Anaerobic digestion technology improving by biogas production safety development

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Abstract. Anaerobic digestion, accompanied by methane liberation, is one of the priority ways of organic waste and sewage sludge disposal. Improving the reliability of biogas stations, including environmental reliability, can be achieved by using plants with high reliability indicators improved with further constructive improvement. For this purpose, reactors with gas holders additional function are considered and its advantages and disadvantages are analyzed. Technical solutions are proposed to increase anaerobic processes stability and biogas accumulation. Solar energy using is assumed to maintain required thermal conditions and to avoid additional heating, necessary for heating the medium gas-holder floats in. An equation is obtained to make it possible to predict the fuel yield depending on organic waste residence time in a methane tank. The proposed function can be used to make amendments for all temperature regimes corresponding to bacteria’s vital activity conditions.

1. Introduction
In the context of agricultural enterprises support through state programs implementation that stimulate cultivated areas and livestock numbers increase, inevitably, question of effective disposal organization of constantly generated significant amounts of organic waste arises. This is, first of all, necessary as a result of sanitary regulations limiting livestock enterprises location near villages and involving reduction of environmental pollution risks.

One of the most promising ways of organic waste recycling is anaerobic digestion in methane tanks with concomitant biogas emission [1,2]. Environmental safety increased and energy independence achieved, especially for areas that do not have extensive gas supply networks, creates favorable conditions for such disposal facilities use. In addition, with progressive investment programs for agriculture and live-stock production development, along with ever-increasing amounts of organic waste, prerequisites for active anaerobic digestion devices distribution are created [3].

2. Reactor reliability and productivity rise
Despite the rather long period of biogas plants use, over the past decades, existing reactor designs have undergone minor changes, that opens up prospects for their further modification, ensuring productivity growth. Along with this, the design of anaerobic processing devices must be accompanied by solving problems of increasing produced gas transportation and storage safety [4,5].

The yield rate and composition of the gas obtained as a result of the digestion of organic waste depends on the quantity and energy value of the incoming raw materials, as well as the supported
thermal conditions [2,6-15]. The extremely difficult regulation of the parameters of the wastewater sludge loaded into the processing process leads to instability of the process, which requires the creation of reliable storage devices, both for the biomass itself and for the produced gas. At the same time, the increased safety must meet, first of all, the capacity for the collection and storage of biogas.

Reactors, frequently used for organic waste processing, having additional gas storage function, are divided into balloon and dome-shaped [1].

Bag shaped balloon plants for waste conversion and produced fuel storage are made of heat-resistant polymers or rubber with supplied pipes for raw materials loading and unloading. Gas accumulation under pressure is provided by a plant material tensile properties. In addition, with sufficient strength and elasticity of a bag, a weight can be placed on it to make it possible to increase gas pressure resulting from digestion. But such an additional load in case of long exploitation is unsafe. Therefore, in order to reduce the risk of premature failure, a valve should be provided with a gas pipeline connected to a cylinder, triggered when operating pressure is exceeded and drains the excess into an additional container. The container can also be a balloon-type.

The advantages of such reactors are: simplicity of design and, as a result, low installation cost, ease of maintenance, including reactor cleaning, loading, mixing and raw materials unloading. Along with the positive characteristics, balloon-type reactors have significant disadvantages. High susceptibility to external weather changes and impacts violates thermal regime for methanogenic bacteria and, over time, reduces the strength characteristics of shell material. As a result, service life is significantly reduced, which, as a rule, does not exceed five years. One of the more reliable versions of balloon reactors are duct-type plants, that usually have a polymeric shelter for protection from solar radiation direct exposure and allows to prolong trouble-free operation.

In dome-shaped reactors for gas accumulation in the upper part can be provided a flexible, stretching material in case of a low probability of damaging a thin shell. In addition, membrane dome reactors should be designed for climatic regions with a sufficiently high air temperature typical only for the southern regions of the Russian Federation.

More reliable plants with a fixed dome for gas gathering consist of a closed reactor, that may have additional capacity for discharging sludge. Recycled biomass is pushed into a tank during raw materials loading. The longer raw material remains in a reactor; the higher gas pressure is.

Plants with a fixed dome reliability ensured its wide distribution. In China, for example, over 12 million of such methane tanks are exploited. They are usually designed for a significant amount of waste or sewage sludge and they represent hollow concrete structures, some of which are located underground to contain internal pressure of up to 0.15 bar and stabilize temperature regime. In addition, innovative technologies allow to made them of reinforced polymeric materials to neutralize decomposing medium aggressive effect on a case’s shell. The minimum recommended size of such reactors is 5 m³, but if necessary, the plants volume can be up to 200 m³. However, an unjustified size increase of a methane tank complicates the conversion process, since it is impossible to create favorable conditions for bacteria’s vital activity and to provide uniform raw materials mixing. With significant intake of sewage sludge, biogas stations should be designed with at least two reactors, to increase processing reliability. Since, fixed dome type of plants have a gas tank in its upper part, to improve concrete layer tightness it is covered with a mixture that reduces sides diffusion. Latex or synthetic paint can be used.

Plants with a floating dome usually composed of a ground or underground reactor and a mobile gasholder. A construction design provides vertical movement of an upper part of a gasholder, that is placed with its bottom part in a special water pocket or directly in the raw material lower part. During biogas accumulation and pressure increases, mobile part of a gasholder rises, that is protected from overturning by a special supporting frame.

