Computer modeling movement of biomass in the bioreactors with bubbling mixing

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Abstract. Recently in the Russian Federation there is an observation of the development of biogas technologies which are used in organic waste conversion of agricultural enterprises, consequently improving the ecological environment. To intensify the process and effective outstanding performance of the acquisition of biogas the application of systems of mixing of bubbling is used. In the case of bubbling mixing of biomass in the bioreactor two-phase portions consisting of biomass and bubbles of gas are formed. The bioreactor computer model with bubble pipeline has been made in a vertical spiral form forming a cone type turned upside down. With the help of computing program of OpenFVM-Flow, an evaluation experiment was conducted to determine the key technological parameters of process of bubbling mixing and to get a visual picture of biomass flows distribution in the bioreactor. For the experimental bioreactor the following equation of V=190 l, speed level, the biomass circulation, and the time of a single cycle of u_{ax}=0,029 m/s; Q_C=0,00087 m^3/s, $\Delta t_{bm.}$=159 s. In future, we plan to conduct a series of theoretical and experimental researches into the mixing frequency influence on the biogas acquisition process effectiveness.

1. Introduction

Lately, the biogas stations and equipment have been introduced into the agricultural industry on the territory of the Russian Federation, whose main objective is the recycling of organic waste [1-3]. The recycling takes place due to active life activity of microorganisms which transform proteins, fats and carbohydrates into methane and carbon dioxide. To provide a comfortable environment for reproduction and activity of microorganisms, it is necessary to maintain a certain uniform temperature and distribution of bacteria all over the biomass. For the solution of these problems lately, a combination use of various design devices is applied, currently the systems of mixing of bubbling type have been installed in the biogas reactor [4-6].

An original design of the bioreactor has been developed (fig. 1) [7]. The novelty of the bioreactor construction is the system of mixing device type which represents an evenly perforated pipe created in a form of vertical spirals formed in a turned down cone towards the base. Hence the biogas enters the bubbling pipeline in bubble forms, which when rising under the tangential force, push the biomass in the vertical direction. As a result of the underlying rising bubbles formed there is a biomass suction discharge. Thus, there is an observation of liquid-gas circulation flow and intensive mixing environment in the bioreactor device.

Currently the main method of bubbling hydrodynamics studies remaining is carried out in the laboratory and industrial experiments, of subsequent mathematical handling data have been obtained [5,

6]. However lately the methods of mathematical and computer modeling of two-phase flows of bubble disperse phase have increased [8].

Figure 1. The bioreactor with system of hashing of bubbling type.

2. Methods

2.1. Mathematical model
A mathematical model of the bubbling stirring biomass, involving the biomass and equations of motion of the bubbles of biogas has been developed [9].

Given the high consumption rate of gas bubbling so the description of the motion adopted in the biomass Reynolds equations for average turbulent motion, have been taken [10, 11]:

$$\frac{du_j}{dx_j} = 0 \tag{1}$$

$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j} \Pi_{ij} + F_i \tag{2}$$

u_i – the velocity vector of biomass, m/s; P – the average pressure value, Pa; μ [mu] – coefficient dynamic viscosity; F_i – strength of interfacial interaction, N; Π_{ij}, – turbulent stress tensor in the biomass, m^2/s^2; ρ [rho] – the density of biomass, kg/m^3.

To describe the motion of bubbles of the biogas a transfer equation of the bubble pulse has been made in a complete quasi environment:

$$\frac{\partial \beta}{\partial t} + \frac{\partial (\beta \upsilon_j)}{\partial x_i} = 0 \tag{3}$$

$$\rho_g \frac{\partial (\beta \upsilon_i)}{\partial t} + \rho_g \upsilon_j \frac{\partial (\beta \upsilon_i)}{\partial x_j} = -\rho_g \beta f_D (\mathrm{Re}_n) \frac{\upsilon_i - u_i}{\tau_P} - \beta(\rho - \rho_g) g_i + \frac{\partial (\beta \Pi_{ij}^P)}{\partial x_j}. \tag{4}$$

β [beta] – The concentration volume of bubbles, %; υ_i [upsilon] – the velocity vector "liquid bubble", m/s; τ_P [tau] - the dynamic relaxation time of bubble, s; f_D - the resistance function; Π_{ij}^P - the turbulent tensor stress in the "liquid bubble", m^2/s^2, ρ_g – [rho] density of the gas fed to the mixing kg/m^3.

