SUBSTANTIATION OF MOTION PARAMETERS OF THE SUBSTRATE PARTICLES IN THE ROTATING DIGESTERS
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ОБҐРУНТУВАННЯ ПАРАМЕТРІВ РУХУ ЧАСТИНОК СУБСТРАТУ В МЕТАНТЕНКАХ, ЩО ОБЕРТАЮТЬСЯ

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ABSTRACT

To prevent inhomogeneity of the substrate, it is proposed to mix the substrate in a rotating digester. To determine the intensity of substrate components mixing, we have found the trajectory and speed of substrate mineral components movement and substrate organic components in the rotating digester. It was found that the uniform mixing and maximum interpenetration of organic and mineral components of the substrate is provided for the rational values of the digester angular velocity from 0.04 to 0.1 rad/s and the digester blades length from 75 to 80% of its internal radius.

АБСТРАКТ

Для уникнення розшарування субстрату пропонуються виконувати перемішування субстрату в обертовому метантенку. Для визначення рівномірності перемішування компонентів субстрату знайдено траєкторію і швидкість руху мінеральних компонентів та органічних компонентів субстрату в обертовому метантенку. Встановлено що рівномірне перемішування та взаємопроникнення органічних та мінеральних складових субстрату забезпечується за раціональних значень кутової швидкості метантенка від 0,04 до 0,1 rad/s та довжині лопаток метантенка від 75 до 80 % його внутрішнього радіуса.

INTRODUCTION

An important direction in renewable energy is the production of biogas *(Golub et al 2017a).* Biogas plants can use a wide variety of raw materials. In particular, biogas production from both plant biomass (*Shah et al, 2018*) and animal husbandry wastes *(Meyer et al, 2018)* has become widespread.

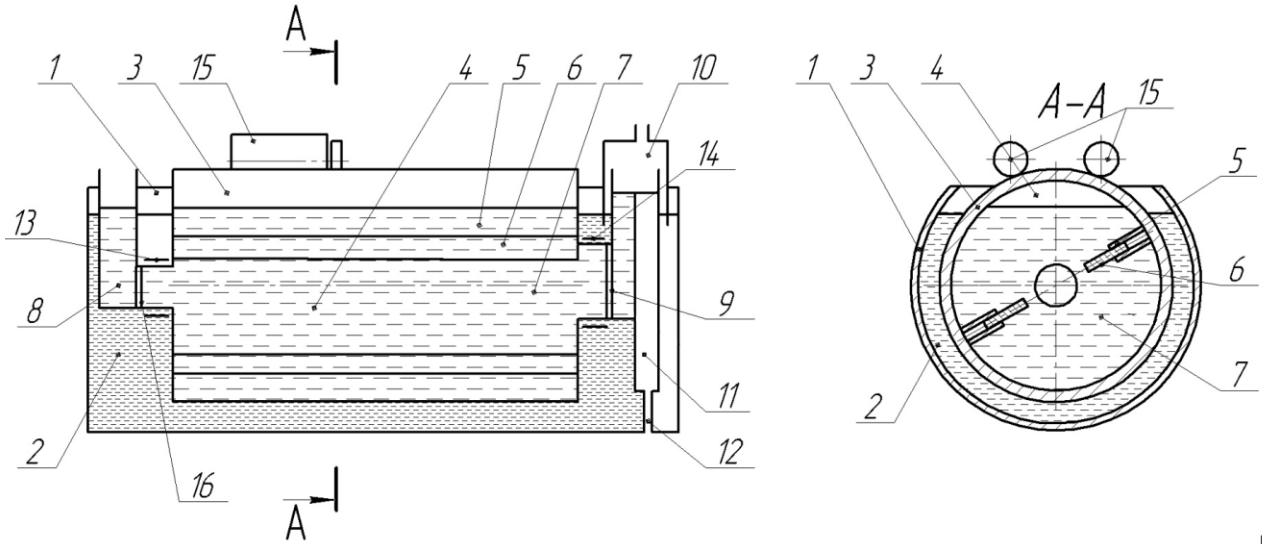
The efficiency of biogas production depends on the characteristics of biomass (density, dry matter content, dry matter particle size) and the characteristics of the digester (mixing intensity, geometric dimensions, the nature of the placement of blades, mixers and partitions inside the digester) *(Adouani et al, 2016; Carrerea et al, 2015)*. The efficiency of operation also depends on the control of energy consumed by the biogas plant (*Ogbonna et al, 2013*).

