



The Effect of Biogas Composition on the Characteristics of The Combustion Process

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ABSTRACT

Biogas can serve as a substitute for natural fuel, but its use is associated with a number of features associated with the difference in its composition from natural gas. Landfill gas generated in the body of MSW landfills is characterized by a significant change in composition. The purpose of the work was a theoretical study of the effect of changing the composition of biogas and the coefficient of excess air on the parameters of the combustion process - gas and air consumption, combustion temperature and on the volume of combustion products. The influence of the ratio of CO₂ and N₂ contained in biogas on the main combustion characteristics was also evaluated. It is concluded that the combustion of biogas of variable composition, subject to ensuring the specified heat output of the furnace or boiler, does not require a change in air flow, but only a change in the flow of biogas depending on the content of methane in it. Reducing the content of methane leads to an increase in the volume of exhaust gases and a decrease in their temperature. Therefore, a decrease in the methane content in biogas can lead to a decrease in the intensity of heat exchange and a decrease in the efficiency of the unit. The ratio of CO₂ and N₂ practically does not affect the thermal parameters of combustion. The results of the study are necessary when designing equipment and determining the operating mode of equipment that burns biogas that is formed in natural conditions, for example, landfill gas generated at HSW landfill.

1. Introduction

Currently, there is an increase in the use of alternative energy sources. This is due to a decrease in the reserves of traditional fuel, environmental requirements, and the energy policy of some states in this area. In developed countries, the trend towards "dematerialization" of products has improved energy efficiency, while the "decarbonization" of fuels should slow down the rates of industrial emissions. The paper considers an alternative type of fuel - landfill gas (biogas).

Biogas is a gas resulting from the fermentation of organic compounds. The source of biogas can be:

- agricultural waste;

- food production waste;
- plant residues;
- solid and liquid household waste,
- specially grown energy crops.

The main use of biogas is its use as a fuel for generating heat and electricity, as well as it can be used as a motor fuel. All fuel-using plants are designed for a constant fuel composition.

When fermenting under natural conditions, such as MSW landfills, constant conditions cannot be ensured. Therefore, the composition of biogas is not constant and depends both on the place of sampling and on time. In [1, 2], as a result of monitoring the biogas output at the MSW landfill, it was found that the methane content in it can vary over a very wide range,

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which requires reconfiguration of the equipment.

Biogas has several applications: it is used as a gaseous fuel for the production of thermal and electric power, the joint production of heat and electricity (cogeneration), as well as refrigeration supply (trigeneration) [3]. After purification and enrichment to methane content of more than 90-95 percent, it can be effectively used as a motor fuel for vehicles running on gas [4].

Features of biogas combustion are determined by the low content of methane compared to natural gas, which affects its calorific value and combustion characteristics. Biogas has fairly wide flammability limits compared to natural gas [5]. Higher methane content can be obtained by improving the quality of biogas by removing CO₂ and other trace components such as H₂S, NH₃ and water vapor [6].

The influence of the components on the combustion characteristics of biogas is considered in a number of works. Sahin et al. [7] conducted numerical research to study the effect of changing the H₂O content in biogas on the biogas combustion characteristics and found that with an increase in the H₂O content in biogas, the temperature of the biogas flame in the combustion chamber decreases due to dilution of the mixture.

With an increase in the H₂O content, the position of the flame zone moves to the lower part of the combustion chamber. The better air-fuel mixture results in lower CO₂ emissions as the H₂O content increases [7].

Nonaka et al. [8] revealed the dependence of CO₂ dilution on the rate of laminar combustion of biogas, and found that dilution reduces the combustion rate and shifts the maximum combustion rate towards leaner mixtures. For stoichiometric mixtures, there is a more pronounced decrease in the combustion rate ranging from 6.9% to 50.2% at dilutions of CO₂ from 10% to 50%. Randy et al. [9] performed numerical calculations for various CH₄/CO₂ ratios in landfill gas at various dilution ratios and various initial mixture temperatures. The combustion rate of methane and LFG70 was measured using the PIV method (optical

measurement of velocity fields in a selected section). As a result of adding more CO₂, the combustion rate decreases (for example, in the stoichiometric state by 0.06 m/s), and therefore the height of the flame front increases, but the combustion rate can be increased by preheating the mixture. Suhaimi et al. [10], emphasizes that the highest flame velocity, hence the combustion rate, was observed at an equivalence factor of 0.8 for both simulated and real biogas. The influence of N₂ and CO₂ in the composition of biogas is shown in more detail in [11].