The advantages of such reactors are maintenance with minimal labor costs, almost constant pressure in a gasholder, determined by its weight, a simple way to calculate gas volume according the height a gasholder is raised. The disadvantages are the high cost of a steel reactor, its corrosion in aggressive environments and, as a result, a shorter service life than fixed-dome plants have. In
addition, during cold period of a year and low temperatures there is high probability of water pocket freezing that reduces the safety of operation.

The last problem can be solved by proposed construction of a floating gasholder (figure 1), if translucent thermal insulation material 5 is used for its upper part, for example, polycarbonate. So solar radiation entering a dome will heat it up. Medium circulation inside formed air gap allows to maintain raw material temperature in a pocket at positive values. In addition, the gasholder, as well as containers made of elastic materials, is not explosive in case of an emergency pressure increase, since an unauthorized discharge of excess may occur without shell destruction. Polycarbonate translucent barrier should have opening transom to air and cool reactor’s outer shell during summer months.

Figure 1. A reactor layout with a floating gasholder and raw materials hydraulic mixing: 1 – methane tank body; 2 – floating gasholder; 3 – reactor thermal insulation; 4 – rollers; 5 – translucent thermal insulation; 6 – corrugated insulation material; 7 – sewage sludge pipeline; 8 – sediment collection; 9 – sewage sludge feed line pump to a digester; 10 - pump discharging ferment sludge;; 11 - gas pipeline

3. Biogas produced quantitative assessment
The amount of gas produced and accumulated in a reactor upper part can be determined by integrating an expression given in the regulatory document [16]

\[ V_C = \frac{\tau_K}{\tau_H} \int_{\tau_H}^{\tau_K} \frac{1}{\rho_C} dq_m d\tau = \int_{M_H}^{M_K} \frac{1}{\rho_C} dM \]

(1)

where \( V_C \) – gas volume under operating conditions, \( \text{m}^3 \); \( \tau_H, \tau_K \) – reporting period start and end time; \( q_m \) – mass gas flow rate, \( \text{kg/s} \); \( \rho_C \) – gas density under standard conditions, \( \text{kg/m}^3 \); \( M_H, M_K \) – gas mass at the beginning and at the end of measurement time, kg.

Passing on to formula (1) to volumetric gas emission \( q_V \) and taking into account that fermentation takes place over a period of \( \tau_{BP} \) in several days, and the beginning of the conversion corresponds to \( \tau_{ef}=0 \) the moment of a reactor charging end, expression (1) can be written as

\[ V_C = \int_{0}^{\tau_K} q_V d\tau \]

(2)
where $q_V$ – biogas volumetric efficiency $q_V = \frac{q_m}{\rho}$, m$^3$/day; $\tau$ – fermentation time, day; $\rho$ – gas density under operating conditions, kg/m$^3$.

The fermentation period $\tau_{BP}$ depends mainly on biomass thermal regime, it is also influenced by loaded raw materials quality. Under thermophilic regime, fermentation can last up to 10–30 days or more. Biogas output at the beginning of the conversion process gradually increases and, reaching a maximum, then gradually decreases. Therefore, volumetric performance with sufficient accuracy can be approximated by the equation

$$q_V = q_V^{\text{max}} \left[1 - \cos^2\left(\frac{\pi \tau}{\tau_{BP}}\right)\right]$$

(3)

where $q_V^{\text{max}}$ - the maximum biogas yield corresponding to intense conversion observed in the middle of the fermentation period, m$^3$/day.

Integrating (3) into formula (2), we obtain

$$V_C = q_V^{\text{max}} \frac{\tau_{BP}}{\pi} \left[\frac{1}{2} \frac{\pi \tau}{\tau_{BP}} + \frac{1}{4} \sin\left(\frac{2 \pi \tau}{\tau_{BP}}\right)\right]$$

(4)

The dependence obtained allows us to determine the volume of produced gas at any stage of fermentation within its period $\tau_{BP}$ and at its early completion, if deep decomposition of raw materials is not allowed by economic reasons. Figure 2 shows gas emitted volume during 1 ton of pig manure conversion, calculated using formula (4) for various values of the maximum daily output. Raw materials residence time in reactor is limited to 50 days, the highest value is $q_V^{\text{max}} = 3$ m$^3$/day taking into account organic mass preliminary enrichment.

The necessary maintenance of comfortable conditions for bacteria vital activity is ensured by constant metagenesis, that requires regular gas supply to a system. So it is necessary to design local gas supply systems, since excess biogas direction in operating centralized systems, that is typical for Western Europe countries, has no legislative force in the Russian Federation. A local gas pipeline can provide fuel both for an enterprise itself and for consumers within its radius of action. Reconfiguration of gas burners, heat generators or household appliances will ensure the safe and efficient fuel burning produced by recycling organic waste.

Figure 2. Biogas produced volume by aerobic digestion of pig manure:
1 – $q_V^{\text{max}} = 2$ m$^3$/day;
2 – $q_V^{\text{max}} = 2,5$ m$^3$/day;
3 – $q_V^{\text{max}} = 3$ m$^3$/day.
4. Conclusion
Taking into account active support of agriculture and livestock by state agribusiness development programs, the amount of organic waste will increase annually. To reduce the negative effect on the environment [6, 8], it is necessary to provide processing by means of aerobic digestion, both at design stage and during existing enterprises reconstruction. Technical solutions aimed at improving biogas stations safety will contribute to waste disposal technology dissemination. It can be achieved in fairly simple ways, including given in the article, that will ensure uninterrupted conversion processes and reduce the regulations coordination with technical oversight organizations.

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