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

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Abstract. *Every year, the use of biogas technologies gives impetus to the development of new methods of handling accumulated waste from agricultural and household facilities. Therefore, the current issue is to reduce energy costs for maintaining the microclimate of fermentation, with the maximum possible formation of biogas from a certain type of raw material. Physico-chemical parameters have a significant impact on the fermentation of raw materials and energy costs. The purpose of the work is to analyze the impact of the specific heat capacity of the raw material fermented in a biogas reactor on the change in the Prandtl criterion and energy costs for heating. The results of theoretical studies are presented, during which the impact of the range of specific heat capacity of raw materials from 1000 to 4000 J/(kg ^{0}C) on energy costs was analyzed The result is graphical dependences that describe the change in the heat transfer coefficient and heat transfer from the heating device to the raw material, the change in the Prandtl and Reynolds criteria depending on the change in the specific heat capacity of the raw material and the speed of rotation of the mixing device. The percentage change in the Reynolds criterion, heat transfer coefficients and heat transfer when changing the speed of rotation of the mixing device is established. It is established that the change in the Prandtl criterion depending on the change in the specific heat capacity of the raw material occurs according to a linear law. The use of the obtained results in combination with previous studies concerning the influence of physicochemical parameters on energy consumption gives an impetus towards establishing a rational speed of rotation of the mixing device from the point of view of energy consumption.*

Keywords*: Reynolds criterion, Prandtl criterion, energy consumption, electric heating, specific heat capacity of raw materials, processing of organic waste*

Introduction. In different countries of the world, there is a dynamic growth in the share of alternative energy sources in the energy system. The issue of energy supply of the population and production facilities is one of the strategic goals in any country. The state is developing various strategies to support the interest of the population and production facilities in the implementation of alternative energy systems, which subsequently leads to the decentralization of energy facilities, a review of methods of distribution and transportation of energy from storage to consumers.

Analysis of literary sources. Also, one of the main issues in the world is environmental safety and environmental cleanliness. Along with this, farmlands and food industry production facilities are the largest sources of organic waste. The storage of which is a source of hazardous emissions of methane and nitrogen oxides into the atmosphere [1-5]. All this pushes the population to search for alternative methods of their disposal and processing. One of such processing methods is anaerobic fermentation of organic waste in biogas reactors with subsequent production of biogas and environmentally friendly fertilizers. According to the conditions of the technological process of anaerobic fermentation, biogas release occurs in three temperature regimes [3, 6]: psychrophilic – 15 – 20 °C, mesophilic – 33 – 37 °C, thermophilic – 55 – 57 °C

The ambient temperature is below the temperature regime at which effective fermentation and methane formation occurs, therefore, heating and mixing devices are used in biogas reactors to maintain the necessary microclimate [4-6]. Most of the biogas plants put into operation are adjusted to operate in the mesophilic temperature regime. This is primarily due to the best sequence of bacterial development and a rational ratio of the amount of energy consumed and the amount of biogas produced.

When analyzing literature sources [6-12], it was found that many systems for heating the substrate. Studies by scientists from different countries of the world indicate that during anaerobic fermentation of raw materials on the surface of mixing and heating devices, reactor walls, measuring equipment and other equipment that is in direct contact with the raw materials, particles stick together. The thickness of the layer has a significant impact on the intensification and uniformity of heat transfer from heating devices to raw materials and from raw materials to the wall of the biogas reactor and the environment. In works [6-8, 11], it is noted that in the absence of mixing, the sticking of raw material particles occurs faster, all this leads to a decrease in the productivity of the biogas reactor. Taking into account the above, it is necessary to consider the raw material heating system in combination with the mixing system.

The physicochemical composition of organic raw materials depends on many factors, such as: acidity, humidity, initial temperature, specific heat, dynamic viscosity, density, etc. Specific heat is one of the main parameters that determines the amount of heat required to change the temperature of one kilogram of a substance by 1 °C. Specific heat is an important value that indicates the ability of the raw material to absorb or give off heat. Therefore, an urgent issue for the design of heating systems is to take into account the influence of the specific heat of the raw material fermented in a biogas reactor on the change in the Prandtl criterion and energy costs for heating.

Purpose. Analysis of the impact of the specific heat capacity of the raw material fermented in a biogas reactor on the change in the Prandtl criterion and energy costs for heating.