With an increase in the amount of CO₂, the combustion temperature decreases [12].

The problem of emissions into the environment has been studied by many authors. When burning biogas or other carbon fuels, there are several types of emissions: CO, CO₂ and NO_x [13]. Even with mixtures containing more CO₂, CO₂ emissions can be lower due to the fact that the kinetics of CO oxidation are favorable at higher temperatures [14].

Because biogas contains a significant amount of CO₂, CO₂ emissions from biogas combustion are higher than from natural gas combustion. CO₂ emissions from biogas combustion can in some cases be double that of pure natural gas [15]. But it must be taken into account that the greenhouse effect from methane is several tens of times stronger than from CO₂ [16], so biogas combustion from a global point of view leads to a decrease in the greenhouse effect.

The purpose of the work was a theoretical study of the effect of changing the composition of biogas and the coefficient of excess air on the parameters of the combustion process - gas and air consumption, combustion temperature and on the volume of combustion products. The influence of the ratio of CO₂ and N₂ contained in biogas on the main combustion characteristics was also evaluated. These dependencies are necessary for designing equipment and determining the operating mode of equipment that burns biogas. A change in the combustion temperature affects the processes of heat transfer in thermal units, the volume of combustion products - on the flue gases velocity. The results of the study are necessary

when designing equipment and determining the operating mode of equipment that burns biogas that is formed in natural conditions, for example, landfill gas generated on HSW. They can be used to design and control burners, furnaces and boilers that use biogas as fuel.

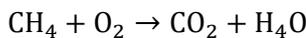
In contrast to existing works, where equipment calculations are always given for a given constant gas composition, in this work, combustion parameters were studied with a change in its composition.

2. Methodology

The problem of fuel combustion in heat engineering units is to obtain a given amount of energy. Usually, combustion is calculated per unit of volume or mass of fuel. This does not allow comparing different regimes when changing the composition of biogas, since different biogas flow rates are required to obtain a given heat output. It is proposed to calculate not per a unit of volume or mass, but per unit of power released during combustion, which makes it possible to evaluate the real parameters of the operation of heat engineering units.

It is assumed that the composition of biogas includes four components: methane CH_4 , carbon dioxide CO_2 ; nitrogen N_2 and oxygen O_2 , vol. ratio %.

Equations for calculating the required amount of air for burning biogas and the volume of combustion products obtained were obtained from the combustion equation:



Specific fuel consumption per 1 MW of heat released during combustion, m^3/MW :

$$k = 1000 / \text{LHV}, \quad (1)$$

where LHV – is the heat of biogas combustion, kJ/m^3 .

Actual specific volume of humid air for combustion, m^3/MW :

$$V_{dAir} = 0.0476 \alpha (2\text{CH}_4 - \text{O}_2) \times \\ \times (1 + 1.293 / 0.805 d_a) k, \quad (2)$$

where α is the coefficient of air excess; d_a is air moisture content, kg/kg of dry air:

$$d_a = 0.622 \varphi p_s / (100 p_b - \varphi p_s), \quad (3)$$

where φ is the relative humidity of the air supplied for combustion, %; where p_b is the barometric pressure, Pa; p_s - partial pressure of water vapor, kPa

$$p_s = \frac{6.4 + 0.10128 t}{1 + 0.00434 t}, \quad (4)$$

where t – is the air temperature, $^\circ\text{C}$.

Specific volumes of combustion products are actual, m^3/W

$$V_{d\text{CO}_2} = 0.01 (\text{CO}_2 + \text{CH}_4) k; \quad (5)$$

$$V_{d\text{H}_2\text{O}} = 0.01 (2\text{CH}_4 + 0.0476 \alpha \times \\ \times (2\text{CH}_4 - \text{O}_2) 1.293 / 0.805 d_a + \\ + p_g / 0.805 d_g) k; \quad (6)$$

$$V_{d\text{N}_2} = (0.037604 \alpha (2\text{CH}_4 - \text{O}_2) + \\ + 0.01 \text{N}_2) k; \quad (7)$$

$$V_{d\text{O}_2} = 0.01 (\alpha - 1) (2\text{CH}_4 - \text{O}_2) k, \quad (8)$$

where ρ_g – is biogas density, kg/m^3 ; d_g – moisture content of gaseous fuel, kg/kg of dry air:

$$d_g = f p_s / (100 p_b - f p_s) R / 461.52, \quad (9)$$

where R is the biofuel gas constant.

