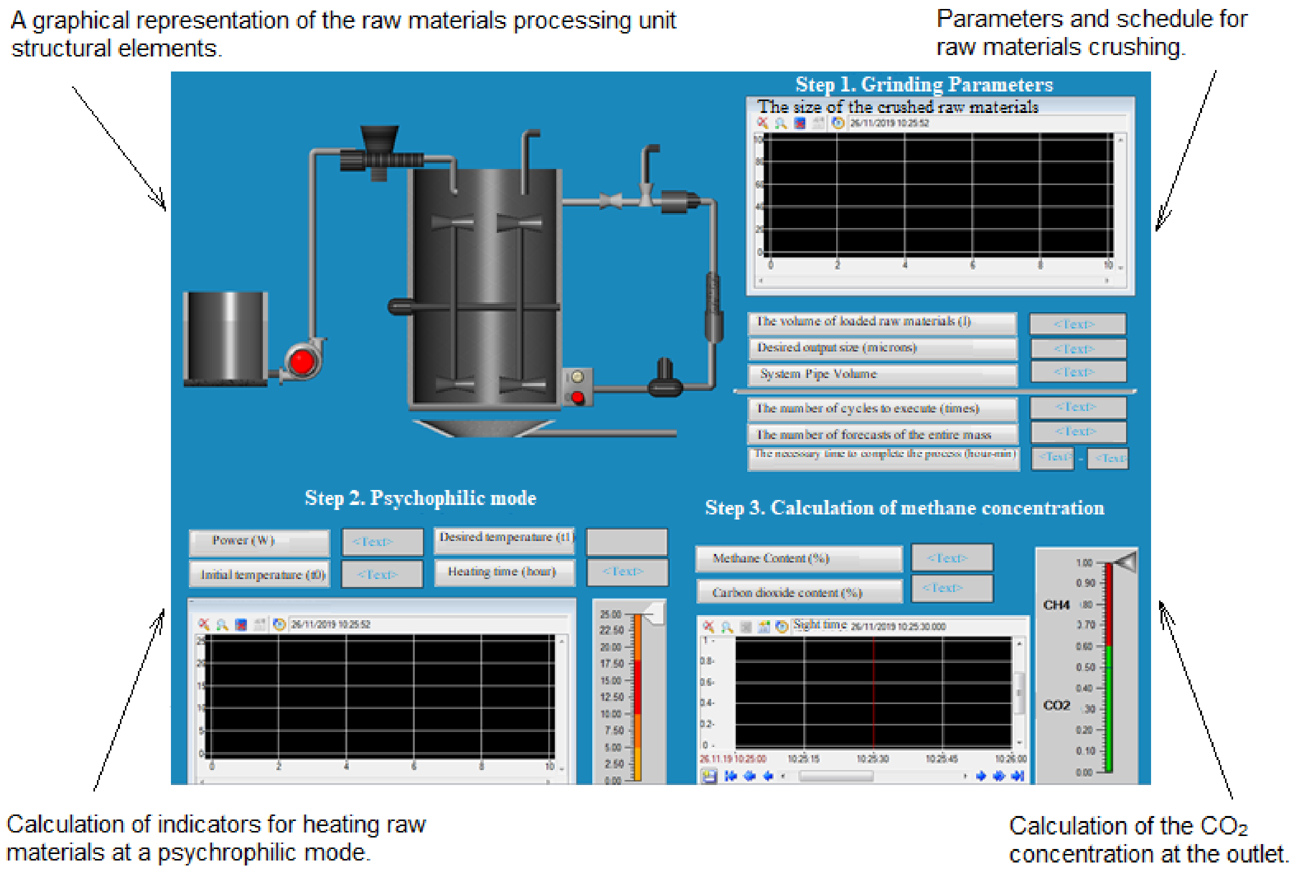

Figure 7. *Four logical zones of an automated system for managing technological processes of organic raw materials recycling. Source: Vedenev* and *Vedeneva (2006)*

