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THE RESULT OF THE INVESTIGATION OF A NEW MICROMODULE GAS BURNER WITH A SUDDEN EXPANSION AT THE OUTLET

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The object of the study is a new micromodule gas burner for small hot water boilers, in which, to stabilize combustion, the phenomena of flow disruption due to sudden expansion at the outlet of the burner are used. Today, there is an urgent task related to the development of new technical solutions for the most efficient and environmentally pure combustion of fuel in power plants, particularly, it is necessary to pay special attention to the stabilization of the flare. The combustion characteristics in this burner have been studied experimentally and theoretically, calculations are given for modeling a micromodule gas burner with a sudden expansion at the outlet, in particular, the model of a burner device for burning natural gas (propane) was modeled in the Ansys Fluent 2021 R1 software package. As a result of the experiment, the length of the torch was reduced, as well as the concentrations of harmful NO_x emissions were reduced with improved indicators of combustion completeness and temperature uniformity of the field. The results of experiments with different nozzles are presented, namely nozzles with slots at the outlet d_1 – 0.12 m and d_2 – 0.15 m. The number of modes in each experiment is 5. Mathematical modeling of this burner with the possibility of evaluating the effectiveness of these measures will allow us to develop optimal operating modes of power plants and develop new technical solutions to reduce the emission of pollutants. Based on the experimental data obtained, graphs were constructed (completeness of combustion, temperature unevenness, concentration of substances), and the results were summarized. In general, these characteristics will increase the efficiency of using this burner in hot water boilers

Keywords: burner device, gas, stabilizers, sudden expansion, recirculation zones, harmful emissions

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1. Introduction

Heating has always been one of the most important needs of mankind, especially, those living in regions with harsh climatic conditions. Therefore, there is a need to strive to optimize costs and improve the environmental sustainability of heating systems. The residential sector, which has a large energy load, has a huge impact on the environment.

Currently, there is an urgent task related to the development of new technical solutions for the most efficient and environmentally friendly combustion of fuel in power plants, including in small hot water boilers for burning natural gas (propane), fuel mixtures based on landfill gases and thermal decomposition products of industrial and municipal waste.

In addition, there are a huge number of small boiler houses in which there is an urgent need to replace outdated equipment or repair and put into operation, but for various reasons these works are not carried out.

The combination of such problematic issues generates great scientific interest in the need for modernization, ensuring the efficiency of old boiler houses and compliance with stricter requirements of environmental legislation. Therefore, research aimed at the development of burner devices for small gas-fired boilers is relevant.

2. Literature review and problem statement

Energy is a key factor in the global economy and the efficiency of energy production and consumption is essential for society and the environment. The economic and environmental problems of liquid and solid fossil fuels have contributed to the use of natural gas as a clean alternative fuel in industry and everyday life [1]. The chemical composition of natural gas includes mainly methane and it is the lightest hydrocarbon fuel. Thus, during the combustion process, it generates low levels of pollutants carbon monoxide and unburned hydrocarbons [2]. Despite these advantages, problems also arise during the combustion process, in particular, the occurrence of high flame temperatures, difficulties in controlling nitrogen oxide emissions, combustion instability and a tendency to reignite.

The paper [3] presents the results of a study of the synthesis gas combustion process, which showed that the combustion process proceeds successfully under conditions of a depleted pre-mixture, but there are unresolved issues related to combustion stability, stabilization of the microfume can be a way to overcome these difficulties, this approach was developed in [4], however here, the combustion of biogas due to the tangential twisting device leads to a low flame propagation rate, which is the reason for the burner failure.

The author of the paper [5] mainly investigated the effect of the temperature of primary air, secondary air and premixed gas on the formation of NO_x, however, there are unresolved problems related to the design characteristics of the burner on combustion processes.

The most effective energy criterion is a diffusion burner [6, 7] for burning natural gas and coal methane, in which the structural elements of the burner are identified, which allows taking into account the influence of turbulence and chemical kinetics of highly twisted reacting gas jets.

In [8] it was determined that combustion in the burner is achieved at an excess air coefficient of 7~26, however, there are unresolved problems with the coefficients of unevenness in these ranges, which would allow to show the efficiency of the burner. The authors of the work [9] examined the composition of synthesis gases, during the combustion of which an increase in the reaction rate was observed, which led to an increase in the amount of harmful substances. To ensure high-quality fuel combustion in relation to various tasks, it is very important to choose the design of the burner device to ensure good mixing of two streams of air and fuel [10, 11].

In [12], the influence of design and operational parameters on combustion was deeply investigated, in which structural changes were revealed to affect heat transfer, flame stability and reverse flame characteristics.

In addition, the requirements for combustion efficiency in burner devices have increased. Swirlers are flame stabilizers that regulate the speed of the mixture depending on the flame velocity [13, 14]. In addition, the creation of a vortex flow inside the burners increases the mixing of various components of the mixture, which makes it possible to improve the control of the combustion process in terms of flame quality and pollutant emissions [15, 16].

The processes of torch combustion are determined by the organization of the preparation of the fuel-air mixture in the burner and directly in the torch, and its very structure. The preparation of an air-fuel mixture, including biogas or synthesis gas, is especially relevant in connection with the phenomena of flame breakdown and overshoot. In order to maintain a stable position in the combustion zone of the ignition zone, that is, in front of the burner, the fuel mixture must enter the ignition zone at a speed equal to the flame propagation velocity [17, 18].

As the air/fuel ratio increases, a «depleted» breakdown occurs, and the energy released during the reaction may not be enough to continue burning, as a result of which the flame goes out and the burner goes out. As a result, when burning a mixture of pre-mixed fuel with air, the parameters of the breakdown of the «depleted mixture» are critical [19–21].