Volume of combustion products m^3/MW

$$V = V_{d\text{CO}_2} + V_{d\text{H}_2\text{O}} + V_{d\text{N}_2} + V_{d\text{O}_2} \quad (10)$$

Fuel combustion temperature, $^\circ\text{C}$:

– adiabatic

$$T_{adiabatic} = Q / V_{c_p} \quad (11)$$

– theoretical (taking into account the dissociation of triatomic gases):

$$T_{theoretical} = (Q - Q_{dis}) / V_{c_p} \quad (12)$$

where

Heat content of combustion products, kJ

$$Q = Q_{rn} + C_{p\text{gas}} t + C_{p\text{Air}} V_{d\text{Air}} t_{air} \quad (13)$$

Heat of triatomic gases dissociation, kJ/mol

$$Q_{dis} = 126.4 V_{\text{CO}_2} \alpha_d + 108 V_{\text{H}_2\text{O}} \beta_d \quad (14)$$

where α_d , β_d are the degree of dissociation of CO_2 and H_2O , %.

To calculate the degree of dissociation of triatomic gases α_d and β_d on the values of temperature t , °C and the partial pressure of carbon dioxide p_{CO_2} and water vapor p_{H_2O} in combustion products, kPa, the approximating equations were obtained:

Range of use:

$$1500^{\circ}\text{C} \leq t \leq 3000^{\circ}\text{C};$$

$$2.943 \text{ кПа} \leq p \leq 98.1 \text{ кПа.}$$

$$\text{Error } r^2 = 0,999.$$

$$\alpha_d = \frac{a + b t + c t^2 + d y + e y^2 + f t y}{1 + g t + h t^2 + i y + j y^2 + k t y}, \quad (15)$$

где $y = \ln p_{CO_2}$; $a = 7.484$; $b = -0.01281$; $c = 0.000005278$; $d = 0.9530$; $e = 0.0004881$; $f = -0.0006387$; $g = -0.0007752$; $h = 0.000000167$; $i = 0.08939$; $j = 0.001787$; $k = -0.00003436$;

Range of use:

$$1600^{\circ}\text{C} \leq t \leq 3000^{\circ}\text{C};$$

$$2.943 \text{ кПа} \leq p \leq 98.1 \text{ кПа.}$$

$$\text{Error } r^2 = 0,9999.$$

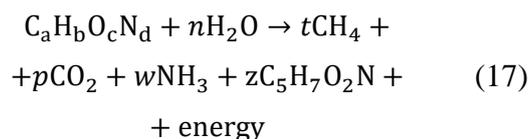
$$\beta_d = \frac{a + b t + c t^2 + d y + e y^2 + f t y}{1 + g t + h t^2 + i y + j y^2 + k t y}, \quad (16)$$

where $y = \ln p_{H_2O}$; $a = -0.6794$; $b = -0.0009382$; $c = 0.0000009682$; $d = 0.4438$; $e = 0.01164$; $f = -0.0003382$; $g = -0.0006592$; $h = 0.0000001158$; $i = 0.05372$; $j = 0.0008807$; $k = -0.00001846$;

The resulting equations make it possible to calculate the combustion of biogas, the combustion temperature and compare the thermal performance of combustion of biogas with different methane content.

3. Results

In the work, a study of the combustion of biogas with a methane content of 30 to 100% was made. It is accepted that biogas includes, in addition to methane, two main gaseous components – CO_2 and N_2 . The stoichiometric formula for the formation of biogas includes two main reaction products, methane and carbon dioxide [17]:



where: $C_a H_b O_c N_d$ is the empirical chemical formula of biodegradable organic substances in solid waste; $C_5 H_7 O_2 N$ is the chemical composition of microbial biomass.

