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# Calculation of energy costs of composite biomass stirring at biogas stations

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**Abstract**. The paper is devoted to the study of the equipment to produce biogas fuel from organic wastes. The bioreactor equipped with a combined stirring system ensuring mechanical and bubbling stirring is designed. The method of energy cost calculation of the combined stirring system with original design is suggested. The received expressions were used in the calculation of the stirring system installed in the 10 m$^3$ bioreactor: power consumed by the mixer during the start-up period made $N_z$=9.03 kW, operating power of the mixer made $N_E$=1.406 kW, compressor power for bubbling stirring made $N_C$=18.5 kW. Taking into account the operating mode of single elements of the stirring system, the energy cost made 4.38% of the total energy received by the biogas station.

## 1. Introduction

At present, alternative energy systems are widely used in many countries worldwide. One of the most dynamically developing areas is biogas production and use. Biogas is an analogue of natural gas and differs in smaller methane content reaching 50-70% [1, 2]. To ensure efficient production of biogas, bioreactors are equipped with stirring systems. Stirring provides for uniform distribution of temperature and nutrient content in all parts of the bioreactor [3, 4].

International and domestic experience highlights three methods of biomass stirring: mechanical, hydraulic and bubbling. Notably, the mechanical stirring with stirring impellers installed vertically in the center of the bioreactor became the most popular. It is known that during operation of mechanical mixers, a considerable radial speed of a biomass flow is created, while the axial component remains insignificant [5]. Consequently, this leads to insufficient efficiency of biomass stirring in the vertical plane of the device, which, in turn, causes the decrease in the growth rate of microorganisms and the reduction of biogas output. Hence, the development of a combined stirring system ensuring uniform distribution of biomass in horizontal and vertical planes is of a vital importance these days.

## 2. Materials and methods

The present work deals with equations of classical hydro- and gas dynamics, theory of mathematical modeling of two-phase gas-liquid flows.

## 3. Energy costs of a combined stirring system

The study covers the development of the bioreactor to produce biogas through the combined stirring system ensuring mechanical and bubbling stirring (Fig. 1) [6]. The bioreactor design implies a tank with an installed mixing device consisting of a mixer presented as hollow tubes with holes, fixed at the bottom of a hollow shaft connected to an electric motor and a heater. The hollow tubes of the mixer are formed by separate elements of different diameters, which decreases from the central part of the tank to periphery.

**Figure 1.** Bioreactor model.

One of the key parameters of the stirring system, characterizing its efficiency is energy consumption for the required stirring ratio.

The paper considers the 10 $m^3$ bioreactor used for treatment of organic farm wastes of 50 cattle heads. Liquid biomass with a density of $\rho$ = 1016.04 $m^3$/kg and dynamic viscosity of $\mu$ = 0.45 Pa·s was chosen as a stirring media, which corresponds to cattle manure with 92% humidity at 37°C.

**Energy of mechanical stirring.**

The energy required for mechanical stirring depends on the density of stirring media and is defined by the following expression:

$$N_{mm} = K_n \rho n_m^3 D^5 , \quad (1)$$

where $K_n$ – power criterion determined from diagrams depending on the centrifugal Reynolds criterion $Re_m$ [7]; $\rho$ – density of stirring media, kg/$m^3$; $n_m$ – mixer speed, r/s; $D$ – mixer diameter, m.

The centrifugal Reynolds number depends on the mixer blade size:

$$\mathrm{Re}_m = \frac{\rho n_m^3 D^2}{\mu} . \quad (2)$$

Power consumption taking into account drive efficiency:

$$N_E = \frac{N_{mm} + N_f}{\eta} , \quad (3)$$

where $N_f$ – friction power in compression, which is often neglected due to its low value; $\eta$ – drive efficiency; for normalized drives $\eta$ = 0.9-0.96.

**Energy of the mixer initial run.**
The frontal area of a blade displacing fluids is generally defined by the following expression:

$$F_b = bh\sin\left(\frac{\pi}{180}B\right), \tag{4}$$

where $b$=$R$ – blade length, m; $h$ – blade height, m; $B$ – blade angle in the direction of its movement, rad.