All this suggests that it is advisable to conduct a study on microfakel combustion with sustainable combustion. Since microfakel combustion provides the best combustion process, in which the microfakel is stabilized and the formation of harmful substances is reduced, in accordance with the results of theoretical and experimental data [22], the authors concluded that combustion with a low emission level can be achieved by stabilizing the microfakel. To solve the above-mentioned problems and achieve clean and stable combustion, a new micromodule gas burner Patent RK No. 36180 [23] was developed. In which, the stabilization of the microfakel occurs due to a sudden expansion at the outlet of the burner. This is explained by the fact that with a sudden expansion of the burner design, the confusor-diffuser channel creates a zone of reverse currents, in which the stabilization and stability of the combustion of fuel assemblies with a low yield of harmful substances occurs.

3. The aim and objectives of the study

The aim of the study of a new micromodule gas burner is to increase efficiency and reliability, the influence of design and operational parameters on combustion processes, which will allow to achieve the process of flame stabilization for sustained low-emission combustion with sudden expansion at the outlet.

To achieve this aim, the following objectives are accomplished:

– to construct dependences based on the results of experiments on the completeness of fuel combustion and temperature irregularities in the burner, depending on the excess air coefficient and on the air velocity in nozzles with diameters d_1 – 0.12 m and d_2 – 0.15 m;

– to identify the flame propagation temperatures inside the burner and to determine the flow patterns at various parameters of air velocities on the results of theoretical studies;

– to identify concentrations of harmful substances with diameters d_1 – 0.12 m and d_2 – 0.15 m of nozzles, to build graphs according to the data obtained from the experiments.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is a new micromodule gas burner with a sudden expansion at the outlet, in which the effect of the diameter ratio on the efficiency of the combustion process and on the formation of toxic harmful substances is investigated.

The realization of the goal and the solution of the tasks set are provided by the use of modern research methods based on the basic principles of hydrogas dynamics, boundary layer, mathematical modeling, system analysis, theory of differential equations, numerical methods, and experimental research methods.

The assumptions made in the work on mathematical modeling of the k-ε turbulence model, also the thermophysical characteristics of materials, are constant and known quantities.

The principle of operation of a micromodule gas burner is that the burner has a cylindrical nozzle of large diameter, and a sharp expansion is formed at the junction of the nozzle with the Venturi tube, which is a good stabilizer. Additionally, secondary air enters through the slots to the nozzle, which ensures high combustion completeness, combined fuel-air mixture with low NO_x output. The result is achieved by burning natural gas in a micromodule gas burner consisting of a Venturi tube, a fuel tube and a sprayer, characterized in that a large diameter cylindrical nozzle with outlet slots is installed to the diffuser part.

Thus, the burner can provide low-emission and sustainable combustion of natural gas in small hot water boilers.

Numerical modeling of aerodynamic air flow at sudden expansion at the outlet has been performed for this burner, the calculations of which have been simulated in the COMSOL Multiphysics software package [24]. The obtained results of the study will be useful for the development of small gas-fired hot water boilers.

The modeling was carried out using Ansys Fluent 2021R1 software package [25]. The geometry was constructed and generated using the ANSYS Workbench Design Modeler. The burner geometry was realized from 4 elements (Fig. 1), and additionally 1 element was added at the burner outlet in the shape of a truncated cone (Fig. 2) for the secondary air supply in this calculation. These elements are combined into one common object in order to achieve the required mesh builder performance and solver optimization.

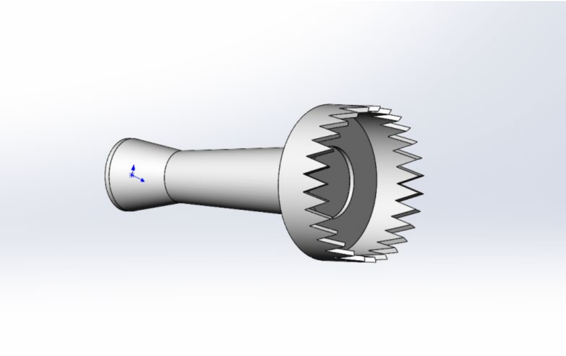

Fig. 1. Burner model

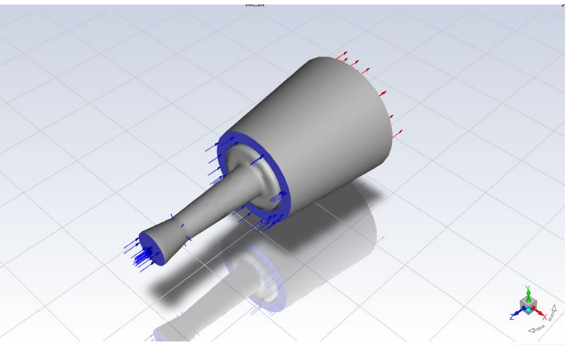

Fig. 2. Burner model for calculation

Meshing. To maximize the convergence of the solution in the computational part, it is necessary to create a proper mesh in which the mesh deformations are ordered with a small number of cells. Typically, the mesh on bulk solids is automatically created using tetrahedral or hexahedral solid elements with a linear or quadratic shape function. The workspace was created using one of the methods for specifying meshes – the Sweep Method (Fig. 3), which allows the creation of higher quality meshes with typically fewer cells. The Sweep Method was applied to all 5 elements of the object.

The overall view of the mesh generation results is shown in Fig. 3. The grid contains 51,750 nodes and 104,247 elements.

Set up. The Non-Premixed Combustion model was selected during the solver setup process. In the Boundary Conditions section, the parameters inlet-air 1, inlet-air 2, inlet-fuel are set. When setting the initial data for the calculation, the parameters of the oxidizer in 3 modes were selected, and then the fuel consumption was changed (Table 1).

