NUMERICAL SIMULATION OF THE AERODYNAMIC FLOW OF AIR AND THE RESULTS OF THE STUDY OF A BURNER DEVICE FOR BURNING SYNTHETIC GAS

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This work contributes to the ecological solution of synthetic gas combustion. The methods and tools that were used to research this topic are briefly described in the article. For the study, two programs were used and stabilizers were considered in terms of angular parameters. The angular stabilizers' dimensions and the optimal aerodynamic cross-section behind the stabilizer were calculated using numerical simulation in the «COMSOL Multiphysics» program. This article also describes an experimental bench for burning syngas in a burner device. Due to the low-reaction characteristics of synthetic gas, its composition is variable. In this regard, to efficiently burn synthetic gas of various compositions, it is necessary to select the optimal angle of stabilizer inclination. During the experiments, the effect of angular stabilizers on the stabilization process, the efficiency of burning synthetic gas due to stable combustion, and the reduction of harmful emissions were investigated. Three different stabilizer angles (45°, 60°, and a semicircle) were presented on an experimental bench to find the optimal stabilizer angle for stable combustion with reduced nitrogen oxide emissions. As a result of the observation, it can be concluded that the combustion completeness of synthetic gas in burner devices depends not only on the angle of the stabilizer, but also on the coefficient of the incoming air, and this, in turn, affects the temperature level of the gases in the combustion zone.

Key words: *angular stabilizers, swirling flows, synthetic gas, combustion completeness, excess air coefficient*

1. Introduction

The relevance of the topic of renewable energy sources (RES) prevails in modern conditions. In particular, for Kazakhstan, where the study was conducted, the method of heat extraction using biogas is the most urgent, as well as the least investigated method. Biogas is extracted from flora and fauna and is used to generate heat during combustion for various needs of agricultural farms. The composition of biogas may vary. In comparison with natural gas in the composition of biogas, the content of methane CH_4 is an order of magnitude less. In this regard, biogas is considered low-reactive, and it constantly changes its composition depending on the gas generator. It is also necessary to take into consideration factors such as the addition of enzymes and the conditions of the regime from the temperature of the biomass. In this regard, it is important to select a universal burner device for efficient combustion of synthetic or biogas of various compositions. Analysis of burner devices revealed the most acceptable option. It is realized using the circulation effect that is available when using microflame combustion with various swirls and with variable return reverse currents. All this contributes to the ignition of biogas and synthetic gas, and for this purpose, it is necessary to have a large volume of gas in the high-temperature zone. Therefore, a preliminary study of the mass of combustible gases is necessary to determine the duration of the process and also to find the most effective and relevant option.

Swirling flow is characterized by three components of velocity - radial, axial, and tangential, which are commensurate with each other near the swirling device (Fig. 1). With weak swirling of the flow, the axial component of the velocity will be maximum along the axis. As the swirl increases, the axial component falls and the velocity profile becomes M-shaped.

With strong swirling, a zone of reverse currents appears along the axis, so-called the central recirculation zone (CRZ) in the burners. A further increase in swirl forms a processing vortex core along the flow axis. One of the most important features of swirling flow is to create a negative pressure gradient both along and across the flow. It was reported that a negative pressure gradient contributed to the destruction of vortices and led to the formation of a recirculation zone [1, 2]. It, in turn, improved the stability of the flame while maintaining lower emission levels [3] and worked as a source of heat and chemical radicals [4].

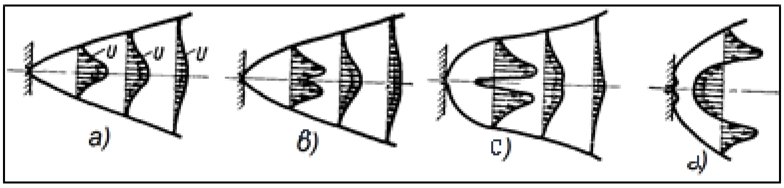


Figure 1. Velocity profile of free flooded jets of various degrees of swirl: a - slightly swirled jet, b - moderately swirled jet, c - strongly swirled closed jet, d - strongly swirled open jet

Increasing the swirling intensity of the airflow entering the combustion chamber is an approach to increasing the speed of mixing fuel with air during combustion without preliminary mixing [5, 6]. In a flame without preliminary mixing, an increase in swirl intensity (swirl number) increases the residence time of combustible substances inside the combustion chamber. This affects flame temperature distribution, flame heat transfer rate, and pollutant formation [7]. The effect of increasing the number of incoming air swirls in liquid fuel burners was investigated by authors [8]. They found that increasing the number of vortices would reduce the emission of nitrogen oxides (NOx) and lead to a lower combustion chamber exhaust temperature.

