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RESEARCH ON THE INFLUENCE OF THE DYNAMIC VISCOSITY OF RAW MATERIAL FERMENTED IN A BIOGAS REACTOR ON HEAT DISTRIBUTION

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Abstract. *Biogas plants are becoming increasingly popular among industry and domestic consumers. This has led to increased interest in conducting research to increase the profitability of such plants. First of all, researchers are focusing their attention on creating systems that will satisfy the conditions for anaerobic digestion and at the same time consume a minimum amount of electrical energy for mixing and heating the substance. After all, for fermentation, raw materials with different physicochemical composition are used, which significantly affects energy costs. The aim of the work is to study the influence of the dynamic viscosity of the raw materials fermented in a biogas reactor on the change in the Reynolds criterion and heat transfer coefficients from the rotating heater to the raw materials. The article presents a mathematical model for conducting theoretical studies. The work considers the change in the dynamic viscosity of the substrate in the range from 0.01 to 0.1 Pa·s. It was found that when the dynamic viscosity of the raw material changes in the range from 0.01 to 0.1 Pa·s, the Reynolds criterion and heat transfer coefficients change according to an exponential law, which is confirmed by the graphical dependencies obtained during the research and presented in this work. The results obtained will further allow us to establish a rational rotation frequency of the mixing device combined with a heating device, taking into account the change in the dynamic viscosity of the raw material, to create and maintain a favorable microclimate for the anaerobic process with the maximum possible formation of biogas.*

Key words: ***reynolds criterion, energy consumption, heat transfer coefficient, dynamic viscosity of raw materials, fermentation, heat transfer coefficient, mixing***

Introduction. The issue of energy supply for the population and industry is one of the most urgent and relevant in any country in the world. Alternative methods of obtaining energy resources are one of the ways of development and providing energy to the population and industry. Supporting the interest of the population and manufacturers in research, construction and implementation of alternative methods of energy supply is achieved through various systems of state support. Farms are the main producer of food products. Along with this, farming is a source of accumulation of animal and plant waste.

This pushes the population to search for alternative methods of utilization and processing of the resulting waste, since storage systems are sources of hazardous emissions of methane and nitrogen oxides [1-3]. In recent years, the use of biogas plants for processing waste and obtaining an energy-valuable resource, namely biogas, has become increasingly widespread. Biogas production occurs in specially designed biogas reactors while maintaining a constant temperature and homogeneity of the fermented raw material (biomass). During the fermentation process, the amount of biogas released depends on the temperature regime in the biogas reactor [3, 4]. Therefore, the intensity and uniformity of the distribution of thermal energy in the fermented biomass plays a major role in the productivity of the biogas reactor.

According to the conditions of the technological process of anaerobic fermentation, biogas release occurs in three temperature regimes [2, 4]: psychrophilic – $15-20\ °C$, mesophilic – $33-37\ °C$, thermophilic – $55-57\ °C$.

Most of the constructed biogas plants operate in the mesophilic temperature regime, because it is observed the greatest intensity of bacterial development and a rational ratio between the energy consumed and the amount of biogas produced.

In the works [4-10], the issue of maintaining the temperature regime in the biogas reactor using various methods was considered. During the fermentation process, biomass deposits occur on the surfaces of the heating and mixing devices and the walls of the biogas reactor, which negatively affect the intensification and uniformity of the heat transfer process. In the absence of mixing, the adhesion of biomass particles occurs faster, which leads to a decrease in the productivity of the biogas reactor. Therefore, it is necessary to consider the biomass heating system together with the mixing system [4-6, 9].

The physicochemical composition of waste depends on many factors, including raw material moisture, dynamic viscosity, amount of dry matter, etc. It is dynamic viscosity that is one of the main parameters that affects the energy costs of mixing raw materials during the fermentation process. The current issue is the study of the influence of the dynamic viscosity of raw materials fermented in a biogas reactor on the energy costs of mixing and changing the Reynolds criterion.

Purpose. Study of the influence of the dynamic viscosity of the raw material fermented in a biogas reactor on the change in the Reynolds criterion and heat transfer coefficients from the rotating heater to the raw material.