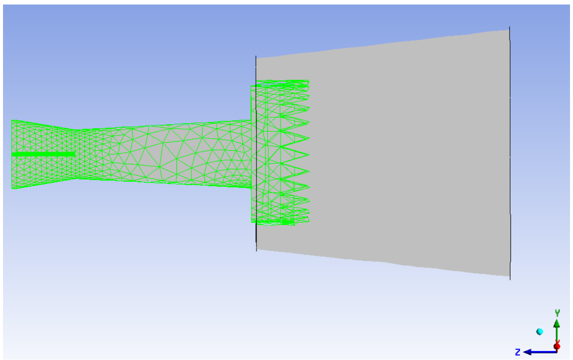

Fig. 3. Burner device mesh generation

Table 1

Boundary conditions for setting the calculation on the burner

No.	Boundary conditions	Value		
1	Fuel	Propane		
2	Inlet-air velocity (inlet-air)	10 m/s	15 m/s	20 m/s
3	Fuel flow rate (inlet-fuel)	0.011 kg/s	0.028 kg/s	0.034 kg/s
4	Turbulence intensity	5 %		
5	Turbulent viscosity coefficient	10		
6	Temperature	300 K		
7	Outlet pressure	–		
8	Initial gauge pressure	0 Pa		
9	Nozzle diameter	0.15 m		

Solution. A pressure-based steady-state solver was used and the standard *k*-ε model was applied, which is widely used to solve turbulent flow problems that aim to achieve high turbulence intensity [25]. In the calculation, the numbers of iterations were chosen to be 200 to maximize the convergence of this calculation.

A model of combustion without premixing was used in the calculation process. The model is well applicable in this particular case due to the fact that the material used for all yield zones is automatically set as a pdf mixture. The constituents of this mixture are the components that were calculated when the PDF reference table was created. Further, according to the results of the solver in the Results-Graphics section, data on different parameters are displayed, namely, Fig. 7 shows temperature parameters at inlet air velocities – 10 m/s, 15 m/s, 20 m/s, Fig. 8 shows flow structures. Propane is supplied through the fuel tube ∅0.04 m, located along the axis of the burner in the narrowest section, there is fuel injection through 6 holes ∅0.01 m perpendicularly along the axis. The nozzle diameter ∅0.15 m.

During the experiment, before the start of each mode, the readings on the counter and the start time were recorded, and after the end of the mode, the end time was recorded with the readings on the counter. Thus, we were able to determine the time and gas consumption in the mode. The gas consumption is determined as follows:

$$G_g = \frac{\Delta G_g}{\Delta \tau}, \text{ kg/s}, \qquad (1)$$

where ΔG_g – gas consumption in kg over a period of time $\Delta\tau$.

We regulate the necessary air by installing a regulator (flap) that regulates the air flow at the fan outlet. In each mode, the static air pressure at the inlet to the burner was measured using the multifunctional measuring system Testo 454 P.

Determining the static air pressure at the inlet to the burner, we determine the air velocity in each mode as follows:

$$w_a = \sqrt{\frac{2 \cdot P_a}{\rho}}, \text{ m/s,}$$

where ρ – the density of air, 1,225 kg/m^3; P_a – the static air pressure at the entrance to the combustion chamber, Pa.

Air consumption, kg/s:

$$G_a = w_a \cdot \frac{\pi \cdot d^2}{4}, \text{ kg/s,} \tag{3}$$

where w_a – the air velocity, m/s; d – the diameter at the fan outlet, m.

The excess air α was calculated using the following equation:

$$\alpha_\Sigma = 3{,}600 \cdot \frac{G_a}{G_g \cdot L_0}, \tag{4}$$

where L_0 – the stoichiometric coefficient.

The coefficient of completeness of fuel combustion. From the equation of the thermal balance of the chamber, attributed to 1 kg of burned fuel:

$$\eta_g = \frac{(1+\alpha_\Sigma \cdot L_0)\cdot\left(c_{pg} \cdot T_g^* - c_{pg} \cdot T_0^*\right) - \alpha_\Sigma \cdot L_0 \cdot \left(c_{pg} \cdot T_a^* - c_{pa} \cdot T_0^*\right) - \left(c_{pg} \cdot T_f^* - c_{pf} \cdot T_0^*\right)}{Q_l^w}, \tag{5}$$

where T_g^* – the temperature of the gases at the outlet of the combustion chamber, K; T_0^* – the standard temperature for determining the heat of combustion of fuel (calorimetry temperature), K; T_a^* – the air temperature at the entrance to the combustion chamber, K; T_f^* – fuel temperature at the nozzle inlet; Q_l^w – the lowest heat of combustion of the working fuel for propane, 47,540 kJ/kg; 91.27 MJ/m^3, 21.800 kcal/m^3; c_{pa} – the average mass heat capacity of air at a temperature relative to the named parameter, kJ/kg*K; c_{pg} – the average mass heat capacity of a gas at a temperature equal to that of the named parameter, kJ/kg*K; c_{pf} – the average mass heat capacity of the fuel (propane) at a temperature equal to the specified parameter, kJ/kg*K.

Determination of the degree of unevenness of the temperature field at the outlet of the combustion chamber. Due to the difficulty of characterizing the temperature field of the exhaust gases in full according to the indications of only a limited number of thermocouples in the measuring area behind the combustion chamber, the assessment of the «Thermal uniformity» of the gas flow is approximate.

When calculating the desired total unevenness, as a result of processing the results obtained during the experiment, the maximum and minimum temperature values are selected:

$$\delta = \frac{T_{g.\max}^* - T_{g.\min}^*}{T_a^*} \cdot 100\,\%, \tag{6}$$

where $T_{g.\max}^*$, $T_{g.\min}^*$ – the temperature of gases at the outlet of the combustion chamber, K; T_a^* – the temperature of the air at the outlet of the combustion chamber, K.

