Hydrodynamics research of bubble mixing biomass process in biogas plants

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Abstract. This paper is devoted to the process of the bubble mixing biomass in biogas plants and its constructive ensuring. Bubble bioreactor is designed & equipped with a gas distributor made of pipe as a vertical spiral cone-shaped base facing down, with evenly placed openings for biogas output. The proposed design of the gas distributor ensures a spatial uniformity of distributing the bubbling gas, reduces stringency of moving chains of pop gas bubbles, what leads to intensification of interfacial bubbles interaction with the fermentation liquid mass, thereby the intensity of stirring is increasing. The hydrodynamic characteristics of the mixing system on the basis of the bubble gas distributing device are studied. There are the equations for determining the basic structural and technological parameters of the bubble mixing system: radial and axial steps between turns of bubbler, bubble pipe length, the relative volume content of the bubble phase, bubbles ascent rate, duration and energy expenses for one cycle of the bubble mixing. The expressions obtained were used for developing and designing industrial biogas plant.

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Introduction

In the Russian Federation the «State Program for Development of Agriculture and Regulation of agricultural production markets, raw materials and food" was adopted which focuses on the construction of livestock and poultry farms [1]. In the connection with it there was an environmental problem of recycling and disposal of manure, which are sources of soil contamination, water and air basin. In Russia annually about 1 billion tons of wastes, including wastes from agricultural enterprises are produced [2].

Currently the promising direction of recycling organic waste breeding complexes is the use of biogas plants [3]. In biogas plants under the certain conditions, there is the process of anaerobic fermentation of organic matter, resulting in the formation of energy product - biogas and highly efficient organic fertilizers [4].

An important parameter of the anaerobic fermentation process of manure in bioreactors is mixing biomass providing the constant contact of micro flora with the nutrient medium. The alignment of temperature distribution & concentration of dissolved and suspended substances promotes intensification of biochemical processes of biogas generation [5].

One of the effective ways of mixing biomass is bubbling, but the bubble mixing process of biomass is not sufficiently studied.

Methods

In this paper we applied the methods of classical hydro-and gas dynamics, the theory of mathematical modeling of two-phase gas-liquid flows.

The main part

Bubbling mixing method is the supply of the part of biogas produced through the gas distributor into the layer of biomass in the bioreactor.

Gas bubbles rising upwards carry away the adjacent layers of liquid biomass, what leads to the formation of its upward flow in the central zone of the reactor. This stream, reaching the free surface of the biomass changes its direction to the opposite one, in the result of this near the reactor walls downward circular flow is formed. Thus, an upward flow of bubbles of bubbling biogas causes the circulation of biomass in meridional reactor sections, what leads to its mixing [6].

Bubbling biomass mixing has some significant advantages over the widely used mechanical way of mixing with the help of stirrers:

- simple design, no moving mechanical parts and as a consequence - high reliability;
- large surface area between the liquid and gaseous (bubble) phases, what improves the conditions of biomass degassing and promotes biogas output increase;
- under bubbling organic material particles are transferred not only by a liquid phase stream, but

also rise (float) in the upper zone of the reactor due to their adhesion to the bubbles of biogas;

- non-contact that does not have the destructive hydrodynamic & cavitations influence on the micro flora;
- bubbling mixing prevents the formation of floating crust of insoluble biomass at its free surface.

It is considered that at the same flow rate of bubbling gas the quality of the mixing is determined by the constrictive features of gas distributor - bubbler [7]. In particular, an important condition for effective mixing is the uniformity of bubbling gas flow distribution through the section of the reactor .By trial it was found that such a gas distribution can be achieved using a vented pipe bent into the form of a flat spiral .

We have developed a bioreactor equipped with a gas distributor of the original design, which is a curved tube with holes in the form of tapered conical helix [8] (Figure 1).

The proposed design of the gas distributor ensures a spatial uniformity of distributing the bubbling gas, reduces stringency of moving chains of pop gas bubbles, what leads to intensification of interfacial bubbles interaction with the fermentation liquid mass.

Fig. 1. Bioreactor with bubbling gas distributor

Bubbler height Hgr (m) , the level of the first turn installation Z_0 (m), the largest radius of the first turn R_1 (m), the smallest radius of the last turn R_2 (m) and the number of turns *n* are given with regard to the size of the bioreactor.