Materials and methods. The technological process of the biogas plant involves unloading part of the spent raw materials once a day and loading the same portion of fresh raw materials. After loading the fresh portion, mixing takes place to establish the average temperature and uniform distribution of the fresh raw materials and those available in the biogas reactor. The following parameters of the biogas reactor and the heating and mixing system were adopted for the research [11]. The biogas reactor is made of stainless steel and insulated with a layer of mineral wool. The reactor volume is 50 liters, fermentation takes place under a mesophilic temperature regime $T_{fer} = 35\,°C$, within the permissible temperature deviation per hour $T_{allow} = \pm 1\,°C$.

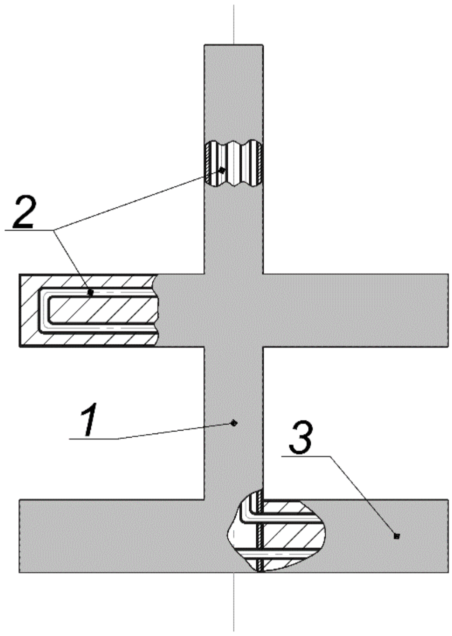

Fig. 1. Combined system for mixing and electric heating: 1 – shaft; 2 – electric heating cable; 3 - paddle

The paddle of the mixing device, in which the electric heater is placed, are made of steel, with a thermal conductivity of $\lambda_{st} = 15\,W/(m \cdot °C)$ and thickness $\delta_{st} = 0{,}012$ m. The mixing and heating system is shown in Fig. 1. Heat transfer from a flexible electric heating element mounted in a mixing device to the fermenting biomass occurs according to the following scheme: heat transfer from the electric heating cable to the paddle wall; heat transfer process in the thickness of the paddle wall; thermal conductivity in the thickness of the adhesion layer on the paddle and shaft; the final stage is heat transfer from the outer surface of the heater to the biomass [4, 12].

For each of the stages, equations [4, 12] have been developed that mathematically describe the nature of the heat flow:

$$q_{heat1} = \alpha_1 \cdot F \cdot \tau \cdot (t_{heat} - t_m)\text{, W;} \quad (1)$$

$$q_{heat\,2} = k \cdot F \cdot \tau \cdot (t_m - t_{sub}), \text{ W}; \quad (2)$$

where α_1 – heat transfer coefficient from electric heating cable to mixing device, $W/(m^2 \cdot °C)$; t_{sub}, t_{heat}, t_m – fermentation temperature of the substrate, electric heating cable and mixing device, respectively, ^{0}C; k – heat transfer coefficient, takes into account the average rate of heat transfer over the heat exchange surface, $W/(m^2 \cdot °C)$; F – heating surface area, m^2; τ – heater operating time, hours.

In equation (2), the heat transfer coefficient (k) depends on various factors, so it is recommended to find it from the following equation [4]:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_{st}}{\lambda_{st}} + \frac{1}{\alpha_2}} \quad (3)$$

where α_2 – heat transfer coefficient from the combined system shown in Figure 1 to the volume of digested biomass, $W/(m^2 \cdot °C)$; λ_{st} – coefficient of thermal conductivity of the mixing device blade material; δ_{st} – paddle thickness, m.

To determine the heat transfer coefficient (α_2) it is necessary to determine the mode of motion of the fluid being mixed.

The evaluation of the mode of motion of the fluid is performed on the basis of the centrifugal Reynolds criterion, which is a dimensionless complex quantity and is calculated according to the dependence [12]:

$$\text{Re}_м = \frac{\rho \cdot n \cdot d_м^2}{\mu}, \quad (4)$$

where ρ – substrate density, kg/m^3; $\text{Re}_м$ – modified Reynolds criterion for mixing; μ – dynamic viscosity of the substrate Pa s; *n* – mixer speed, rpm; $d_м$ – mixer diameter, m.