Materials and methods. The paper presents the results of research for which the following initial conditions were adopted. Geometric dimensions of an insulated biogas reactor made of stainless steel: volume 50 liters, mesophilic temperature regime $T_{fer} = 35$ °C. The mixing system is made in the form of a two-tier paddle mixer, in the paddles of which an electric heating device is placed. The paddles and the shaft are made of steel with thermal conductivity $\lambda_{st} = 15\ W/(m^2 \cdot °C)$ and thickness $\delta_{st} = 0.012\ m$ [13]. The mixing and heating system is given in [6, 14, 15]. Heat transfer from a flexible electric heating element mounted in the mixing device to the fermenting biomass occurs in two stages. The equations that describe the nature of the heat flow for each of the stages are given in [14, 15].

The heat transfer coefficient k, which is part of the equations describing the nature of heat distribution, depends on various factors, therefore it is calculated according to the equation [6, 14]:

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

where α_2 – heat transfer coefficient from the heating system to the raw material, $W/(m^2 \cdot °C)$; λ_{st} – coefficient of thermal conductivity of the mixing device paddle 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 that is being mixed. The estimation of the mode of fluid motion is performed on the basis of the centrifugal Reynolds criterion, which is a dimensionless complex quantity and is calculated according to the dependence [8, 15]:

$$\mathrm{Re}_{м} = \frac{\rho \cdot n \cdot d_{м}^2}{\mu}\ , \quad (2)$$

where ρ – substrate density, kg/m^3; $\mathrm{Re}_{м}$ – 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/m3. The research was conducted for the winter period when the average ambient temperature is $t_{out} = -15\ ^0$C. According to the recommendations given in [3], the temperature of the heating device is maintained at 60 ^{0}C. There are no deposits on the surface of the heating device [14].

The calculation of the heat transfer coefficient α_2, is carried out using the equations of convective heat transfer and taking into account that the heat distribution over the volume of the raw material is uniform:

$$\alpha_2 = 1{,}01 \cdot \frac{\lambda}{d_{in}} \cdot (\mathrm{Re}_{\text{м}})^{0{,}62} \cdot (\mathrm{Pr})^{0{,}36}, \qquad (3)$$

where λ – thermal conductivity coefficient of the substrate, $\lambda = 0.1\ W/(m \cdot °C)$; d_{in} – internal diameter of the tank, m; Pr – Prandtl similarity criterion [6, 14].

$$\mathrm{Pr} = \frac{c \cdot \mu}{\lambda}, \qquad (4)$$

where c – specific heat capacity of raw materials, $J/(kg \cdot °C)$; μ – dynamic viscosity of the raw material, 0.05 Pa s.

Using equations (1-4) and those given in [15], numerical studies of the influence of the specific heat capacity of the raw material on the change in the Prandtl criterion, heat transfer coefficient (k) and heat transfer coefficient (α_2) were conducted. The change in the specific heat capacity of the raw material occurs from 1000 to 4000 $J/(kg \cdot °C)$, for a stirring frequency (n) from 30 to 50 rpm. Calculations were performed in the Wolfram Mathematica program.

Results and Discussion. As a result of the conducted research, graphical dependences of the change in the Reynolds criterion, heat transfer coefficient (k), heat transfer coefficient (α_2) and Prandtl criterion were obtained depending on the change in the speed of the mixing device and the change in the specific heat capacity of the raw material, Fig. 1 – Fig. 4.

