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Results of Experimental Research on Microflame Burners for Hot Water Boilers and Gas Turbines

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Abstract: The study aims to address the need for cleaner and more efficient combustion technologies in the context of global energy demand and sustainability goals. It focuses on microflame techniques to enhance the performance of gas turbines and water heating boilers. This research investigated, for the first time, the operation of a micromodular burner for hot water boilers and a microflame burner for gas turbines, based on patented inventions. Methods for assessing efficiency included analyzing heat flows, fuel conversion rates to thermal energy, and emission analysis. Using high-precision measuring equipment, such as TESTO 350-XL, thermocouples, flow meters, and others, optimal operating modes were determined for the gas turbine combustion chamber and hot water boiler. This resulted in achieving high efficiency and reducing harmful emission levels (NO_x < 15 ppm, CO < 140 ppm). Theoretical calculations were compared with experimental data, confirming the reliability of the results obtained.

Keywords: experimental setup; microflame combustion; burner; micromodular burner; water heating boiler; gas turbine; propane

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1. Introduction

In the modern world, many countries are striving to transition to renewable energy sources as part of efforts to combat climate change and reduce dependence on fossil fuels. However, in regions with an extreme continental climate, like Kazakhstan, where winters can be extremely harsh with temperatures dropping as low as −52 °C in the capital Astana [1], ensuring heating for the population remains a critical challenge. It is important to note that renewable energy sources alone cannot fully meet the country's demand for thermal energy due to climate peculiarities and unpredictable weather patterns.

Natural gas continues to play a pivotal role in meeting global energy needs [2]. Propane, methane, natural gas, and synthetic gases serve not only as efficient energy sources but also as vital components of environmentally friendly energy solutions [3,4]. Kazakhstan, endowed with extensive natural resources, is incentivized to transition from coal to gas as a primary energy source, aiming to improve environmental conditions and reduce greenhouse gas emissions [5]. However, despite the shift toward cleaner fuels, maintaining ecological balance requires innovative technologies capable of meeting modern environmental standards.

Enhancing combustion efficiency and reducing harmful emissions into the atmosphere are crucial tasks in the energy sector. According to modern environmental requirements and international agreements on carbon neutrality [6], countries, including Kazakhstan, are tasked with developing and implementing new, more efficient technologies aimed at reducing the environmental impact and ensuring sustainable development.

Gas turbines [7] play a significant role in modern energy infrastructure, providing reliable electricity generation and heat supply for various industrial sectors and residential areas. Known for their high efficiency and operational flexibility, gas turbines are integral to the energy complex of many countries worldwide [8,9]. Nevertheless, advancements in gas turbine technologies to improve energy efficiency and decrease the ecological footprint remain a vital area of research.

Water boilers [10], critical for heating and hot water supply in the private sector, also face challenges related to efficiency and environmental safety. Despite considerable technological advancements in boiler production, optimizing combustion processes and reducing emissions remain pertinent issues [11,12].

This study aims to develop and experimentally investigate new microflame combustion technologies for gas turbines and water boilers. This approach involves creating tiny flames for fuel combustion, promising more complete combustion and lower emission of harmful substances. The chosen technology is associated with several advantages. Various authors [13,14], despite the limited amount of experimental data on the application of microflame combustion in combustion chambers of fuel-burning installations, have highlighted the main benefits of microflame systems, such as:

- High combustion efficiency ($\eta = 0.985 \div 0.995$);
- Wide stable burning limits ($\alpha_{air} = 2 \div 25$);
- Minimal hydraulic losses ($\sigma = 1.5 \div 3\%$ of total pressure);
- High thermal intensity of the working volume ($H = 1 \div 5$ MJ/m^3·h·Pa);
- Low levels of smoke and nitrogen oxide emissions ($C_{NO} = 15$ ppm);
- Compact combustion chamber dimensions and ease of integration into engine circuits.

The research aims to evaluate operational efficiency and identify harmful emissions when utilizing this technology. It is anticipated that developing new combustion methods and optimizing burner designs will significantly enhance combustion quality, reduce specific fuel consumption, and decrease emissions into the atmosphere. This holds strategic importance for ensuring sustainable and environmentally safe development of the energy sector.

Therefore, research into gas combustion technologies represents a critical step toward improving existing energy technologies and achieving global sustainable development goals. It not only enhances energy production efficiency and economic viability but also meets the challenges posed by contemporary environmental policies aimed at reducing harmful impacts on the environment.

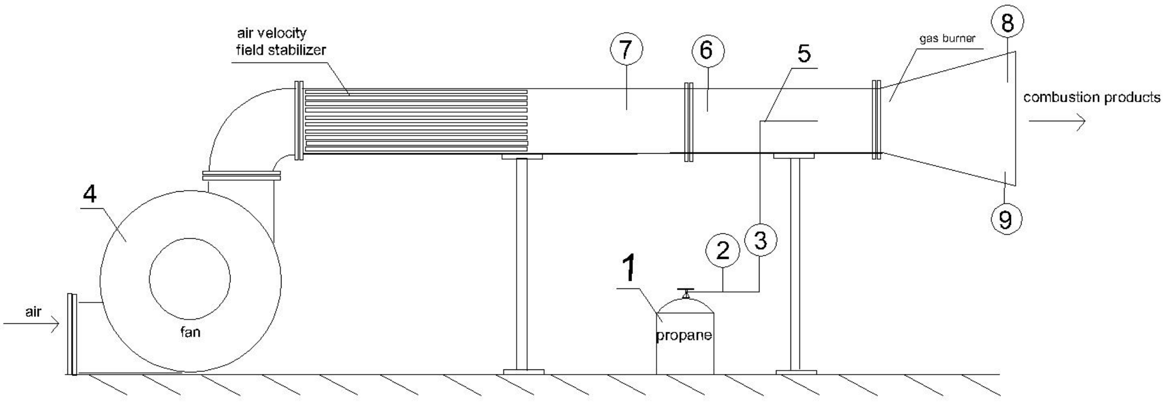
2. Materials and Methods

Experimental studies were conducted on an experimental setup described below. The setup for studying burner devices that utilize the microflame method of fuel combustion is shown in Figure 1a,b. The important components of the experimental setup are:

1. Air supply system;
2. Fuel supply system;
3. Ignition system;
4. Instrumentation system with measuring equipment.

Fuel was supplied from gas cylinder 1, and the gas temperature corresponded to the temperature of the outdoor air, which ranged from 20 to 25 °C. Before fuel was supplied to the burner, measurements of the main fuel characteristics were obtained using pressure gauge 2 and gas meter 3.