When conducting research, we assume that the specific density of the fermented raw material is constant and is 1000 kg/m^3.

Using the criterion equation of convective heat transfer between the heating surface and the substance, and also taking into account that the temperature distribution throughout the volume of the substance is uniform, the calculation of the heat transfer coefficient α_2, mathematically it will have the following form:

$$\alpha_2 = 1{,}01 \cdot \frac{\lambda}{d_{in}} \cdot (\mathrm{Re}_м)^{0,62} \cdot (\mathrm{Pr})^{0,36}, \tag{5}$$

where λ – thermal conductivity coefficient of the substrate, $\lambda = 0{,}031\ W/(m \cdot °C)$; d_{in} – internal diameter of the tank, m; Pr – Prandtl similarity criterion.

$$\mathrm{Pr} = \frac{c \cdot \mu}{\lambda}, \tag{6}$$

where c – specific heat capacity of the substrate, $c = 4060\ J/(kg \cdot °C)$.

The temperature of the heating device is maintained at 60 ^{0}C, as higher temperatures lead to the death of bacteria and increased adhesion of biomass to the heating device [2].

Using equations (1-6), numerical studies were conducted on the influence of the dynamic viscosity of the substrate on the change in the Reynolds criterion, heat transfer coefficient, and heat transfer coefficient.

Calculations were performed in the absence of deposits on the surface of the mixing device, in which an electric heating cable is installed, while the ambient temperature is constant and is $t_{out} = -15$ ^{0}C, the change in the dynamic viscosity of the raw material occurs from 0.01 to 0.1 Pa·s, for a mixing frequency (n) from 30 to 50 rpm. Calculations were performed in the Wolfram Mathematica program.

According to the results of the calculations, graphs of the change in the Reynolds criterion depending on the change in the dynamic viscosity of the substrate and the frequency of rotation of the working body of the mixing device (Fig. 2), the heat transfer coefficient depending on the change in the dynamic viscosity of the substrate and the frequency of rotation of the working body of the mixing device (Fig. 3), the heat transfer coefficient depending on the change in the dynamic viscosity of the substrate and the frequency of rotation of the working body of the mixing device (Fig. 4) were obtained.