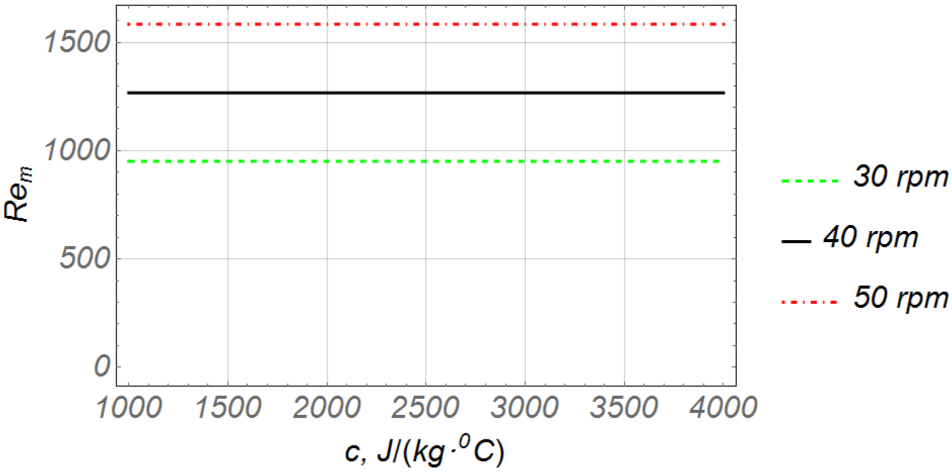

Fig. 1. Dependencies of the change in the Reynolds criterion depending on the change in the specific heat capacity of the raw material and the speed of rotation of the mixing device

The analysis of the dependence of the change in the Reynolds criterion (Fig. 1) showed that the change in the specific heat capacity of the raw material does not affect the change in the Reynolds criterion at stable speeds of the mixing device. This is characterized by the linearity of the Reynolds criterion (Fig. 1) for speeds of 30, 40 and 50 rpm. According to the initial conditions used in the research, the maximum value of the Reynolds criterion for the speed of rotation: 30 rpm – 951; 40 rpm – 1263; 50 rpm – 1570. From the graphical dependence, it was established that the percentage change in the Reynolds criterion when changing the rotation frequency from 30 to 40 rpm is on average 25%, while when changing the rotation frequency from 40 to 50 rpm – 20%.

Having analyzed the graphical dependences of the change in the heat transfer coefficient (Fig. 2), it was found that the change in the coefficient with an increase in the specific heat capacity of the raw material also increases, regardless of the frequency of rotation of the working body of the mixer. The maximum value of the heat transfer coefficient is observed at a specific heat capacity of the raw material of 4000 $J/(kg\cdot°C)$, and on average is for the frequency of rotation: 30 rpm – 296; 40 rpm – 353.5; 50 rpm – 405. At the same time, the minimum value of the heat transfer coefficient is observed at 1000 $J/(kg\cdot°C)$, and on average is for the frequency of rotation: 30 rpm – 171; 40 rpm – 214.3; 50 rpm – 245.7.

A comparative analysis of the curves of the change in the heat transfer coefficient was carried out and it was found that the percentage increase in the heat transfer coefficient when changing the rotation frequency from 30 to 40 rpm with a specific heat capacity of the raw material of 4000 $J/(kg\cdot°C)$ is 16.3%, while when changing the rotation frequency from 40 to 50 rpm – 12.7%. While, when changing the rotation frequency from 30 to 40 rpm with a specific heat capacity of the raw material of 1000 $J/(kg\cdot°C)$ is 20.2%, while when changing the rotation frequency from 40 to 50 rpm – 12.8%.

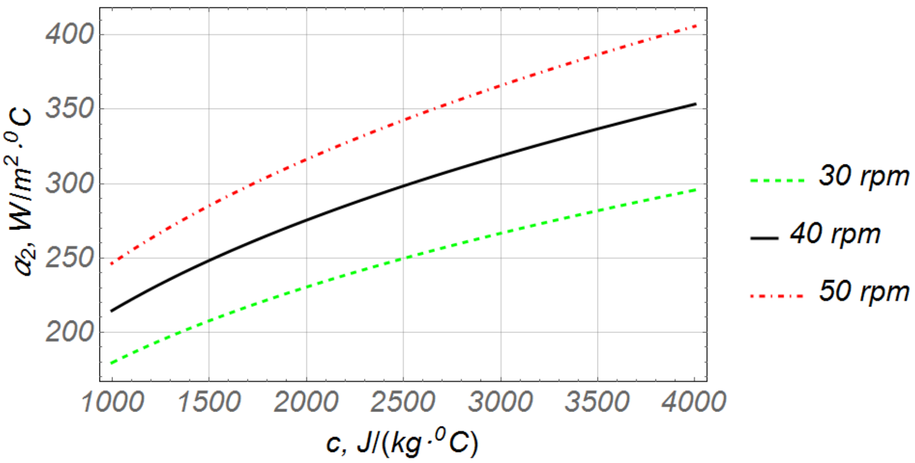

Fig. 2. Dependencies of the change in the heat transfer coefficient (α_2) depending on the change in the specific heat capacity of the raw material and the speed of rotation of the mixing device

