BIO Web of Conferences **103**, 00031 (2024) https://doi.org/10.1051/bioconf/202410300031
FIES 2023

Improving the quality of biogas fuel combustion in a household gas burner

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Abstract. The technology of energy production from waste of various origins is one of the most promising areas of the energy industry. Improving the efficiency of using alternative energy sources, as well as reducing the negative impact of organic waste of various origins on the environment are important tasks of modern science. One of the alternative types of energy is biogas. Moreover, the production of biogas is accompanied by the simultaneous processing of waste into organic fertilizers. However, biogas has a lower calorific value, and as a result, lower efficiency when burned in standard gas appliances. To find a solution to this problem, a study of the process of burning biogas in a gas burner of a household gas stove was conducted. Mathematical expressions are obtained in the form of regression equations and response surfaces describing the efficiency (η, %) and the content of toxic components (CO, mg/m^3) in the combustion products during the combustion of biogas in the original gas burner equipped with a thermal divider. As a result, the most rational design parameters of the thermal divider of the gas burner were determined. The developed original design of the gas burner device, equipped with a thermal divider providing preheating of the gas-air mixture, showed high efficiency and acceptable content of toxic impurities in the composition of combustion products.

1 Introduction

With the growth of the population, the negative impact on the environment increases – every year the amount of organic waste generated and the areas of landfills for the disposal of solid waste increases, the volumes of greenhouse gases emitted increase. So, at the beginning of 2022, the leading countries in terms of greenhouse gas emissions are: China, the USA, India. The Russian Federation is in fourth place – the amount of CO_2 generated in 2022 amounted to 1500 million tons [1].

An important problem of our time is the uncontrolled release of landfill gas from landfills and landfills of solid household waste. Canada is one of the largest producers of waste per capita worldwide – 36.1 tons per person per year, in the USA this figure is 26 tons per person per year. For the Russian Federation, this indicator is 450 kg per person per year, and the annual volume of municipal solid waste produced in Russia is about 65 million tons per year [2]. According to open information sources, the area of landfills in Russia is more than 4 million hectares, in the USA the total area of landfills is about 3 million hectares, in China the total area of landfills is 53 thousand hectares [3, 4].

Organic waste from crop production and animal husbandry is a valuable source of biomass, the anaerobic processing of which makes it possible to obtain organic fertilizer and an alternative to natural gas – biogas fuel. Another type of biogas fuel is landfill gas, the organized collection of which makes it possible to reduce the harmful impact of landfills of solid household waste on the environment.

Biogas fuel, depending on the composition of the initial substrate and the nature of its origin, may have a different composition. On average, the combustible part includes methane 35–85%, the non-combustible part – ballast impurities: carbon dioxide 15–65%, hydrogen sulfide < 5% and water vapor [5, 6].

The scope of application of biogas fuel is quite extensive, it is used as an automobile fuel, a source of electric and thermal energy, it is purified to the state of natural gas and supplied to gas networks.

In the modern world, the most common use of biogas in cogeneration plants for the production of thermal and electrical energy. At the same time, these installations require sufficiently large gas consumption (over 100 m^3/h) and their use is advisable on a large industrial scale, provided there is a sufficient amount of feedstock for the production of biogas. For relatively small volumes of biogas produced (up to 100 m^3/h), its use as a complete or partial replacement of natural gas in local and local gas supply systems is more rational.

However, the use of biogas fuel in gas supply systems is not widespread enough. This is due to the fact that this type of fuel is characterized by a relatively low methane content and the presence of ballast impurities – as a consequence, lower heat of combustion.

Thus, when burning in standard gas equipment, technical problems arise associated with reduced

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combustion efficiency and the formation of a significant carbon monoxide content.

Theoretical and experimental studies of domestic and foreign scientists are devoted to the study of the organization of high-quality combustion of combustible gases, including biogas, the development of new designs of gas-burning devices.

The work of the authors Cohé C., Chauveau C., Gökalp I., Kurtulus D. F. is devoted to the study of the effect of the concentration of CO2 in a mixture with methane on the combustion process [7]. In this work, the dependences of the impact of the height of the turbulent flame, the structure of the surface, the intensity of the combustion process with changes in pressure and CO2 concentration were revealed.