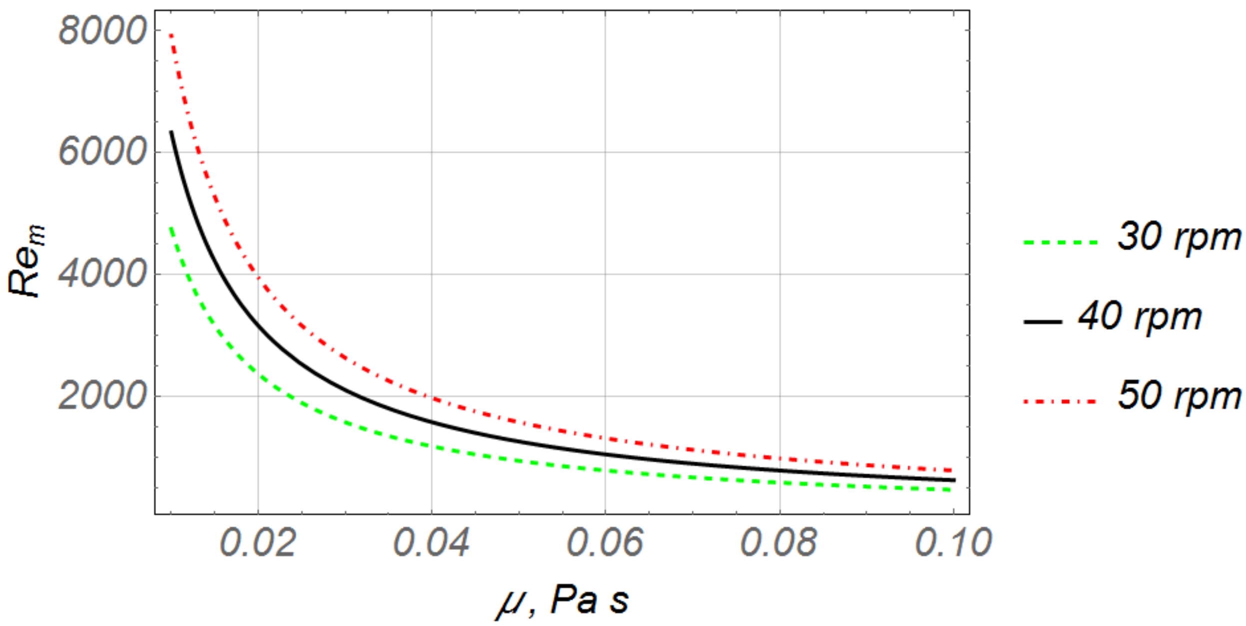

Fig. 2. Dependencies of the change in the Reynolds criterion depending on the change in the dynamic viscosity of the substrate and the frequency of rotation of the working body of the mixing device

After analyzing the graphical dependences of the change in the Reynolds criterion (Fig. 2), it was found that regardless of the rotation speed of the working body of the mixing device, the change in the criterion depending on the change in the dynamic viscosity of the substrate occurs according to an exponential law. The maximum value of the Reynolds criterion for the rotation speed is: 30 rpm – 4780; 40 rpm – 6350; 50 rpm – 8000. After analyzing the graphical dependence, it was found that regardless of the change in the dynamic viscosity of the substrate, the percentage increase in the Reynolds criterion when changing the rotation speed from 30 to 40 rpm is 25%, while when changing the rotation speed from 40 to 50 rpm – 21%. It was found that with an increase in the rotation speed, the percentage value of the change in the Reynolds criterion in accordance with the previous value of the rotation speed decreases.

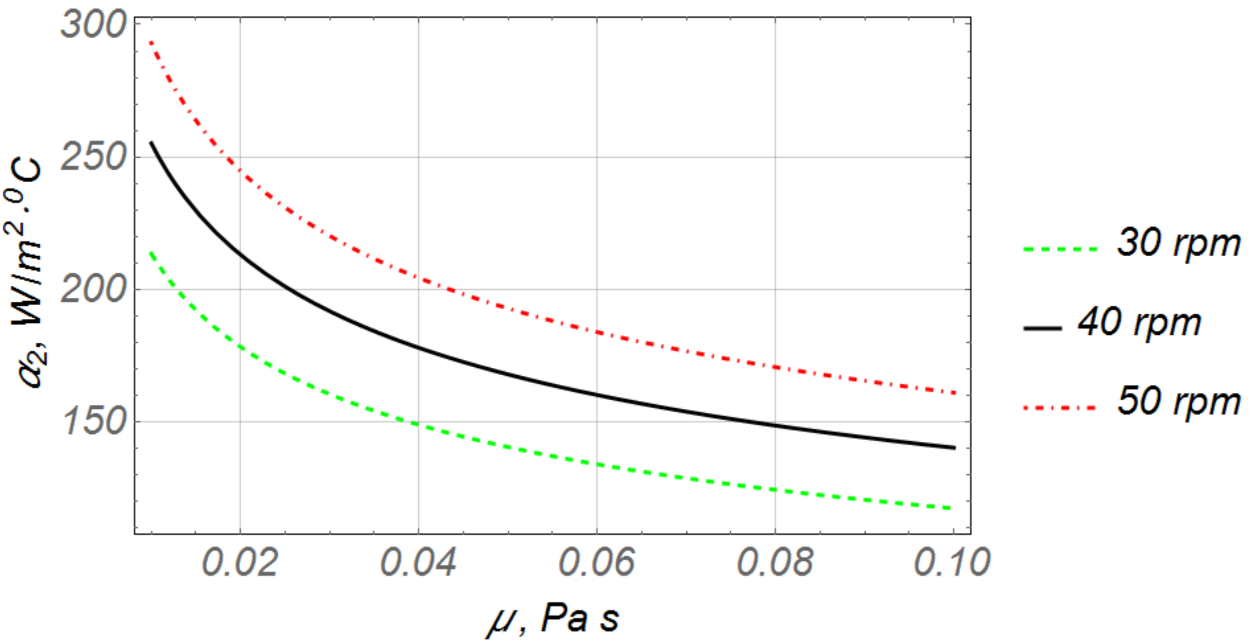

Fig. 3. Dependencies of the change in the heat transfer coefficient (α_2) depending on the change in the dynamic viscosity of the substrate and the frequency of rotation of the working body of the mixing device