Air was supplied by fan 4, and a stabilizing tube was installed at the fan outlet. The stabilizing tube had a length of 1500 mm and a diameter of ϕ 150 mm. Inside the tube, there was a bundle of small-diameter tubes for equalizing the velocity fields, with a length of 1200 mm inside the tube.



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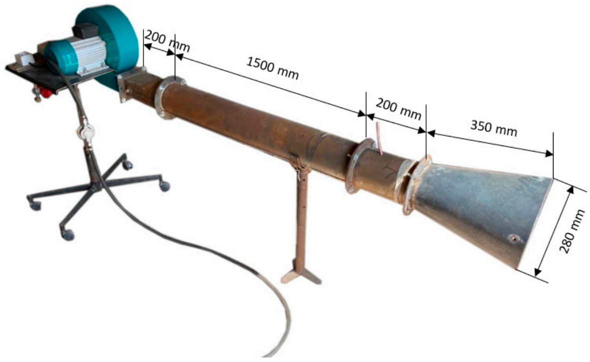


(**b**)

Figure 1. (**a**) Diagram of the experimental setup with measuring instruments: 1—gas cylinder (propane), 2—pressure gauge, 3—gas meter, 4—fan, 5—fuel supply tube, 6—multifunctional measuring system TESTO 454-P (Testo AG, Lenzkirch, Germany), 7—chromel-copel thermocouple, 8—chromel-alumel thermocouple, and 9—gas analyzer TESTO 350-XL (Testo AG, Lenzkirch, Germany). (**b**) Experimental setup with geometric dimensions.

Propane was stored in gas cylinders, the pressure and flow rate of which were regulated by a valve and pressure gauge. The fuel flow was controlled by an electric flow meter with an accuracy of 1.25% over the entire measurement range. Fuel was supplied from the gas cylinder to the fuel pipe. The fuel pipe (ϕ 4 mm for the micromodular burner, ϕ 8 mm for the two-tier burner) was installed at the narrow section of the burner. In the stabilizing tube, static pressure collectors and full pressure nozzles were installed, which were part of multifunctional measuring system 6, "TESTO 454-P", for determining the flow rate and velocity fields. The air temperature at the inlet was determined using chromel-copel thermocouple (CCT) 7, "Metran 232-02" (Metran Industrial Group, Chelyabinsk, Russia), which was designed to measure air temperature values up to 800 °C. The CCT was secured in a hole on the top of the stabilization pipe using mounting clamps to ensure a tight fit with the tube.

For igniting gaseous fuel, a spark ignition system installed at the burner outlet was used.

To measure the temperature of combustion products at the combustion chamber exit, radial chromel-alumel thermocouple (CAT) 8 with a diameter of 0.5 mm,"Metran 231-02" (Metran Industrial Group, Chelyabinsk, Russia), was installed, with a measurement range from −40 °C to +1200 °C. Gas analysis, temperature measurements, and gas flow velocities were conducted at the burner outlet using gas analyzer 9, "TESTO 350-XL", from the TESTO analyzer family, which has demonstrated high accuracy in previous studies [15].

Before the experiments, manual selection of modes was performed, and the most efficient and optimal mode was determined by visual flame quality (flame color), gas consumption, air velocity, and instrumental analysis of the exhaust gases. The sampling point for analyzing the exhaust gases was selected at a distance of 150–200 mm from the flame core along the visual flame length.

Data collection from all measuring instruments of the experimental setup was performed using a portable computer.

The following microflame burner devices were investigated: 1. a two-tier microflame burner device for the combustion chamber of a gas turbine installation (TMFBD) (patent 1 of Section 6); and 2. a micromodular gas burner for propane combustion (MMGB) (patent 2 of Section 6).

The fuel combustion completeness coefficient was calculated based on the experimentally obtained data using Formula (1) from the heat balance equation [16], as follows:

$$\eta = \frac{\left(1 + \frac{L_0}{\varphi_{out}}\right) \cdot \left(c_{pg} T_g - c_{pg} T_0\right) - \frac{L_0}{\varphi_{out}}\left(c_{pair} T_{air} - c_{pair} T_0\right) - \left(c_{pfuel} T_{fuel} - c_{pfuel} T_0\right)}{Q_l^w} \quad (1)$$

where

T_g—the temperature of 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_{air}—the air temperature at the entrance to the combustion chamber, K;

T_{fuel}—the fuel temperature at the nozzle inlet, K;

Q_l^w—the lowest heat of combustion of the working fuel for propane, kJkg^{-1};

c_{pair}—the average mass heat capacity of air at a temperature that is a multiplier of the named parameter, kJkg^{-1}K^{-1};

c_{pg}—the average mass heat capacity of a gas at a temperature that is a multiplier of the named parameter, kJkg^{-1}K^{-1};

c_{pfuel}—the average mass heat capacity of fuel (propane) at a temperature that is a multiplier of the named parameter, kJkg^{-1}K^{-1}.

The data obtained from the experiment were used to construct graphs described in the following sections.

Error Estimations in Measurements

In our experimental studies involving direct measurements of air flow velocity (w_{air}), fuel pressure (p_{fuel})—propane gas, fuel volumetric flow rate and fuel consumption time (ΔG_F), temperature before (T_{fuel}) (chromel-copel thermocouple) and after the combustion chamber (T_g (chromel-alumel) and $T_g^* \ (TESTO\ 350 - XL)$), and concentrations of nitrogen oxides (C_{NOx}) and carbon monoxide (C_{CO}) $(TESTO\ 350 - XL)$, we determined the following parameters: air flow rate (ΔG_{air}), mass flow rate of fuel per unit time (ΔG_F), air–fuel ratio (α_{air}), and combustion completeness (η).

The uncertainties of direct measurements are provided in Table 1.

Table 1. Errors of direct measurements of operating parameters.