In the work of I.Ya. Sigal [8] it is shown that biogas can be used as boiler fuel and can replace natural gas in existing boilers, provided that the burner devices are reconstructed or replaced. During the experiments, it was shown that the length of a biogas flare is less than the length of a natural gas flare of the same thermal power, the toxicity of the release of biogas combustion products is less than that of natural gas.

Scientists Marinenko E.E., Komina G.P., [9] carried out theoretical and experimental studies of the properties of biogas, according to the classification of biogas, analytical dependencies were obtained to assess their combustible properties, the characteristics of the combustion of biogas and its mixtures with natural gas were investigated, the effect of the composition of biogas on the content of harmful components in combustion products was investigated. A universal industrial gas burner for biogas combustion has been developed.

The gas-burning equipment of boiler installations, process furnaces, gas generators, etc. is characterized by high productivity and is more advanced in comparison with gas burners of household gas equipment. Consequently, there is a problem of the applicability of biogas as a fuel, as well as the organization of high-quality combustion of biogas in household gas equipment. Therefore, the study of the combustion process of biogas fuel and the development of household gas burners that allow efficient combustion of this fuel is a very relevant area of research.

For the use of biogas fuel in household gas burners, more rational methods of modernization include the organization of preheating of the mixture, as well as ensuring high-quality mixing. Considering the above, we have proposed a gas burner for a household gas stove equipped with a primary air supply regulator and a thermal divider (Figure 1) [10, 11].

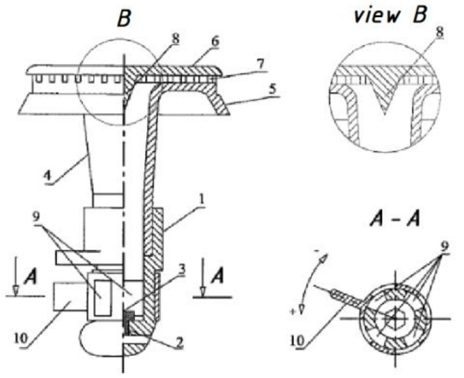

Fig. 1. The design of the gas burner device: 1 – housing; 2 – gas nozzle; 3 – axial outlet; 4 – mixer; 5 – outlet end of the mixer; 6 – lid; 7 – firing holes; 8 – divider; 9 – primary air supply holes; 10 – primary air supply regulator

A distinctive feature of this device is the use of a conical thermal divider. This solution allows preheating the gas-air mixture inside the burner by intensifying heat transfer from the heated lid. The use of a primary air supply regulator in the lower part of the housing allows for uniform intake and regulation of primary air flow into the burner mixer. This stabilizes the flow of the gas-air mixture in the preheating area, including in the case of the use of gases of various compositions.

The main objective of the study is to determine the optimal geometric parameters of the thermal divider of the gas burner device, which will ensure efficient combustion of gas, for a greater value of the efficiency of the gas burner device with a minimum carbon monoxide content in the combustion products.

2 Methods and materials

To study the influence of the design parameters of the thermal divider of a gas burner during operation on biogas, it is necessary to conduct full-scale experimental studies.

Figure 2 shows a schematic diagram of an experimental installation to study the operation of a gas burner device [12].