2.2. Computer model

The developed mathematical model of bubbling mixing of biomass was made by means of software computing aerodynamics package of OpenFVM-Flow. The volume control method is applied to modeling of the spatial two-phase flow.

The basic data used in the computer modeling of bubbling mixing of biomass are constructive and technological parameters of the experimental bioreactor: the bioreactor height is H_b=1 m, the internal diameter of the bioreactor D_b = 0,5 m, the biomass column height H_{bm}=0,7 m, the density and viscosity of biomass are respectively equal to: ρ=1040 kg/m^3, μ=1,25·10^{-3}, the hole number of the bubbler is n_h=27, the diameter of a hole is d_h=0,001 m, the velocity of the escaping bubbling gas is v_h=30 m/s, the rotation number of bubbling in the pipeline is n_t=4, the external diameter of the bubbling pipe is d_{bp}=0,017 m, the bubbling gas consumption is Q_g=0,00064 m^3/s, its determined velocity is v_r=0,0032 m/s, the average diameter of the bubbling gas is d_b=0,005 m.

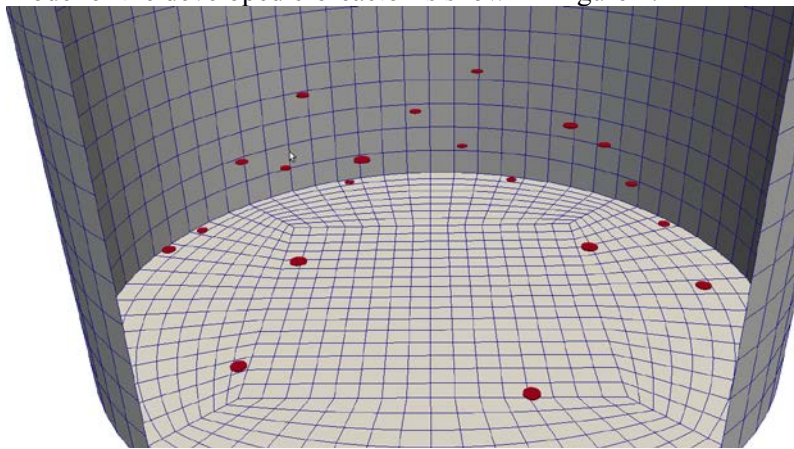The computer model of the developed bioreactor is shown in figure 2.

Figure 2. Computer model of the bioreactor with bubbling mixing of biomass:
• - holes of the bubbling gas-distributor.

3. Results and discussions

The results of computer modeling experiments of the bubbling mixing of biomass are given in the figure 3.

In figure 3 it is possible to visualize that the biomass movement initiated by a column of emerging bubbles of the bubbling gas has a complicated spatial feature. It has equally been confirmed that the bubbled biomass has characteristic movement:

– the bubbled movement of the biomass has circular character: the central area of the reactor is occupied by the escaping biomass, reaching the free surface, turning in the opposite direction, forming a circular along the container of the bioreactor;

– the axial component of velocity of the flow of the biomass $u_z(R)$ c with the reduced value of R increases and reaches the maximal value of the reactor axis which is u_{ax};

– the biomass flow velocity occupying the circular area, increases the R in absolute value, reaching the maximum value $R=R_1$, and then reducing to zero against the internal surface of the reactor case.

To preserve the mass of substratum it is necessary that its current complete circulation should be equal to zero:

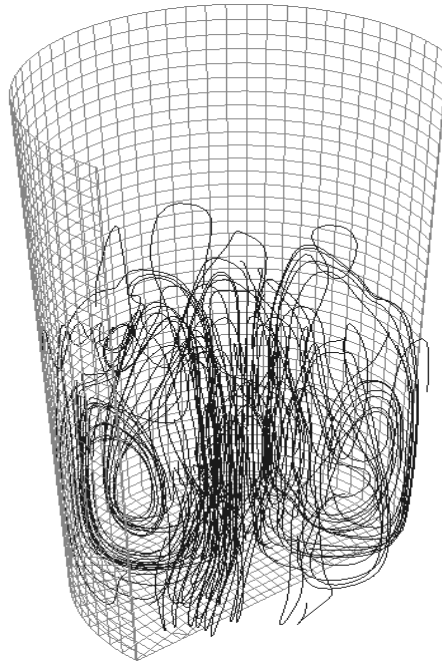$$Q = \int_0^{R_b} u_z(R)\, R\, dR = 0 \qquad (5)$$

Figure 3. Visual lines of the current of the bubbled biomass.