One of the main problems in the biogas production is the inhomogeneity of the substrate biomass inside the digester *(Golub et al, 2017b)*. The inhomogeneity of the substrate causes a violation of the availability of organic elements for the supply of methane-forming bacteria (*Theuerl et al, 2019*). Methane-producing bacteria have a density greater than the average density of the substrate in the biogas reactor and therefore, together with mineral particles, are accumulated in the lower part of the digester. And the bacteria food elements (the organic component of the substrate), having a density lower than the average density for the substrate, are accumulated in the upper part of the digester. Therefore, for effective interaction of anaerobic bacteria with biomass, substrate mixing is necessary *(Zhai et al, 2018*). However, too much mixing can disrupt the necessary contact between organic elements and methane-forming bacteria *(Uçkun et al, 2016)*. To solve this problem, it is proposed to use slow or periodic rotation of mixers (*Satjaritanuna et al, 2016)*. However, when using mechanical mixers, it is impossible to completely eliminate the inhomogeneity of biomass in the digester. Such mixing does not essentially eliminate stratification into mineral sediment and organic floating biomass (*Golub et al, 2017b; Theuerl et al, 2019)*.

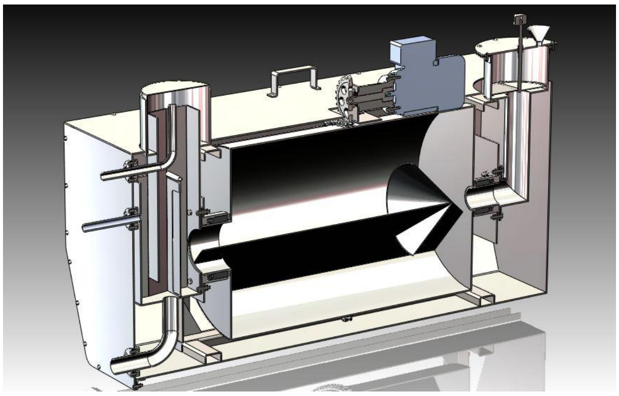
To eliminate biomass stratification, it is proposed to use rotating digester (*Golub et al, 2017b*; *Uvarov et al, 2017)*. In rotating digesters, substrate mixing is performed by raising the mineral component of biomass and methane-forming bacteria accumulating in the lower part of the digester and immersing the organic component of biomass accumulating in the upper part of the digester. Such mixing is effective due to energy consumption *(Golub et al, 2017b)*. However, there are no studies on the intensity of mixing of substrate components necessary to ensure uniform placement of biomass components in the methane tank. To determine the intensity of the substrate components mixing, it is necessary to find the trajectory and movement speed of mineral components (together with methane-forming bacteria) and organic components of the substrate in the rotating digester.

MATERIALS AND METHODS

It is proposed to perform mixing of the substrate in a rotating digester. The body of the digester is made in the form of a horizontal cylinder (fig. 1) which rotates around the horizontal axis. There are flat blades in the digester body. The digester rotates in the liquid, which is located in the outer casing. This design creates lift for the rotating digester by unloading the support bearings. The friction force in the bearings is reduced and, accordingly, the energy spent on the digester rotation and substrate mixing is reduced. The design of the digester eliminates the possibility of the formation of a floating organic part and submerged mineral sediment.



a)