To develop an effective combustion system, it is necessary to study the basic combustion properties of the fuel mixture, flame instability and velocity in a wide range of compositions [9], the angle of stabilizer inclination [10-12], biomass combustion (synthetic mixture) for reducing NOx emissions and improving the environmental characteristics of burner systems [13].

The purpose of the research work is to develop a new microflame burner for burning synthetic gases (biogas) and to study physical and mathematical models, to describe processes in twisted streams to reduce experiments. Also, the goal was to create a universal burner device that can effectively burn synthetic or biogas of different compositions.

2. Numerical simulation methods

Simulation using Ansys Fluent and COMSOL Multiphysics was conducted to optimize the design of the burner device, allowing for a reduction in the number of real experiments. The experiments were aimed at verifying and validating these numerical models.

Comsol Multiphysics is a versatile tool that allows engineers and scientists to model complex interactions between various physical phenomena, such as fluid dynamics, heat transfer, structural mechanics, electromagnetism, optics, and photonics, making it valuable across a wide range of scientific and engineering disciplines.

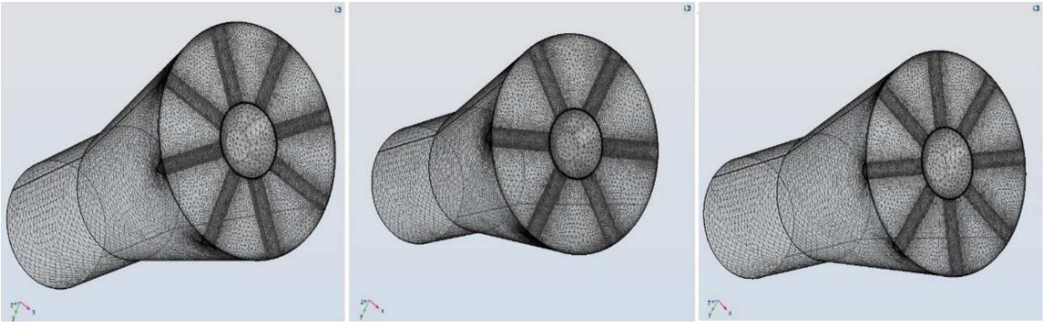
The simulation process is represented by constructing a model in 3-dimensional space using the realizable k-ε turbulence model. The model is based on the relationship between the values of air velocity and pressure in the study area and the initial air parameters (Tab. 1), which enter the burner device from the inlet and exit through the front section.

Table 1. Initial Parameters

	Initial Air Velocity (m/s)	Initial Air pressure (Pa)	Air temperature (K)
Parameters	6-14	101325	300

Using mesh generation for the studied burner device, a tetrahedral adaptive mesh was obtained (Fig. 2).

The number of elements in the area shown in Fig. 2a is 4820, in Fig. 2b is 3640, and in Fig. 2c is 4505. The mesh is represented by a group of tetrahedrons, which ensures efficient computation of various stress field scenarios and achievement of high-accuracy results.



a) **b)** **c)**

Figure 2. Mesh of the modeled area in COMSOL Multiphysics 6.0
a) Angle stabilizer at a 45° angle; b) Angle stabilizer at a 60° angle; c) Angle stabilizer in the shape of a semicircle

Then, based on the Navier-Stokes equations, the program simulates the airflow streamlines. Ansys Fluent is a powerful software for numerical simulation of fluid and gas flows. It is used to solve complex problems in fluid dynamics, heat transfer, and chemical reactions. Fluent is part of the Ansys toolset and offers extensive capabilities for simulating and analyzing various physical processes.