Under real condition the axial velocity component of biomass depends not only on R, but also on the axial movements of Z. In particular, $u_z=0$ in the reactor base and the free biomass surface. In this regard $u_z(R)$ is the axial velocity of the biomass averagely distributed on all the layer height:

$$u_z(R) = \frac{\int_0^{H_{bm}} u_z(R,Z)\, dZ}{H_{bm}} \qquad (6)$$

The features of distribution of the axial biomass component velocity can approximately be defined along the bioreactor radius in the fourth multifunctional degree:

$$\tilde{u}(x) = Ax^4 + Bx^3 + Cx^2 + Dx + E \qquad (7)$$

$\tilde{u}(x) = u_Z/u_r$, $x = R/R_b$.

The coefficients of equation (7) are defined in the system of linear equations which are stated in the following conditions:

$$D = 0, \quad E = \tilde{u}_{ax} \qquad (8)$$

$$Ax_0^4 + Bx_0^3 + Cx_0^2 + \tilde{u}_{ax} = 0 \qquad (9)$$

$$4Ax_1^2 + 3Bx_1 + 2C = 0 \qquad (10)$$

$$A + B + C + \tilde{u}_{ax} = 0 \qquad (11)$$

$$\frac{A}{6} + \frac{B}{5} + \frac{C}{4} + \frac{\tilde{u}_{ax}}{2} = 0 \qquad (12)$$

$\tilde{u}_{ax} = u_{ax}/u_r$, $x_0 = R_0/R_b$, $x_1 = R_1/R_b$.

The coefficients of A, B, and C are defined in the equations of (9…12):

$$A = -\frac{15x_0^3 - 18x_0^2 + 3}{3x_0^4 - 5x_0^3 - 2x_0^2} \cdot \tilde{u}_{ax} \tag{13}$$

$$B = \frac{5 \cdot (3x_0^4 - 4x_0^2 + 1)}{3x_0^4 - 5x_0^3 - 2x_0^2} \cdot \tilde{u}_{ax} \tag{14}$$

$$C = -\frac{2 \cdot (9x_0^4 - 10x_0^3 + 1)}{3x_0^4 - 5x_0^3 - 2x_0^2} \cdot \tilde{u}_{ax} \tag{15}$$

According to the defined coefficients A, B and C x_1 is determined in relation to the radius on which the velocity of the down biomass flow reaches a maximum value:

$$x_1 = \frac{-3B \pm \sqrt{9B^2 - 16AC}}{8A} \tag{16}$$

The selection of two possible x_1 values depends on the equation obtained out of $x_0 < x_1 < 1$.

To resolve ratio equations of (7), (13...15), that provide the profile determination of the axial biomass velocity it is necessary to calculate the value of $\tilde{u}_{ax}$ and x_0.

A series of computing experiments was conducted to investigate the dependence on the technological parameters which have the greatest impact on the bubbling biomass mixture intensity: at specified velocity of the bubbling gas υ_r (0,0025≤υ_r≤0,1 м/с) and the reactor diameter D_b (0,25≤D_b≤10 м).