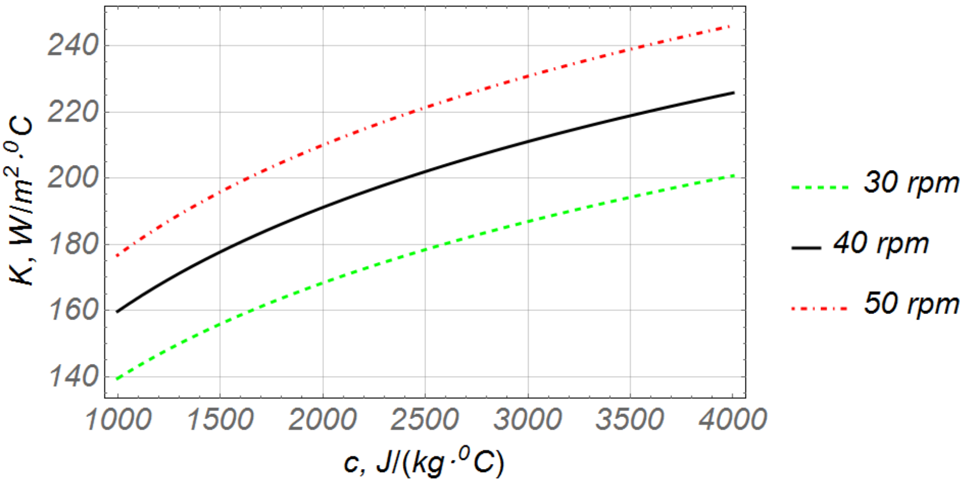

Fig. 3. Dependencies of the change in the heat transfer coefficient (k) depending on the change in the specific heat capacity of the raw material and the rotation frequency of the mixing device

Having analyzed the graphical dependences of the change in the heat transfer coefficient (Fig. 3), it was found that the change in the coefficient with an increase in the value of the specific heat capacity of the raw material also increases, regardless of the frequency of rotation of the working body of the mixer. The maximum value of the heat transfer coefficient is observed at a specific heat capacity of the raw material of 4000 $J/(kg\cdot°C)$, and on average is for the frequency of rotation: 30 rpm – 200.6; 40 rpm – 226.5; 50 rpm – 245.8. At the same time, the minimum value of the heat transfer coefficient is observed at 1000 $J/(kg\cdot°C)$, and on average is for the frequency of rotation: 30 rpm – 139; 40 rpm – 159.5; 50 rpm – 176.5.

A comparative analysis of the curves of the change in the heat transfer coefficient was carried out and it was found that the percentage increase in the coefficient when changing the rotation frequency from 30 to 40 rpm with a specific heat capacity of the raw material of 4000 $J/(kg\cdot°C)$ is 11.4%, while when changing the rotation frequency from 40 to 50 rpm – 7.9%. While, when changing the rotation frequency from 30 to 40 rpm with a specific heat capacity of the raw material of 1000 $J/(kg\cdot°C)$ is 12.9%, while when changing the rotation frequency from 40 to 50 rpm – 9.6%.

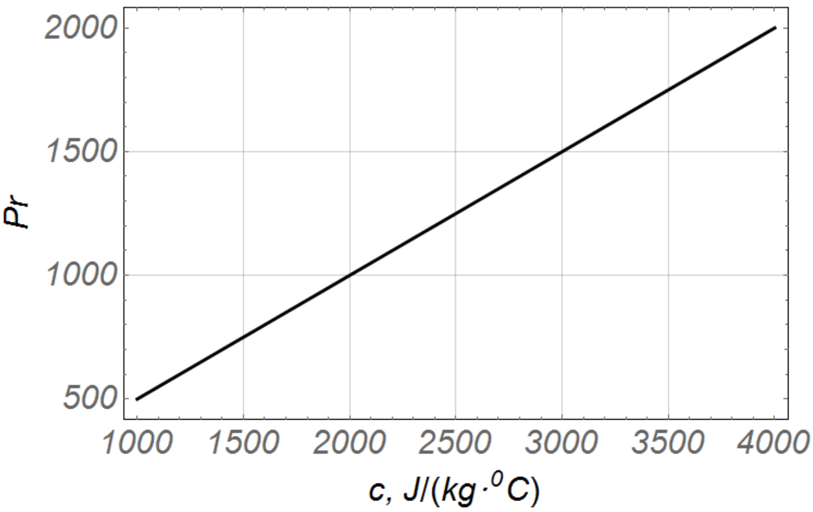

Fig. 4. Dependence of the change in the Prandtl similarity criterion on the specific heat capacity of the raw material

According to the results of calculations, for a biogas reactor with geometric parameters according to the initial conditions, the Prandtl similarity criterion changes linearly with an increase in the value of the specific heat capacity of the raw material (Fig. 4). A linear change in the Prandtl similarity criterion also occurs when the dynamic viscosity of the raw material changes, which is described in [15].