Based on the characteristics of the studied burner device and the objectives, we selected the turbulent combustion model with chemical reactions, k-ε Releasable, with the combustion model: Non-premixed combustion.

We determined the input parameters (Tab. 2), such as the temperature and velocity of the incoming fuel and oxidizer flows, as well as their concentrations.

The model grid shown in Fig. 3 was created for the simulation.

Table 2. Assigned Initial Parameters

Velocity, m/s	Pressure, Pa	Ambient Temperature, K	Fuel
6, 11, 14	101325	300	synthetic gas

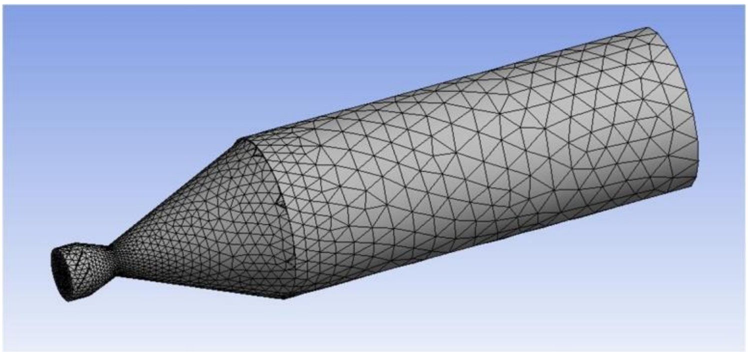


Figure 3. Finite-difference grid for simulation of the biogas combustion process in a burner device

2.1. Mathematical model and boundary conditions

The CFD synthetic gas combustion study was performed in the Ansys Fluent software suite. Numerical simulation was carried out by the RANS method, in which the system of Navier-Stokes equations averaged by Reynolds is solved by the method of finite volumes.

The Navier-Stokes equation system, which describes turbulent flow, consists of:

- continuity equation;
- pulse equation;
- energy equation;
- equation of state.

In the combustion chamber, the boundaries of the design area are solid walls and other elements. Other elements include inlet and outlet sections. Initial conditions include the following variable values $u = 0$, $v = 0$, $w = 0$, $P = 0$, $T = 0$, $C = 0$, $k = 0$, $\varepsilon = 0$. Table 3 shows the boundary conditions of the values (velocity, temperature, concentration of the mixture components, kinetic energy of turbulence, and the rate of its dissipation).

Table 3. Boundary conditions

№	Parameter	Value
Temperature boundary conditions		
1	Inlet temperature	300 K
2	Wall temperature	300 K
Boundary conditions for mass		
1	Inlet air mass flow rate	3.3-4.2 kg/h
2	Wall temperature	300 K
3	Excess air ratio	2-5

2.2. Mesh independence test

The mesh independence test is used to find the optimal grid condition with the smallest number of grids without generating a difference in the numerical results based on the evaluation of various grid conditions [16].

In Fig. 4, points 1 and 2 are shown, where temperature values were measured.

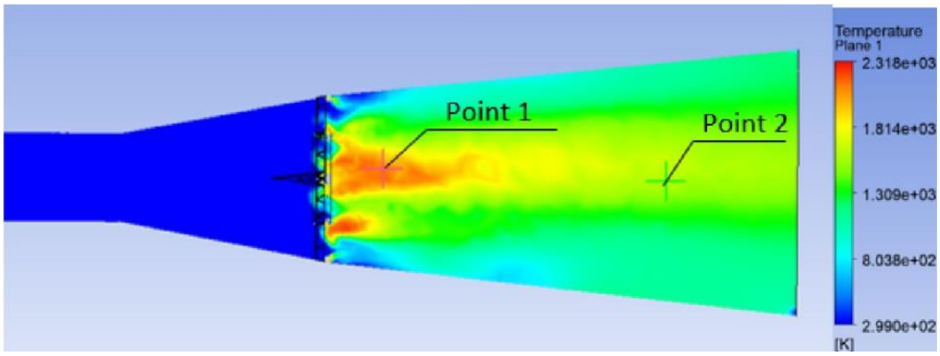


Figure 4. Mesh independence test points

When changing the mesh size, both the total number of mesh elements and the average temperature values at each point changed. These values are presented in Table 4.

