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RESEARCH ON THE INFLUENCE OF THE SPECIFIC DENSITY OF THE RAW MATERIAL FERMENTED IN A BIOGAS REACTOR ON HEAT DISTRIBUTION

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Abstract. *Biogas technologies are becoming increasingly widespread in industrial and domestic facilities. However, the profitability of biogas production depends on the energy consumption to support the fermentation process, so it is necessary to conduct research aimed at reducing energy costs for heating and mixing the raw material being fermented. Raw materials with different physicochemical compositions are used for fermentation, which significantly affects energy costs. The aim of the work is to study the influence of the specific density of the raw material being fermented in a biogas reactor on the energy costs for mixing and changing the Reynolds criterion. The paper presents the constructed mathematical model and research results. The research considered a wide range of changes in the specific density of the substrate from 750 to 1500 kg/m*^{3}*. According to the research results, graphical dependences of the change in the Reynolds criterion, heat transfer coefficient and heat transfer coefficient were obtained, depending on the change in the specific density of the raw material and the frequency of rotation of the working body of the mixing device. It has been established that the change in the criterion and coefficients depending on the change in the density of the raw material occurs according to a linear law. The results obtained will allow setting 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 the raw material.*

Key words: *Reynolds criterion, heat transfer coefficient, heat transfer coefficient, specific density of raw materials, anaerobic digestion, 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 – $15-20\ {}^{\circ}C$, mesophilic – $33-37\ {}^{\circ}C$, thermophilic – $55-57\ {}^{\circ}C$.

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 the moisture content of the raw material, the amount of dry matter, the density of the substance, etc. It is the density of the substance that affects the energy costs for mixing the raw material during the fermentation process. A topical issue is the study of the influence of the specific density of the raw material fermented in a biogas reactor on the energy costs for mixing and changing the Reynolds criterion, heat transfer coefficients and heat transfer.

Purpose. Study of the influence of the specific density of the raw material fermented in a biogas reactor on the energy costs for mixing and changes in the Reynolds criterion and heat transfer and heat transfer coefficients.

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, the fermentation temperature regime is mesophilic, $T_{fer} = 35\,°C$, allowable deviation of temperature $T_{allow} = \pm 1\,°C$, per hour.

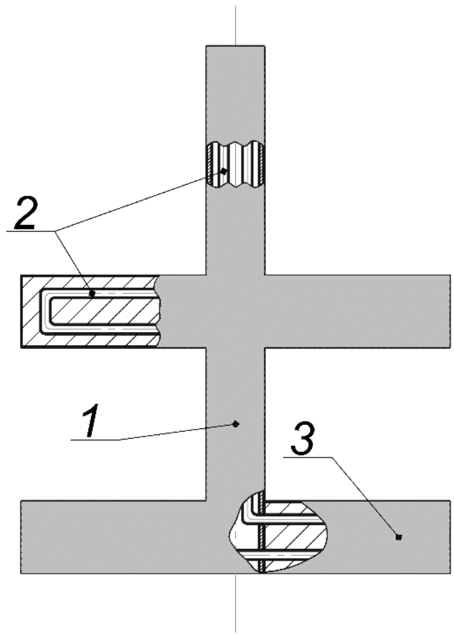

Fig. 1. Combined system for mixing and electric heating: 1 – shaft; 2 – electric heating cable; 3 - paddle.

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].

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

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

$$q_{heat2} = k \cdot F \cdot \tau \cdot (t_m - t_{sub}), \text{ W}; \tag{2}$$

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]:

$$k = \frac{1}{\dfrac{1}{\alpha_1} + \dfrac{\delta_{st}}{\lambda_{st}} + \dfrac{1}{\alpha_2}} \tag{3}$$

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 [4, 6]:

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

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 viscosity of the substrate is constant and is $\mu = 0{,}048\ Pa \cdot s$ [11].

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:

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

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.

$$\mathrm{Pr} = \frac{c \cdot \mu}{\lambda}, \quad (6)$$

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 specific density of the substrate on the change in the Reynolds criterion, heat transfer coefficient and heat transfer coefficient.

The calculations were carried out in the absence of deposits on the surface of the mixing device, in which an electric heating cable is installed, the ambient temperature $t_{out} = -15\,^0$C, change in specific density from 750 to 1500 kg/m^3 for a mixing frequency (n) from 30 to 50 rpm. Calculations were performed in the program Wolfram Mathematica.