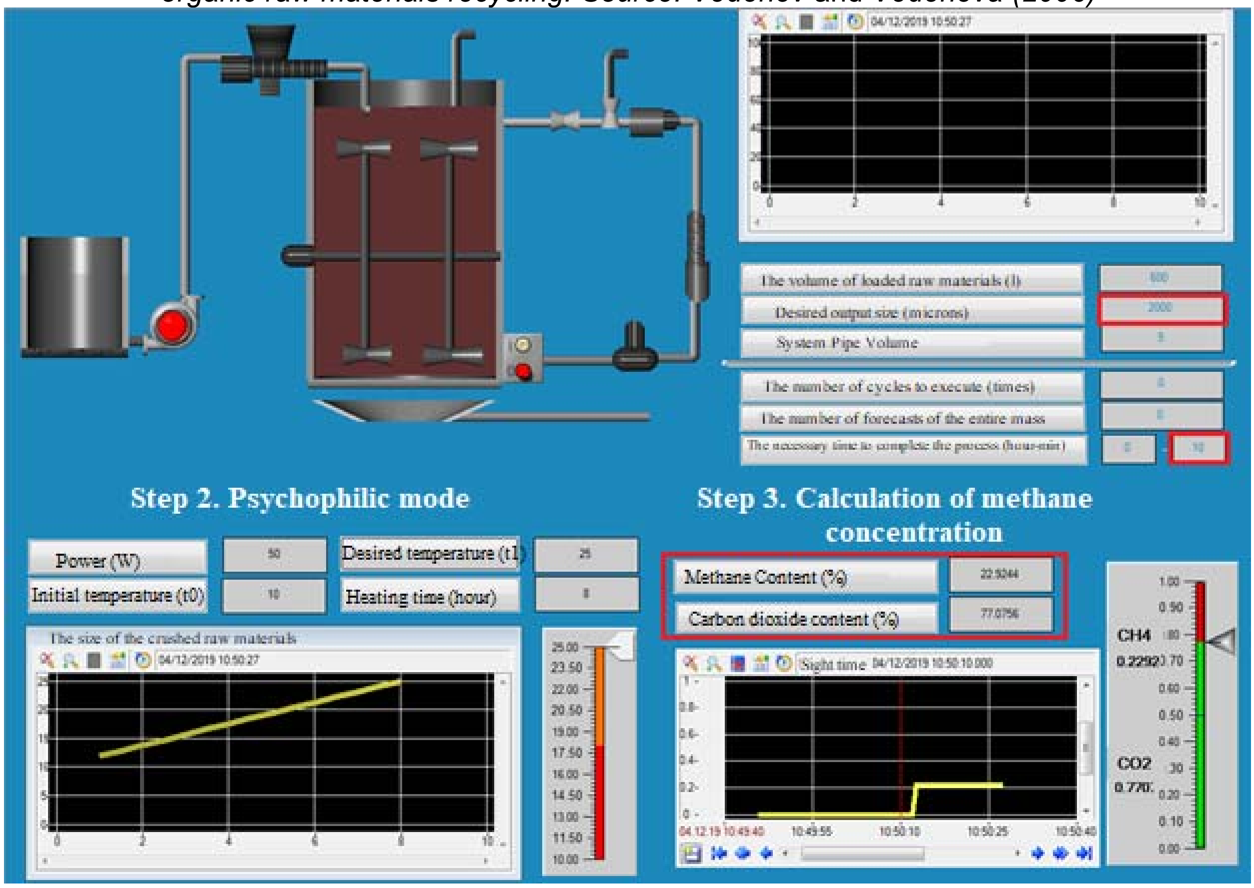

Figure 8. *The calculation of the outlet parameters*

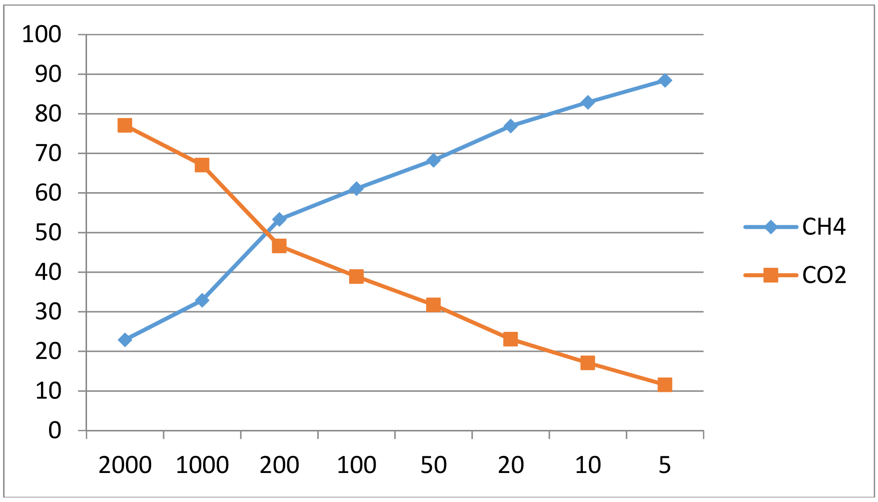

Figure 9. *The relationship