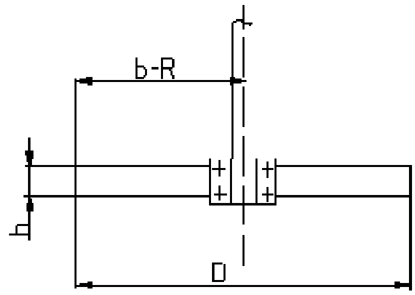

**Figure 2.** Design parameters of a bladed mixer.

Centroidal blade velocity $w_c$ m/s:

$$w_c = \frac{\pi R n_m}{30}. \tag{5}$$

Mass of the fluid displaced by the blade is defined by the following expression:

$$G = F_b w_c \rho g. \tag{6}$$

The fixed blade is rotated with the given frequency and, having imparted fluid speed $w_0$, operates equally to actual moving mass of fluid $T$:

$$T = \frac{G w_c^2}{2g} = \frac{F_b w_c^3 p}{2}. \tag{7}$$

In the same frontal area, the blade makes different operations, which depend on $b/h$ relation, and therefore actual operation $T_1$ that initiates the rotation of one blade with frequency $n$ (r/m) is as follows:

$$T_1 = \frac{\varphi F_b w_c^3 \rho_l}{2}, \tag{8}$$

$\varphi$ – coefficient dependant on a blade form.

For horizontal rectangular blades with $b$=$D$/2, where $D$ – diameter of a circle cleaned by a mixer blade and $w_c = \frac{3w}{4}$, where $w$ – tip speed, m/s.

The energy consumed by the mixer during start-up is determined by the following equation:

$$N_z = \frac{2zT_1}{102\eta} = \frac{54\,\varphi\, z\, F_b\, w^3 \rho_l}{13056\,\eta}, \tag{9}$$

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where $z$ – number of mixer blade pairs; $\eta$ – mechanical efficiency.

The start-up time of electric motor without loading and mass of the given mechanism equals 2 … 3s [8].

**Energy of bubbling stirring.**

The main objective of bubbling stirring calculation is to determine the pressure of gas supplied to a bubbling pipe. The pressure of gas supplied to a biomass mixing device for bubbling stirring is defined taking into account stirring intensity, mixer design and the working pressure of biogas in the bioreactor.

Gas pressure can be calculated via Bernoulli's equation consisting of three components:

$$P = P_1 + P_2 + P_3 , \tag{10}$$

where $P_1$ – pressure upon fluid column crossing, Pa; $P_2$ – dynamic pressure, Pa; $P_3$ – gas pressure in the bioreactor, Pa.

Pressure upon fluid column crossing (biomass):

$$P_1 = H \rho_l g , \tag{11}$$

where $H$ – biomass column height, m; $\rho_l$ – substrate density, kg/m$^3$.

The dynamic pressure is defined proceeding from the fermentation mass consisting of 90% water and 10% manure solid.

The dynamic pressure looks as follows:

$$P_2 = \frac{\rho_g w_g{}^2}{2}(1 + \lambda \frac{l}{d} + \sum \zeta_{l.r}) , \tag{12}$$

where $w_g$ – gas speed in a pipe, m/s; $\rho_g$ – gas density, kg/m$^3$; $\lambda$ – friction coefficient; $l$ and $d$ – pipe length and diameter, m; $P_0$ – gas pressure over a substrate, Pa; $\Sigma\zeta_{l.r.}$ – sum of local resistance coefficients.

Gas pressure in the bioreactor:

$$P_3 = P_0 , \tag{13}$$

where $P_0$ – gas pressure over biomass, Pa.