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

According to the results of calculations, for a biogas reactor with geometric parameters according to the initial conditions, the Prandtl similarity criterion for different rotation frequencies of the working body of the mixing device and the specific density of the raw material is $\mathrm{Pr} = 6286{,}45$.

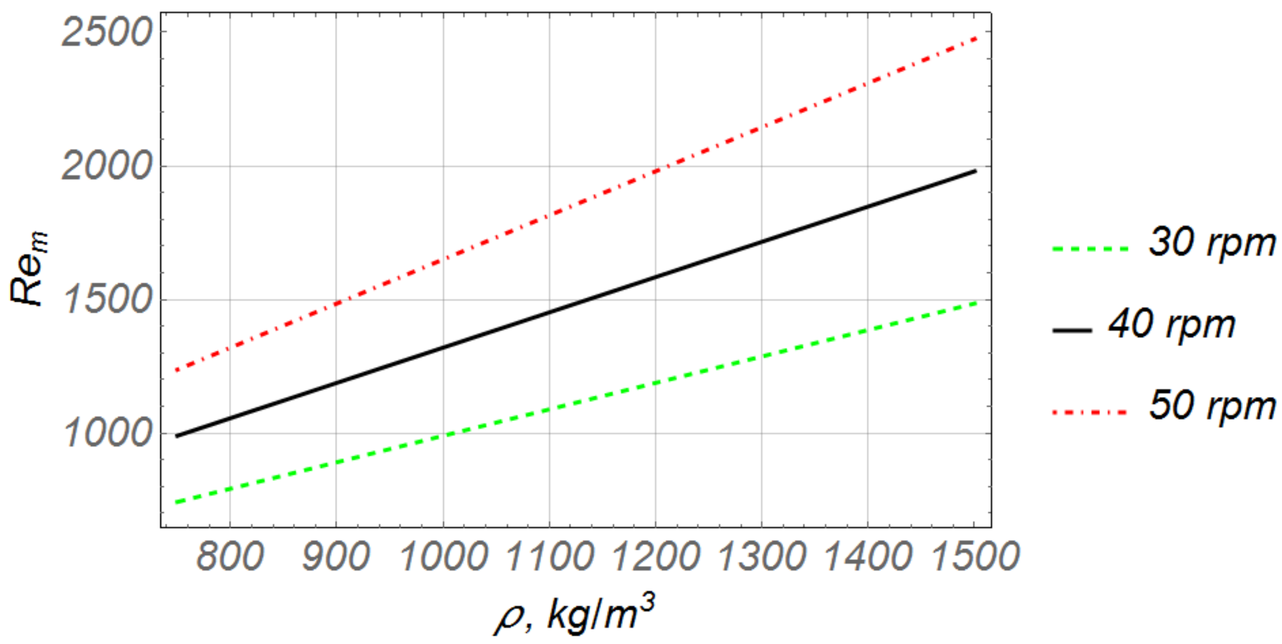

Fig. 2. Dependencies of the change in the Reynolds criterion depending on the change in the specific density of the substrate and the frequency of rotation of the working body of the mixing device.

After analyzing the graphical dependences of the change in the Reynolds criterion (Fig. 2), it was found that regardless of the rotation frequency of the working body of the mixing device, the change in the criterion depending on the change in the specific density of the raw material occurs according to a linear law. The maximum value of the Reynolds criterion for the rotation frequency is: 30 rpm – 1485; 40 rpm – 1981; 50 rpm – 2476. After analyzing the graphical dependence, it was found that at a specific density of the raw material of 1500 kg/m^3, the percentage increase in the Reynolds criterion when changing the rotation frequency from 30 to 40 rpm is 25%, while when changing the rotation frequency from 40 to 50 rpm – 20%. It was found that with an increase in the rotation frequency, the percentage value of the change in the Reynolds criterion in accordance with the previous value of the rotation frequency decreases.