But in practical measurements of the composition of biogas [1, 2], it was found that the sum of the content of methane and CO_2 is much lower than 100%. It is assumed that the remaining volume in it is occupied by N_2 . Therefore, for calculations, three options for the composition of biogas were considered:

1) CO_2 and N_2 content are equal:

$$N_2 = CO_2 = (100 - CH_4) / 2;$$

2) CO_2 content is twice the N_2 content:

$$N_2 = (100 - CH_4) / 3;$$

$$CO_2 = N_2$$

3) there is no nitrogen in biogas:

$$CO_2 = (100 - CH_4).$$

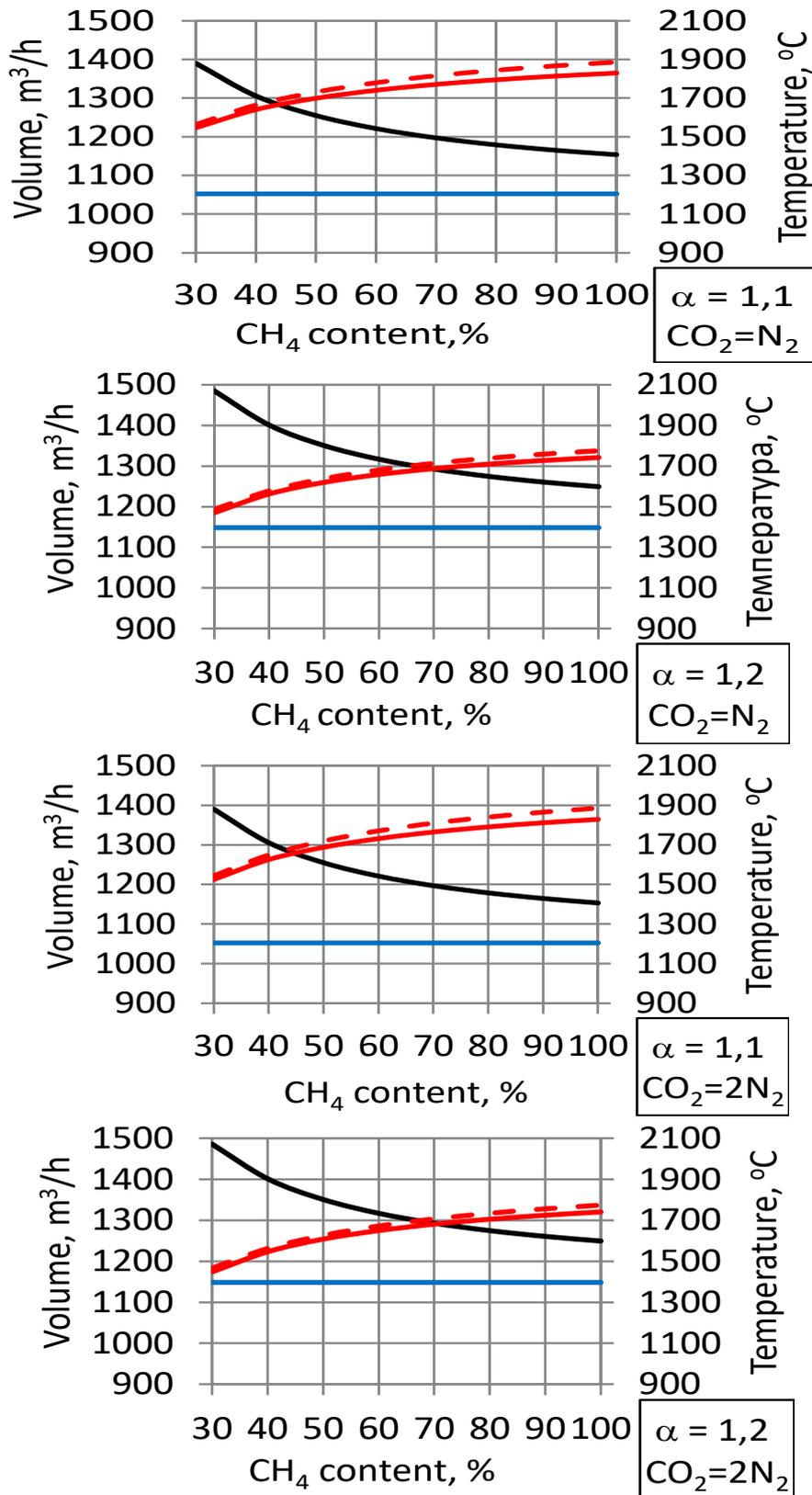
To calculate the combustion of biogas, gaseous fuel was used as well as the theoretical composition of biogas was used (Table 1).

