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ESTABLISHMENT OF REGULARITIES OF ISOTHERMAL FLOW AND MIXTURE FORMATION IN MICROJET BURNERS WITH THREE-ROW JET FUEL SUPPLY

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The object of this research is the aerodynamics and mixture formation of fuel and oxidizer in stabilizer-type burners with a three-row system of fuel jets, focused on operation at coefficients of excess air 1.1...1.5. The study was conducted on the basis of CFD modeling using the RANS (Reynolds Averaged Navier-Stokes) approach.

The analysis of the basic regularities of the course of these processes in the proposed microjet burners was carried out. In this case, special attention was paid to the consideration of the characteristics of flow and mixture formation in the aft region of the flame stabilizer, where vortex structures are formed that are responsible for stabilizing the torch.

The regularities of influence on the flow and mixture formation in the proposed burner devices of such factors as the row number N_R of the jet fuel supply, the relative pitch, S/d, of the location of gas supply holes and the coefficient of excess air, α, have been investigated. The presence of noticeable differences in the structure of flow and mixture formation in burners during fuel supply to different rows of gas supply holes has been established. It is shown that aerodynamics and the pattern of mixing fuel and oxidizer undergo significant changes when varying the value of S/d.

For the considered burner devices, rational design parameters of the fuel supply system have been determined, at which favorable conditions for mixture formation in the field of flame stabilization are ensured. In particular, it is shown that the rational S/d values are 5.4; 5.6; and 5.8, respectively, for the first, second, and third sections of the fuel supply.

The results can be widely used in energy practice for objects operated under conditions of variable values of the coefficient of excess air

Keywords: microjet burners, flow structure, mixture formation of fuel and oxidizer, jet fuel supply

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1. Introduction

The aerodynamics and mixture formation of fuel and oxidizer in burners of various types largely determine the course of all components of the working process of such devices.

Relevant are studies aimed at establishing the effects of the influence of various factors on the structure of the flow and mixture formation of fuel and oxidizer in the burners under consideration. In particular, the task of finding, on the basis of the performed parametric studies, the rational design parameters of the proposed burner devices seems important.

The developed burners are designed to implement the possibility of regulating the composition of the fuel mixture in the flame stabilization zone and, in general, to ensure high efficiency of fuel combustion under their operating conditions at different values of the excess air coefficient.

2. Literature review and problem statement

The study of the workflows of burner devices based on CFD (Computational Fluid Dynamics) modeling is receiving increasing attention. CFD modeling is an effective and powerful tool for investigating various elements of the working process of burners, namely aerodynamics, mixture formation of fuel and oxidizer, flame stabilization, fuel burnout, etc. [1].

On the basis of CFD modeling, studies of the working processes of burners of various types integrated into different fuel combustion devices are carried out. Thus, in [2], the issues of modeling processes in the methane steam reforming unit are discussed. There, the computational model is developed for an industrial-scale installation consisting of 336 reforming reactors, 96 burners, and 8 flue gas tunnels. The paper notes that the use of a computational model of the installation is designed to avoid expensive parametric field studies. Article [3] reports the development of CFD modeling methodology to describe combustion processes in modern spark-ignition engines. There, similarly to work [2], the developed technique is justified by comparison with the relevant experimental data. In [4], the issues of modeling the flame of a pre-mixed and partially mixed mixture are discussed. The paper reports a comprehensive analysis of the use of Flamelet Generated Manifold (FGM) techniques based on LES and RANS approaches. Paper [5] presents an overview of new computational approaches to modeling combustion processes. A general conclusion is made about the presence of unconventional opportunities for modeling these processes.