Radial h_R (m) and axial h_z (m) steps of bubbler are calculated by the formulas:

$$h_R = \frac{R_1 - R_2}{n},\ h_z = \frac{H_{gr}}{n}. \qquad (1)$$

Parametric equations of a helix, on which bubble pipe is bent, have the following:

$$x = R(\varphi)\cos\varphi,\quad y = R(\varphi)\sin\varphi,\quad z = z_0 + h_z \cdot \frac{\varphi}{2\pi}, \qquad (2)$$

where $R(\varphi) = R_1 - h_R \dfrac{\varphi}{2\pi}$, φ (phi) - angle of rotation of the radius OM', where M' - the projection of the point *M* (*x, y, z*) on the plane $z=z_0$, $0 \le \varphi \le \varphi_2$, φ_2 - the final value of the rotation angle φ.

The length of the bubble pipe l_{bp} (m) depends on the final angle value of its rotation φ_2:

$$l_{bp}(\varphi) = \int_0^{\varphi_2} \sqrt{dx(\varphi)^2 + dy(\varphi)^2 + dz(\varphi)^2}\, d\varphi =$$

$$= \frac{R}{2\gamma_R}\left(\sqrt{1+\gamma^2} - (1-\gamma_R\varphi)\right)\sqrt{(1-\gamma_R\varphi)^2 + \gamma^2} - \gamma^2 \ln\frac{1-\gamma_R\varphi + \sqrt{(1-\gamma_R\varphi)^2+\gamma^2}}{1+\sqrt{1+\gamma^2}}, \qquad (3)$$

where $\gamma_R = h_R \big/ 2\pi R_1$, $\gamma^2 = (h_R^2 + h_z^2)/4\pi^2 R_1^2$.

If the gas distributor comprises n complete turns n , i.e. $\varphi = \varphi_2 = 2\pi n,$ then for the length of the bubble pipe from the formula (3) we obtain:

$$l_{bp} = \frac{\pi}{h_R}\left(R_1\sqrt{h^2+R_1^2} - R_2\sqrt{h^2+R_2^2} - h^2 \ln\frac{R_2+\sqrt{h^2+R_2^2}}{R_1+\sqrt{h^2+R_1^2}}\right), \qquad (4)$$

where $h^2 = (h_R^2 + h_z^2)/4\pi^2$,

$R_2 = R_1 - h_z \cdot n.$

Biomass, which is regarded as a continuous liquid phase, is a suspension of an aqueous solution of a number of chemicals and suspended there organic and ballast particles of dry component of manure. For effective process of biogas production at which the highest yield of biogas is achieved it is necessary to conserve biomass humidity and volume solids content of (dry) manure should not exceed 8,8-10 % [4]. Further we will calculate the volume water content, ie biomass humidity equals W = 0,9, and the volume content of the solid component of the biomass 1 -W = 0,1. Then the fermentation mass density ρ (rho), is given by:

$$\rho = W\rho_v + (1 - W)\rho_t, \quad (5)$$

where ρ_v = 1000 kg/m^3 - the density of water ; ρ_t = 1400 kg/m^3 - density of dry (solid) the substance of manure.

According to formula (5) biomass density is ρ = 1040 kg/m^3.

Biomass viscosity μ (Pa·s) depends not only on the volume content of dry substance & is determined by the following [7]:

$$\mu = \mu_v(1 + 2,5(1 - W)), \quad (6)$$

where μ_v = 0.001 Pa·s - dynamic viscosity of water.
It follows from formula (6) μ = 1,25 · 10-3 Pa·s.

The relative volume content of the bubble phase can be expressed in terms of volumetric flow rate of bubbling gas, bubble rise rate and the volume of the biomass. Let's assume that the biogas is supplied to the reactor & is not dispersed in the form of bubbles but ascends as a continuous compact flow with cross-sectional area F_g (m^2) and a rate equal to the average bubble rise rate υ_{av} (m/s), (Fig. 2). Then the volumetric gas flow Q (m^3/s) and occupied volume V_g (m^3) are defined:

$$Q = F_g\upsilon_{av}, \quad (7)$$

$$V_g = F_g H_{bm}, \quad (8)$$

where H_{bm} - layer height of bubbled biomass, m.

The relative volume content of the bubble phase - is equal to the ratio of volume occupied by bubbling gas to the across the volume of gas-liquid mixture V_m (m^3):

$$W_b = \frac{V_g}{V_m} = \frac{F_g H_{bm}}{F_{br} H_{bm}} = \frac{Q}{\upsilon_{av} F_{br}} = \frac{\upsilon_{re}}{\upsilon_{av}}, \quad (9)$$

where $\upsilon_{re} = Q / F_{br}$ - the given rate of bubbling gas, m/s, F_{br} - the cross sectional area of the reactor, m^2.