Experimental studies were carried out on the experimental bench described below. The stand for the study of burner devices with different nozzles, which refer to the micro-flare method of fuel combustion is presented in Fig. 4, 5. The stand was located on the territory of LLP «KazKotloService».

The experimental stand for studying the operation of burner devices with different nozzle diameters, which are stabilizers, simulates the operation of small hot water boilers.

The important components of the experimental setup are:
– air supply system;
– fuel supply system;
– ignition system;
– instrumentation complex with measuring equipment.

The fuel was supplied by gas cylinder 1, the gas temperature corresponded to the outside air temperature, which was 18÷23 °C.

Before feeding to the micromodule gas burner, measurements of the main characteristics of the fuel were made by manometer 2 and gas meter 3.

The air was supplied by fan 4, at the outlet of fan 4 a stabilization pipe was installed, the length of which was 1.2 m and the diameter ∅0.15 cm. It was designed to equalize the velocity fields.

The fuel tube ∅0.04 m is installed on the narrow section of the burner, in the stabilization tube there are static pressure manifolds and full pressure nozzle 6, which are included in the multifunctional measuring system «TESTO 454-p», to determine the flow rate and flow velocity field, and the air temperature at the inlet was determined with the help of a chromel-peel thermocouple (TPC) «Metran 232-02» 7, which is designed to measure air temperature values up to 80 °C.

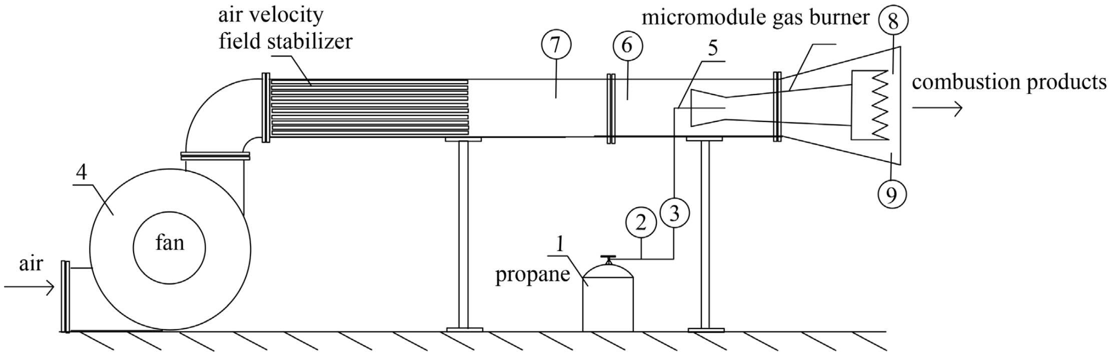

Fig. 4. Schematic diagram of the experimental setup with measuring devices: 1 — gas cylinder (propane); 2 — pressure gauge; 3 — gas meter; 4 — fan; 5 — fuel supply tube; 6 — multifunctional measuring system Testo 454 p; 7 — chromel-peel thermocouple; 8 — chromel-alumel thermocouple; 9 — gas analyzer Testo 350

The temperature of combustion products was measured with the help of chromel-alumel thermocouple (TCA) «Metran 231-02» 8, the measuring range of which is from –40 °C to +1,200 °C.

At the burner outlet, gas analysis, measurement of temperatures, velocities of gas media flows were carried out using a gas analyzer «TESTO 350» 9. Samples of combustion products for chemical analysis were analyzed at the exhaust with the probe «Testo-350» at a distance of 13–15 cm from the flame core.

Using a portable computer, data were collected for all measuring devices of the experimental stand.

As a micro-flare burner device, a micromodule gas burner for combustion of natural gas (propane) according to the patent for invention RK No. 36180 was used [23].

The burner device for natural gas combustion consists of a body with the tapering-expanding channel, at the outlet – on the burner axis there is a distributing cone connected inside with the burner body. Propane is supplied through a copper fuel pipe ∅0.04 m, located in the narrowest section of the burner axis, and fuel is injected through 6 holes ∅0.01 m perpendicular to the axis. The micromodule gas burner has a cylindrical nozzle of large diameter, and a sudden expansion is formed at the junctions between the nozzle and the venturi tube, which is a stabilizer. Additionally, secondary air is supplied to the nozzle through slots, which ensures high combustion completeness, combined fuel-air mixture with low NO_x output.

Cylindrical nozzles with slots at the outlet for the experimental stand were presented in two variants: d_1 – 0.12 m and d_2 – 0.15 m, the purpose of which is to select the optimum diameter for stabilization, at which there is stable combustion with low output of harmful emissions of nitrogen oxides. A general view of cylindrical nozzles is presented in Fig. 5.

During the experiment, the influence of nozzle diameters on stabilization and mixing processes was investigated, as well as efficient combustion of natural gas (propane) with stable combustion and reduced formation of harmful emissions. The experimental setup is presented in Fig. 6.

Propane was in gas cylinders, the pressure and flow rate of which were regulated by a valve, manometer. The fuel flow rate was controlled by an electric flow meter, with an accuracy of 1.25 % over the entire range of measurements. Fuel was fed into the fuel tube, located axially in the narrow cross-section of the burner, and gas distribution was carried out by copper tubes ∅0.04 m perpendicularly through 6 holes. The air was blown in by a fan. Mixing of the fuel-air mixture took place at a narrow section inside the Venturi tube, and secondary air was supplied through the slots of the cylindrical nozzle.

Fig. 5. General view of cylindrical nozzles (d_1 – 0.12 m, d_2 – 0.15 m)

Fig. 6. Burner device research bench

A spark ignition system installed at the burner outlet was used to ignite the gaseous fuel. To measure the temperature of air and fuel combustion products, radial thermocouples with diameters of 0.5 mm (chromel-alumel) were installed at the outlet of the combustion chamber. The parameters of flue gases were measured by a stationary gas analyzer with an extended sensor suite having an error of 5 % over the entire measurement range. A high-resolution camera was used for images.