Studies discussed above [2–5] focus mainly on the methodological aspects of CFD simulation of the workflows of burners. Although for energy practice, studies of the main features and characteristics of these processes are of great interest. Works [6–8] can serve as examples of studies in which combustion processes in various fuel-burning devices are analyzed on the basis of CFD modeling, and issues of increasing their efficiency are considered. Thus, in [6], on the basis of CFD modeling, the characteristics of various micro-incineration modes are investigated – with a depleted mixture and a flameless mode without prior mixing of methane with air. There, special attention is paid to the formation of temperature fields in the combustion zone and flame stabilization. In study [7], three-dimensional computer modeling methods were used to determine the effects of the influence of various schemes of burner devices and the method of feeding the fuel mixture on the main characteristics of transfer processes in the furnace space of a power boiler. It is shown that the use of vortex burners with twisting of the air mixture flow makes it possible to improve exchange processes in the furnace space and reduce emissions of harmful substances into the atmosphere. Work [8] considers the use of mixtures of hydrogen and traditional hydrocarbons in gas turbines. In this work, the laboratory burner with preliminary mixing was investigated on the basis of a three-dimensional URANS approach. It is noteworthy that at the initial stage of the study, numerical modeling was performed under cold purging, that is, the structure of the isothermal flow was studied.

A number of works consider issues related to computer modeling of highly efficient micro jet combustion of fuel in burner devices of various types [9, 10]. In this case, much attention is paid to the study on the basis of CFD modeling of working processes of new modifications of micro jet stabilizer burners. Thus, in [9], burners with asymmetric fuel supply, focused on operation at relatively high values of the excess air coefficient, were subject to consideration. On the basis of CFD modeling, an analysis of the effects of the ratio of primary and secondary air consumption on the characteristics of the working processes of these devices is carried out. Work [10] reports a study of fuel combustion processes in micro jet burners with cylindrical flame stabilizers. These burner devices are designed for energy objects of relatively low productivity. Work [10] used computer modeling to consider the possibility of regulating the process of mixture formation in the specified burners.

Many of the works discussed above concern the finding of rational design characteristics of burner devices and technological modes that meet the conditions for efficient combustion of fuel [7–9]. Thus, in study [9], rational ratios of the width of the near-wall and interstabilizer channels of the considered micro jet burners were to be determined, in which favorable values of their energy-ecological characteristics are realized.

Our review of the literature data reveals that for a number of new promising technical solutions of micro jet burners, many questions related to their work processes remain unexplored. In particular, for new combustion devices, studies of the structure of flow and mixture formation in these devices, as processes that largely determine the efficiency of fuel combustion, are of considerable interest. Important are studies aimed at determining the rational design parameters of such burners. It also follows from the review that computer simulation of the working processes of burner devices is becoming an increasingly common and effective method of their analysis.

3. The aim and objectives of the study

The aim of this work is to establish the regularities of isothermal flow and mixture formation in stabilizing burner devices with a three-row system of jet fuel gas supply, which makes it possible to determine the rational design parameters of the fuel supply system of these devices.

To accomplish the aim, the following tasks have been set:

– to perform a set of computational experiments to identify the basic laws of aerodynamics and mixing of fuel and oxidizer in the proposed burner device with a multi-row fuel supply system;

– to establish the effects of the influence of various factors on the characteristics of flow and mixture formation in the burner devices under consideration;

– on the basis of the data of parametric analysis of the studied processes, to determine the rational design parameters of the fuel supply system of these devices that meet the favorable conditions of mixture formation in the flame stabilization zone.

4. The study materials and methods

The object of this study is the processes of flow and mixture formation of fuel gas and oxidizer in a burner device designed for operation under conditions of various values of the excess air coefficient ($1.1 \leq \alpha \leq 1.5$). The main hypothesis of the research is the choice of rational design parameters of the fuel supply in the proposed burners based on the analysis of the mixture formation pattern in the aft region of the flame stabilizer. As for the prerequisites adopted in the work, they include the following. The constancy of the velocity profile of the air at the inlet to the channel and natural gas in the gas supply holes. The invariability of the intensity of turbulence in the input section of the channel. An important simplification adopted in the work is the consideration of the area corresponding to half of the object under study, which is justified by its geometric symmetry and the symmetry of the corresponding physical processes.