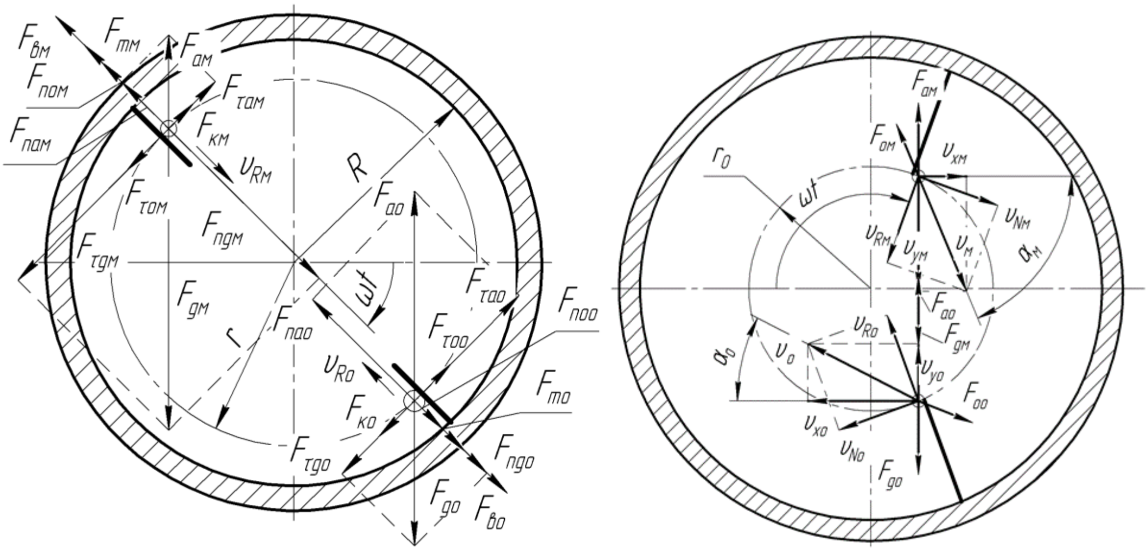


b)

Fig. 1 - Biogas plant

a – scheme, b – model: 1 – horizontal outer housing; 2 – liquid; 3 – rotating digester; 4 – fermentation chamber; 5 – partition; 6 – movable plates; 7 – organic mass; 8, 12 – sockets; 9, 16 – interpolator 10 – gas collector; 11 – the discharge chamber; 13, 14 – bearing joints; 15 – external drive.

To determine the relative velocity and establish the trajectory of the biomass particles, it is necessary to take into account the forces acting on the particles of the substrate mineral component (together with methane-producing bacteria) and on the particles of the substrate organic component. These forces are shown in the cross section image of the digester (fig. 2).



a b

Fig. 2 - Scheme of action of forces on mineral (*M*) and organic (*O*) substrate particles
(a – when interacting with the blades, b – in free movement)

F_g – gravitation force, N; F_a – Archimedes' force, N; F_m – friction force, N; $F_к$ – compound centrifugal force, N; $F_в$ – centrifugal force of inertia, N; F_o – the resistance of the substrate, N; $F_{τg}$, $F_{τa}$, $F_{τo}$ – the components of the forces of gravity, Archimedes and the resistance of the substrate, perpendicular to the blade, N; F_{ng}, F_{na}, F_{no} – the components of the forces of gravity, Archimedes and the resistance of the substrate along the blades, N; r – the current radius of the substrate particle position, m; R – the inner radius of the reactor, m; r_0 – the radius at which the blades end, m; υ – absolute particle velocity, m/s; $υ_R$ – relative particle velocity, m/s; $υ_N$ – the normal speed of the particle during the descent off the blade, m/s; $υ_x$ – the projection of the absolute velocity of a particle on the axis x, m/s; $υ_y$ – the projection of the absolute velocity of a particle on the axis y, m/s; α – the angle between the absolute velocity and its projection on the axis x, rad; ωt – the angle of the reactor rotation, rad

The substrate particles moving on the blades of the digester during its rotation are influenced by friction force, resistance force of the medium, centrifugal force, Archimedes' force and compound centrifugal force.

The friction force is determined by the forces which press the particles to the blade or tear them off the blade:

$$F_m = f\left(F_{\tau o} \pm F_{\tau g} \mp F_{\tau a} - F_{\kappa}\right), \tag{1}$$

where:

$F_{τo}$ – component resistance force of the substrate is directed perpendicular to the blade, [N];

$F_{τg}$ – the component of the particle's gravity force is directed perpendicular to the blade, [N];

$F_{τa}$ – the component of Archimedes' force for a particle directed perpendicular to the blade, [N];

$F_к$ – compound centrifugal force of the particle, [N];

f – friction coefficient of the substrate over the reactor blade material, [rel. un.].