Table 1: Theoretical biogas content

CH ₄ , content %		30	40	50	60	70	80	90
1) CO ₂ = N ₂	CO ₂	35	30	25	20	15	10	5
	N ₂	35	30	25	20	15	10	5
2) CO ₂ = 2N ₂	CO ₂	46.7	40	33.3	26.7	20	13.3	6.7
	N ₂	23.3	20	16.7	13.3	10	6.7	3.3
3) N ₂ = 0	CO ₂	70	60	50	40	30	20	10
	N ₂	0	0	0	0	0	0	0

The calculation was made for two values of the excess air coefficient, $\alpha = 1.1$ and $\alpha = 1.2$. The calculation results are shown in Figure 1.

The biogas consumption to provide a power of 1 MW is shown in Figure 2. The resulting graphs provide information on the required parameters of biogas combustion.



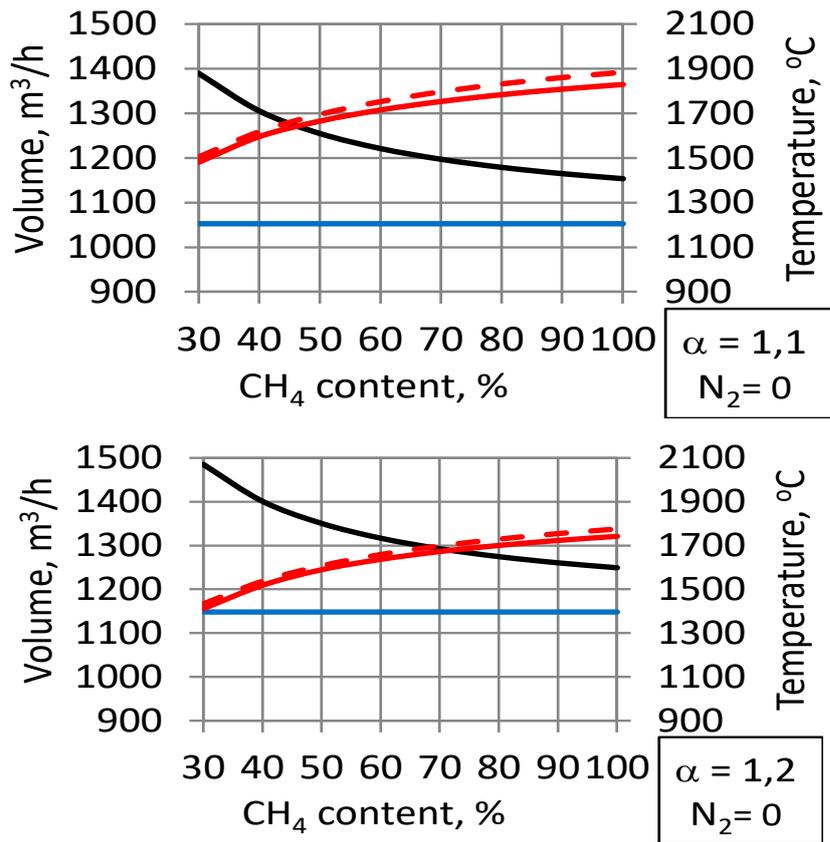


Figure 1. The volumes of gases required to obtain a thermal power of 1 MW, and the combustion temperature during the combustion of biogas of variable composition (— combustion air consumption, m³/h; — volume of combustion products, m³; — adiabatic combustion temperature °C; - - - theoretical combustion temperature, °C)

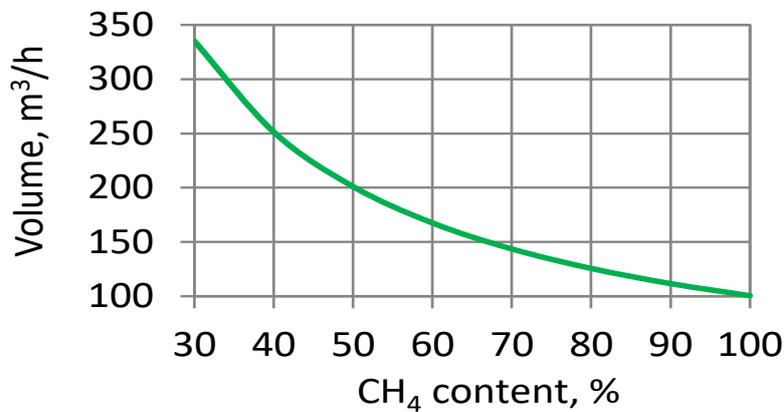


Figure 2. Consumption of biogas at different methane content, m³/h (at a combustion power of 1 MW)

4. Discussion

Pure biogas obtained under anaerobic conditions contains 55% CH₄ and 45% CO₂ by volume and a small amount of H₂S and NH₃ formed from sulfur and nitrogen contained in the organic part of the waste [17]. Biogas can also contain oxygen. It can get into biogas with air suction, while the ratio of nitrogen and

oxygen in biogas is equal to their ratio in atmospheric air 79/21 = 3.76. Air can also enter the waste layer, after which oxygen participates in the microbiological process. In this case, the nitrogen content in the landfill gas will be determined by the amount of incoming air, and can be either low or high.