As for the design of burner devices of the type under consideration, it is based on the modular principle. This makes it possible to provide the required power of such devices by means of a certain number of burner modules. A separate module includes a flame stabilizer and related interstabilizer zones. And since the transfer processes in a separate module and module included in the system of modules are almost identical, it is advisable to limit the modeling to a single burner module. The burner module consists of a flat flame stabilizer 2 located in channel 1 at some distance from the walls of the channel (Fig. 1). Fuel supply to the flame stabilizer is carried out through one of three, separated from each other, sections I, II, III. Each of these sections corresponds to the supply of fuel gas at a certain value of the excess air coefficient from this range. On the side surfaces of the flame stabilizers there is a three-row system of round holes 3, through which the gas is supplied directly to combustion into the oxidizer blowing stream. Such a fuel supply system, as already noted, is designed to ensure the possibility of regulating the composition of the fuel mixture in the flame stabilization zone. An important parameter by which this adjustment can be made is the relative step of the location of the gas supply holes, S/d. In this case, each of the rows of gas supply holes must meet a certain S/d value that meets the specified requirements in terms of the composition of the fuel mixture in the flame stabilization zone.

The research was conducted on the basis of mathematical modeling using the RANS approach to the study of turbulent flows. The implementation of numerical solutions was carried out using FLUENT code.

The mathematical model of the process under study for a single burner module is represented in the form of:

– equation of motion:

$$\frac{\partial}{\partial \tau}\left(\rho \vec{U}\right)+\nabla \cdot\left(\rho \vec{U} \cdot \vec{U}\right)= =-\nabla P+\nabla \cdot\left(S^{*}\right); \qquad (1)$$

– continuity equation:

$$\frac{\partial \rho}{\partial \tau}+\nabla \cdot\left(\rho \vec{U}\right)=0; \qquad (2)$$

– equation of conservation of mass of the i-th chemical component:

$$\frac{\partial}{\partial \tau}\left(\rho Y_i\right)+\nabla \cdot\left(\rho \vec{U} Y_i\right)=-\nabla \cdot \vec{J}_i, \ \mathrm{i}=1, 2, \ldots, \mathrm{N}-1; \qquad (3)$$

– equation of state for a multicomponent mixture:

$$\rho=\frac{P}{R \cdot T \sum_i^N \frac{Y_i}{M_i}}, \qquad (4)$$

where $\vec{U}$ is the velocity vector; τ – time; P – static pressure; S^* is a stress tensor that takes into account viscous stresses and additional stresses due to turbulence; ρ is density; Y_i – mass concentration of the i-th component; $\vec{J}_i$ – mass flow of the i-th component due to diffusion and turbulent transfer; M_i is the molecular weight of the i-th component; N is the number of components of the mixture; T is the absolute temperature; R is a universal gas constant.

The boundary conditions for the above system of equations were defined in the following way. In the sections corresponding to the inlet to the channel of the burner device and to the gas supply holes, as already noted, constant values of velocities, concentrations, etc. were set. In the output section of the channel of the burner device, the so-called «soft» boundary conditions were set – equality to zero of the longitudinal derivatives of all dependent variables. On the impermeable boundary surfaces of the stabilizer, adhesion conditions were set.

To close the system of equations (1) to (4), we performed the verification of turbulent transfer models. To this end, the data of experimental studies presented in [11] were compared with solutions to problems obtained using the main models of turbulence that appear in the modern catalog of closing models. Namely, the k-ε model in the Standard, Realizable, and RNG versions, the Spalart-Allmares model, the SST model of Menter (k-ω model) and BSL – the k-ω model.