No.	Parameter Designation	Unit of Measurement	Normalization (According to the Device) the Upper Value of the Parameter	Maximum Absolute Error of the Device (±)	Upper Limit of Measurement of the Experimental Parameter	Maximum Relative Error of Measuring a Parameter in an Experiment
1	w_{air}	m/s	40	0.3	28	0.70
2	p_{fuel}	MPa	0.6	2.5	0.07	0.14
3	ΔG_F	m^3/h	1.6	1.5	1.5	0.95
4	T_{fuel}	K	1073	0.05	298	0.28
5	T_g	K	1523	0.05	1373	0.90
6	T_g^*	K	1643	3.0	1073	0.68
7	C_{NOx}	ppm	4000	5.0	15	0.05
8	C_{CO}	ppm	10,000	5.0	140	0.06

Thus, the conducted analysis of errors demonstrated that the maximum relative measurement uncertainties were sufficiently satisfactory to justify the proposed methodology of engineering calculations based on the obtained experimental results.

3. Description of the TMFBD

In the TMFBD (patent 1 of Section 6), as shown in Figure 2, compressed air is supplied from the fan. Closer to the combustion front, fuel enters the fuel annular collectors through the fuel supply pipeline, depending on the operating mode, either into two tiers simultaneously or into each tier (external or internal) separately.

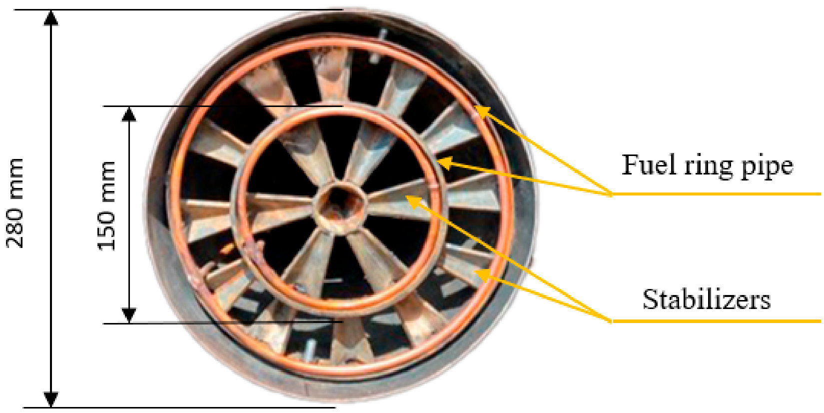


Figure 2. TMFBD with dimensional characteristics.

The experimental study of the TMFBD was conducted using liquefied gas—propane (C_3H_8). Gas flow adjustment was regulated by a fine control valve, then passed through an electromagnetic shut-off valve and a flow metering device (fuel consumption was measured volumetrically). The gas was supplied into fuel ring pipes during the operation of two tiers simultaneously, and into one of the fuel ring pipes depending on the mode (internal or external pipe).

Fuel from the ring pipes was injected through nozzle holes into the inner concave part of each stabilizer. The internal tier had eight stabilizers, while the external tier had sixteen.

Corner stabilizers at the burner outlet provided microflame combustion, which resulted in low-emission combustion due to the absence of local high-temperature zones. The corner stabilizers, shaped like semicircles, created numerous flame recirculation flows that ignited fresh portions of the fuel–air mixture, thereby enhancing combustion stability.

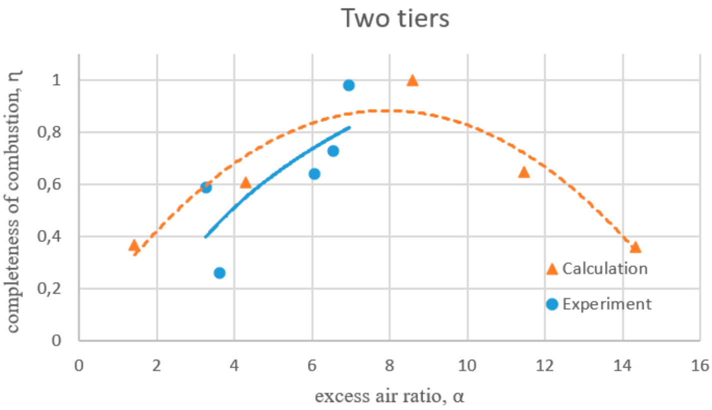
During the experimental investigation, each tier of the front device was analyzed separately, as well as operation of the two tiers together. Experiments were conducted to determine flame blowout for each tier and for the entire burner to identify the range of stable operation. The experiments on the stand were repeated 5 times for each operating mode, including operation with only the external tier, only the internal tier, and simultaneous operation of the two tiers. The propane gas flow rate was kept constant at 0.015 MPa, while the air flow rate varied from 5 to 28 m/s. Due to the limitation of the fan's operation (up to 28 m/s), theoretical calculations were conducted for operating modes with initial air velocities ranging from 5 to 50 m/s.

Theoretical calculations to determine the combustion completeness of the fuel were performed based on numerical simulations of combustion processes using Ansys Fluent 2022 R1 [17] and analysis of the aerodynamics of air flow using Comsol Multiphysics version 6.0 [18]. Ansys Fluent was employed to model combustion processes, enabling the assessment of fuel combustion efficiency under specified conditions, specifically with initial air velocities ranging from 5 to 50 m/s. As a result of these computational studies, data on temperatures at the inlet and outlet of the combustion chamber were obtained, facilitating calculations using Formula (1).

3.1. Results

3.1.1. Combustion Completeness

During the conducted experimental research of the simultaneous operation of both tiers (Figure 3a), it was found that the optimal air excess ratio to achieve high fuel combustion efficiency, calculated using Formula (1) (indicated as α air = 6.55 ÷ 6.96), coincided with the theoretical data, confirming a high fuel combustion completeness coefficient (η = 0.90 ÷ 0.99). This allowed for optimizing the operation of the two tiers, which is an important result of the research.



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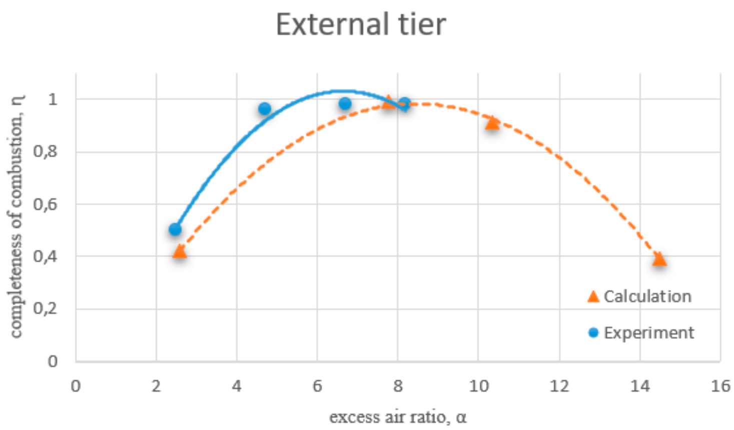