After analyzing the graphical dependences of the change in the heat transfer coefficient (Fig. 3), it was found that regardless of the rotation speed of the working body of the mixing device, the change in the coefficient depending on the change in the dynamic viscosity of the substrate occurs according to an exponential law.The maximum value of the heat transfer coefficient for the rotation speed is: 30 rpm – 214.9; 40 rpm – 255.8; 50 rpm – 294.3. After analyzing the graphical dependence, it was found that regardless of the change in the dynamic viscosity of the substrate, the percentage increase in the heat transfer coefficient when changing the rotation speed from 30 to 40 rpm is 16%, while when changing the rotation speed from 40 to 50 rpm – 13%.

It was found that with an increase in the rotation speed, the percentage value of the change in the heat transfer coefficient in accordance with the previous value of the rotation speed decreases.

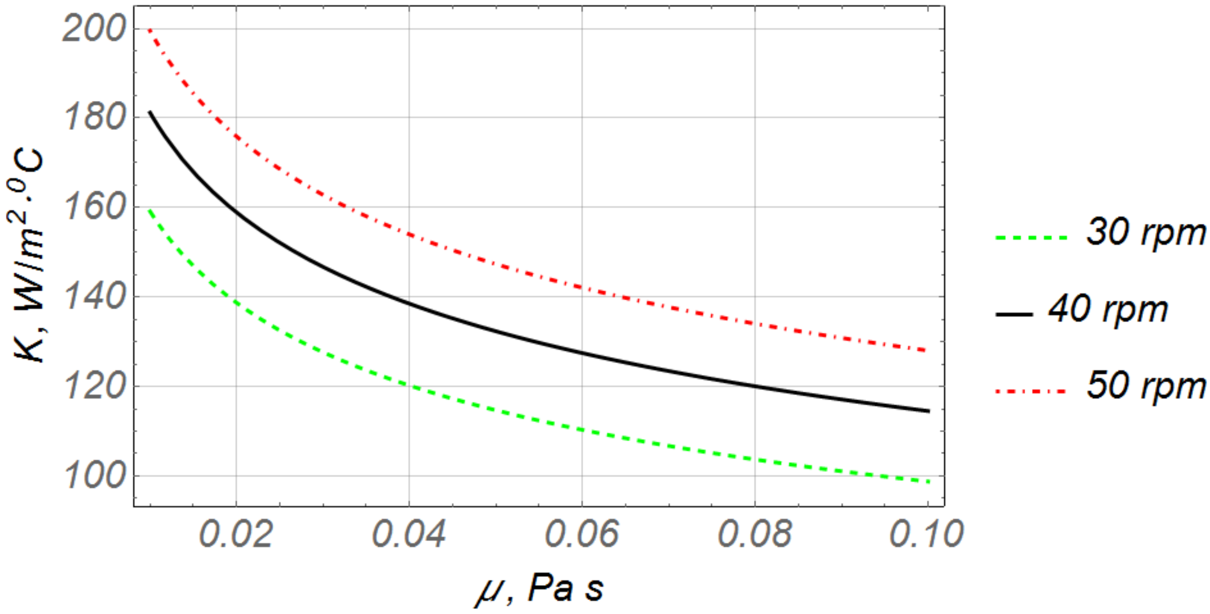

Fig. 4. Dependencies of the change in the heat transfer coefficient (k) depending on the change in the dynamic viscosity of the substrate and the frequency of rotation of the working body of the mixing device