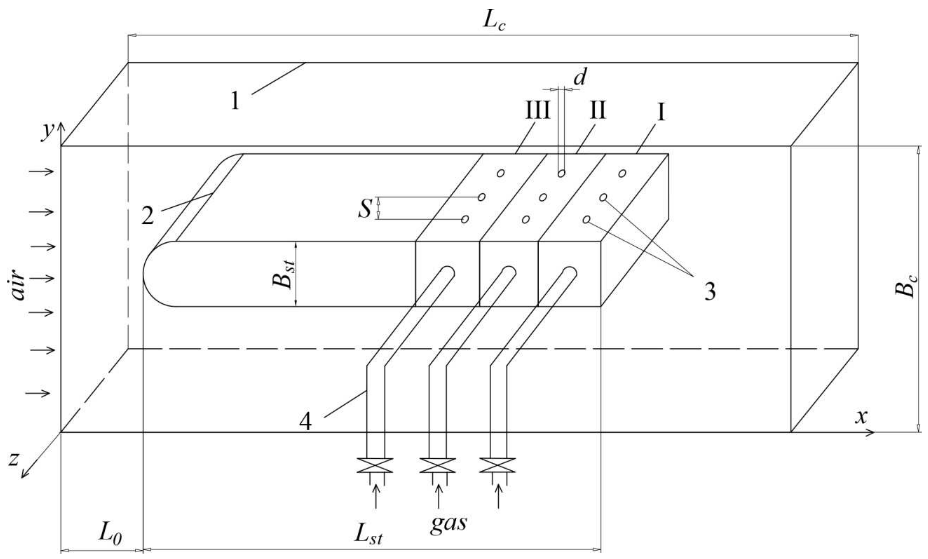

Fig. 1. Scheme of the module of the micro jet burner of the stabilizer type with a three-row fuel supply system: 1 – flat channel; 2 – flame stabilizer; 3 – gas supply holes; 4 – gas supply pipes; I, II, III – gas supply sections with different values of the relative pitch of the gas supply holes, corresponding to different values of the excess air coefficient

According to the data obtained, the smallest relative deviations of the results of experimental and computational studies occur when using the RNG k-ε model. For this model, these relative deviations are: by the length of the reverse current zone in the aft region of the stabilizer – 7.2 %, by the absolute value of the maximum speed in this zone – 6.2 %, by the Strouhal number – 6.7 % (here, the Strouhal number is $Sh=\left(f\cdot B_{st}\right)/U_{in}$, where f is the frequency of separation of vortices).

In the simulation, as noted above, in view of the geometric symmetry of the burner module and the symmetry of the physical processes relative to the axis of the interstabilizer channels, the region corresponding to half of the module was to be considered.

In the course of the research, computational experiments were carried out for the calculation area, the discretization of which was carried out as follows. The area was covered with an uneven unstructured grid with a significant thickening to the walls of the flame stabilizer and contained about a million cells. The wall step was set at 10^{-4} m. In the area of the close trace of the flame stabilizer, the minimum step was $5\cdot10^{-4}$ m.

5. Results of flow and mixture formation studies in burners with a three-row jet fuel supply system

5. 1. Results of studies of the basic laws of aerodynamics and mixture formation in the proposed burner devices

Mathematical modeling was carried out at the following values of the initial parameters: B_{st}=0.03 m; B_c=0.075 m; L_c=1.3 m; L_0=0.1 m; L_{st}=0.2 m; d=$2.5\cdot10^{-3}$ m. Relative pitch of the gas supply holes S/d=5.6; distance L_1 between the stall edge of the stabilizer and the first, second, and third row of gas supply holes $L_1=10\cdot10^{-3}$ m; $20\cdot10^{-3}$ m; $30\cdot10^{-3}$ m. Clogging coefficient of flow area channel k_f=0.3 ($k_f=B_{st}/B_c$); air velocity at the inlet to the channel $U_{in}^{a}=10$ m/s; turbulence intensity Tu in the inlet section of the channel Tu=3 %. Natural gas was used as fuel, air was used as an oxidizer.

Studies were performed for different values of the excess air coefficient of 1.1≤α≤1.5. In computer simulations, variation in α was achieved by changing the natural gas flow rate at a fixed air flow rate. In Fig. 2, as an example, data corresponding to the supply of fuel gas to the first fuel supply section are given.

In Fig. 2, *c,* subregions A, B correspond to zones with excess air and fuel gas, respectively, subregion C – the zone of formation of the mixture within the concentration limits of ignition.

5. 2. Results of studies of the influence of various factors on the flow and mixture formation in the proposed burner devices

In the course of the research, the regularities of the influence of the following factors on the characteristics of the flow and mixture formation in the burners under consideration were studied. Firstly, the distance of a row of gas supply holes from the stall edge of the flame stabilizer, secondly, the relative step of the location of the gas supply holes, S/d, and, thirdly, the value of the excess air coefficient.