Table 4. The values for the mesh independence test

	Total Mesh Elements	Size (m)	T1 (K)	T2 (K)	dT (K)
1	1121658	0.035	1848.17	1556.92	1702.55
2	1184842	0.030	1979.13	1524.08	1751.61
3	1277731	0.025	2128.36	1625.99	1877.18
4	1328770	0.023	2096.40	1555.37	1825.89
5	1390000	0.021	1779.12	1574.05	1676.59
6	1470900	0.019	1694.77	1564.27	1629.52
7	1584224	0.017	1740.11	1600.26	1670.19

The best way to check the independence of the solution from the mesh is to plot a graph (Fig. 5) of the resulting value of the monitor point against the number of elements in the simulation. This is illustrated below, where we have results from our monitor points for the average temperature at the outlet.

We can see that with element sizes ranging from 0.023 to 0.035, we have a result that shows significant fluctuations in values with an imbalance above 3%. By increasing the mesh resolution and reducing the element sizes from 0.017 to 0.021, we observe a balanced average temperature within acceptable deviations (+/-3 percent).

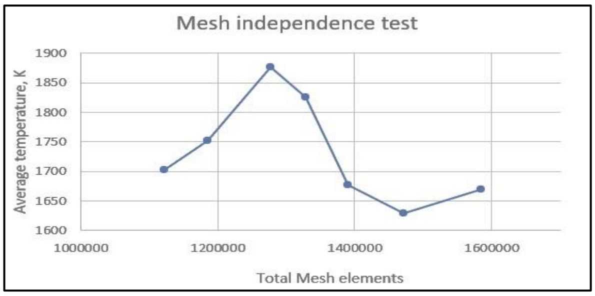


Figure 5. Mesh independence test

2.3. Flow structure

Figure 6 shows stabilizers and vortex currents formed behind them. As seen from Fig. 6, stabilizers of a semicircle shape have the highest vortex formation, and stabilizers with the smallest angle of 45^0 have the smallest vortex formation. Also, it is seen from the figure, that an increase in velocity leads to an increase in swirling zones, and in cases for a semicircle, such a zone at high velocities is thrown over the wall area, further creating a mixing area.

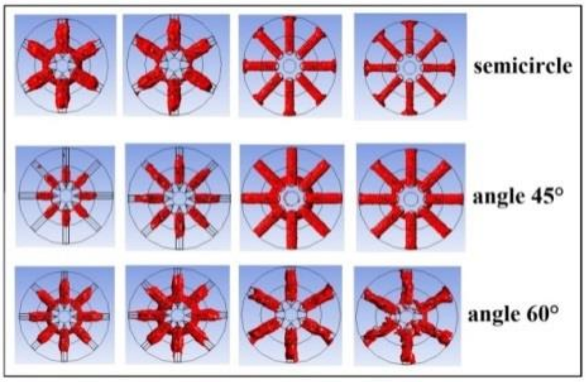


Figure 6. Vortex currents behind stabilizers

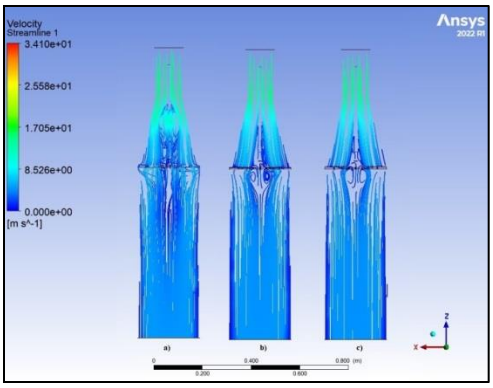


Figure 7. Current profiles

Figure 7 (a,b,c) shows the fuel-air mixture flow profiles at different stabilizers. The most effective flow is observed for stabilizers of a semicircular shape (Fig. 7a). Angular stabilizers have a similar character, but the complexity of the flow is determined by the angle between the generatrices.