After analyzing the graphical dependences of the change in the heat transfer coefficient (Fig. 4), it was found that regardless of the rotation frequency of the working body of the mixing device, the change in the coefficient depending on the change in the dynamic viscosity of the substrate occurs according to an exponential law. The maximum value of the heat transfer coefficient for the rotation frequency is: 30 rpm – 160; 40 rpm – 181.6; 50 rpm – 200. After analyzing the graphical dependence, it was found that regardless of the change in the dynamic viscosity of the substrate, the percentage increase in the heat transfer coefficient when changing the rotation frequency from 30 to 40 rpm is 13%, while when changing the rotation frequency from 40 to 50 rpm – 10%. It was found that with an increase in the rotation frequency, the percentage value of the change in the heat transfer coefficient in accordance with the previous value of the rotation frequency decreases.

According to the results of calculations, for a biogas reactor with geometric parameters according to the initial conditions, the Prandtl similarity criterion changes according to a linear law with an increase in the dynamic viscosity of the substrate (Fig. 5).

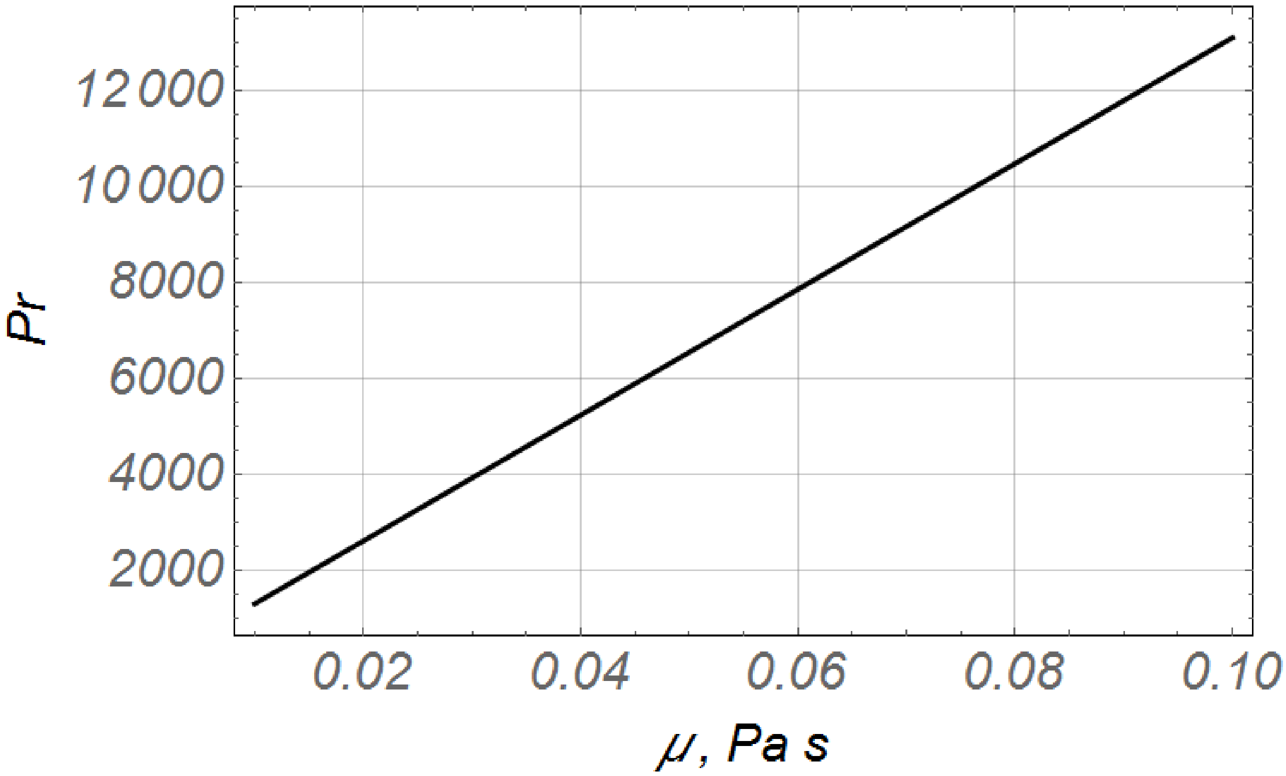

Fig. 5. Dependence of the change in the Prandtl similarity criterion on the change in the dynamic viscosity of the substrate