It is also well-known that:

$$F_{в} = mr\omega^2;\; F_g = mg;\; F_a = \rho_c gV;\; F_{\kappa} = 2m\omega\frac{dr}{dt};F_{no} = mk_1\frac{dr}{dt};\; F_{\tau o} = mk_1 r\omega, \tag{2}$$

where: *m* – particle weight, [kg];

ω – the angular velocity of the reactor rotation, [rad/s];

r – the current radius of the substrate particle position, [m];

g – acceleration of gravity, [m/s^2];

V – the volume of the particle, [m^3];

k_1 – coefficient of proportionality in laminar flow of the substrate around the particles, [s^{-1}]; $k_1=18\eta/(\rho_c d_E^2)$;

k_2 – the ratio of the density of the substrate and the particle, $k_2=\rho_c/\rho$; ρ_c – substrate density, [kg/m^3];

ρ– particle density, [kg/m^3];

η – dynamic viscosity of the substrate, [Pa s];

d_E – equivalent particle diameter, [m].

The substrate particles, moving inside the reactor after descent off the blades, are influenced by the friction force, Archimedes' force and the force of the medium resistance:

$$F_g = mg;\ F_a = mk_2 g;\ F_o = mk_1 \upsilon . \tag{3}$$

To establish the trajectory of the biomass particles, differential equations of substrate particles motion over the digester blade and after the decent of the blades inside the rotating digester are composed.

A research facility has been designed in order to provide evidence to the theoretical research (fig.3).

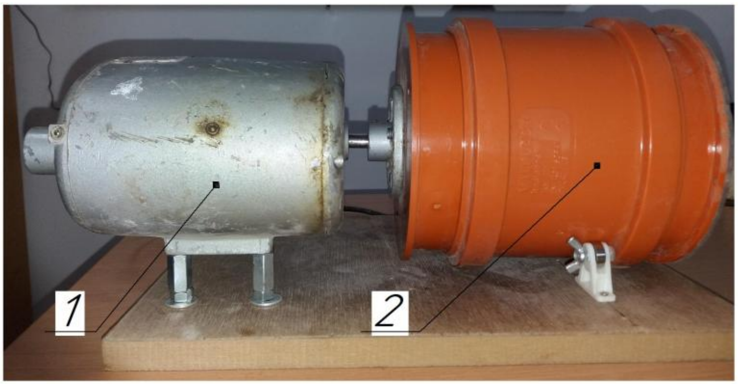


Fig. 3 - Research plant

1 – electric drive, 2 –the body of the plant (horizontal cylinder)

The body of the research plant is made in the form of a horizontal cylinder which rotates around the horizontal axis. There are two flat blades in the body of the plant. The inside radius of the body is 0.2 m and the blade length is 0.15 m. The electric drive can change the plant's rotation frequency.

For this research plant were chosen the substrate components which provide the average substrate density in the range of 1020-1050 kg/m^3, the density of the mineral substrate part in the range of 1150-1250 kg/m^3 and the density of the organic substrate part in the range of 800-900 kg/m^3. The content of the organic substrate part is 8% of the whole substrate volume, the content of mineral substrate part is 5% of the whole substrate volume.

RESULTS

The differential equation of the substrate particle motion in the form of a material point over the rotating reactor blade will have the following form:

$$m\frac{d\bar{\upsilon}_R}{dt} = \bar{F}_{na} + \bar{F}_{в} + \bar{F}_m + \bar{F}_{no} + \bar{F}_{ng}\ , \tag{4}$$

where $F_в$ – centrifugal force of the particle inertia, [N]; F_m – particle friction force, [N]; F_{na} – the component of Archimedes' force directed along the blade, [N]; F_{no} – component force of the substrate resistance directed along the blade, [N]; F_{ng} – the component of the particle's gravity directed along the blade, [N]; υ_R – relative velocity of the particle while moving along the blade, [m/s].

