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To cite this article: L A Kuschev et al 2017 IOP Conf. Ser.: Earth Environ. Sci. 52 012025

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Computer modeling movement of biomass in the bioreactors with bubbling mixing

L A Kuschev, D YuSuslov, A I Alifanova
Belgorod Shukhov State Technological University, Street Kostyukova, 46, Belgorod, 308012, Russia
E-mail: Suslov1687@mail.ru

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 $V=190 \text{ l}$, speed level, the biomass circulation, and the time of a single cycle of $u_{ax}=0.029 \text{ m/s}$; $Q_C=0.00087 \text{ m}^3/\text{s}$, $\Delta t_{bm}=159 \text{ s}$. 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]:

\[
\frac{du_i}{dx_j} = 0 \quad (1)
\]

\[
\rho \frac{\partial u_i}{\partial t} + \rho u_i \frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j} \Pi_{ij} + F_i \quad (2)
\]

\(u_i\) – the velocity vector of biomass, m/s; \(P\) – the average pressure value, Pa; \(\mu\) \([\text{mu}]\) – coefficient dynamic viscosity; \(F_i\) – strength of interfacial interaction, N; \(\Pi_{ij}\) – turbulent stress tensor in the biomass, m\(^2\)/s\(^2\); \(\rho\) \([\text{rho}]\) – 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:

\[
\frac{\partial \beta}{\partial t} + \frac{\partial (\beta u_i)}{\partial x_i} = 0 \quad (3)
\]

\[
\rho_s \frac{\partial (\beta u_i)}{\partial t} + \rho_s u_i \frac{\partial (\beta u_i)}{\partial x_j} = -\rho_s \beta f_D(\text{Re}_s) \frac{\partial u_i}{\partial x_j} - \beta (\rho - \rho_s) \frac{\partial u_i}{\partial x_j} - \frac{\partial (\beta \Pi_{ij})}{\partial x_j}. \quad (4)
\]

\(\beta\) \([\text{beta}]\) – The concentration volume of bubbles, %; \(u_i\) \([\text{upsilon}]\) – the velocity vector "liquid bubble", m/s; \(\tau_p\) \([\text{tau}]\) - the dynamic relaxation time of bubble, s; \(f_D\) - the resistance function; \(\Pi_{ij}^p\) - the turbulent tensor stress in the "liquid bubble", m\(^2\)/s\(^2\); \(\rho_s\) \([\text{rho}]\) 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: $\rho=1040$ kg/m$^3$, $\mu=1.25\cdot10^{-3}$, 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 $u_h=30$ 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 $u_r=0.0032$ 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 $u_z(R)\text{c}$ 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:

$$Q = \int_0^R u_z(R) R dR = 0$$

(5)
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:

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

(6)

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

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

(7)

$$\bar{u}(x) = u_z/u_z, \quad x = R/R_b.$$  

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

$$D = 0, \quad E = \bar{u}_m$$

(8)

$$Ax_0^4 + Bx_0^3 + Cx_0^2 + \bar{u}_m = 0$$

(9)

$$4Ax_1^2 + 3Bx_1 + 2C = 0$$

(10)

$$A + B + C + \bar{u}_m = 0$$

(11)

$$\frac{A}{6} + \frac{B}{5} + \frac{C}{4} + \frac{\bar{u}_m}{2} = 0$$

(12)

$$\bar{u}_m = u_m/u_z, \quad x_0 = R_0/R_b, \quad x_1 = R_1/R_b.$$  

The coefficients of $A, B, \text{and } C$ are defined in the equations of (9…12):
According to the defined coefficients $A$, $B$ and $C$, $x_j$ is determined in relation to the radius on which the velocity of the down biomass flow reaches a maximum value:

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

(16)

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

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 $\tilde{u}_{\text{ax}}$ 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 $v_r$ ($0.0025 \leq v_r \leq 0.1 \text{ m/s}$) and the reactor diameter $D_b$ ($0.25 \leq D_b \leq 10 \text{ m}$).

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

$$\text{Re}_b = \frac{v_r D_b \rho}{\mu}$$

(17)

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

$$\tilde{u}_{\text{ax}} = 1.06l^2 \text{Re}_b - 12.43l \text{Re}_b + 37.25$$

$$x_0 = 0.66 - 0.022l \text{Re}_b$$

(18)

(19)

For the experimental bioreactor the following values have been arrived at $\text{Re}_b=1373$; $\tilde{u}_{\text{ax}}=8.7$; $x_0=0.59$; $x_j=0.83$; $R_0=0.15 \text{ m}$; $\tilde{u}_{\text{ax}}=0.029 \text{ m/s}$, and the equation (7) describing the axial biomass profile velocity is shown in figure 4.

$$\tilde{u}_{\text{ax}} = 5.63x^4 - 4.39x^3 - 2.24x^2 + 1$$

(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:

$$Q_c = 2\pi \int_0^{R_0} u_x(R) R dR = 2\pi R_0^2 \tilde{u}_{\text{ax}} \int_0^{R_0} \left(5.63x^4 - 4.39x^3 - 2.24x^2 + 1\right) x dx$$

(21)

For the bioreactor with a biomass volume $V_{bm}=0.1372 \text{ m}^3$ the following parameters were received: $u_{\text{ax}}=0.029 \text{ m/s}$; $x_0=0.59$; $Q_c=0.00087 \text{ m}^3/\text{s}$.

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:
The size of the reverse coefficient of mixing is equal to the minimum duration of $\Delta t_{bm}$ 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, $\Delta t_{bm}=159$ 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.

Acknowledgments

This work was supported by the Russian President's Scholarship SP - 1716.2015.1.

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