As for the specified remoteness of a number of gas supply holes, as already noted, situations were considered when the first row of these holes is located at a distance of $L_1=10\cdot10^{-3}$ m from the stall edge, the second – $20\cdot10^{-3}$ m, and the third – $30\cdot10^{-3}$ m.

When studying the influence of the relative step of the location of gas supply holes S/d, its value ranged from 4.0 to 5.6. The change in the S/d value was ensured by changing the diameter of the holes from $2.5\cdot10^{-3}$ m to $3.5\cdot10^{-3}$ m with the same step value $S=14\cdot10^{-3}$ m.

Regarding the influence of the excess air coefficient, it changed from 1.1 to 1.5 during the studies in accordance with the operating conditions of the burner device.

Characteristic results of computer modeling to determine the effects of the influence of the distance of a row of gas supply holes from the stall edge of the flame stabilizer are shown in Fig. 3. Here, as an example for the conditions of fuel gas supply through the 1st, 2nd, and 3rd row of holes, important characteristics of flow and mixture formation are given. Namely, the length of the reverse current zone L_z and the average value of methane concentration in the reverse current zone $\bar{C}_m$.

The results of studies to establish the regularities of the influence of the relative step of the location of gas supply holes S/d on the flow and mixture formation in the burner device are illustrated in Fig. 4, 5.

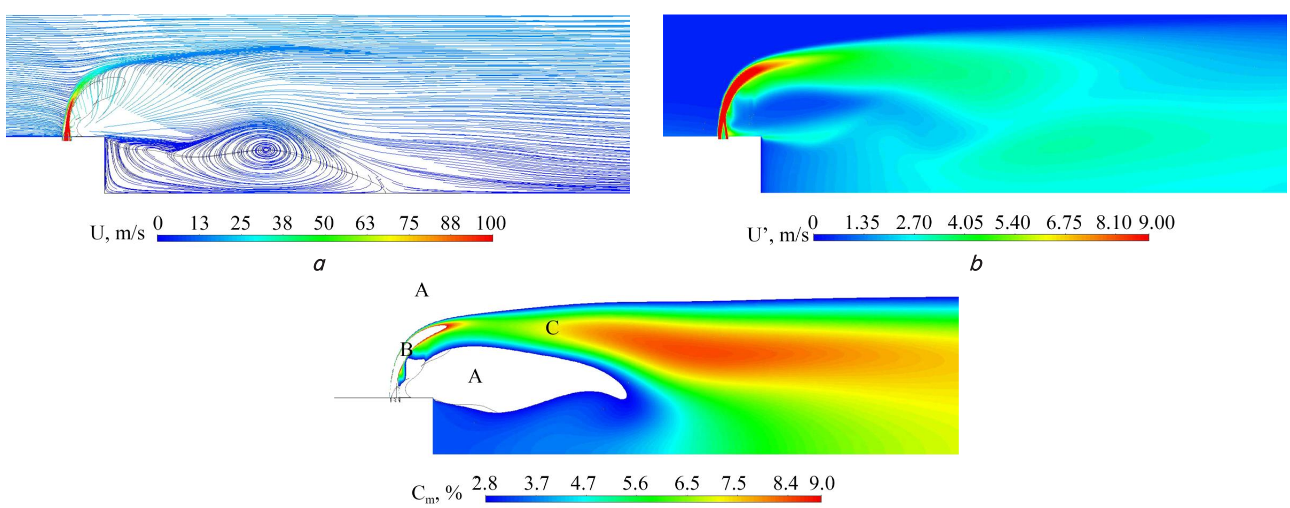

Fig. 2. Flow and mixture formation characteristics in the longitudinal section of the burner module passing through the axis of the gas supply holes, at α=1.1; $L_1=10\cdot10^{-3}$ m: *a* — current lines; *b* — field of root mean square pulsations of velocity U'; *c* — methane concentration field C_m