Subject to Eq. (1) and Eq. (2), Eq. (4), the differential equation of a substrate particle motion over the surface of the rotating reactor blade, can be written as follows:

$$\frac{d^2 r}{dt^2} + \left(2f\omega + k_1\right)\frac{dr}{dt} - \left(\omega^2 - fk_1\omega\right)r = -g\left[f\left(1-k_2\right)\cos\left(\omega t\right) + \left(1-k_2\right)\sin\left(\omega t\right)\right] \tag{5}$$

This equation is a second-order linear equation with constant coefficients and the right-hand side as a trigonometric polynomial.

The complete solution of the differential equation of motion has the form:

$$r = C_1\exp\left(\lambda_1 t\right) + C_2\exp\left(\lambda_2 t\right) + \frac{g\left(1-k_2\right)}{\omega\sqrt{4\omega^2 + k_1^2}}\sin\left(\operatorname{arctg}\frac{4f\omega + k_1\left(1-f^2\right)}{2\left[\omega\left(1-f^2\right) - fk_1\right]} + \omega t\right)\ , \tag{6}$$

where:

$$\lambda_1 = -\left(f\omega + \frac{k_1}{2}\right) + \sqrt{\omega^2\left(1+f^2\right) + \frac{k_1^2}{4}};\ \lambda_2 = -\left(f\omega + \frac{k_1}{2}\right) - \sqrt{\omega^2\left(1+f^2\right) + \frac{k_1^2}{4}}\ .$$

In this case, the relative velocity of the substrate particle while moving over the blade will be:

$$\upsilon_R = \frac{dr}{dt} = \lambda_1 C_1 \exp(\lambda_1 t) + \lambda_2 C_2 \exp(\lambda_2 t) + \\ + \frac{g(1-k_2)}{\sqrt{4\omega^2 + k_1^2}} \cos\left(\text{arctg} \frac{4f\omega + k_1(1-f^2)}{2\left[\omega(1-f^2) - fk_1\right]} + \omega t \right). \quad (7)$$

Considering the initial conditions: t=0, r=R (where R – the inner radius of the reactor), υ_R=0, stable integration can be defined by the expressions:

$$C_1 = \frac{\lambda_2}{\lambda_2 - \lambda_1}\left[R - \frac{g(1-k_2)}{\omega\sqrt{(4\omega^2 + k_1^2)}}\sqrt{1 + \frac{\omega^2}{\lambda_2^2}} \sin\left(\text{arctg} \frac{4f\omega + k_1(1-f^2)}{2\left[\omega(1-f^2) - fk_1\right]} - \text{arctg}\frac{\omega}{\lambda_2} \right) \right],$$
$$C_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1}\left[\frac{g(1-k_2)}{\omega\sqrt{(4\omega^2 + k_1^2)}}\sqrt{1 + \frac{\omega^2}{\lambda_1^2}} \sin\left(\text{arctg} \frac{4f\omega + k_1(1-f^2)}{2\left[\omega(1-f^2) - fk_1\right]} - \text{arctg}\frac{\omega}{\lambda_1} \right) - R \right]. \quad (8)$$

Using the obtained solutions of the differential equation of particle motion it is possible to find the distance (movement) covered by the biomass particles and the speed of its movement for a set period of time.

For example, the calculated displacements and velocity of a mineral particle (together with methane-producing bacteria) for an angular velocity of 0.1 rad/s of a digester with an internal radius of 2 dm are shown in fig. 4.