Value W_b is the magnitude averaged over the entire volume of the bioreactor volume concentration of bubbles value β (beta), equal to the total volume of the bubbles are in 1 m^3 bubbled liquid mixture:

$$W_b = \frac{\iiint_{V_{bm}} \beta(x,y,z)\,dx\,dy\,dz}{V_{bm}} \quad (10)$$

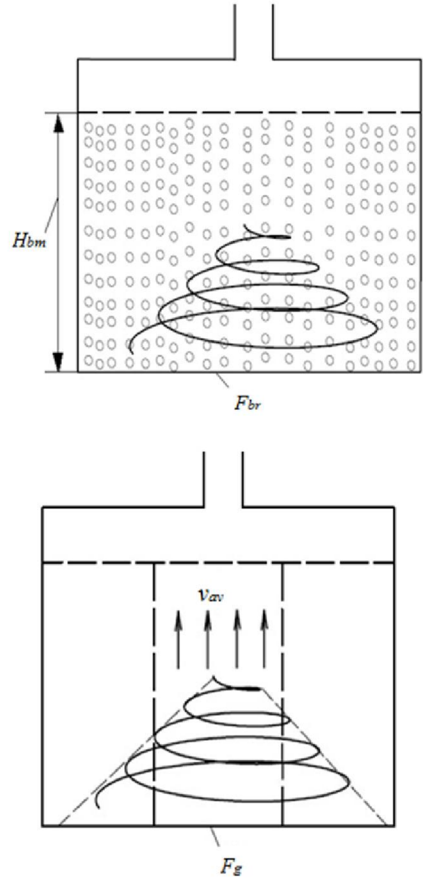

Fig.2. Calculation schemes for determining the relative volume of bubble phase content

The important characteristics of the bubble phase are also the average size of the bubbles, the mode of their formation and ascent rate. The size of the bubbles is determined by the mode of biogas output from bubbler holes. For the diameters of bubbler holes d_0 and biogas output rate υ_0, the following intervals of their rational values: $1 \le d_0 \le 3$ mm, and $20 \le \upsilon_0 \le 40$ m/s were established by experiment. Thus volume flow of the bubbling gas must meet the limit $\upsilon_{re} \ge 1$ m/s [6].

The nature of the bubble formation process and their size are determined by the dimensionless parameter F [7]:

$$F = 1 + \left(1 + \frac{We^2}{Fr}\right)^{1/2} \quad (11)$$

where $We = \upsilon_0^2 d_0 \rho / \sigma$ - Weber criterion $Fr = \upsilon_0^2 / (gd_0)$ - the Froude criterion; σ - (sigma) the surface tension of biomass, which is approximately equal to the surface tension of water σ =0,0727 N/m; g - acceleration of gravity , m/s^2 .

Expression (11) reduces to:

$$F = 1 + \left(1 + \frac{\upsilon_0^2 d_0^3 \rho^2 g}{\sigma^2}\right)^{1/2} = 1 + \left(1 + \frac{16 Q_o^{\ 2} \rho^2 g}{\pi^2 d_0 \sigma^2}\right)^{1/2} \quad (12)$$

where Q_0 - volumetric flow rate of bubbling gas through a single hole of the gas distributor m^3/s.

Schedule dependence $F(d_0, \upsilon_0)$ is shown in Fig. 3. At F<27 holds there is a free mode of formation and ascent of bubbles when the adjacent bubbles rise without touching , with some temporal and spatial intervals. With increasing flow of biogas under the condition F>27 chain mode of bubbles ascent occurs when they are due to the rapid formation touch each other and rise as the winding chains. From Figure 3, it follows that at $d_0 \geq 1$ mm and $\upsilon_0 \geq 20$ m/s chain mode of formation and bubbles ascent always arises.

In this case the diameter of the biogas bubbles can be found by the formula:

$$d = 0{,}5\left(\frac{3\sigma d_0 F}{\rho g}\right)^{1/3} \quad (13)$$

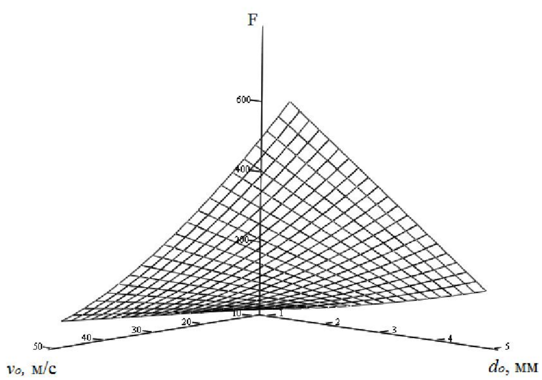

Fig. 3. Schedule dependence of *F* parameter on the speed of the expiry of the bubbling gas υ_o and diameter of the gas distributor holes d_o

According to formula (13) the size of the biogas bubbles under bubble mixing biomass may exceed 10 mm , however, bubbles with the size of d> 5 mm are unstable and decompose into smaller ones. The rate of bubble accent which are rising in chain mode can be found with the help of the following ratio [9]:

$$\upsilon_b = 1{,}5\left(\frac{\sigma g(\rho - \rho_g)}{\rho^2}\right)^{0{,}25} \quad ,(14)$$

where ρ_g - (rho) density of the gas fed to the mixing kg/m^3.