Due to the high humidity of the waste, the resulting biogas has a relative humidity close to

100%. After the outlet of biogas during its transportation to the place of use, it is cooled to ambient temperature. Saturated water vapor pressure at 20°C is 2.3 kPa and the volume content of water vapor in biogas is 2.3%. At a lower temperature, this value is even lower. Therefore, the content of water vapor in biogas is constant and insignificant, and their influence on the combustion process was not considered.

To determine the composition of biogas, gas analyzers for the main components contained in it are used. Determining the CO₂ content in the range of more than 5% by volume requires the installation of an optical infrared sensor, which is equipped with gas analyzers only of expensive models. In practice, only three indicators of practical importance are monitored

in biogas systems: CH₄, O₂ and H₂S. The content of methane determines the energy value of biogas, oxygen determines the amount of suction in the system, the presence of hydrogen sulfide affects the corrosion of equipment. Typically, the rest of the composition, in which the main components are CO₂ and N₂, is unknown.

Analysis of the composition of biogas, carried out at the MSW landfill by the authors of the study using professional multicomponent gas analyzers, showed that the amount of CH₄ + O₂ + CO₂ content varied from 67% to 97% (Table 2). The rest of the volume is presumably occupied by nitrogen. Similar results were obtained by Calbry-Muzyka et al. [18].

Table 2: The results of measuring the composition of biogas emitted at landfill MSW

Location of analysis	Date of measurements	Gas analyzer	Content, vol. %				Estimated content N ₂ (100 – Amount)	N ₂ /O ₂
			CH ₄	O ₂	CO ₂	Amount H ₂ + O ₂ + CO ₂		
Landfill "Streletskoye", section "South", technological line from 44 wells	14.09.2018	Drager X-am 7000	57	1,8	38	96,8	3,2	1,8
Landfill "Streletskoye", section "North", technological line from 44 wells [2, 19]	17.11.2017	MRU Vario Plus	30,6	2,55	33,5	66,65	33,35	13,1
Landfill "Streletskoye", section "South", experimental section from three wells [2, 19]	17.11.2017	MRU Vario Plus	32,8	0,85	57,8	91,45	8,55	10,1

From the results of the calculation, it can be concluded that the volumetric flow rate of combustion air remains constant when the methane content in biogas changes. This is due to the fact that to maintain a thermal power of 1 MW, the same amount of methane is needed, and, therefore, with a constant coefficient of air excess, the air flow will also be unchanged.

With an increase in the air excess coefficient, the combustion temperature

decreases, and the volume of combustion products increases.

When the methane content decreases from 100% to 30% the combustion temperature decreases by 150–200°C. This is due to an increase in the content of CO₂ and H₂O in biogas. This is also associated with an increase in the volume of combustion products by 250 m³/h (about 20%).

The ratio of CO₂ and N₂ has practically no effect on the thermal parameters of combustion, with various options for calculating the composition, the combustion temperature changed by 1–3°C. In this section, it is explained the results of research.

5. Conclusions

In this work, the influence of the composition of biogas and the coefficient of excess air on the flow rate of gas and air, on the combustion temperature (adiabatic and theoretical), as well as on the volume of combustion products was studied. In the course of the work, a combustion calculation was carried out for biogas with a methane content of 30 to 100% and a different ratio of CO₂ and N₂ content in biogas.

Combustion of biogas of variable composition, provided that the specified thermal power of the furnace or boiler is provided, does not require a change in air flow, but only a change in biogas flow depending on the content of methane in it. A decrease in the methane content leads to an increase in the volume of exhaust gases and a decrease in their temperature. Therefore, a decrease in the methane content in biogas can lead to a decrease in the intensity of heat exchange and a decrease in the efficiency of the unit. The ratio of CO₂ and N₂ practically does not affect the thermal parameters of combustion.

The results of the study are necessary when designing equipment and determining the operating mode of equipment that burns biogas that is formed in natural conditions, for example, landfill gas generated at HSW landfill.

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