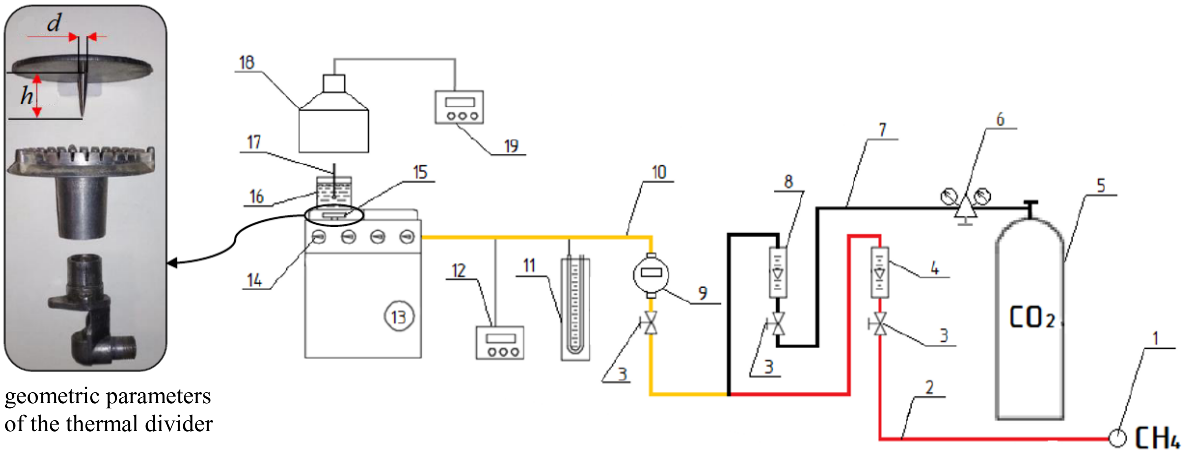

Fig. 2. Schematic diagram of an experimental biogas combustion plant: 1 – indoor gas pipeline; 2 – natural gas supply hose (CH_4); 3 – ball valve; 4 – rotameter (CH_4); 5 – cylinder (CO_2); 6 – reducer; 7 – supply hose (CO_2); 8 – rotameter (CO_2); 9 – gas meter; 10 – biogas supply hose; 11 – U-shaped liquid pressure gauge; 12 – portable gas analyzer (CH_4); 13 – household gas stove; 14 – table burner tap handle; 15 – gas burner; 16 – test vessel; 17 – thermometer (temperature sensor); 18 – CO sampling device; 19 – flue gas analyzer

As optimization parameters, the following are accepted: the efficiency of the burner η, %, is selected as an indicator of energy efficiency and the carbon monoxide content in the combustion products CO, mg/m^3, the variable factors are the diameter d, mm and height h, mm of the thermal divider.

The experiment plan provides for conducting 17 experiments on a gas burner with a nominal thermal power of 2.8 kW using biogas with a component composition of CH_4 = 50% vol., CO_2 = 50% vol. The first experiment on a gas burner of a standard design (without a thermal divider), and the remaining 16 experiments are carried out with various combinations of values of the diameter and height of the thermal divider. The values of the diameter (d, mm) of the thermal divider are varied in the range from 6 to 12 mm in increments of 2 mm, the height (h, mm) of the divider from 6 to 24 mm in increments of 6 mm.

The study of the efficiency of the biogas combustion process in a gas burner device was carried out on the basis of the methodology specified in the document [13]. According to which, a test vessel designed to determine the efficiency is installed on a burner configured and fixed at rated thermal power, and preheated for 10 minutes. A test vessel with a diameter of 260 mm, filled with water weighing 6.1 kg. The temperature sensor is placed in the geometric center of the volume of water and the temperature is measured. The initial temperature of the water in the test vessel should be (20 ± 1) °C. Measurement of gas consumption begins from the moment of installation of a vessel designed to determine the efficiency.

The water temperature in the used vessel is increased to (90 ± 1) ° C, after which the gas supply to the burner is stopped and, accordingly, the gas flow measurement is stopped.

After that, the calculation of the energy efficiency indicator of the $EE_{gasburner}$, % is performed according to the formulas:

$$EE_{gasburner} = \frac{E_{theoretic}}{E_{gasburner}} \cdot 100\%$$

$$E_{theoretic} = 4.186 \cdot 10^{-3} m_e \left(t_2 - t_1\right)$$

$$E_{gasburner} = V_c \cdot H_s$$

where $EE_{gasburner}$ is the energy efficiency of the gas burner, %; $E_{gasburner}$ is the amount of energy consumed by the gas burner to ensure heating to the appropriate temperature, MJ; $E_{theoretic}$ is the theoretically required minimum energy for heating to the appropriate temperature, MJ; m_e is the equivalent mass of the test vessel with water, kg; t_1 is the initial temperature of the water in the test vessel, °C; t_2 the final temperature of the water in the test vessel, °C; V_C the volume of gas consumed during the tests, m^3; H_S the highest heat of combustion of the gas, MJ / m$_3$.

The percentage concentration of CH_4 and CO_2 in biogas is monitored using a portable gas analyzer «FARMEK FP34». The volume of gas consumed is considered using the electronic gas meter « Grand-1,6». The water temperature in the test vessel is determined by a digital multimeter DT-878 with a thermometric sensor. Sampling of combustion products during the tests was carried out over a burner with a test vessel with water installed on it, 20 minutes after the start of the test. The CO content in the combustion products is monitored by the flue gas analyzer «Testo 320 LX».