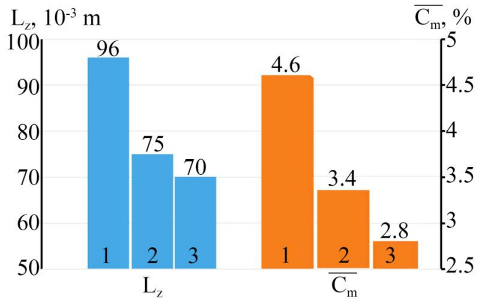

Fig. 3. The values of the inverse current zone length L_z and the average methane concentration $\overline{C}_m$ in this zone at α=1.1; S/d=5,6; d=2.5·10^{-3} m for different rows of gas supply holes: 1, 2, 3 – number of row of holes N_R corresponding to L_1=10·10^{-3} m; 20·10^{-3} m, and 30·10^{-3} m, respectively

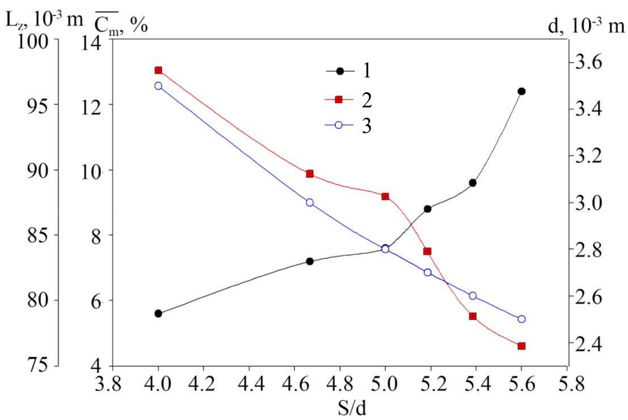

Fig. 4. Dependence of the characteristics of the reverse current zone behind the flame stabilizer and the diameter of the gas supply holes d on the relative pitch of their location at α=1.1; L_1=10·10^{-3} m: 1 – the length of the reverse current zone L_z; 2 – the average value of methane concentration $\overline{C}_m$ in this zone; 3 – the diameter of the gas supply holes

Fig. 4 shows the dependences on the value of S/d of the length of the reverse current zone L_z and the average concentration of methane $\overline{C}_m$. Fig. 5 shows the fields of methane concentrations in the longitudinal section of the burner module at different values of the relative pitch S/d.

Characteristic data of computer modeling for the analysis of the influence of the coefficient of excess air α on the characteristics of the flow and mixture formation in the burner module under consideration are given in Table 1.

Table 1

The length of the reverse current zone L_z behind the flame stabilizer and the average value of methane concentration $\overline{C}_m$ in this zone for different rows N_R of gas supply holes at different values of the excess air coefficient α

α	N_R=1		N_R=2		N_R=3	
	L_1, 10·10^{-3} m		L_1, 20·10^{-3} m		L_1, 30·10^{-3} m	
	S/d=5.4		S/d=5.6		S/d=5.8	
	L_z, 10^{-3} m	$\overline{C}_m$, %	L_z, 10^{-3} m	$\overline{C}_m$, %	L_z, 10^{-3} m	$\overline{C}_m$, %
1,1	89.0	5.5	75.0	3.4	72.2	2.5
1.3	81.5	7.8	70.4	5.4	67.0	4.3
1.5	76.2	8.6	64.2	7.4	61.3	6.1

Table 1 gives the results of computational experiments at different α for cases corresponding to the supply of fuel through each of the three rows of fuel supply holes.

5. 3. Results of the study to determine the rational design parameters of the burner fuel supply system

Within the framework of this study, as already noted, for the burners under consideration, the task of determining the rational design parameters of their fuel supply system that meet the favorable conditions of mixture formation in the flame stabilization zone was to be solved. Relevant research data for various rows of jet fuel gas supply are given in Table 2.