Taking into account dependences (11-13), the gas pressure supplied for stirring is defined according to the following expression:

$$P = H \rho_l g + \frac{\rho_g w^2}{2}(1 + \lambda \frac{l}{d} + \sum \zeta_{l.r}) + P_0 . \tag{14}$$

Since produced biogas consisting of 65% methane and of 35% carbon dioxide is used for bubbling stirring, the density and viscosity of biogas is accepted according to its composition $\rho_g$=1.16 kg/m$^3$, $\gamma_g$ =11.05·10$^{-6}$, m$^2$/s.

The friction coefficient for turbulent conditions serves the function of pipe roughness and Reynolds criterion, and is defined according to Altshul's formula:

$$\lambda = 0{,}11\left(\varepsilon + \frac{68}{\mathrm{Re}}\right)^{0{,}25} , \tag{15}$$

where ε – relative roughness of a pipe; *Re* – Reynolds number.

The relative roughness depends on the height of pipe internal surface peaks and is expressed by the relation of absolute roughness Δ to the pipe diameter:

$$\varepsilon = \frac{\Delta}{d_{bt}} . \tag{16}$$

The Reynolds criterion reflects the gas flow modes and is determined by the following formula:

$$\mathrm{Re} = \frac{w_g d_{bt}}{\gamma_g} . \tag{17}$$

Pressure losses upon crossing the local resistance occur due to changes of the gas flow speed value and direction. When calculating the combined stirring system, it is suggested to calculate the local resistance of gas output from openings, in stop valves, pipe bend and mixer blades:

$$\Sigma\zeta_{lr}=\zeta_h+ \zeta_v+ \zeta_{tp} +\zeta_{bm} , \tag{18}$$

where $\zeta_h$ – coefficient of local resistance of gas output from openings; $\zeta_v$ – coefficient of local resistance of stop valves; $\zeta_{tp}$ – coefficients of local resistance of pipe bends, $\zeta_{bm}$ – coefficient of local resistance of mixer blades.

The sum of resistance coefficients in stop valves depends on the number and type of fittings. When calculating coefficients of local resistance of pipe bends, it is necessary to consider quantity and nature of bends.

Gas consumption for bubbling stirring is defined as follows:

$$V_g = kFP , \tag{19}$$

where *k* – trial coefficient dependant on stirring intensity; *F* – area of fluid surface in the device prior to stirring, $m^2$; *P* – gas pressure, atm.

Operation in case of gas compression is defined according to the following formula:

$$A_n = \frac{n}{n-1} P_i V_i \left[ (\frac{P_f}{P_i})^{\frac{(n-1)}{n}} -1 \right], \tag{20}$$

where *n* – polytropic coefficient defined by $pV^n$ = const; $P_i$ – initial gas pressure, Pa; $P_f$ – final pressure of compressed gas, Pa; $V_i$ – initial specific gas volume, or volume of 1 kg of gas during absorption, $m^3$.

$$n = \frac{c - c_p}{c - c_v} , \tag{21}$$

where *c* – biogas thermal capacity in this process, $c_p$ and $c_v$ – thermal capacity at constant pressure and volume respectively.

Compressor motor capacity $N_C$ (kW) is defined by the following expression:

$$N_C = \frac{A_n V_g}{\eta_c \eta_{mt}} 10^{-3}, \qquad (22)$$

where $V_g$ – compressor consumption, m$^3$/s; $\eta_c$ – indicated efficiency of a compressor considering energy losses during actual operation; $\eta_{mt}$ – efficiency of mechanical transmission between the compressor and the engine.

The obtained dependences allow defining energy costs for the mechanical and bubbling stirring system.

## 4. Conclusions

The method of energy cost calculation for the mechanical and bubbling stirring system is developed. The obtained equations were used to calculate the stirring system of the 10 m$^3$ bioreactor used for treatment of organic farm wastes of 50 cattle heads. The energy consumed by the mixer during the start-up period made $N_z$=9.03 kW; the operating power of the mixer made $N_E$=1.406 kW, the compressor power for bubbling stirring made $N_C$=18.5 kW. Taking into account the operating mode of single elements of the stirring system, the energy cost made 4.38% of the total energy received by the biogas station.

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