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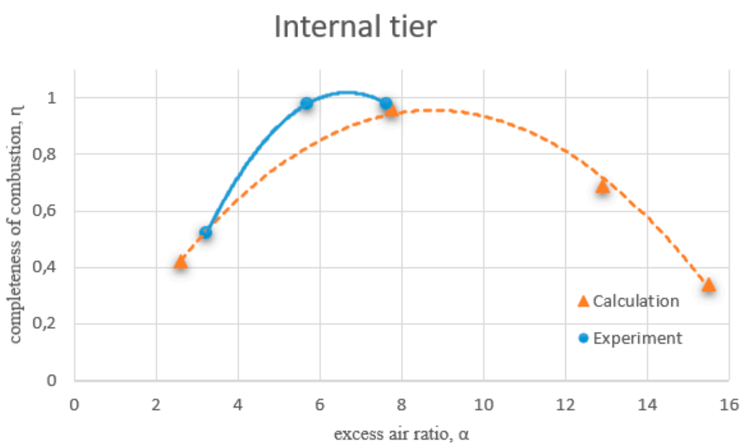


(**c**)

Figure 3. The dependence of the fuel combustion completeness coefficient on the air excess ratio during operation: (**a**) two tiers; (**b**) external tier; and (**c**) internal tier.

Similarly, in experiments with the operation of the external (Figure 3b) and internal (Figure 3c) tiers, optimal values of the air excess ratio (α air = 6.70 ÷ 8.19 and α air = 5.71 ÷ 7.63, respectively) were recorded, which aligned with the high values of the fuel combustion completeness coefficient (η = 0.98). These results confirmed the effectiveness of the selected operating modes of the tiers and could be used to optimize the combustion process in the gas turbine installation.

Thus, experimental and theoretical data coincided in determining the optimal operating modes of different tiers, highlighting the significance of the achieved results for enhancing combustion efficiency and reducing emissions of harmful substances.

3.1.2. Harmful Emissions

Gaseous fuel is considered the cleanest organic fuel because, upon complete combustion, only nitrogen oxides are produced from toxic substances. In the case of incomplete combustion, carbon monoxide (CO) is present in emissions.

During the experimental study, the TESTO 350-XL gas analyzer was used to measure the concentrations of carbon monoxide and nitrogen oxides in the exhaust gases. Figure 4a–c depict the dependence of concentrations of carbon monoxide (CO) and nitrogen oxide (NOx) in emissions on the air–fuel ratio.

According to the graphs in Figure 4a–c, the emissions of carbon monoxide (CO) and nitrogen oxides (NO_x) were directly proportional when burning propane in the combustion chamber of a gas turbine. This can be explained by the chemical reactions occurring during fuel combustion. When propane is burned, the main reaction involves the oxidation of carbon and hydrogen to carbon dioxide (CO_2) and water (H_2O). However, under insufficient oxygen supply (fuel-rich conditions), incomplete combustion may lead to the formation of carbon monoxide (CO) instead of carbon dioxide (CO_2) [19]. Therefore, a higher air–fuel ratio (α air) would promote complete combustion and reduce CO emissions.

On the other hand, the formation of nitrogen oxides (NO_x) is attributed to the high temperature in the combustion chamber, which facilitates the formation of nitrogen oxides from atmospheric nitrogen [20]. Thus, with an increase in combustion temperature or residence time of gases in the high-temperature zone, the level of NO_x also increases.

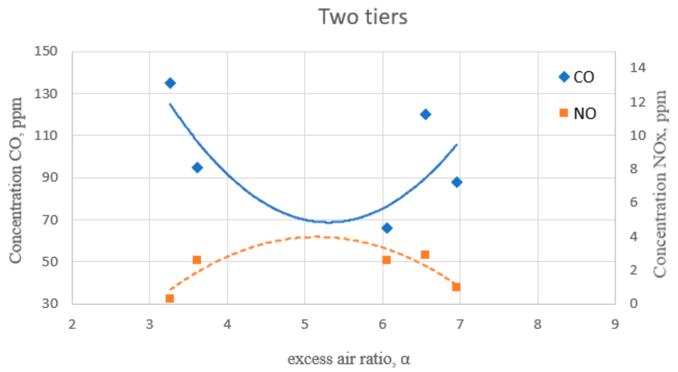
Hence, when burning propane in a gas turbine, increasing the air–fuel ratio, on one hand, leads to a reduction in CO emissions due to increased combustion completeness. However, on the other hand, it may also contribute to an increase in combustion temperature, leading to increased NO_x emissions. This can explain the observed proportionality between CO and NO_x emissions with changes in the air–fuel ratio.

The optimal emissions of carbon monoxide and nitrogen oxides were observed at the following air–fuel ratio values: when both tiers operated simultaneously—α air = 6.06, C_{CO} = 66 ppm, and C_{NOx} = 2.6 ppm; for the external tier—α air = 6.70, C_{CO} = 97 ppm, and C_{NOx} = 2.1 ppm; and for the internal tier α air = 3.23 ÷ 5.71, C_{CO} = 67 ÷ 81 ppm, and C_{NOx} = 2.9 ÷ 5.4 ppm.

Moreover, the high concentration of carbon monoxide in emissions exceeding 140 ppm could be explained by the type of combustion chamber—open type. This type of combustion chamber is characterized by a short residence time of the fuel–air mixture in the combustion zone. Consequently, carbon monoxide does not have enough time for complete oxidation to CO_2.

The nitrogen oxide emissions did not exceed 15 ppm.

Figure 5 shows photographs illustrating the operation of the tiers.



