Mathematical Modeling of the Process of the Gas Generation and Gas Purification of the Biogas on Polygon of Residential Solid Waste

O N Medvedeva¹, S D Perevalov¹
¹Yuri Gagarin State Technical University of Saratov, 77 Politekhnicheskaya street, Saratov, 410054, Russia

E-mail: medvedeva-on@mail.ru, ya.yaskay@gmail.com

Abstract: The article presents the prospects of using biogas fuel. Mathematical model of processes proceeding at the gas purification in amine installation unit has been developed. A software package has been proposed that allows to determine the quantitative yield of methane, design and thermal insulation characteristics of a biogas reactor by anthropogenic load. We determine the main parameters and energy efficiency of the biogas plant for the conditions of the Saratov, efficiency of energy-saving measures at the biogas fuel usage is shown. The practical significance of the work lies in the use of the developed model in the design of anaerobic reactors on polygon of residential solid waste (RSW), small settlements and microdistricts distant from other sources of energy supply.

1. Introduction
The most important consequences of the rapid development of the productive forces - the growth of environmental pollution, which becomes dangerous for the health and existence of mankind. One of the most important issues that should be given special attention - is the storage, recycling, burial and disposal of waste [1÷9]. Today the growth rate of the residential solid waste exceeds the ability of specialized landfills to take them and recycle.

This situation occurs in many regions of Russia. According to the Federal Service for Supervision of Natural Resource Usage, in 2016 in the Russian Federation formed 5.4 billion tons of industrial and residential waste. According to statistics, level of waste utilization increased from 40% in 2006 to 60% in 2016. Analysis shows that no more than 10÷30% of waste is utilized, depending on the value of the fraction for the market. On condition of processing all manufactured and food waste is processed, for example, in the Saratov region in 2018, the loss of profits amounted to about two billion rubles [10].

Problem issues in the solid waste management system were marked by the President of the Russian Federation V.V. Putin in the annual message to the Federal Assembly (February 20, 2019) and set out to form a safe system for the treatment and disposal of solid waste, the transition to clean environmental solutions.

Today there is a negative trend in Russia: development of methods for extracting useful resources from waste does not keep pace with the increase in the amount of garbage. In most regions garbage is stored in the landfills or, at best, is dumped at the landfills. If a waste recycling plant is installed, it is represented by a waste sorting complex. About 65% of recycled material is recovered from garbage presented in the form of waste paper, plastic and metals. The largest morphological component of the...
trash stream in most regions is food waste. This fraction is most often subject to disposal at the site, which is the reason for the formation of the biogas in its body. To prevent explosions and maintain fire safety requirements, degassing facilities must be installed. It is proposed to install a biogas collection system instead of a degassing system. This event will gather a valuable resource that can be used for commercial purposes after the procedure of certain processing [11÷14].

The purpose of this article is mathematical modeling of the processes occurring in the cleaning process, and adaptation of the amine column to the needs of the landfill for solid residential waste.

2. Materials and methods
After sorting, waste is collected from the waste recycling plant. In the course of 15 days of the biogas complex operation, 70% of the mass is transferred to the biogas, which can be converted into the following types of energy resources: electric energy - due to the operation of a cogeneration plant and / or the gas engine generator; heat energy - due to the operation of the cogeneration plant and / or boiler; biomethane (Figure 1).

![Diagram of biogas process at RSW landfill](image)

Figure 1. Shows the process of the biogas formation at the RSW landfill.

Obtained energy resources can be used to meet the needs of both the enterprise and external consumers. Biogas contains up to 45% of carbon dioxide, which in the process of enrichment is separated and it can also be used as marketable products and, accordingly, to receive additional income. The positive effect of the introduction of the biogas circuit into the production process of the landfill is to obtain a significant amount of high-quality fertilizer, since the slurry remaining after anaerobic digestion in the bioreactor is rich in nutrients. All the technologies used in the complex are tested and guaranteed, the overall composition of the equipment is not unique - the risk of losing time and effort in order to balance and optimize the operation of the complex is practically reduced to zero.

Among the undesirable chemical impurities contained in the biogas are toxic and corrosive sulfur-containing compounds and carbon dioxide. Various methods are used for purification, for example, the method of chemisorption using ethanolamines. Monoethanolamine (MEA) has the maximum absorption capacity in relation to carbon dioxide [12, 15, 16].