3. Description of the experimental bench

The purpose of the experimental study of burner devices with different angle stabilizers is the burning of synthetic gas based on a swirling flow on the experimental bench shown in Fig. 8. Synthetic gas was supplied from a gas pipeline (1), the gas temperature was 26° -30°C, which corresponded to the ambient temperature. With measuring instruments: pressure gauge (2) and gas meter (3), the main characteristics of the fuel were measured before being supplied to the burner device. The air source is a radial centrifugal high-pressure fan "Venus DF5" (4). A stabilizing pipe (5) with a length of 120 cm and a diameter of ø15 cm is installed at the fan outlet to equalize the velocity fields. In the stabilizing pipe of the diffuser of the front device with burner (7) there is a measuring section 6 for measuring the parameters of the supply air from the fan. In the measuring section (6), static pressure collectors and full pressure nozzles (8) are installed, which are included in the TESTO 454-p multifunctional measuring system to determine the flow rate and flow velocity field, and the Fluke 52 II contact thermometer (9) to determine the inlet air temperature. The temperature of the combustion products was measured using the Metran 231-02 by chromel–alumel thermocouple (TSA) (10) (measurement range from -40° C to +1200° C), and the air temperature at the burner outlet was measured using the Metran 232-02 by chromel–copel thermocouple (11). This thermocouple measures air temperatures up to 800°C. Gas analysis and measurement of temperature and velocity of gas medium were carried out at the outlet of burner 7 using TESTO 350 gas analyzer. Analysis of combustion product samples for chemical analysis was performed on the exhaust with probe "Testo-350" (12).

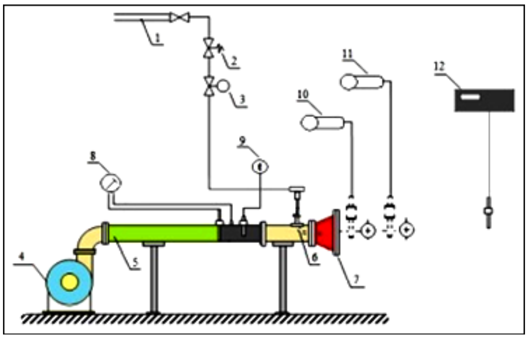


Figure 8. Schematic of the experimental bench with measuring instruments: 1–gas pipeline, 2–valve, 3 - gas meter, 4–fan, 5–stabilizing pipe, 6 – fuel supply tube, 7–stabilizers, 8 – multifunctional measuring system testo 454 n, 9–contact thermometer Fluke 52 II, 10 –chromel-alumel thermocouple, 11–chromel- copel thermocouple, 12–Testo 350 gas analyzer.

A microfiber burner was used to burn synthetic gases [14] and biogas [15]. The experimental bench for testing burner devices is shown in Fig. 9.

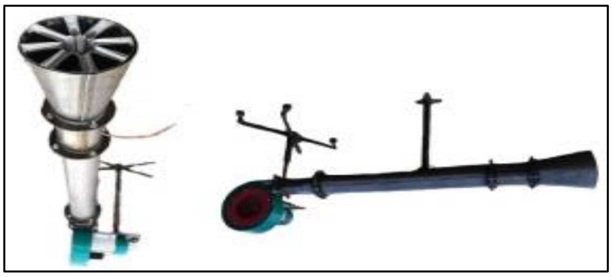


Figure 9. Experimental test bench for burner devices

Synthetic natural gas is a homogeneous mixture of liquefied hydrocarbon gas (propane-butane mixture) and air. However, propane and butane have different characteristics. To obtain the required heat of combustion as a result of their mixing, the following is taken: 68% propane and 32% air, relative density - 1.361, the heat of combustion - 63.89 MJ/m^3.

In our experimental studies on direct measurements of pressures, pressure drops, temperatures, fuel consumption time, linear dimensions of the reverse flow zone, fuel and air consumption, excess air coefficient, gas temperature, specific gas volume, air and gas velocity, residence time of combustion products, effective temperature and nitrogen oxide emissions were determined. Errors of direct measurements are given in Tab. 5.