The processing results of the computing experiment have shown that the parameters of $\tilde{u}_{ax}$ and x_0 can be presented in the form of functions of the Reynolds figures of the bioreactor:

$$\mathrm{Re}_b = \frac{\upsilon_r D_b \rho}{\mu} \tag{17}$$

The method of the smallest squares on depending on the $\tilde{u}_{ax}(\mathrm{Re}_b)$ и $x_0(\mathrm{Re}_b)$ has been also arrived at by the following expressions:

$$\tilde{u}_{ax} = 1,06 lg^2 \mathrm{Re}_b - 12,43 lg \mathrm{Re}_b + 37,25 \tag{18}$$

$$x_o = 0,66 - 0,022 lg \mathrm{Re}_b \tag{19}$$

For the experimental bioreactor the following values have been arrived at by Re_b=1373; $\tilde{u}_{ax}$=8,7; x_0=0,59; x_1=0,83; R_0=0,15 m; $\tilde{u}_{ax}$=0,029 m/s, and the equation (7) describing the axial biomass profile velocity is shown in figure 4.

$$\frac{u}{u_{ax}} = 5,63x^4 - 4,39x^3 - 2,24x^2 + 1 \tag{20}$$

According to the obtained profile from the axial biomass velocity (fig. 4) we were able to determine that the circulation equals to the spatial volume flow:

$$Q_C = 2\pi \int_0^{R_0} u_Z(R) R\,dR = 2\pi R_b^2 u_{ax} \int_0^{x_0} \left(5,63x^4 - 4,39x^3 - 2,24x^2 + 1\right) x\,dx \tag{21}$$

For the bioreactor with a biomass volume V_{bm}=0,1372 m^3 the following parameters were received: u_{ax}=0,029 m/s; x_0=0,59; Q_C=0,00087 m^3/s.

As one of the characteristics of intensity of the bubbling mixing, the coefficient of mixing of biomass in the bioreactor which is K_m [12], is similar to the coefficient of air exchange in the ventilated production rooms and equals to the used volume of the current circulating to biomass amount:

$$K_m = \frac{Q_C}{V_{bm}}$$

(22)

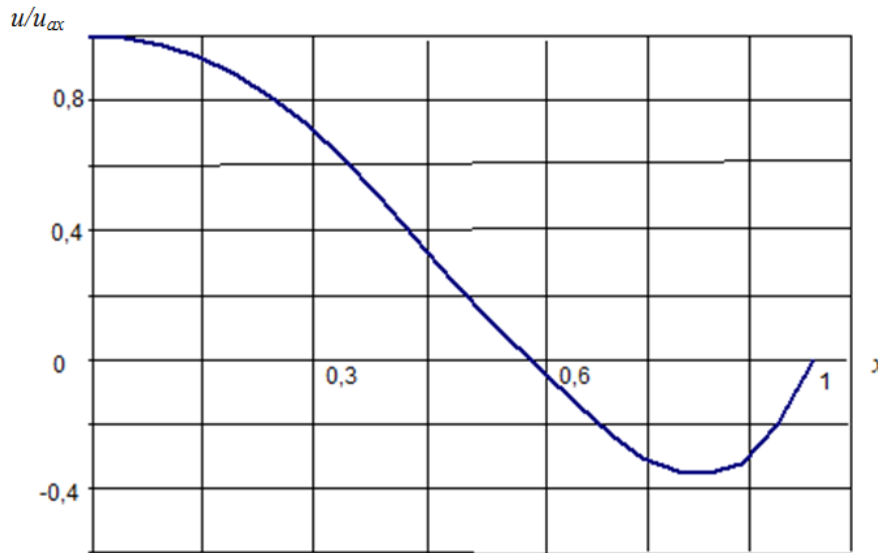**Figure 4.** The profile of the average axial biomass velocity.

The size of the reverse coefficient of mixing is equal to the minimum duration of Δt_{bm} one cycle of bubbling mixing of biomass during one cycle of the whole volume:

$$\Delta t_{bm} = \frac{1}{K_m}$$

(23)

4. Conclusion
On the basis of the developed mathematical computing model experiment the key parameter processes of the bubbling mixing has been determined and a visual picture of distribution of biomass flows in the bioreactor has been received. As a result of the data processed the experiment of the axial profile velocity of biomass flow was obtained. For the experiment in the bioreactor, the volume of V=190 l, the velocity, the circulation time of the biomass and one cycle time of mixing the following equation has been used u_{ax}=0,029 m/s; Q_C=0,00087 m^3/s, Δt_{bm} =159 s. The results of the entire research were used in the industrial calculation of constructive and technological parameters in industrial bubbling bioreactors. In future, we plan to conduct a series of theoretical and experimental researches into the mixing frequency influence on the biogas acquisition process effectiveness.

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