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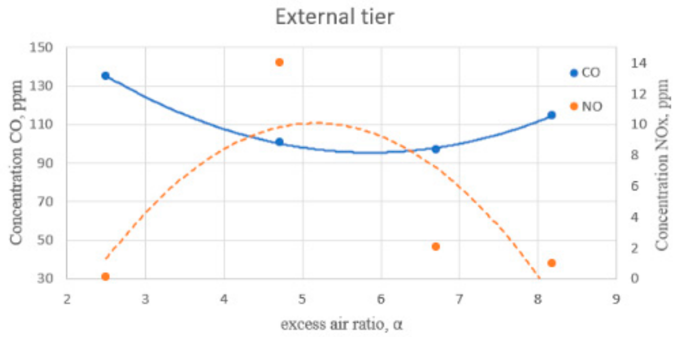

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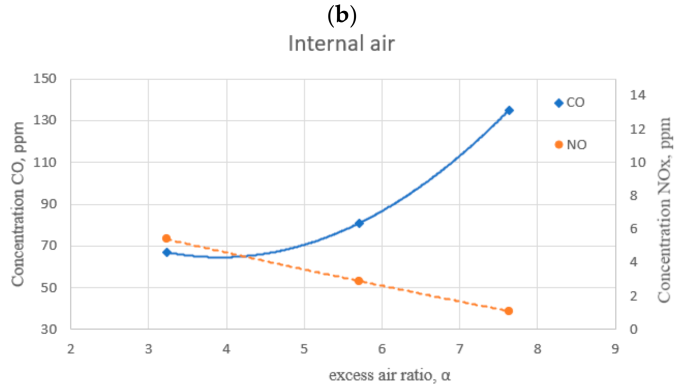


(**c**)

Figure 4. The dependence of the air–fuel ratio on the concentrations of carbon monoxide (CO) and nitrogen oxides (NO_x) in emissions during operation: (**a**) two tiers; (**b**) external tier; and (**c**) internal tier.

(**a**)

(**b**)

(**c**)

Figure 5. Photo of the TMFBD in operation: (**a**) two tiers; (**b**) external tier; and (**c**) internal tier.

3.2. Discussion

The main results of the study demonstrated that the optimal operating modes of the TMFBD corresponded to high combustion completeness coefficients. The optimal air excess ratio for the simultaneous operation of both tiers was α air = 6.5 ÷ 6.96, with a fuel combustion completeness coefficient of η = 0.90 ÷ 0.99; for the external tier, α air = 6.70 ÷ 8.19 and η = 0.98; for the internal tier, α air = 5.71 ÷ 7.63 and η = 0.98. This indicated high combustion efficiency and allowed for the optimization of the operation processes of both tiers of the burner device. Experimental data confirmed the theoretical calculations, emphasizing the significance of the achieved results for improving the efficiency of combustion processes and reducing emissions of harmful substances.

The analysis of harmful emissions showed that, with the proper adjustment of the TMFBD operation, it was possible to significantly reduce the concentrations of carbon monoxide and nitrogen oxides in the exhaust gases. The optimal operating parameters of the TMFBD minimized harmful emissions, contributing to the improvement of the ecological cleanliness of combustion processes and reducing the impact on the environment. The high concentration of carbon monoxide in emissions exceeding 140 ppm was explained by the type of combustion chamber—open. Nitrogen oxide emissions did not exceed 15 ppm.

Thus, the research results confirmed the efficiency of the developed TMFBD in burning propane and its potential to enhance combustion processes in gas turbine installations. The implementation of the developed technologies can contribute to improving the energy efficiency and environmental safety of industrial processes.

4. Description of the MMGB

The developed new micromodular gas burner, the principle of which is a new method of stabilization and ignition in the case of a sudden expansion for the burners of hot water boilers, is based on the separation of the flow. During separation, the current line coinciding with the streamlined surface deviates, departs from it, and an oncoming return current approaches the place of separation, which ensures the stabilization of combustion.

The burner device for burning propane gas consists of a housing with a converging-diverging channel. At the outlet, along the burner axis, there is a distributor cone connected internally to the burner housing. Propane is supplied through a fuel copper pipe with a diameter of 4 mm, located along the burner axis at the narrowest section. Fuel injection occurs through 6 holes with a diameter of 1 mm perpendicular to the axis.

The MMGB has a cylindrical nozzle with a large diameter, and a sudden expansion occurs at the junction of the nozzle with the Venturi tube, which serves as a stabilizer. Additionally, secondary air is supplied through slots to the nozzle, ensuring high combustion completeness, resulting in a fuel–air mixture with low NO_x emissions.

Cylindrical nozzles with slots at the outlet for the experimental setup were presented in two variants: d1 = 120 mm and d2 = 150 mm. The aim of the experiment was to select the optimal diameter for stabilization, ensuring stable combustion with low emissions of harmful nitrogen oxides. The general view of the cylindrical nozzles is shown in Figure 6.

Fuel was supplied to the fuel pipe located along the axis at the narrow section of the burner, and gas distribution occurred through copper tubes with a diameter of 4 mm perpendicular to the 6 holes. Air was supplied by a fan. Mixing of the fuel–air mixture occurred at the narrow section inside the Venturi tube, with secondary air being supplied through slots in the cylindrical nozzle.

During the experiments, the influence of nozzle diameter on stabilization and mixture formation processes, as well as on the efficient combustion of propane gas with stable burning and reduced formation of harmful emissions, was investigated. Two experiments were conducted: the first with a diameter of d1 = 120 mm, and the second with d2 = 150 mm. Each experiment comprised 6 modes, with 6–7 measurements obtained for each mode. Each measurement took approximately 1.2–1.5 min.

Figure 6. General view of cylindrical nozzles (d1 = 120 mm, d2 = 150 mm).

Prior to the start of the experiments, a quantitative selection of modes was manually performed, and the most effective and optimal mode was determined by the visual quality of combustion (flame color), gas consumption, and air velocity, and an instrumental analysis of the exhaust gases was carried out, with a selection point for the analysis of the exhaust gases at a distance of 130–150 mm from the core of the torch along the visual length of the torch. At the beginning of each experiment, studies were carried out to select the optimal mode for gas consumption and air velocity. During the experiments, the influence of nozzle diameter on stabilization and mixing processes, as well as on the effective combustion of natural gas (propane) with stable combustion and reduction of harmful emissions, was studied.

A spark ignition system installed at the outlet of the burner was used to ignite the gaseous fuel. To measure the temperature of the air and fuel combustion products, a radial thermocouple with a diameter of 0.5 mm (chromel-alumel) was installed at the outlet of the combustion chamber. The parameters of the exhaust gases were measured by a stationary gas analyzer with an extended sensor complex having an error of 5% over the entire measurement range. A high-resolution camera was used for the pictures. Based on the experimental data obtained, graphs were constructed (completeness of combustion, temperature unevenness, concentrations of substances), and the results were summarized.