Under mass bubbling of biomass, which is set under the gas expiry from many holes with speed $\upsilon_o \geq 30$ m/s, polydisperse bubble mass is formed characteristics of which can't be defined theoretically. It is established experimentally that the average size of the bubbles arising from the mass bubbling is in the range of 4 to 5 mm, and the average speed of their ascent is approximately 0.28 m/s [7].

The main task of the rational design of bubble mixing biomass system is to achieve a sufficient degree of homogeneity of its characteristics with minimum energy consumption.

Power transmitted by bubbled biomass can be estimated using the ratio [6]:

$$N = p_0 Q \ln \frac{p_0}{p_2} \quad (15)$$

where p_0 - the gas pressure at the outlet from the bubbler holes, p_2 - biogas overpressure above the free surface of the fermenting mass.

Pressure p_0 must exceed pressure p_{bm} of biomass post with the height H_{bm}:

$$P_{bm} = \rho g H_{bm} \ , \quad (16)$$

and the pressure ΔP_{bm} required to gas passing through the layer of biomass.

The following estimate of the value is found empiricall ΔP_{bm}:

$$\Delta P_{bm} = (1{,}2 - 1{,}25) P_{bm} \quad (17)$$

To estimate the total energy consumption for maintaining the bubble mixing biomass it is necessary also take into account the loss of gas pressure in the bubble pipeline. It is known that the pressure loss in the bubbling pipe is about 20 % of post biomass pressure [10].

Then

$$P_0 = P_{bm} + \Delta P_{bp} = (2{,}40 \div 2{,}45)\rho g H_{bm} \quad (18)$$

Energy consumptions per cycle of bubble biomass mixing are determined by the ratio:

$$E = N \cdot \Delta t \ , \quad (19)$$

where Δt - the duration of one cycle of the bubble mixing, s.

Intensity of vertical mass exchange of bioreactor can be characterized by bubble mixing coefficient K_b:

$$K_b = \frac{Q_c}{V_{bm}} \quad (20)$$

where Q_c - volumetric flow rate of the circulating flow of biomass , m^3/s.

Volumetric flow rate of circulating flow of biomass is define by the ratio :

$$Q_c = 2\pi\int_0^{r_0} u_z(r)dr = \frac{\pi R_p^2 u_{av} x_0^2 (x_0^5 - 3x_0^4 + 2x_0^3 + 2x_0^2 - 3x_0 + 1)}{3x_0^2 - 5x_0 + 2}, \quad (21)$$

where u_{av} - averaged axial velocity of the biomass flow, m/s.

Value reciprocal to K_b is equal to the minimum duration of one cycle of bubble mixing Δt, during which the whole volume of biomass is involved into mass exchange circulating:

$$\Delta t = \frac{1}{K_b} = \frac{V_{bm}}{Q_c} \quad (22)$$

In view of formula (22) ratio (19) to calculate the energy consumptions for mixing bubbling takes the following ratio:

$$E = p_0 V_{bm} \ln\frac{p_0}{p_2} \quad (23)$$

Formula (23) implies that the energy consumption for one cycle of bubble mixing do not depend on the flow of gas bubbling, and determined only by its pressure drop and the amount of biomass.

Conclusion

Ratios (1, 4, 15-23) were used in the calculation and design of industrial biogas plant. According to the specifications given bioreactor complex (diameter bioreactor D_{br} = 11,8 m; height bioreactor H_{br} = 10,9 m; bioreactor volume V_{br} = 1300 m^3;biomass V_{bm} = 1200 m^3) parameters of bubble mixing system were defined: u_{re} = 0,013 m/c; P_2 = 10000 Pa ; P_0 = 272955 Pa; Q_c = 0,245 m^3/s; Δt = 82 min., E = 300 kW/hr.

Results

The hydrodynamic characteristics of the proposed bubble gas distributor device were studied and formulas for the determination of major structural and technological parameters of the bubble mixing system were obtained such as: radial and axial steps between turns bubbler bubble pipe length, the relative volume content of the bubble phase, ascent bubble rate, duration and energy consumption per one cycle of the bubble mixing.

Application of bubble mixing system allows intensifying the process of biomass mixing in the bioreactor and improves the efficiency of the biogas plant operation.

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