The study of energy performance of biogas from agricultural waste

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Abstract. The article is devoted to determination of energy indicators of the alternative source of energy - biogas derived from agricultural waste. The main energy indicators of the burning process of biogas fuel are lower heat value, Wobbe index, ignition range, flame propagation rate, as well as amount of oxygen and air required for complete combustion of biogas. The energy indicators of biogas produced from corn silage, technical fat, pig manure, cattle manure and poultry droppings are determined during the study. It has been found out that biogas obtained from technical fat and poultry droppings is characterized by the highest energy indicators, and biogas from corn silage - by the lowest indicators. Wobbe index of biogas is more than 2 times lower than index of natural gas. The biogas produced from technical fat has the highest rate of flame propagation - 23 cm/s, which is 1.5 times lower than the rate of flame of natural gas. Biogas has a wider ignition range than natural gas: the lower limit, the upper limit. The average value of the theoretic air volume required for complete combustion of biogas is 5.8 m³, which is 1.7 times less than the value for natural gas.

1. Introduction
In many developed countries, much attention is paid to the development of alternative energy systems. One of the promising areas of alternative power generation is the production and use of biogas [1, 2]. Biogas is formed in the process of anaerobic fermentation of organic substances, which, as a rule, are waste products of various industries [3-6].

The most effective use of biogas technology is in agricultural enterprises. This is due to the proximity of the energy source of organic waste and the consumer of biogas, power plants of enterprises [7, 8]. Biogas is a gaseous fuel consisting of methane (40-70%), carbon dioxide (30-40%) and other gases (0-5%). The amount of biogas and methane produced depends on the composition of the organic part of the waste, containing fats, proteins and carbohydrates [4, 6, 9].

Currently, the biogas produced is mainly used in cogeneration plants to generate electricity and heat [4-6]. A promising direction for the use of biogas is burning in burner devices of boilers and furnace units [10]. The study of the combustion process of biogas and other low-calorie gases devoted a lot of work of domestic and foreign scientists [11-18]. However, given the high content of carbon dioxide in the composition of biogas, the burning of biogas in traditional burners of natural gas will not be effective [17, 18]. Therefore, it is relevant to determine the characteristics of the combustion process of biogas fuel with the high content of carbon dioxide and the development of burner equipment.
2. Materials and Methods
Most of the foreign and domestic biogas plants use corn silage, fats, pig manure, cattle manure and poultry droppings as an initial substrate [1-6]. The volume and composition of biogas obtained from different types of organic waste were determined as a result of experimental studies of the process of anaerobic fermentation at a temperature of 42 °C (see table 1).

| Substrate type         | The volume of biogas per ton of starting substrate | The volume of biogas per ton of dry matter | CH₄, % | CO₂, % | Other gases |
|------------------------|---------------------------------------------------|-----------------------------------------|--------|--------|-------------|
| Corn silage            | 213.5                                             | 710.5                                   | 51.9   | 45.4   | 2.7         |
| Technical fat          | 1500.7                                            | 1509.8                                  | 67.4   | 29.8   | 2.8         |
| Pig manure             | 14.7                                              | 299.6                                   | 60.8   | 36.5   | 2.7         |
| Cattle manure          | 98.5                                              | 392.6                                   | 61     | 36.1   | 2.9         |
| Poultry droppings      | 106.2                                             | 719.5                                   | 64.4   | 32.7   | 2.9         |

The main energy indicators of gaseous fuel are lower heat value, Wobbe index, flame propagation rate, lower and upper ignition limits, as well as the amount of oxygen and air required for complete combustion of biogas [19]. To determine the energy indicators of the burning process of biogas, equations based on chemical reactions of methane burning were used [20].

The lower calorific value of the gas is determined depending on the component composition of the gaseous fuel [21]. Given the composition of biogas and purification technology, in which hydrogen sulfide is removed from gas, the lower calorific value is determined by the composition of methane:

\[
LHV = 357.97 \times CH_4
\]

357.97 – lower calorific value of the 1% methane; 
CH₄ – methane content, % (by volume).

The Wobbe index is defined as the ratio of the volumetric lower calorific value to the square root of relative density of the gaseous fuel [22]:

\[
W = \frac{LHV}{\sqrt{\frac{\rho_g}{\rho_{air}}}}
\]

\(\rho_g\) – biogas density, kg/m³; \(\rho_{air}\) – air density, kg/m³.

The lower and upper limits of ignition of combustible gases is determined by the following formulas [21-24]:

\[
LEL = \frac{100 \times CH_4}{LEL_t}
\]

\[
UEL = \frac{100 \times CH_4}{UEL_t}
\]

\(LFL_t, UFL_t\) – upper and lower limits for the ignition of methane, %.

The rate of flame propagation is an important energy parameter, which determines the combustion temperature and thermal power of gas equipment [25, 26].

The propagation rate of the flame front for combustible gas is determined by the formula [22-24]:

\[
\]
The normal flame propagation rate of methane is given by the formula:

$$V_f = \frac{CH_4 \cdot V_{fl}}{100}$$

(5)

$V_f$ – normal flame propagation rate of methane, cm/s.

The main task for efficient and safe combustion of gaseous fuel is the supply to the place of combustion of the volume of oxygen required for complete combustion of 1 m$^3$ of gas of the given composition. In practice, gas units in the combustion area is supplied with atmospheric air, consisting of 79% nitrogen and 21% oxygen. If the amount of air is insufficient to completely burn the fuel, carbon oxide is formed in the combustion products, which is a highly toxic gas and dangerous to human health. Otherwise, when the amount of air significantly exceeds the required volume, a large amount of air remains in the combustion products, which is not involved in the combustion reaction and reduces the heat output of the burner.