between particle size* and *biogas concentration*

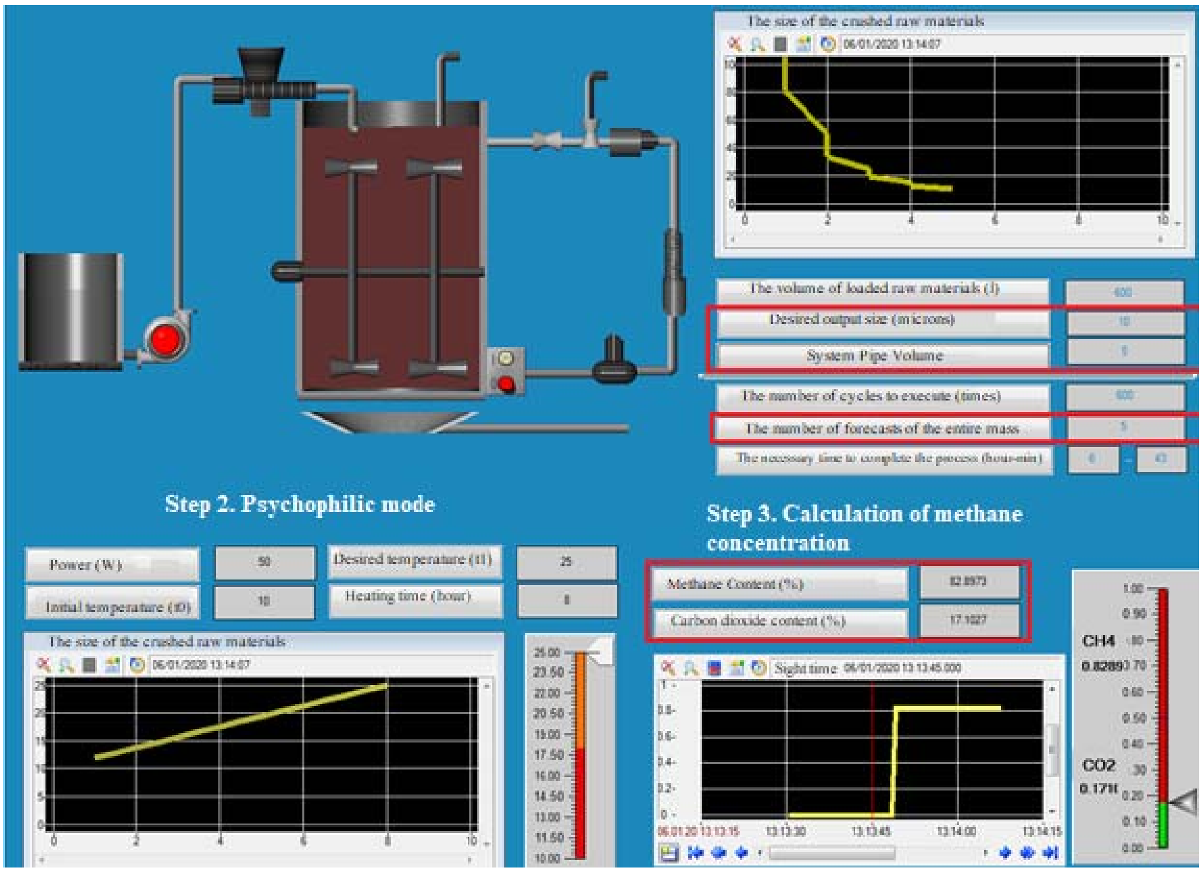

Figure 10. *The process of particles crushing by less than 10 microns*