4.1. Results

4.1.1. Combustion Completeness

The new structural solutions for the gas burner device in the form of a diffuser-convergent channel of the Venturi tube with a sudden expansion at the outlet, which serves as a stabilizer, based on modeling and experiments, proved stable combustion with low emissions of harmful substances. This was achieved by identifying the optimal air–fuel ratio for stable combustion, calculated using Formula (1) (at α air = 3.5 $\div$ 4.0), which coincided with the theoretical data, confirming a high combustion completeness coefficient ($\eta \leq 0.98$). This ensured stable combustion with low emissions of harmful substances, which is an important research outcome. This relationship indicated that the presence of a large amount of air increased combustion completeness due to the increase in the air–fuel ratio, resulting in increased entrainment from the combustion zone. In the larger diameter nozzle, there was a sharp increase in combustion completeness due to the reduction in gas residence time in the recirculation zone, and the greatest change in combustion completeness occurred in this nozzle.

According to the graph in Figure 7, the most complete combustion, namely $\eta = 0.981 \div 0.987$, was provided in the larger nozzle, with a diameter of d2 = 150 mm at α air = 3.5 $\div$ 4.0, which corresponded to the stoichiometric ratio of fuel and air. When using the smaller nozzle, $\eta = 0.970 \div 0.975$ at α air = 3.0 $\div$ 3.5. The most effective nozzle in terms of combustion completeness was the one with the larger diameter. This was explained by the most effective fuel–air mixing in the recirculation zone. The smaller nozzle with d1 = 120 mm was also effective, as it had the least impact on the flow structure and created the smallest recirculation zones.

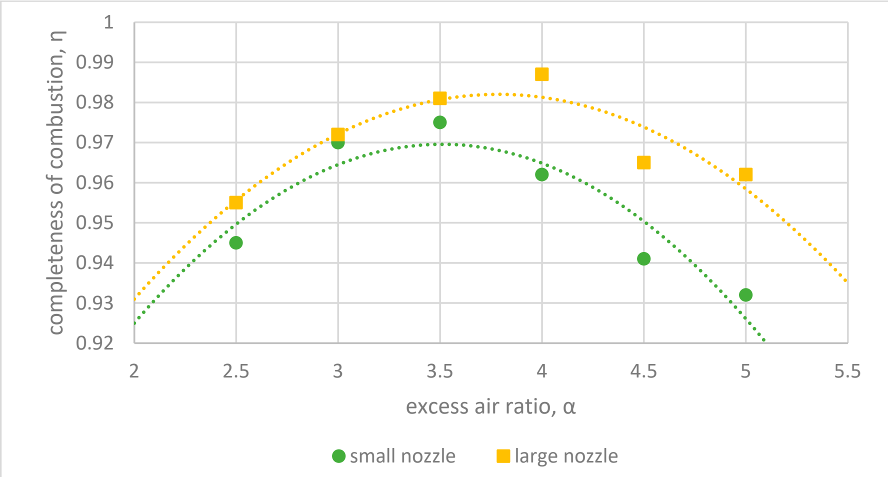


Figure 7. The dependence of the combustion completeness coefficient on the air–fuel ratio for the large and small burner nozzles.

4.1.2. Harmful Emissions

Figure 8 shows the dependence of nitrogen oxide concentration on the air–fuel ratio. Logically, the gas temperature 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. This is explained by the fact that various chemical processes occur during fuel combustion. Due to the influx of a large amount of air into the combustion zone and the decrease in temperature, the concentration of nitrogen oxides decreased, as shown in the graph. The lowest concentration of nitrogen oxides was detected in the larger diameter nozzle. Optimal carbon monoxide and nitrogen oxide emissions were observed at the following air–fuel ratio values: for operation with the larger nozzle—α air = 3.5, C_{CO} = 63 ppm, and C_{NOx} = 8.8 ppm; for operation with the smaller nozzle—α air = 3.5, C_{CO} = 64 ppm, and C_{NOx} = 8.5 ppm. Nitrogen oxide emissions did not exceed 10 ppm. Moreover, increasing the air–fuel ratio led to a reduction in the formation of these substances due to the decrease in temperature and incomplete fuel combustion.

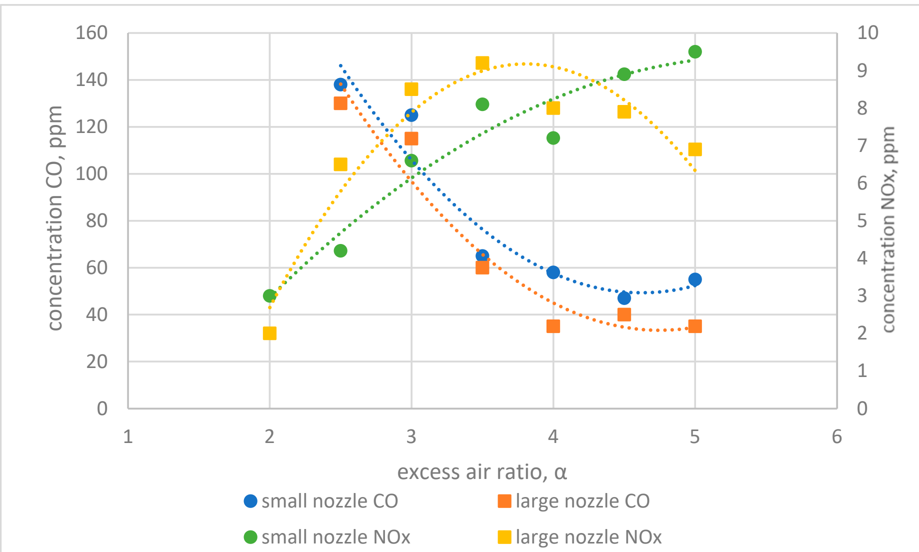
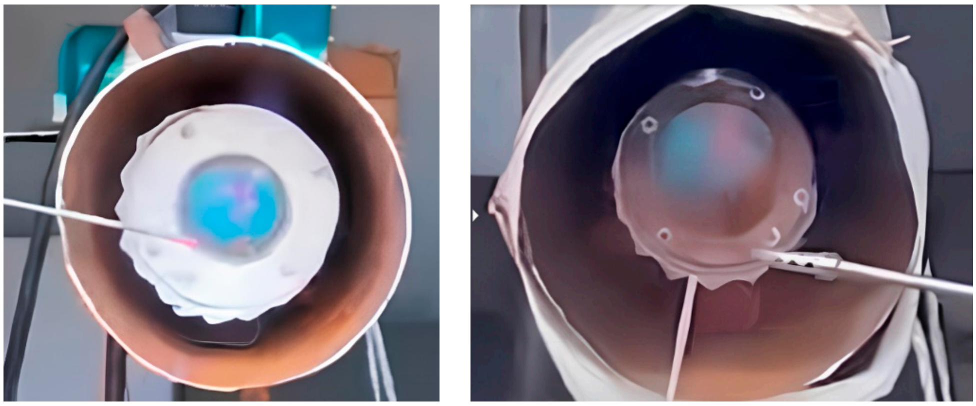


Figure 8. The dependence of the air–fuel ratio on the concentrations of carbon monoxide (CO) and nitrogen oxide (NO_x) in emissions with the large and small burner nozzles.