According to an experimental study of a burner device for burning natural gas (propane), an optimal combustion mode with a low concentration of harmful substances yield was selected and the effects of nozzle diameters on stabilization and mixing processes, as well as effective combustion of natural gas (propane) with stable combustion.

Two experiments were conducted, the first one with diameter d_1 – 0.12 m and the second one with diameter d_2 – 0.15 m. There were 5 modes in each experiment, with 5–7 measurements in each mode, it took 1–1.5 minutes per measurement. Before the beginning of experiments, a quantitative selection of modes was manually made, the most effective and optimal mode was determined by the visual quality of combustion (flame color) and by gas flow and air velocity, as well as conducted instrumental analysis of flue gases, with the sampling point for the analysis of flue gases were selected points at a distance of 13–15 cm from the core of the flame on the visual length of the flame. At the beginning of each experiment, studies were carried out to select the optimal mode in terms of gas flow rate and air velocity, and in subsequent modes either air velocity or gas flow rate were constant.

Sufficient experiments were conducted to reduce the absolute error values. After collecting all the required data for the studied parameters, arithmetic or geometric mean values were calculated. The flame was kindled at an average fuel consumption of 0.0028 kg/s and variable air flow in the range of 5–27.8 m/s (Fig. 10) at a fuel supply pressure of 0.02–0.14 MPa.

5. Research results of a micromodule gas burner with a sudden expansion at the outlet

5. 1. The temperature of the flame in the burner and the structure of the air flow at different air speeds

As can be seen from Fig. 7, the temperature distributions along the channels of the confuser-diffuser part are uneven, this is due to the fact that at different values of oxidizer velocities, a reverse current zone of hot combustion products is formed on the burner axis. They at the exit from the micromodule gas burner create a high-temperature concentrated flame area. The flame temperature at 20 m/s 90–100 K is higher compared to the other parameters. The degree of flow turbulence formation at 10 m/s (Fig. 7, *a*) is similar to the conditions at 15 m/s (Fig. 7, *b*), which confirms the conclusions from the figures above. Flame slippage into the interior of the micromodule gas burner is observed to a greater extent (Fig. 7, *c*) at 20 m/s.

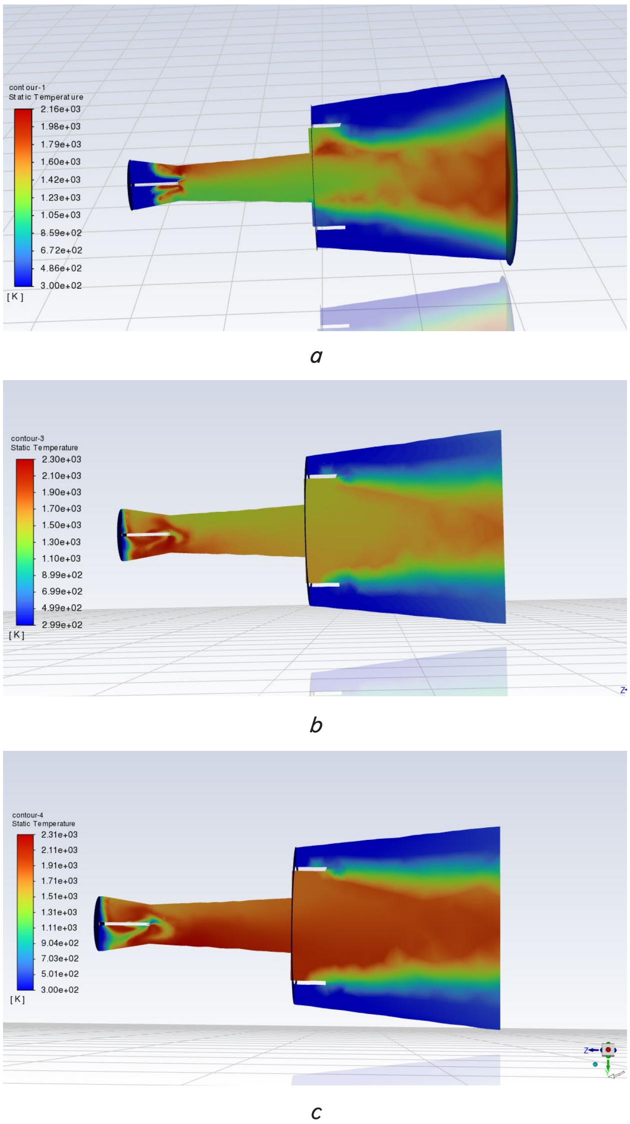

Fig. 7. Flame temperature: *a* — at 10 m/s; *b* — at 15 m/s; *c* — at 20 m/s

Fig. 8 shows the flow structures at different air velocity parameters. Obviously, the higher the oxidizer velocity, the higher the fuel combustion completeness factor, which leads to less formation of harmful substances at the burner outlet. To ensure the greatest intensity of turbulent flow of the fuel-air mixture flow in this burner, it is necessary to maintain the oxidizer velocity within 15–20 m/s (Fig. 8, *b* and Fig. 8, *c*), which, in turn, will allow to achieve low-emission and stable combustion of the fuel-air mixture.