Having analyzed the graphical dependencies obtained during the research (Fig. 2 – Fig. 5), it can be concluded that in order to accelerate the heat transfer from the heating device to the substrate, which is filled with the biogas reactor, it is necessary to increase the rotation frequency of the mixing device, which is connected to the heating device. At the same time, it was found that regardless of the dynamic viscosity of the substrate, the percentage change in the heat transfer coefficients and heat output decreases with increasing rotation frequency in accordance with the previous value of the rotation frequency.

The use of the obtained results gives impetus to further research in the direction of establishing a rational rotation frequency of the mixing device in which the heating device is located from the point of view of energy consumption for the processes of mixing and electric heating of the raw material.

Conclusions. The work investigated the influence of the dynamic viscosity of the raw material being fermented in a biogas reactor on the change in the Reynolds criterion, heat transfer coefficients and heat transfer. The work presents a mathematical model for determining the value of the heat flow to the raw material being fermented using an electrothermal system. Graphical dependences of the change in the Reynolds criterion, heat transfer coefficients (k) and heat transfer (α_2) were obtained at different values of the dynamic viscosity of the raw material. It was established that the change in the Reynolds criterion and coefficients depending on the change in the dynamic viscosity of the raw material occurs according to an exponential law. It was established that the change in the Prandtl criterion depending on the change in the dynamic viscosity of the raw material occurs according to a linear law. It was established that regardless of the value of the dynamic viscosity of the substrate, the percentage value of the change in the heat transfer coefficients and heat transfer decreases with an increase in the rotation frequency in accordance with the previous value of the rotation frequency. The results obtained provide an impetus for further research in the direction of establishing a rational rotation frequency of the mixing device in which the heating device is located from the point of view of energy consumption for the processes of mixing and electrical heating of raw materials.

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ДОСЛІДЖЕННЯ ВПЛИВУ ДИНАМІЧНОЇ В'ЯЗКОСТІ СИРОВИНИ, ЩО ЗБРОДЖУЄТЬСЯ У БІОГАЗОВОМУ РЕАКТОРІ, НА ТЕПЛОРОЗПОДІЛ

М. О. Сподоба, О. О. Сподоба

Анотація. *Все більшої популярності серед промисловості та побутових споживачів набувають біогазові установки. Це спонукає до підвищення зацікавленості щодо проведення досліджень у напрямку підвищення рентабельності таких установок. У першу чергу дослідники зосереджують свою увагу на створенні систем, що будуть задовільняти умови для протікання анаеробного зброджування, та при цьому споживати мінімальну кількість електричної енергії на перемішування та нагрівання речовини. Адже для ферментації використовується сировина з різним фізико-хімічним складом, що суттєво впливає на енергетичні витрати. Метою роботи є дослідження впливу динамічної в'язкості сировини, що ферментується в біогазовому реакторі, на зміну критерію Рейнольдса та коефіцієнтів тепловіддачі від нагрівача, який обертається, до сировини. У статті представлено математичну модель для проведення теоретичних досліджень. У роботі розглянуто зміну динамічної в'язкості субстрату в діапазоні від 0,01 до 0,1 Па·с. Встановлено, що при зміні динамічної в’язкості сировини в діапазоні від 0,01 до 0,1 Па·с критерій Рейнольдса та коефіцінти теплопередачі змінюються за екпоненціальним законом, що підтверджується графічними залежностями, отриманими при проведенні досліджень та наведеними у цій роботі. Отримані результати надалі дозволять встановити раціональну частоту обертання змішувального пристрою, поєднаного з нагрівальним пристроєм, враховуючи зміну динамічної в’язкості сировини для створення та підтримки сприятливого мікроклімату для анаеробного процесу з максимально можливим утворенням біогазу.*

Ключові слова: ***критерій Рейнольдса, енергетичні витрати, коефіцієнт теплопередачі, динамічна в'язкість сировини, зброджування, коефіцієнт тепловіддачі, перемішування***