Figure 9 presents photographs depicting the operation of the burner with both the large and small nozzles.



(**a**) (**b**)

Figure 9. Photographs of the MMGB in operation: (**a**) with the large nozzle; and (**b**) with the small nozzle.

4.2. Discussion

Dependencies were determined based on the results of the experiments on fuel combustion completeness in the MMGB with nozzle diameters of d1 = 120 mm and d2 = 150 mm. The most complete combustion was achieved with the large nozzle, with a diameter of d2 = 150 mm at α air = 3.5 $\div$ 4.0, corresponding to the stoichiometric ratio of fuel and air ($\eta \leq 0.98$). When using the small nozzle, completeness of combustion was η = 0.970 $\div$ 0.975 at α air = 3 $\div$ 3.5.

The lowest concentrations of nitrogen oxides were found with the larger diameter nozzle. Optimal carbon and nitrogen emissions were observed at the following excess air coefficient values: for the larger nozzle—α air = 3.5, C_{CO} = 63 ppm, and C_{NOx} = 8.8 ppm; for the smaller nozzle—α air = 3.5, C_{CO} = 64 ppm, and C_{NOx} = 8.5 ppm. Nitrogen oxide emissions did not exceed 10 ppm.

As a result, efficient propane combustion was achieved, leading to stable and rational burning, reduced flare length, and lower harmful emissions. The experiment demonstrated that the nozzle with a diameter of d2 = 150 mm was the most suitable for efficient propane combustion. Thus, the MMGB with microflame combustion and a stabilizer in the form of a large-diameter outlet proved its effectiveness when used in gas burners. Based on the results of the experimental research, data are being collected and further analyzed for efficient burning of natural gas with stable combustion and reduced emissions. This work may be useful in the development of low-emission devices for small boiler rooms.

Analyzing and studying the MMGB, it can be noted that the new design solutions in the form of a diffuser-convergent channel of the Venturi tube and a sudden expansion at the outlet, which acts as a stabilizer, based on modeling and experiments, demonstrated stable combustion with low emissions.

5. Conclusions

The main results of the research on the two-tier microflame burner device (TMFBD) for gas turbines and the micromodular gas burner (MMGB) for hot water boilers demonstrated the high efficiency and environmental cleanliness of the fuel combustion process.

Optimal operating modes of the TMFBD were achieved at high combustion completeness coefficients, where the optimal air excess coefficient (α air) for simultaneous operation of both tiers was 6.5 $\div$ 6.96, with a fuel combustion completeness coefficient (η) of 0.90 $\div$ 0.99. For the outer tier, these parameters were α air = 6.70 $\div$ 8.19 and η = 0.98, while for the inner tier, they were α air = 5.71 $\div$ 7.63 and η = 0.98. These indicators confirmed the high efficiency of combustion and allowed for optimizing the operation process of the burner unit.

The experimental data confirmed the theoretical calculations, underscoring the significance of the achieved results for improving the efficiency of combustion processes and reducing emissions of harmful substances. The analysis of emissions showed that, with the proper adjustment of TMFBD operation, the concentrations of carbon monoxide and nitrogen oxides in exhaust gases could be significantly reduced, with nitrogen oxide emissions not exceeding 15 ppm. The high concentration of carbon monoxide in emissions exceeding 140 ppm was explained by the type of open combustion chamber.

The research results confirmed the effectiveness of the developed TMFBD in burning propane and its potential for improving combustion processes in gas turbines. The implementation of these technologies can contribute to enhancing the energy efficiency and environmental safety of industrial processes.

The MMGB with nozzle diameters d1 = 120 mm and d2 = 150 mm also demonstrated high efficiency. The most complete combustion was achieved with the larger nozzle, with a diameter of d2 = 150 mm at α air = 3.5 $\div$ 4.0, corresponding to the stoichiometric ratio of fuel and air ($\eta \leq 0.98$). For the operation of the smaller nozzle, $\eta = 0.970 \div 0.975$ at α air = 3 $\div$ 3.5.

Optimal carbon monoxide and nitrogen oxide emissions were observed at the following excess air coefficient values: for operation with the larger nozzle—α air = 3.5, C_{CO} = 63 ppm, and C_{NOx} = 8.8 ppm; for operation with the smaller nozzle—α air = 3.5, C_{CO} = 64 ppm, and C_{NOx} = 8.5 ppm. Nitrogen oxide emissions did not exceed 10 ppm.

The experiments showed that the MMGB with microflame combustion and a stabilizer in the form of a large-diameter outlet was the most effective for burning propane, providing stable and efficient combustion while reducing emissions. This work could be useful in creating low-emission devices for small-scale boiler systems.

The investigated new micromodular gas burner, the principle of which is to detach the flow, and, when detached, the current line coinciding with the streamlined surface breaks off and an oncoming zone of reverse currents approaches the place of separation, thereby ensuring stabilization of combustion. The results of the experimental studies were precisely correlated with the theoretical calculations, confirming the relevance of the results obtained to improve the environmental efficiency of combustion processes and reduce emissions of harmful substances. According to the analysis of harmful emissions, it could be seen that, with the correct choice of the ratio of nozzle diameters for the MMGB, the concentrations of carbon monoxide and nitrogen oxides in exhaust gases could be significantly reduced.

Overall, the study demonstrated stable combustion with low levels of harmful emissions due to new design solutions such as the diffuser-convergent-divergent channel of the Venturi tube and a stabilizer with a sudden expansion at the outlet. These technologies can significantly enhance the environmental safety and energy efficiency of fuel combustion processes.

6. Patents

1. Makzumova, A.K.; Dostiyarov, A.M.; Anuarbekov, M.A.; Vernickas, P.A.; Sarakeshova, N.N.; Biakhmetov, B.A. Two-Tier Microflame Burner Device. Patent for the invention of the Republic of Kazakhstan №36479, 24 November 2023. [21].
2. Sarakeshova, N.N.; Dostiyarov, A.M. Micro-Module Gas Burner. Patent for the invention of the Republic of Kazakhstan №36180, 21 July 2023. [22].