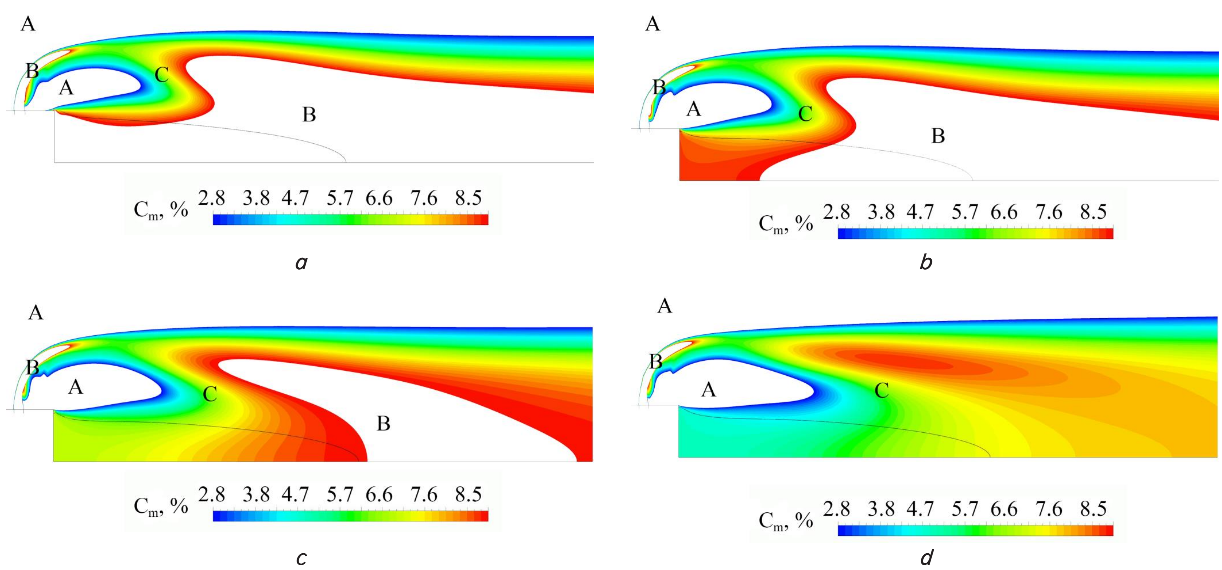

Fig. 5. Methane concentration fields in the longitudinal section of the burner module passing through the axis of the gas supply holes at α=1.1; L_1=10·10^{-3} m for different values of the relative pitch S/d of the location of the holes: *a* – S/d=4.7; *b* – S/d=5.0; *c* – S/d=5.2; *d* – S/d=5.4

Table 2

Rational design parameters of the three-row jet fuel supply system, the average value of methane concentration $\overline{C}_m$ in the reverse current zone behind the flame stabilizer and the relative deviation δ of this concentration from the value C_m^e

N_R	α	L_1, 10^{-3} m	S/d	d, 10^{-3} m	$\overline{C}_m$, %	δ, %
1	1.1	10	5.4	2.6	5.5	6.8
2	1.3	20	5.6	2.5	5.4	8.5
3	1.5	30	5.8	2.4	6.1	3.4

With regard to these favorable conditions, the work took as such the conditions of equality between the average concentration of methane in the reverse current zone behind the flame stabilizer and its concentration corresponding to the middle of the ignition range C_m^e. At the same time, it was assumed that this equality should be satisfied with an error δ not exceeding 10 %.

6. Discussion of results of the flow and mixture formation studies in burners with a three-row jet fuel supply system

The flow and mixture formation of fuel and oxidizer when fuel gas is supplied to different rows of gas supply holes have common patterns. Fig. 2 illustrates, as an example, the current lines, RMS fields of velocity U' and mass concentration of methane C_m for the conditions for the supply of fuel gas to the first, closest to the stall edge, rows of gas supply holes. As can be seen from Fig. 2, *a*, fuel jets develop in the oxidizer drift stream. In the aft region of the flame stabilizer, a vortex structure is formed responsible for stabilizing the flame. As for the pulsations of the velocity U' (Fig. 2, *b*), the region of their maximum values corresponds to the initial stage of the development of the jets. There, the pulsations U' reach 10 m/s. In the sub-jet region, there is a very low level of these pulsations (≈1.3 m/s). Low values of the pulsations of the velocity also characterize a zone of reverse currents behind the flame stabilizer. Although near the boundaries of this zone, the velocity pulsations are noticeably higher (≈2.7 m/s).