The consumption of oxygen and air is to be determined on the basis of the reaction of combustion of methane in the air:

$$\text{CH}_4 + 2\text{O}_2 + 7.52 \text{N}_2 = \text{CO}_2 + 7.52 \text{N}_2 + 2\text{H}_2\text{O}$$

(6)

In accordance with the equation of combustion of methane, the volume of oxygen required for the combustion of 1 m$^3$ of biogas is determined by the formula:

$$V_{O_2} = 0.01(2\text{CH}_4)$$

(7)

The volume of air required for complete combustion of the gas is calculated given the oxygen content:

$$V_{\text{air}} = \frac{100}{21} V_{O_2} = 4.76 \cdot V_{O_2}$$

(8)

3. Results and Discussion

The results of the calculation of the lower calorific value and Wobbe index are presented in figure 1.

Analyzing fig. 1, we can conclude that biogas obtained by processing technical fat and poultry droppings is characterized by the highest rates of lower calorific value and Wobbe index, while biogas from corn silage - by the lowest ones. It can be seen that the value of Wobbe index for biogas is more than 2 times lower than the value of natural gas.
Figure 2. Normal flame propagation rate of natural gas and biogas of different composition.

From figure 2 it can be seen that the normal rate of flame propagation of biogas obtained from different types of organic waste varies in the range of 17–23 cm/s. The highest rate of flame is in biogas produced from technical fat – 23 cm/s, which is 1.5 times lower than the rate of flame of natural gas (34 cm/s).

Figure 3. Explosive limits of biogas and natural gas

Taking into consideration the low methane content (figure 3), biogas has rather wide ignition range as compared to natural gas. Biogas from corn silage has the widest limits of ignition, and the narrowest ones - biogas from technical fat. So, in corn silage biogas, the lower limit is 10% and the upper limit is 27%. Due to the high lower limit of ignition, it can be concluded that biogas is a less explosive gas.

The obtained average value of the theoretic volume of air required for complete combustion of biogas is 5.8 m³, which is 1.7 times less than the value for natural gas (figure 4).

From the comparison of the obtained energy parameters of biogas of different composition, it can be concluded that for efficient combustion of biogas of variable composition there is a need to improve the existing gas burner devices and to develop new gas burner devices.

During the operation of industrial gas units, there is a practice of transferring burners to work on a gas of a different composition due to changes in heat of combustion and gas density. To do this, one has to recalculate the design parameters of the burners [22, 28, 29].
To preserve the thermal power of the low-pressure gas injection burner when switching to gas fuel of the different composition, it is necessary to change the diameter of the gas nozzle, which is determined by the formula:

$$d_2 = d_1 \sqrt{\frac{\text{LHV}}{\text{LHV}^\prime} \cdot \frac{\rho_2 \cdot \rho_g^\prime}{\rho_1 \cdot \rho_g}}$$

(9)

$d_1$ – the diameter of the gas nozzle opening when working on the gas of the initial composition, mm; 
LHV and LHV$^\prime$ – calculated and actual combustion energy of the gas, kJ/m$^3$; 
$\rho_1$ and $\rho_g^\prime$ – calculated and actual density of the gas, kg/m$^3$; 
$p_1$ – calculated gas pressure, Pa; 
$p_2$ – gas pressure when working on gas of the different composition, Pa.

When calculating the parameters of blast burners with improved mixing, it is necessary to recalculate the area of the gas discharge openings, however, the gas and air velocities should be constant. The area of the discharge openings is determined by the formula, m$^2$:

$$F_1 = F \cdot \frac{\text{LHV}}{\text{LHV}^\prime}$$

(10)

$F$ – the area of the discharge openings during gas combustion of the initial composition, m$^2$.

Also, to preserve the heat output of the burner, it is possible to change the gas pressure before the burner while maintaining its structural dimensions, Pa:

$$p_2 = p_1 \left(\frac{\rho_g^\prime}{\rho_1} \cdot \left(\frac{\text{LHV}}{\text{LHV}^\prime}\right)^2\right)$$

(11)

However, in this case it is necessary to make a verification calculation so that the range of stable operation of the burner is not less than the set value.

Taking into consideration the variable composition of biogas, it can be concluded that for efficient combustion of biogas produced at various agricultural enterprises, it would be advisable to use a burner equipped with a device to control the flow of air into the burner body.

The design of a gas stove burner for biogas combustion has been developed. The main structural elements of the proposed gas burner are: a nozzle, a mixing chamber, gas-air mixture outlet openings, a preheating device and a regulator air primary (figure 5).
The use of pre-heating device provides heating of the gas-air mixture in the burner body. This allows you to increase the rate of flame propagation and the temperature of combustion. The use of a primary air regulator allows the use of biogas of different composition with high efficiency.

4. Conclusion
During the study, the energy indicators of biogas produced from various types of organic waste were identified: lower calorific value, Wobbe index, ignition range, flame propagation rate, volume of oxygen and air required for complete combustion of biogas. It has been studied out that biogas obtained from technical fat and poultry droppings is characterized by the highest energy indicators, and biogas from corn silage has the lowest indicators. At the same time, energy indicators of biogas are on average 1.5 times lower than those of natural gas. Biogas has a wider ignition range than natural gas, but the high value of lower ignition limit makes biogas less explosive. The design of a gas stove burner has been developed for efficient combustion of biogas of various compositions.

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