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References

1. *Climate Risk Country Profile: Kazakhstan*; The World Bank Group and the Asian Development Bank: Washington, DC, USA, 2021; Volume 32.
2. Zhang, B.; Xiu, G.; Bai, C. Explosion characteristics of argon/nitrogen diluted natural gas–air mixtures. *Fuel* **2014**, *124*, 125–132. [CrossRef]
3. Pourhoseini, S.H. A novel configuration of natural gas diffusion burners to enhance optical, thermal and radiative characteristics of flame and reduce NOx emission. *Energy* **2017**, *132*, 41–48. [CrossRef]
4. Chen, C.; Qin, C.; Chen, Z. Experimental and simulation study of key parameters of low NO_x water-cooled burners. *Case Stud. Therm. Eng.* **2022**, *40*, 102576. [CrossRef]
5. Hernik, B.; Brudziana, P.; Klon, R.; Pronobis, M. Numerical Studies of the Influence of Flue Gas Recirculation into Primary Air on NO_x Formation, CO Emission, and Low-NO_x. *Energies* **2024**, *17*, 2227. [CrossRef]
6. Ongar, B.; Iliev, I.K.; Smagulova, G.K.; Mergalimova, A.K. Numerical simulation of the formation of nitrogen oxides in pulverized furnaces. *J. Eng. Sci. Technol. Rev.* **2020**, 171–175. Available online: https://www.researchgate.net/publication/340399245_Numerical_Simulation_of_the_Formation_of_Nitrogen_Oxides_in_Pulverized_Furnaces (accessed on 8 May 2024).
7. Decisions of the 21st Session of the UN Conference of the Parties on Climate Change; Draft Decision 1/CP.21//—Paris. 2015. Available online: https://www.unfccc.int (accessed on 22 June 2024).
8. Wirkowski, P.; Markowski, J.; Imilkowski, P.; Iliev, I.; Jesionek, K.; Badur, J.; Dlugiewicz, P.; Madry, J.; Wieczorkiewicz, G.; Benedict, P. Modeling of pollutant emissions from the turbine engine of the main propulsion of a vessel in operating conditions. *Int. Conf. Electron. Eng. Phys. Earth Sci.* **2023**, *404*, 1–13.
9. Lefebvre, A. *Gas Turbine Combustion*; Hemisphere Publishing, Co.: Washington, DC, USA, 1983; p. 531.
10. Amiri, M.M.; Ameli, M.T.; Strbac, G.; Pudjianto, D.; Ameli, H. The Role of Flexibility in the Integrated Operation of Low-Carbon Gas and Electricity Systems: A Review. *Energies* **2024**, *17*, 2187. [CrossRef]
11. Rajendran, K.; Aslanzadeh, S.; Taherzadeh, M.J. Household Biogas Digesters—A Review. *Energies* **2012**, *5*, 2911–2942. [CrossRef]
12. KazEnergy Association. *Review of State Policy of the Republic of Kazakhstan in the Field of Energy Saving and Energy Efficiency Improvement*; MURPHY Design Studio: Astana, Kazakhstan, 2014; p. 211.
13. Baltyan, V.N.; Efimov, N.N.; Tskhayev, A.D. On the Issue of Modernizing Boiler Equipment of Coal-Fired Power Plants. *Proc. High. Educ. Institutions. North Cauc. Region. Tech. Sci.* **2017**, *1*, 50–53. Available online: https://cyberleninka.ru/article/n/k-voprosu-modernizatsii-kotelnogo-oborudovaniya-ugolnyh-tes (accessed on 20 December 2023).
14. Wan, J.; Fan, A.; Maruta, K.; Yao, H.; Liu, W. Experimental and Numerical Investigation on Combustion Characteristics of Premixed Hydrogen/air Flame in a Micro-Combustor with a Bluff Body. *Int. J. Hydrogen Energy* **2012**, *37*, 19190–19197. [CrossRef]
15. Szyszlak-Bargłowicz, J.; Wasilewski, J.; Zajac, G.; Kuranc, A.; Koniuszy, A.; Hawrot-Paw, M. Evaluation of Particulate Matter (PM) Emissions from Combustion of Selected Types of Rapeseed Biofuels. *Energies* **2023**, *16*, 239. [CrossRef]
16. Pchelkin, Y.M.; Lebedev, V.P. *Characteristics of the Combustion Chambers of the Gas Turbine Engine*; Pchelkin, Y.M., Ed.; Higher Technical School Named after, N.E. Bayman: Moscow, Russia, 1978; p. 64.
17. Dostiyarov, A.M.; Makzumova, A.K.; Aidymdayeva, Z.A.; Sadykova, S.B. Research of a New Micro-flame Burner Using the Ansys Fluent Program. *Power Eng.* **2024**, *1*, 481–489. [CrossRef]
18. Makzumova, A.K.; Sarakeshova, N.N.; Dostiyarov, A.M.; Iliev, I.K. Study of the aerodynamics of air flow in burners using the Comsol Multiphysics software. In Proceedings of the 28th Conference of the Faculty of Power Engineering and Power Machines at the Technical University of Sofia InnoEE, Sofia, Bulgaria, 17–19 May 2023; pp. 1–9.
19. Robin, D.V.; Harshal, K.; Vishnu, H.; Sudarshan, K. Effect of CO content on laminar flame burning rates of a premixed synthesis gas-air mixture at elevated temperatures. *Fuel* **2018**, *214*, 144–153.
20. Krishnamoorthi, M.; Malayalamurthi, R.; He, Z.; Kandasamy, S. A review on low temperature combustion engines: Performance, combustion and emission characteristics. *Renew. Sustain. Energy Rev.* **2019**, *116*, 109404. [CrossRef]

21. Makzumova, A.K.; Dostiyarov, A.M.; Anuarbekov, M.A.; Vernickas, P.A.; Sarakeshova, N.N.; Biakhmetov, B.A. Two-Tier Microflame Burner Device. Patent for the Invention of the Republic of Kazakhstan №36479, 24 November 2023.
22. Sarakeshova, N.N.; Dostiyarov, A.M. Micro-Module Gas Burner. Patent for the Invention of the Republic of Kazakhstan №36180, 21 July 2023.