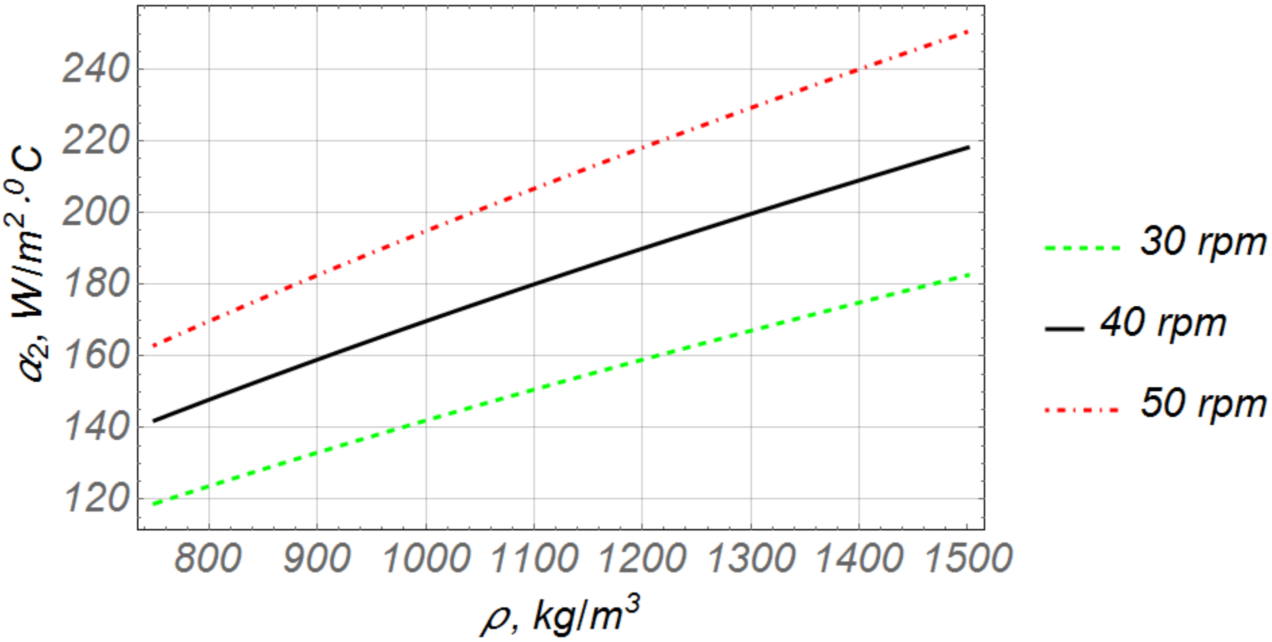

Fig. 3. Dependencies of the change in the heat transfer coefficient (α_2) depending on the change in the specific density of the substrate and the frequency of rotation of the working body of the mixing device.

After analyzing the graphical dependences of the change in the heat transfer coefficient (Fig. 3), it was found that regardless of the rotation frequency of the working body of the mixing device, the change in the coefficient depending on the change in the specific density of the raw material occurs almost according to a linear law. The maximum value of the heat transfer coefficient (α_2) for the rotation frequency is: 30 rpm – 182.6; 40 rpm – 218.2; 50 rpm – 250.62. After analyzing the graphical dependence, it was found that at a specific density of the raw material of 1500 kg/m^3, the percentage increase in the heat transfer coefficient (α_2) when changing the rotation frequency from 30 to 40 rpm is 16%, while when changing the rotation frequency from 40 to 50 rpm – 13%.

It was found that with an increase in the rotation frequency, the percentage value of the change in the heat transfer coefficient (α_2) in accordance with the previous value of the rotation frequency decreases.