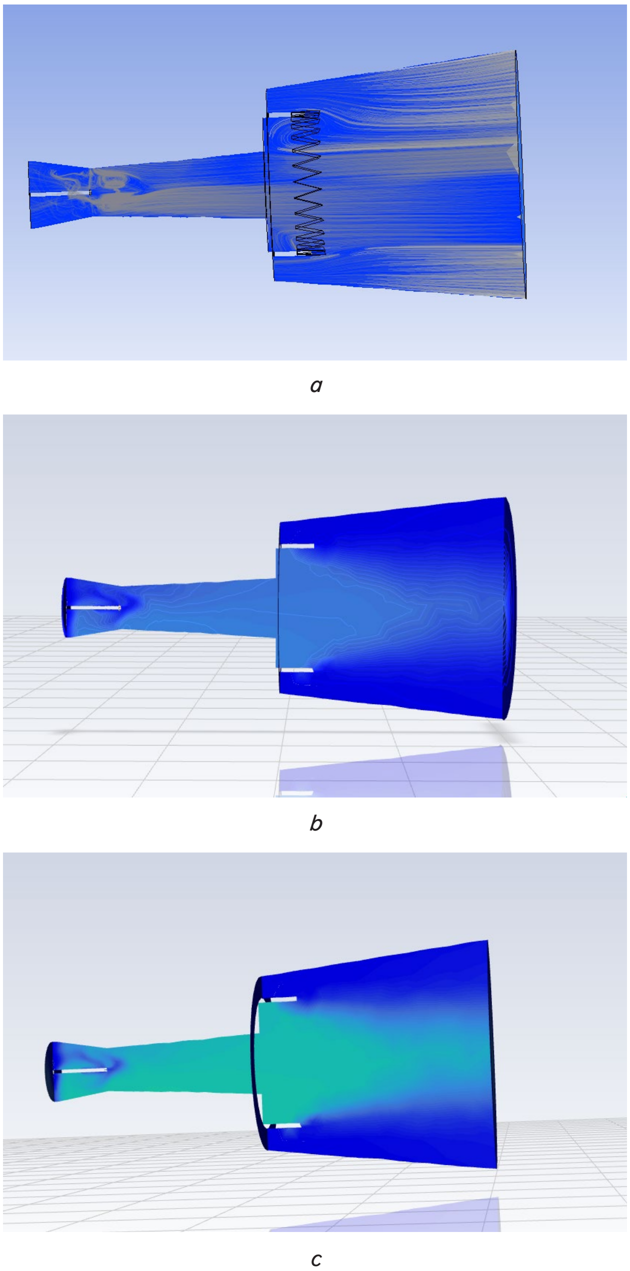

Fig. 8. Flow structure: *a* — at 10 m/s; *b* — at 15 m/s; *c* — at 20 m/s

5. 2. The dependence of the completeness of combustion, temperature unevenness on the excess air coefficient and on the air velocity

Completeness of combustion. Fig. 9 shows the changes in the completeness of fuel combustion from the excess air coefficient (5). The dependence of the completeness of combustion on the excess air coefficient depends on the presence of a large amount of air, in this case, there is an increase in the completeness of combustion with an increase in the excess air coefficient, thereby affecting an increase in entrainment from the combustion zone. There is a sharp increase in the completeness of combustion in a large diameter nozzle due to a decrease in the time spent by gases in the recirculation zone, and there is also the greatest change in the completeness of combustion in this nozzle.

Fig. 10 shows the dependence of the combustion completeness on the air velocity (5). Judging by the graph, the most complete combustion is provided in a large nozzle, the diameter of which is d_2 – 0.15 m at speeds in the range of 9–11 m/s, which corresponds to the stoichiometric ratio of fuel and air. The most effective nozzle in terms of completeness of combustion is a nozzle with a larger diameter. This circumstance is explained by the most efficient mixing of fuel with air in the recirculation zone. No less effective is the small nozzle d_1 – 0.12 m, since this nozzle has the least effect on the flow structure – it creates the smallest recirculation zones.

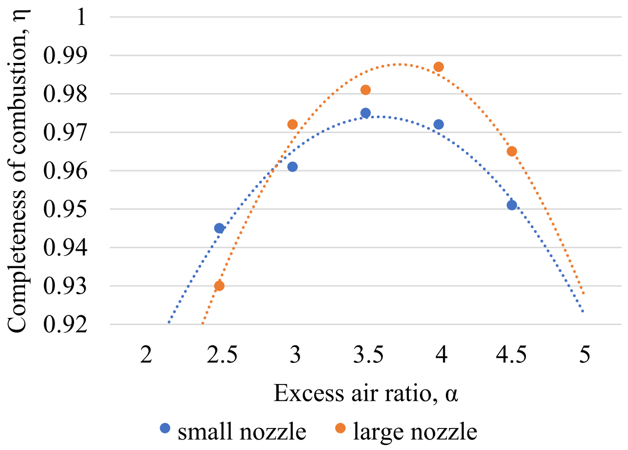

Fig. 9. Dependence of the combustion completeness on the excess air coefficient

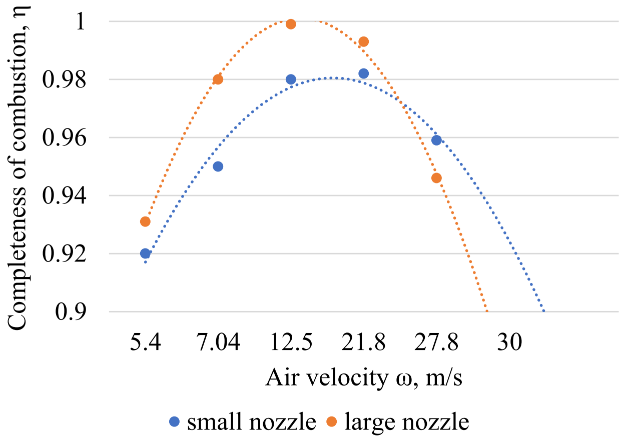

Fig. 10. Dependence of combustion completeness on air velocity

Temperature unevenness. Fig. 11 shows the dependence of the temperature unevenness on the coefficient of excess air (6). As can be seen from the figure, an increase in excess air, i.e. an increase in air consumption leads to an increase in unevenness due to an increase in turbulence in the combustion zone. A large air flow creates large disturbances, which leads to the formation of uneven currents, the entrainment of hot streams to the side and other processes.