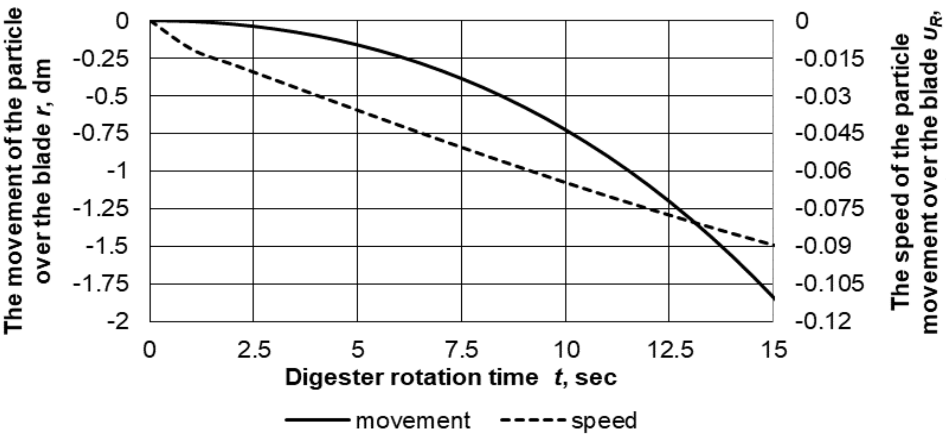


Fig. 4 - The dependence of the movement over the digester blade and the speed of the mineral particle on the rotation time (angular velocity of the digester rotation ω=0.1 rad/s, **inner radius *R*=2 dm)**

The minus sign on the charts indicates that the mineral particle relative to the digester blade is moving to its centre, that is, the current radius of the substrate particle position is decreasing.

The displacement and velocity of the organic particle for the digester rotation angular velocity of 1 rad/s with an internal radius of 2 dm are shown in fig. 5.

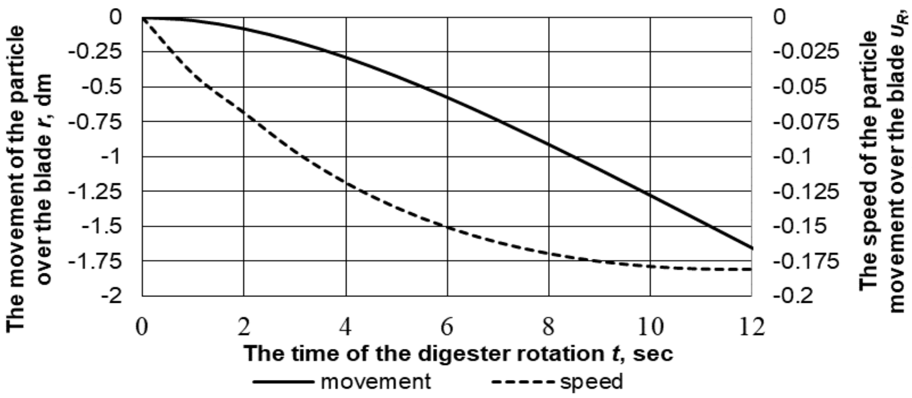


Fig. 5 - The dependence of the movement over the digester blade and the speed of the organic particle on the rotation time (angular velocity of the digester rotation ω=0.1 rad/s, inner radius *R*=2 dm)

A minus sign on the graph indicates that the organic particle relative to the digester blade is also moving to its centre, that is, the current radius of the substrate organic particle position is decreasing.

The calculated scheme of the effect of forces on the substrate mineral and organic particles, which are in free motion in the rotating reactor volume is shown in fig. 2, b.

According To Eq. (3) and taking into account that the mineral particle will sink and the organic one will float, it was composed the equation of motion of such particles mass centre:

$$\begin{cases} \dfrac{d^2x}{dt^2} = \mp k_1 \upsilon \cos\alpha, \\ \dfrac{d^2y}{dt^2} = g\left(k_2 - 1\right) \pm k_1 \upsilon \sin\alpha, \end{cases} \tag{9}$$

where:

x – the movement of the particle along the abscissa axis, [m];

y – the movement of the particles along the axis of ordinates, [m];

t – the time of particle movement after descent off the reactor blade, [s].

To determine the trajectories of mineral and organic particles after the descent off the reactor blades, it was used the method of sequential differentiation, which gives approximate solutions of the systems Eq. (9) in the form of Taylor series.

Considering the initial conditions corresponding to the absolute velocity at the time of the biomass particle descent off the blade $\upsilon=\upsilon_0$, the angle between the absolute velocity and its projection on the axis at this moment is $\alpha=\alpha_0$, and $x_0=0$, $y_0=0$, it can be written:

$$\begin{cases} x = \dfrac{\upsilon_0 \cos\alpha_0}{k_1}\left[\pm 1 \mp \exp\left(-k_1 t\right)\right] \\ y = \dfrac{\upsilon_0 \sin\alpha_0}{k_1}\left[\pm \exp\left(-k_1 t\right) \mp 1\right] \pm \dfrac{g\left(1-k_2\right)}{k_1^2}\left[1 - k_1 t - \exp\left(-k_1 t\right)\right] \end{cases} \tag{10}$$