The combustion products from the burner must enter the sampling device placed at a height of 20 to 80 mm above the surface of the gas stove table.

3 Results and discussion

The results of a full-scale experiment to study the operation of a gas burner equipped with a thermal divider during the combustion of biogas (CH_4 = 50% vol., CO_2 = 50% vol.) are presented in the form of regression equations [12]:

$$\eta,\ \% = 36.3092 + 2.6658 \cdot d + 0.6133 \cdot h - 0.119 \cdot d^2 - 0.0282 \cdot d \cdot h - 0.0102 \cdot h^2 \quad (1)$$

$$CO,\ mg/m^3 = 707.7833 - 62.9042 \cdot d - 20.7408 \cdot h + 2.4896 \cdot d^2 + 1.3939 \cdot d \cdot h + 0.3021 \cdot h^2 \quad (2)$$

The change in the energy efficiency (η, %) of the gas burner from the diameter d and height h of the thermal divider when working on biogas (CH_4 = 50% vol., CO_2 = 50% vol.), which describes equation 4, is shown in Figure 3 as a response surface (a) and a graphical dependence (b).

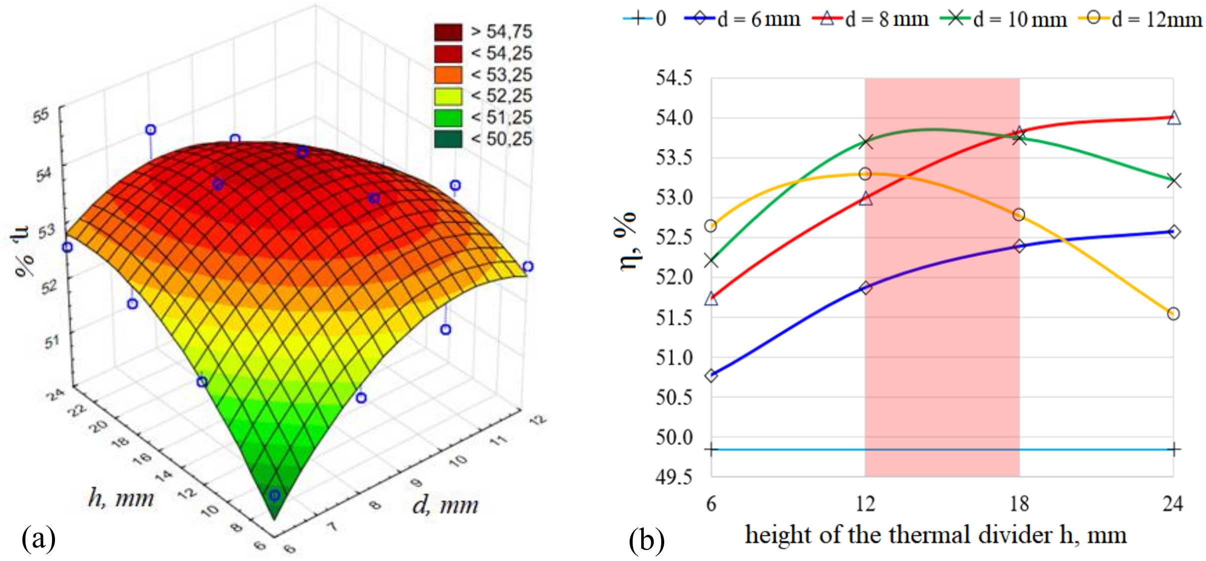

Fig. 3. The dependence of the efficiency η, % of the burner on the diameter d, mm and height h, mm of the thermal divider: (a) – the response surface; (b) – the graph of the dependence

The analysis of equation (1) and the graphical dependencies based on it in Figure 3 shows that with a thermal divider with parameters d = 6 mm and h = 6 mm, the efficiency of the burner takes a minimum value equal to 50.78%. This is 0.93% more than when the burner is operating without a thermal divider. With this combination of parameters of the thermal divider, the useful heat exchange area of the divider has a minimal value and has less impact on the efficiency of the combustion process. With increasing diameter d and height h, the efficiency gradually increases and takes maximum values of 53.75 ... 53.84 % with the height of the thermal divider h = 18 mm and diameters – d = 8 ... 10 mm – these dimensions give an optimal combination of gas dynamic mode and heat transfer inside the burner. With a further increase in the height and diameter of the thermal divider, a gradual decrease in efficiency occurs – which is caused by an increase in the gas-dynamic resistance from the divider to the flow of the gas-air mixture.