Fig. 12 shows the dependence of the temperature unevenness on the air velocity (6). As can be seen from Fig. 12, the most effective, in terms of ensuring uniform temperature distribution, is a nozzle with a diameter of d_2 – 0.15 m. Studies have shown that an increase in velocity leads to an increase in temperature unevenness, this is explained by an increase in turbulence of the flow.

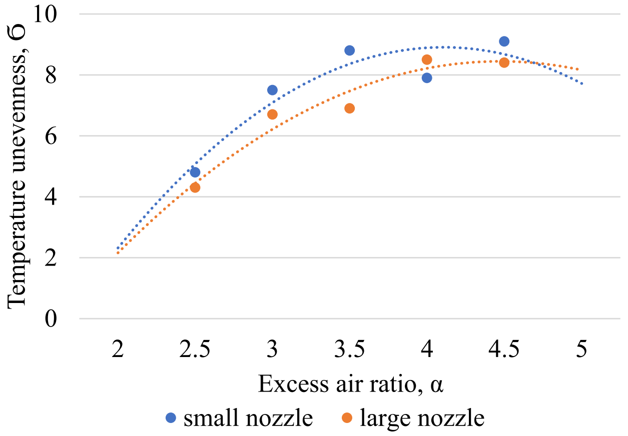

Fig. 11. Dependence of the temperature unevenness on the coefficient of excess air

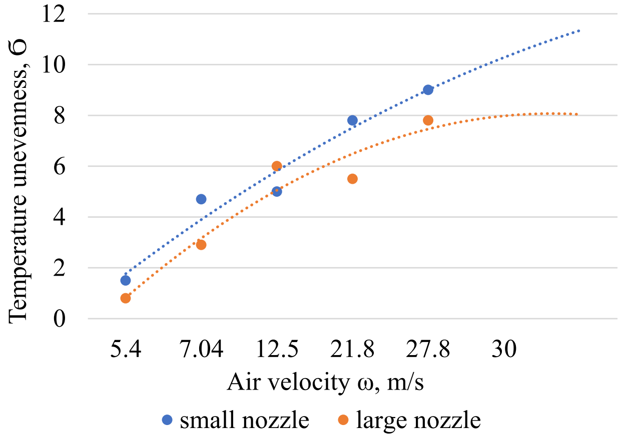

Fig. 12. Dependence of the temperature unevenness on the air velocity

5. 3. Concentrations of substances

Fig. 13 shows the dependence of the concentration of nitrogen oxides on the coefficient of excess air.

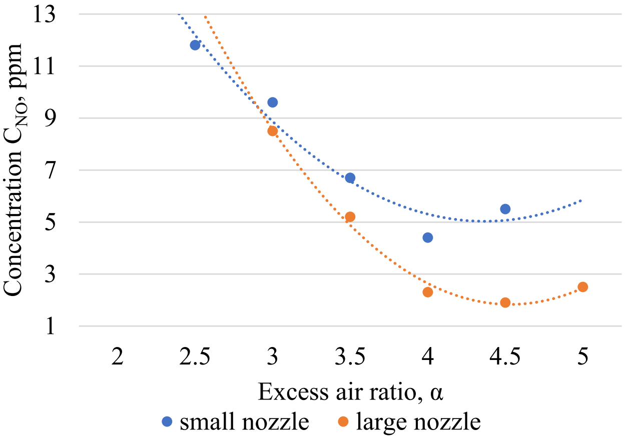

Fig. 13. Dependence of C_{NO} on the coefficient of excess air

It is natural that the temperature of gases depends on the amount of air entering the combustion zone, and with an increase in its volume in the combustion zone, the average temperature decreases. Due to the intake of a large amount of air into the combustion zone and with a decrease in temperature, the concentrations of nitrogen oxides decrease, which is shown in the graph. The lowest concentrations of nitrogen oxides were detected in a large diameter nozzle.

Fig. 14, 15 show the dependences of CO and C_nH_m concentrations on the excess air coefficient. An increase in air leads to a decrease in the formation of these substances, due to a decrease in temperature and a decrease in underburning of fuel.