The first equation of the system (10) allows determining the time of particle motion:

$$t = \frac{1}{k_1}\ln\left(\pm 1 \mp \frac{x k_1}{\upsilon_0 \cos\alpha_0}\right) \tag{11}$$

After substituting Eq. (11) in the second equation of the system (10) we obtain the equation of the particles trajectory after their descent off the digester blades:

$$y = x tg\alpha_0 + \frac{g\left(1-k_2\right)x}{k_1 \upsilon_0 \cos\alpha_0} + \frac{g\left(1-k_2\right)}{k_1^2}\ln\left(\pm 1 \mp \frac{x k_1}{\upsilon_0 \cos\alpha_0}\right) \tag{12}$$

where

α_0 – the angle between the absolute velocity of the mineral particle and its projection on the abscissa axis at the moment of particle decent of the digester blade, [rad];

υ_0 – absolute speed of the mineral particle at the moment of the decent of the digester blade, [m/s];

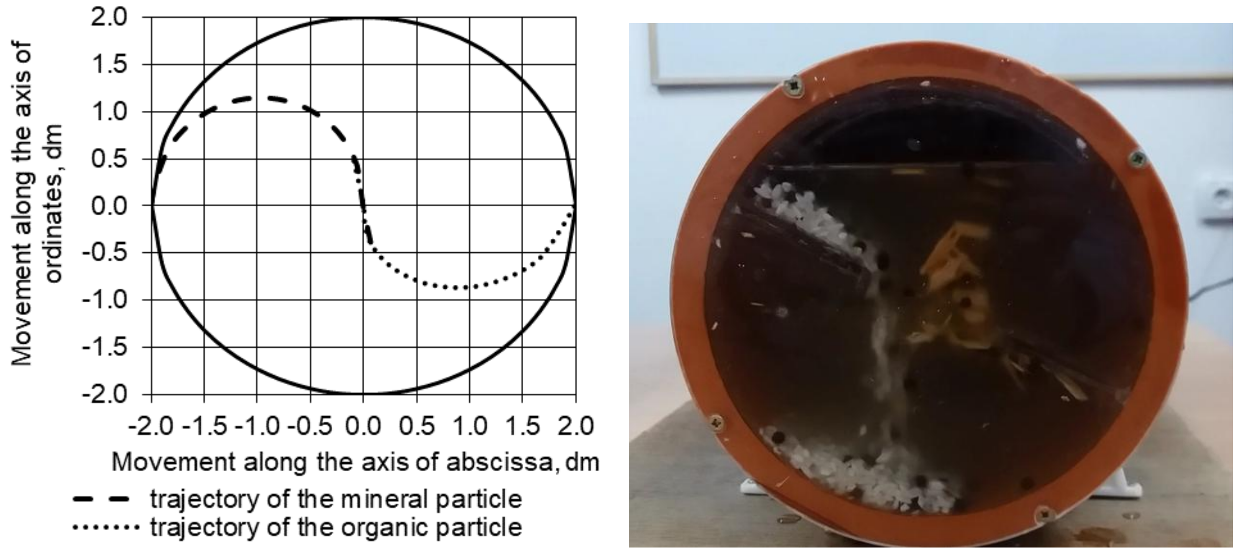
x – moving of the mineral particle along the axis of abscissa, [m];

y – moving of the mineral particle along the axis of ordinates, [m].

According to Eq. 12, the trajectory of the components particles after the decent of the blade can be found.

In the rational values range of the digester rotation angular velocity and its internal (working) radius based on the equations of motion of substrate components mineral and organic particles over the digester blades and after the descent off the blades, the trajectory of particles inside the digester was found (fig. 6 and fig. 7).