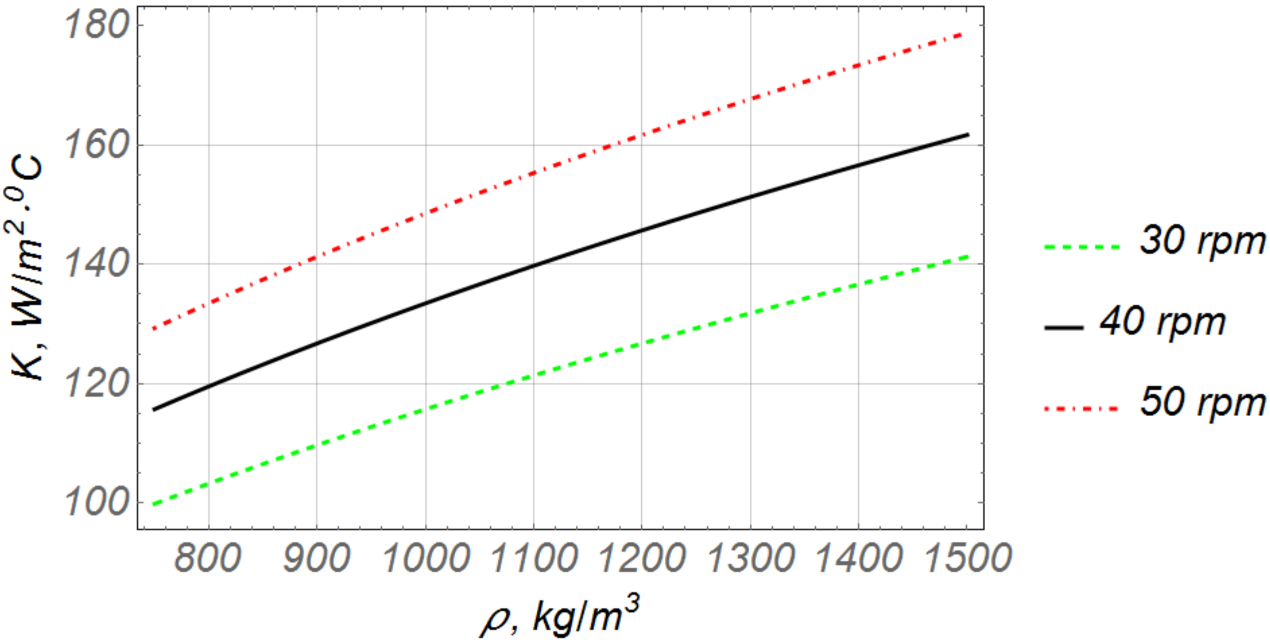

Fig. 4. Dependencies of the change in the heat transfer coefficient (k) depending on the change in the specific density of the substrate and the frequency of rotation of the working body of the mixing device.

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 specific density of the raw material occurs almost according to a linear law. The maximum value of the heat transfer coefficient (k) for the rotation frequency is: 30 rpm – 141.3; 40 rpm – 161.8; 50 rpm – 179. After analyzing the graphical dependence, it was found that at a specific density of the raw material of 1500 kg/m^3, 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 (k) in accordance with the previous value of the rotation frequency decreases.

As a result of the analysis of the obtained graphical dependencies, it can be concluded that an increase in the rotation frequency leads to an acceleration of heat transfer from the heating device to the raw materials and objects located in the biogas reactor. At the same time, the percentage value of the change in the heat transfer coefficients and heat output decreases with an increase in the rotation frequency in accordance with the previous value of the rotation frequency.

The results obtained will allow you to set 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 materials.

Conclusions. The work conducted a study of the influence of the specific density 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. It was established that the change in the criterion and coefficients depending on the change in the density of the raw material occurs according to a linear law. The results obtained will allow setting a rational frequency of rotation of the mixing device in which the heating device is placed from the point of view of energy consumption for the processes of mixing and electric heating of the raw material.

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ДОСЛІДЖЕННЯ ВПЛИВУ ПИТОМОЇ ГУСТИНИ СИРОВИНИ, ЩО ЗБРОДЖУЄТЬСЯ В БІОГАЗОВОМУ РЕАКТОРІ НА ТЕПЛОРОЗПОДІЛ

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Анотація. *Біогазові технології набувають все більшого розповсюдження на виробничих та побутових об'єктах. Однак, рентабельність біогазового виробництва залежить від витрати енергії на підтримку процесу бродіння, тому необхідним є дослідження націлені на зниження енергетичних витрат на підігрів та перемішування сировини, що зброджується. Для зброджування використовують сировину з різним фізико-хімічним складом, що суттєво впливає на енерговитрати. Метою роботи є дослідження впливу питомої густини сировини, що зброджується у біогазовому реакторі на енергетичні витрати на перемішування та зміну критерію Рейнольдса. У роботі наведено побудовану математичну модель та результати досліджень. При дослідженнях розглядався широкий діапазон зміни питомої густини субстрату від 750 до 1500 кг/м^3. За результатами досліджень отримано графічні залежності зміни критерію Рейнольдса, коефіцієнту тепловіддачі та коефіцієнту теплопередачі, в залежності від зміни питомої густини сировини та частоти обертання робочого органу перемішуючого пристрою. Встановлено, що зміна критерію та коефіцієнтів в залежності від зміни густини сировини відбувається за лінійним законом. Отримані результати дозволять встановлювати раціональну частоту обертання перемішуючого пристрою, в якому розміщено нагрівальний пристрій з точки погляду енергетичного споживання на процеси перемішування та електричного підігріву сировини.*

Ключові слова: ***критерій Рейнольдса, коефіцієнт теплопередачі, коефіцієнт тепловіддачі, питома густина сировини, анаеробне зброджування, перемішування***