The change in the CO content, mg/m^3 in the combustion products from the diameter d and height h of the thermal divider when working on biogas (CH_4 = 50% vol., CO_2 = 50% vol.), which describes equation 2, is shown in Figure 4 as a response surface (a) and graphical dependence (b).

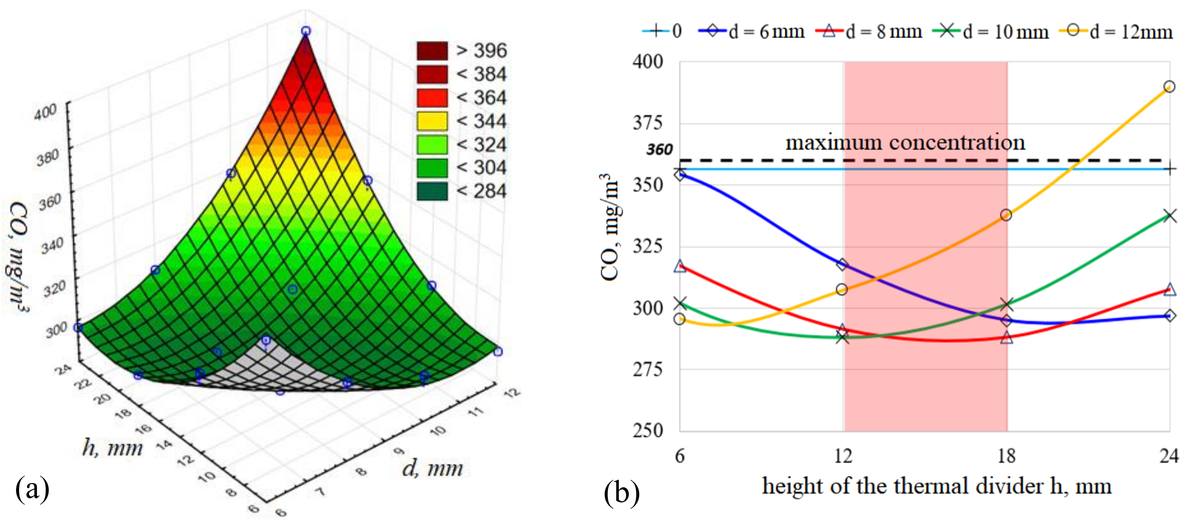

Fig. 4. The dependence of the CO content, mg/m^3 in the combustion products on the diameter d, mm and height h, mm of the thermal divider: (a) – the response surface; (b) – the graph of the dependence

According to Table 2 [14], the maximum content of carbon monoxide in combustion products should not exceed 0.03% by volume or 360 mg/m^3, this value corresponds to the dashed line indicated in the graph Figure 4 (b).

The analysis of equation (2) and the graphical dependencies based on it in Figure 4 shows that the minimum CO content = 288.33 mg/m^3 in combustion products during burner operation is formed when using thermal dividers with parameters d = 8 mm, h = 18 mm and d = 10 mm, h = 12 mm. The maximum values of the CO content, mg/m3 in the combustion products equal to 354 mg/m^3 and 390 mg/m^3 are observed at the parameters of the divider, respectively, d = 6 mm, h = 6 mm and d = 12 mm, h = 24 mm.

4 Conclusion

Experimental studies of the biogas combustion process in the burner of a household gas stove equipped with a thermal divider have been carried out. As a result of processing experimental data, regression equations and response surfaces of the burner efficiency and carbon monoxide content were obtained. The influence of the geometric dimensions of the divider on the combustion efficiency and the content of combustion products has been established. The most rational parameters of the divider during the combustion of biogas with a methane content of 50% and carbon dioxide of 50% are determined: height h = 10 mm, diameter d = 12 mm.

Thus, it can be concluded that the effect of preheating the gas-air mixture plays a positive role and contributes to the intensification of the combustion process of biogas and other types of gaseous fuels.

Acknowledgments

This work was realized in the framework of the Program «Priority 2030» on the base of the Belgorod State Technological University named after V.G. Shukhov. The work was realized using equipment of High Technology Center at BSTU named after V.G. Shukhov.

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