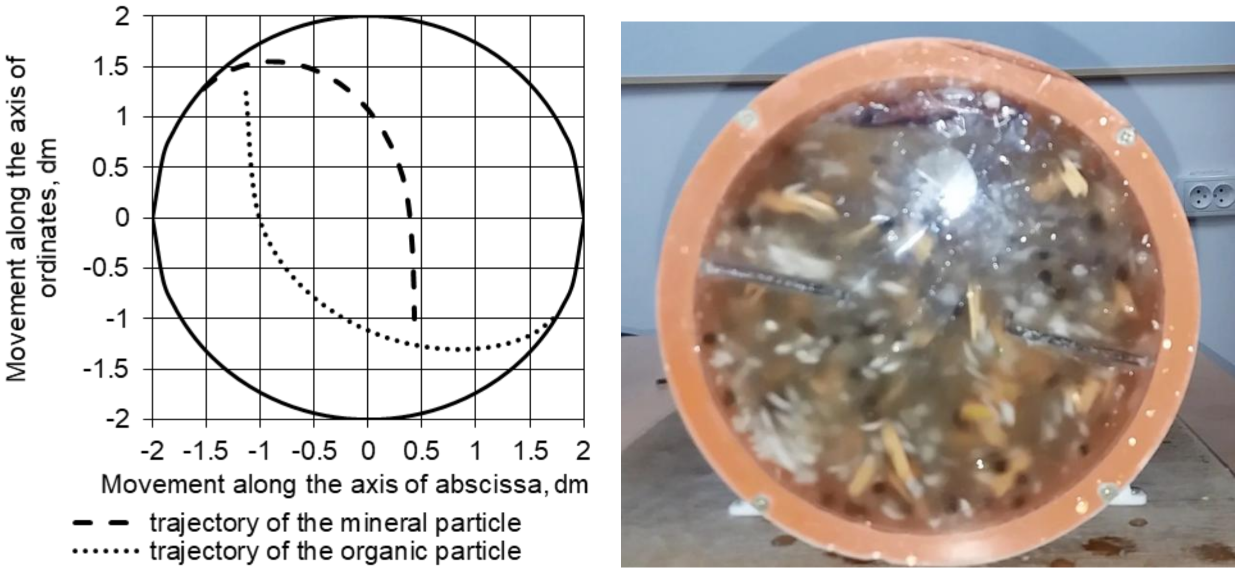
Based on the theoretical obtained solutions of the equations, it is established that at the average density of the substrate ρ_c = 1025-1050 kg/m^3, the mineral part of the substrate $\rho_м$=1150-1250 kg/m^3 and the organic part of the substrate ρ_o = 800-900 kg/m^3 the rational values of the digester angular velocity are ω=0.04-0.1 rad/s. The length l of the digester blade: $l=(0.75\text{-}0.8)R$.



a) b)

Fig. 6 - An example of the trajectory of the movement of the substrate particles (angular velocity of the digester rotation less than 0.04 rad/s, inner radius 2 dm)

a – theoretical results; b– experimental results



a) b)

Fig. 7.- An example of the trajectory of substrate particles movement (angular velocity of the digester rotation 0.1 rad/s, inner radius 2 dm)

a – theoretical results; b – experimental results

It has been experimentally proved that the angular velocity of 0.1 rad/s will provide uniform mixing and interpenetration of the substrate components. Under the rotary speed of less than 0.04 rad/s the mixing is not sufficient.

CONCLUSIONS

It is proposed to perform mixing of the substrate in a rotating digester. The body of the digester is made in the form of a horizontal cylinder that rotates around a horizontal axis. Inside the digester, there are flat blades. The digester rotates in the liquid, which is located in the outer casing. This design creates lift for the rotating digester by unloading the support bearings. The friction force in the bearings is reduced and, accordingly, the energy spent on the digester rotation and substrate mixing is reduced. The design of the digester eliminates the possibility of creating a floating organic part and submerged mineral sediment.

It was found that the uniform mixing and interpenetration of organic and mineral components of the substrate is provided for the rational values of the angular velocity of the digester from 0.04 to 0.1 rad/s and the length of the reactor blades from 75 to 80 % of its internal radius. At these values of the angular velocity and blade length, the mineral particles (together with methane-producing bacteria) will rise to the upper part of the digester, after which the particles will separate from the blade and move downwards, and the substrate organic particles will sink into the lower part of the digester, after which they will be separated from the blade and move upwards, thereby ensuring uniform mixing and interpenetration of the substrate components.

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