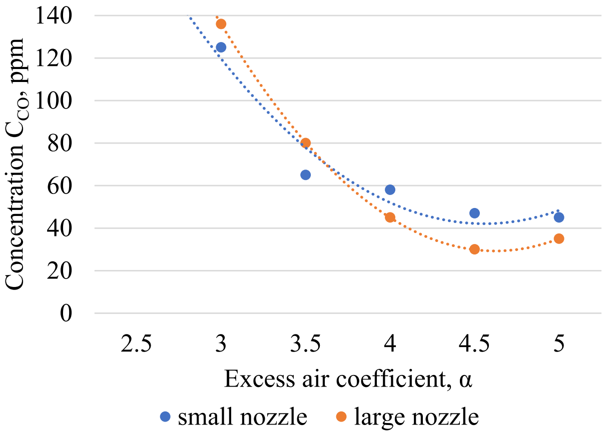

Fig. 14. Dependence of C_{CO} on the coefficient of excess air

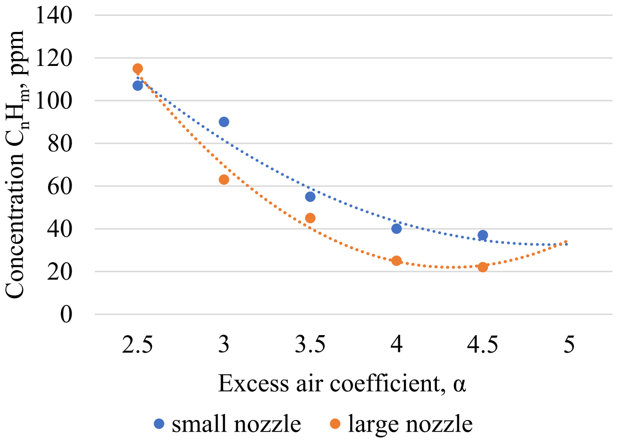

Fig. 15. Dependence of C_nH_m on the coefficient of excess air

6. Discussion of experimental results of a micromodule gas burner

When the flap was opened at an angle of φ=30° at an air flow velocity of 5.8 m/s (Fig. 9) and a pressure gauge reading of 0.02 MPa, a flare failure was recorded, this can be explained by the fact that in this range there is an increase in the completeness of combustion with an increase in the excess air coefficient, thereby affecting an increase in entrainment from the combustion zone, in addition, there is a sharp increase in the completeness of combustion in a large diameter nozzle due to a decrease in the time spent by gases in the recirculation zone, as well as the greatest change in the completeness of combustion in this nozzle.

The optimal combustion mode was fixed in a nozzle with a diameter of d_2 – 0.15 m (Fig. 10), this is explained by the fact that in this nozzle, when the angle φ=50° was opened and the air flow velocity was within 12.5–21.8 m/s at a fuel supply pressure of 0.11 MPa, the fuel-air mixture was mixed with stable combustion due to the phenomenon of flow disruption with sudden expansion at the outlet of the burner. And at an air flow rate of 21.8 m/s at the opening of the angle 55°, at a fuel supply pressure of 0.13 MPa, the most optimal mode with stable and sustainable combustion was set in this nozzle, which was evidenced by the blue flame burning at the outlet of the combustion.

Fig. 11 shows an increase in excess air, i.e. an increase in airflow, which leads to an increase in unevenness, this is due to increased turbulence in the combustion zone. Fig. 12 shows the dependence of the temperature irregularity on the air velocity. As can be seen from the figure, the most effective, in terms of ensuring uniform temperature distribution, is a nozzle with a diameter of d_2 – 0.15 m. Studies have shown that an increase in velocity leads to an increase in temperature unevenness, this is due to an increase in flow turbulence.

As a result of the experiment in Fig. 13, incomplete combustion of fuel was observed in a nozzle with a diameter of d_1 – 0.12 m, this can be interpreted by the fact that due to the undeveloped reverse current zone at the outlet of the burner, concentrations of harmful substances increased, and there was also a decrease in the concentration of harmful substances formation with an excess air ratio of 3–5 (Fig. 13–15). In addition, reverse current zones and high-quality mixing of the fuel-air mixture were created in this mode.

The proposed experimental results allow us to close the question of the problems of sustainable combustion in the work of the author [3] on the basis of an experimental study of a burner device for burning natural gas (propane), in which optimal combustion modes with a low concentration of harmful substances were determined. And also, according to the results of the work [4], the burner failure was recorded at low oxidizer velocities in the range of 8–9 m/s, which was influenced by low flame propagation speeds, however, thanks to the tests carried out, the new burner has wide control possibilities not only for changes in the excess air coefficient, but also for the effects of the diameter ratio nozzles for stabilization and mixing processes. As a result, it was possible to achieve efficient combustion of natural gas (propane) and stable and sustainable combustion with a decrease in the length of the torch, and a reduction in harmful emissions. The experiment showed that a nozzle with a diameter of d_2 – 0.15 m is the most suitable for efficient propane combustion.

The advantages of the obtained results over the known ones:

– the possibility of regulating the reduction of harmful emissions, in particular NO_x, by burning depleted fuel assemblies and changing the ratio of nozzle diameters;

– the possibility of reducing the length of the torch, as well as experimental studies, were supplemented by calculations on Ansys FluentWeaknesses of the study:

– the research was carried out in an open flare at atmospheric pressure;

– the temperature of the burner metal was not measured.

Thus, a micromodule gas burner with micro-flame combustion and a stabilizer, as a large diameter outlet, has proven its effectiveness when used in gas-powered burners. Based on the results of experimental studies, data are collected and further analyzed for the efficient combustion of natural gas with stable combustion and reduced generation of harmful emissions. This work can be useful for creating low-emission devices for small boilers.

The first stage of the burner study has been completed. Further research is planned in order to commercialize it, which will comprehensively consider recommendations for practical use. Also, the following studies will be conducted in an experimental 1.5 kW boiler based on «Kazkotloservice» LLP, where air supply speeds and pressure will be increased. The development of this research will be expanded with tests in a small hot water boiler. In addition, tests are being conducted with the addition of hydrogen H_2 in order to reduce greenhouse gas emissions, in particular, at the moment the proportion of hydrogen H_2 has been increased to 40 %. Another solution for this burner is to use a mixture of landfill gases from a landfill for solid waste disposal with hydrogen H_2. The first approbation showed positive results.

7. Conclusions

1. Dependences are constructed based on the results of experiments on the completeness of fuel combustion and the unevenness of temperature in the burner, depending on the excess air coefficient and on the air velocity in nozzles with diameters d_1 – 0.12 m and d_2 – 0.15 m. The most complete combustion is provided in a large nozzle, the diameter of which is d_2 – 0.15 m at speeds ranging 9–11 m/s, which corresponds to the stoichiometric ratio of fuel and air.

2. The flame propagation temperatures inside the burner were calculated and the flow structure was determined at various air velocity parameters based on the results of theoretical studies in the Ansys Fluent 2021R1 program with a nozzle diameter d_2 – 0.15 m. The flame temperature at 20 m/s is 90–100 K higher than the other parameters.

3. Concentrations of harmful substances were detected at nozzle diameters d_1 – 0.12 m and d_2 – 0.15 m, graphs were plotted in accordance with the data obtained as a result of experiments, the lowest concentrations of nitrogen oxides were detected in a nozzle with a larger diameter.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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