Table 5. Errors of direct measurements for operating parameters

№ п/п	Parameter	Unit	The upper value of the parameter (by device)	Limit absolute error of the device (±)	The upper limit of the parameter in the experiment	Limit the relative error of the measured parameter in the experiment
1	ΔG_g	kg/s	1000	1	500	0.200
2	$T_{ch\text{-}k}$, $T_{ch\text{-}a}$	^{0}C	100	0.05	80	0.063
3	p, p*, ΔP_p	kgf/s	1.5	0.0075	1.5	0.500
4	B_0	mbar	1090	0.5	1000	0.050
5	$H(P_A^*), H(P_{calc}^*)$		4000	16	3200	0.500
6	t_{cham}	^{0}C	1300	3.35	1100	0.295
7	l	m	-	-	-	0.100
8	F(bx)	m^2	-	-	-	0.250
9	α		-	-	-	0.600

The following notations of operating parameters are adopted in Tab. 5:

ΔG_g - gas flow rate is measured by the BETAR SGK-1.6 jet meter;

$T_{ch\text{-}k}$, - air temperature at the burner outlet was measured by a chromel-copel thermocouple «Metran 232-02»;

$T_{ch\text{-}a}$, - combustion products temperature was measured by a chromel-alumel thermocouple type «Metran 231-02»;

p, p*, ΔP_p - static pressure and total pressure were measured using the "multifunctional measuring system «Testo 454 p»

B_0 - barometric pressure;

$H(P_A^*), H(P_{calc}^*)$ - gas analysis, measurement of temperatures, and gas flow rates by the gas analyzer «Testo 350». Analysis of combustion product samples for chemical analysis was performed at the exhaust using the probe "Testo-350";

t_{cham} – the gas temperature at the outlet of the combustion chamber;

l – burner length;

F(bx) – burner area;

α - pressure excess factor.

4. Experimental study results and discussion

During the experiment, the effect of the angle of stabilizers on the processes of stabilization, the formation of harmful emissions of nitrogen oxides, and the efficiency of combustion of synthetic gas was studied.

Three experiments with different stabilizer angles 45^0, $60^{0,}$ and the semicircle were carried out. Every experiment was conducted at 7 modes and consisted of 15-20 measurements, and it was taken 1-1.5 minutes for one measurement. At the beginning of each experiment, an optimal mode was established for gas flow and air velocity. In the following modes, the air velocity changed, and the gas flow rate was constant. After each mode, a break of 10-15 minutes was made and all measuring instruments were checked. Fuel consumption and overall burner design in 3D space (physical model) were calculated using Ansys Fluent software. The flame was ignited with an average fuel flow of 0.0011 kg/s and a variable airflow in the range of 7–16 m/s.

In experiments with stabilizers with an angle of 45° (Fig. 10) incomplete fuel combustion was observed due to poor mixing of fuel with air and underdeveloped backflow zones on the stabilizers, which led to an increase in fuel consumption to 1.2 g/s.

Figure 10. Angular stabilizers with an angle of 45^0

Figure 11. Angular stabilizers with an angle of 60^0

In an experiment with 60° angle stabilizers (Fig. 11) , the number of stabilizers was changed from eight to six, which made it possible to increase the distance between the stabilizers and reduce fuel consumption to 0.92 g/s. However, during the experiment, unstable combustion of the lean mixture was observed.

Figure 12. Angular stabilizers in the shape of a semicircle

Experiments were carried out with semicircular angular stabilizers (Fig. 12), and blue flame combustion was observed at the burner outlet, which is associated with a developed reverse current zone and high-quality mixing of fuel assemblies. Sufficient experiments were performed to reduce the absolute error. Arithmetic means were calculated after collecting all necessary data on the studied parameters. According to the data obtained during the experiments, the following graphs were plotted.