The principle of the amine purification column is as follows: untreated gas is fed to the bottom of the amine purification column and rises up. In the upper part of the column is fed an amine solution, part of which is regenerated. Absorber are plates of amine purification are along the entire length, which, by virtue of their structure, allow the amine fully absorb the acidic components contained in the untreated gas. At temperatures of 20÷40 °C there is a process of absorption of the acid gases, and at a temperature of 105÷130 °C and a pressure close to atmospheric, the absorber regenerates and releases. To reduce the amount of energy for heating unregenerated amine, the regenerated amine solution coming out of the bottom of the stripping column passes through heat exchanger. To separate the evaporated amine solution and return it to the column, acidic gases from the top of the column pass through the refrigerator and are removed from the system.

Along with the standard purification scheme, we can use efficient biogas combined purification plants working by the principle of dissolving carbon dioxide in the water: water, with carbon dioxide dissolved in it, enters the heat exchanger, then is heated in a water heater to the temperature needed for regeneration and sprayed into a desorber where under the action of pressure drop occurs desorption
of CO₂. Purified biogas enters the separator where moisture is condensed from the gas as a result of throttling, after which the gas is sent for final drying to the adsorber [17-19].

The absorption in the absorber of acidic components with a solution of MEA is described by the following stoichiometric equations:

\[
2RNH_2 + CO_2 + H_2O \rightleftharpoons (RNH_3)_2CO_3 \tag{1}
\]

\[
(RNH_3)_2CO_3 + CO_3 + H_2O \rightleftharpoons 2RNH_2HCO_3 \tag{2}
\]

\[
2RNH_2 + HS \rightleftharpoons (RNH_3)_2S \tag{3}
\]

\[
(RNH_3)_2S + HS \rightleftharpoons 2RNH_2HS \tag{4}
\]

An aqueous solution of MEA contains both CO₂ and HS⁻ in dissolved and chemically bound states. To calculate regeneration of the absorber in the desorber, we determine the amounts of acidic components that interact with monoethanolamine according to reactions (1) – (4).

Taking into account the pressure in the apparatus and the reactions in the solution, the equilibrium constants can be written in the following form:

\[
k_1 = \frac{[RNH_2]^2 [CO][H_2O]}{[(RNH_3)_2CO_3]} (\frac{10.2\pi}{\sum n_i})^{\Delta n_1}; \quad k_2 = \frac{[(RNH_3)_2CO_3][CO_2][H_2O]}{[RNH_2HCO_3]} (\frac{10.2\pi}{\sum n_i})^{\Delta n_2};
\]

\[
k_3 = \frac{[RNH_2]^2 [H_2S]}{[(RNH_3)_2S]} (\frac{10.2\pi}{\sum n_i})^{\Delta n_3}; \quad k_4 = \frac{[(RNH_3)_2S][H_2S]}{[RNH_2HS]} (\frac{10.2\pi}{\sum n_i})^{\Delta n_4}, \tag{5}
\]

where \(\pi\) is the pressure in the apparatus, MPa; \(n_i\) is the total number of moles of the reaction mixture; \(\Delta n\) is the difference in the number of moles of products and initial reagents in reactions (1) – (4).

The formulas in square brackets represent the number of moles of substances. The sequence of calculations of transformations according to reactions (3) and (4) corresponds to the calculations according to reactions (1) and (2). Next, we will calculate the diameter of the absorber in the most loaded lower section:

\[
D_{obs} = \frac{1800L + \sqrt{(K_0C + 35)\frac{3600G}{\rho_g(\rho_{abs} - \rho_g)^{0.5}}}}{(K_0C + 35)} , \tag{6}
\]

where \(L\) is the consumption of saturated absorbent from the apparatus; \(\rho_{abs}\) is the density of saturated absorbent; \(K_0\) is the valve plate coefficient; \(C\) is the coefficient for absorbers when the distance between the plates is \(0.6\) m; \(G\) is the gas consumption in the apparatus; \(\rho_g\) is the gas density.