Analyzing the graphical dependencies shown in (Fig. 1 – Fig. 4), it was concluded that the acceleration of heat transfer from the heating device to the fermented raw material occurs with an increase in the rotation frequency of the mixing device connected to the heater. This confirms the feasibility of combining heating devices with mixing systems in order to save energy for the operation of systems for intensification of the fermentation of raw materials in reactors. It was found that regardless of the change in the parameter of the specific heat capacity of the raw material, with an increase in the rotation frequency in accordance with the previous value of the rotation frequency, the percentage change in the coefficients decreases. The use of the obtained results in combination with previous studies concerning the influence of physicochemical parameters on energy consumption provides an impetus for further research towards 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.

Conclusions. The authors of the work conducted a study and analysis of the influence of the specific heat capacity of the raw material, which is fermented in a vertical-type reactor, on the change in the Prandtl criterion, heat transfer (k) and heat transfer coefficients (α_2), as well as the Reynolds criterion. Graphical dependences were obtained that characterize the change in the value of the heat transfer and heat transfer coefficients depending on the change in the specific heat capacity and the speed of rotation of the mixing device. The percentage change in the Reynolds criterion, heat transfer and heat transfer coefficients when changing the speed of rotation of the mixing device in which the heating element is installed was established. It was established that the change in the Prandtl criterion depending on the change in the specific heat capacity of the raw material occurs according to a linear law. The use of the obtained results in combination with previous studies concerning the influence of physicochemical parameters on energy consumption provides an impetus for further research towards 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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ВПЛИВ ПИТОМОЇ ТЕПЛОЄМНОСТІ СИРОВИНИ, ЩО ЗБРОДЖУЄТЬСЯ У БІОГАЗОВОМУ РЕАКТОРІ НА ТЕПЛОРОЗПОДІЛ

М.О. Сподоба, О.О. Сподоба

Анотація: *З кожним роком, використання біогазових технологій дає поштовх до розробки нових способів поводження з накопиченими відходами сільськогосподарських та побутових об’єктів. Тому, актуальним питанням є зниження енергетичних витрат на підтримку мікроклімату зброджування, з максимально можливим утворенням біогазу із певного виду сировини. Фізико-хімічні параметри мають суттєвий вплив на зброджування сировини та енергетичні витрати. Метою* *роботи є аналіз впливу питомої теплоємності сировини, що зброджується у біогазовому реакторі на зміну критерію Прандтля та енергетичні витрати на підігрів. Наведено результати теоретичних досліджень, під час яких було проаналізовано вплив діапазону питомої теплоємності сировини від 1000 до 4000 Дж/кг ^{0}С на енергетичні витрати. Результатом є графічні залежності, які описують зміну коефіцієнту тепловіддачі та теплопередачі від нагрівального пристрою до сировини, зміну критеріїв Прандтля та Рейнольдса в залежності від зміни питомої теплоємності сировини та частоти обертання перемішуючого пристрою. Встановлено відсоткову зміну критерію Рейнольдса, коефіцієнтів тепловіддачі та теплопередачі при зміні частоти обертання перемішуючого пристрою. Встановлено, що зміна критерію Прандтля в залежності від зміни питомої теплоємності сировини відбувається за лінійним законом. Використання отриманих результатів у поєднанні з попередніми дослідженнями, які стосуються впливу фізико-хімічних параметрів на енергетичне споживання, дають поштовх у напрямку встановлення раціональної частоти обертання перемішуючого пристрою з точки погляду енергетичного споживання.*

Ключові слова: ***критерій Рейнольдса, критерій Прандтля, витрати енергії, електричний підігрів, питома теплоємність сировини, переробка органічних відходів***

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