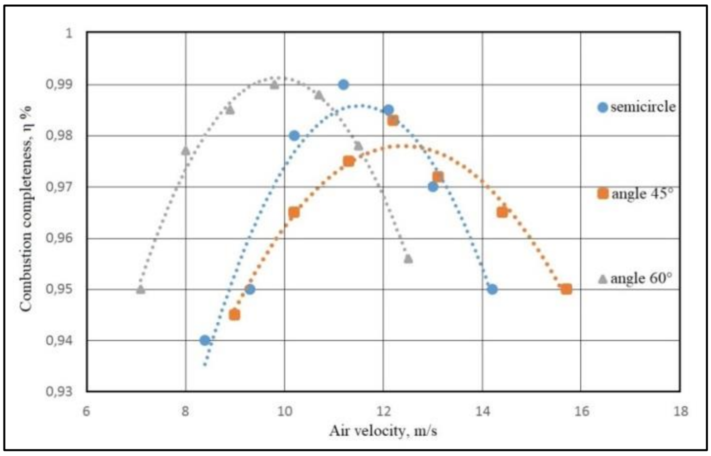


Figure 13. Dependence of combustion completeness on air velocity

Figure 13 shows a graph of combustion completeness versus air velocity using different types of stabilizers. It can be seen from the figure that the most complete combustion is achieved using a stabilizer in the shape of a semicircle. The method of calculating of fuel combustion completeness is given in reference [16]. As shown in the figure, the most complete combustion of fuel occurs at air velocities from 10 m/s to 12 m/s, which corresponds to the optimal ratio of fuel and air. The semicircular stabilizer is the most efficient in terms of complete combustion because it provides the most efficient mixing of fuel with air in the recirculation zone. The least effective is the 45° angle stabilizer since it has the least effect on the flow pattern and creates fewer recirculation zones.

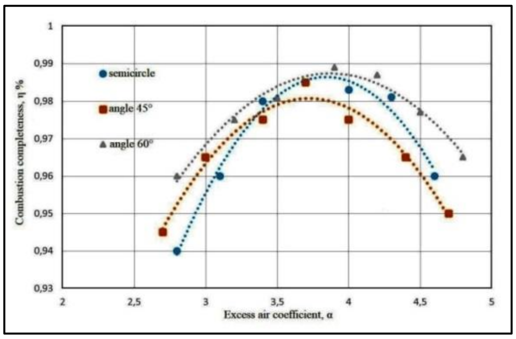


Figure 14. Dependence of combustion completeness on excess air coefficient

Figure 14 shows the diagram of fuel combustion completeness versus excess air. As can be seen in the figure, the most efficient combustion is achieved with a stoichiometric excess air ratio from 3.7 to 4.0. The method of calculating stoichiometric excess air is given in the reference [17]. With an increase in this coefficient, a decrease in the completeness of combustion occurs, since a large amount of air entrains fuel from the combustion zone. The smallest decrease in combustion completeness is observed in stabilizers with a semicircular shape. Stabilizers with an angle of 45° cause the greatest changes in the completeness of combustion, since they reduce the residence time of gases in the recirculation zone.

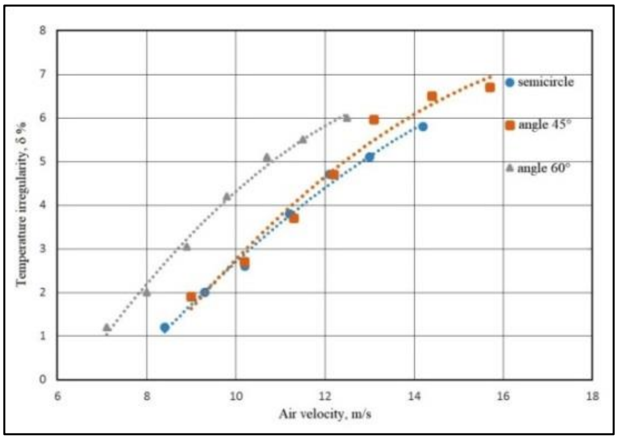


Figure 15. Dependence of temperature unevenness on air velocity

Figure 15 shows a graph of the relationship between temperature unevenness and air velocity. It can be seen from the graph that semicircular stabilizers are most effective in providing uniform temperature distribution. Angular stabilizers have similar characteristics. The method for calculating temperature unevenness is given in the reference [18]. Studies show that an increase in air velocity leads to an increase in temperature unevenness, as this is associated with an increase in flow turbulence.