### 3. Results

To determine the load, size, thermal insulation and heat losses of the bioreactor and the purification plant, it is more convenient to use a specially developed software package that allows determine consumption volumes of the amine solution and the main parameters of the biogas purification (Figure 2). These programs are a set of algorithms for the automated calculation of the required parameters, as a result they will certainly find application in design process [20].
When the amine circulates through the closed absorber-desorber system, the initial installation of the plant provides for the installation of two refrigerators for cooling water vapor with acid gases and the regenerated amine solution before irrigating the amine column. Since the gas comes from the body of the landfill, its temperature at different periods of the year will differ, which means that it must be heated. To do this, instead of the refrigerator, it is planned to design a heat exchanger on the pipe passing from the stripping column to the separator. This solution will allow to spend significantly less energy on heating the "untreated" gas before pumping it into the amine purification column.

According to the calculation made on the basis of [21], the specific output of the biogas for the period of its active generation during methane fermentation will be, $kg \cdot (kg \text{ waste})^{-1}$:

$$Q = 10 - 6 \cdot R \cdot (100 - W) \cdot (0.92 \cdot F + 0.62 \cdot C + 0.34 \cdot P) = 0.2044, \quad (7)$$

where $R$ is the organic content in waste (70%), $W$ is the waste moisture (50%), $F$ is the content of fat-like substances in waste organic matter (2%), $C$ is the content of carbohydrate-like substances in waste organic matter (83%), $P$ is the protein content in organic waste (15%). The quantitative yield of biogas for the year, related to one ton of waste, $kg \cdot (ton \text{ of waste per year})^{-1}$:

$$B_W = \frac{Q}{t_{fer}} = 9.5, \quad (8)$$

where $t_{fer}$ is the period of complete fermentation of the organic part of the waste.

Taking the average density of landfill biogas $\rho_B = 1.254 \text{ kg} \cdot \text{m}^3$, we get that 7.58 m$^3$ of biogas is formed from 1 ton of waste [2].

As a result of calculations, the amount of the biogas released during the period from the beginning of the operation of the landfill and over the next 20 years will be more than 1 billion m$^3$, with about 1500 m$^3$ of the biogas being produced per hour.

4. Conclusions

Thus, the main objective of the project was to create a complex for the processing of industrial and consumer wastes, involving the production of biogas with maximum output and soil-ground mixtures,
transfer of waste processing from the cost to the revenue budget, software development for automated biogas complex RSW landfill. Proposed project is aimed at economic and environmental rehabilitation of territories. All the technologies used in the developed complex are tested and guaranteed, the overall composition of the equipment is not unique - the risk of losing time and effort to balance and optimize the operation of the complex is practically reduced to zero. In the case of operating its own biogas complex, the landfill will fully or partially be able to meet its own needs and the needs of various consumer categories in gas fuel, motor fuel, electrical energy, thermal energy, bio-fertilizers, which will reduce the use of external material resource flows. Software for automated design of a bioreactor allows to determine the constructive, energy and material flows of the biogas complex, selecting the appropriate equipment, modeling the optimal distribution of the biogas in order to convert it into various types of energy resources to achieve the maximum value of the net present value project performance. With the help of software, it is possible to optimize transportation costs for the delivery of solid waste and the possibility of obtaining an analysis of consumer demand for final products and recycled products. The calculations show that this project will become self-sustaining after 5.6 years, taking into account the full repayment of borrowed funds.

Ecological benefits from the biogas complex use: reduction of the methane emissions into the atmosphere, formed during storage of residential waste in the open air; reduction of the air pollution with nitrogenous compounds; reducing the use of chemical fertilizers and, as a result, improving the soil, groundwater and the ecosystem as a whole.

Economic benefits from the use of the biogas complex lies in increase financial sustainability of the landfill site through the production and sale of environmentally friendly products (bio-fertilizers for farms and greenhouses, biogas for various needs), which is one of the final goals of this project.

The net present income for the project (for the life of the project) will be the difference between the cost of bio-fertilizers, energy resources and technological materials (biomethane, carbon dioxide, electric and thermal energy) obtained using biogas, the implementation of software and the costs of acquiring and operating the relevant energy equipment (cogeneration plant, heat generating equipment, biogas enrichment module, automobile gas filling compressor station) [22]. Profitability index - not less than one; profitability index – 0.78±1.3; the net present income index is 0.64±2085. The cost of the biogas is 5.88 rubles per cubic meter. The internal rate of return is higher than the interest rate on loans. Payback period is economically minimal.

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