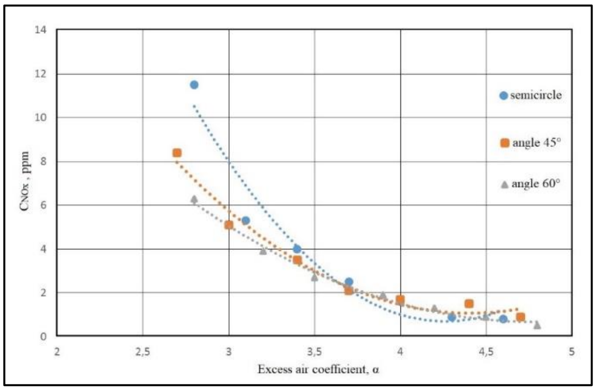


Figure 16. Dependence of C_{NOx} on excess air coefficient

Figure 16 shows the plot of nitrogen oxide concentration versus excess air coefficient. It is known that the temperature of the gases in the combustion zone depends on the volume of the incoming air. As the amount of air increases, the average temperature in the combustion zone drops. Similar to the previous graph, a decrease in gas temperature due to a large amount of air in the combustion zone also leads to a decrease in the concentration of nitrogen oxides. The lowest concentrations of nitrogen oxides are observed in stabilizers in the shape of a semicircle.

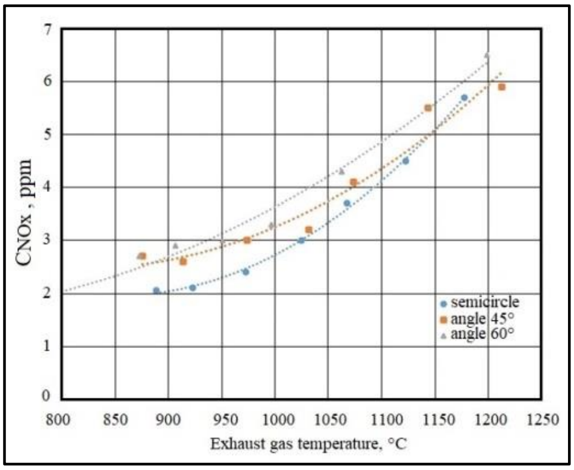


Figure 17. Dependence of C_{NOx} on exhaust gas temperature

According to the graph presented in Fig. 17, it can be concluded that the concentration of nitrogen oxides depends on the temperature of the exhaust gases. Nitrogen oxides show an exponential temperature dependence, so an increase in temperature in the combustion zone has a positive effect on the formation of these oxides. This is due to the activation of nitrogen molecules as the temperature rises and the amount of free oxygen molecules increases. The greatest increase in the concentration of nitrogen oxides is observed at angle 60^0, as they create strong recirculation zones where high-temperature gas is trapped. This phenomenon leads to an increase in the concentration of nitrogen oxides.

The experimental results confirmed the accuracy and reliability of the numerical models. The correlation between experimental data and simulation results showed that the optimal stabilizer angles calculated using COMSOL Multiphysics corresponded to the most effective combustion conditions found during the experiments, specifically the semicircular stabilizer. This confirms the correctness of the chosen numerical methods and models.

5. Conclusions

The combination of numerical simulation and experimental research allowed for high achievements in optimizing the burner device design. Simulation enabled the prediction of system behavior and reduced the number of required experiments, ultimately leading to the creation of a more efficient and environmentally friendly burner device. Thus, numerical simulation and experimental research complemented each other, resulting in significant achievements in optimizing the design and operating parameters of the burner device.

The dimensions of the angular stabilizers, the inter-stabilizer distance, and the optimal aerodynamic cross-section behind the stabilizer were calculated using numerical simulation in the COMSOL Multiphysics program. The calculated velocities were used in experimental studies. The selection of an effective stabilizer in the process of stable combustion of synthetic gas is carried out using the Ansys Fluent program. Experimental results show that the most suitable stabilizers for the efficient combustion of synthetic gases are semicircular stabilizers. It may be noted that in several modes when installing stabilizers with angles 45^0 and 60^0, the presence of a blue flame was recorded, but about the total number of calculated modes, these cases are insignificant. Based on the results of the experimental studies, data are collected and further analyzed for effective combustion of synthetic gas with stable combustion and reduced formation of harmful emissions.

The practical significance of the work may be considered as the obtained results can be applied in practice: the developed and studied burner can be used in various fuel-burning devices where biogas will be used as fuel; the obtained research results will be useful for creating low-toxic combustion chambers, heat generators, and hot water boilers.

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