As for the pattern of mixture formation of fuel and oxidizer, attention is drawn to the presence of zones A and B, in which the mixture is outside the concentration limits of ignition. Namely, in zones A located above and below the jet, the mass concentration of methane is less than the lower concentration limit of ignition. In zone B, corresponding to the initial section of the fuel jet, the concentration of methane exceeds the upper concentration limit. That is, zones A are characterized by excess air, and zone B – fuel gas.

An important fact is that in the aft region of the flame stabilizer, where the stabilization of the torch occurs, the fuel mixture is within the concentration limits of ignition. Thus, the average mass concentration of methane in the zone of reverse currents behind the stabilizer is 3.5 % in the analyzed case.

Based on the results of computer simulation, an analysis was performed of the dependence of the studied processes in burners of the type under consideration on the number N_R of rows of the jet fuel supply, the relative step S/d of the location of the fuel supply holes, and the coefficient of excess air α.

With regard to the row number, the data indicate that the flow and mixture formation characteristics differ markedly when fuel gas is supplied through the first, second, and third row of gas supply holes. Namely, the farther the fuel supply range is from the stall edge of the flame stabilizer, the lower the range of fuel jets and the shorter the length of the return current zone L_z behind the flame stabilizer. As can be seen from Fig. 3, at α=1.1, S/d=5.6, the length of the reverse current zone L_z is $96\cdot10^{-3}$ m, $75\cdot10^{-3}$ m, and $70\cdot10^{-3}$ m, respectively, when fuel is supplied through the first, second, and third row of gas supply holes.

As for the pattern of mixture formation of fuel and oxidizer, it is largely determined by the peculiarities of the flow in the burner module. At a distance of the fuel supply from the stall edge, most of the section passing through the end of the stabilizer is occupied by a mixture that meets the concentration limits of ignition. As for the average concentration of methane $\overline{C}_m$ in the zone of reverse currents, it decreases. According to the data given in Fig. 3, this concentration for the first, second, and third rows of fuel supply is 4.6 %, 3.4 %, and 2.8 %, respectively.

The results of our studies performed to identify the effects of the relative step of the location S/d of gas supply holes on the flow and mixture formation in the burner module under consideration showed the following. With the increase in S/d, there is an increase in the range of fuel jets and the length L_z of the reverse current zones behind the flame stabilizer. With regard to the latter, the increase is relatively small in the area of S/d values ($4.0 \leq S/d \leq 5.0$) and more significant with a further increase in S/d (Fig. 4).

According to the data obtained on the mixture formation of fuel and oxidizer, with an increase in the relative pitch of the gas supply holes, the average concentration of methane $\overline{C}_m$ in the reverse current zone decreases. However, here, as in the case of the dependence $L_z = L_z(S/d)$, a much sharper change in concentration is observed in the region of large values of S/d.

Our studies have also shown that the required methane concentration in the reverse current zone is realized only at certain values of the relative pitch S/d. As can be seen from Fig. 5, at S/d=4.7, almost the entire zone of reverse currents is occupied by a mixture with an excess of fuel gas. With an increase in S/d up to 5.0 in the aft region of the flame stabilizer, due to the increase in the range of fuel jets, a small zone is formed in which the mixture is within the concentration limits of ignition. With a further increase in the pitch of the location of the gas supply holes to 5.2, the size of this zone increases. An S/d value of 5.4 meets the conditions when the entire reverse current zone and the area beyond it are occupied by a mixture within the ignition concentration range. In the course of the research, an analysis of the regularities of the influence on the considered processes of the coefficient of excess air α for the conditions for supplying fuel gas to different rows of gas supply holes is carried out. The data obtained (Table 1) indicate that the nature of the influence of α is qualitatively the same for all fuel supply rows. Thus, with an increase in α, there is a decrease in the length of the reverse current zone L_z and an increase in the average mass concentration of methane $\overline{C}_m$ in this zone. Regarding this increase in $\overline{C}_m$, it is due to a drop with an increase in the α range of fuel supply jets, which leads to an increase in the proportion of fuel in the aft region of the flame stabilizer. Thus, when fuel is supplied through the first row of gas supply holes, the relative range of the jets is 0.6; 0.56; and 0.51 for α=1.1; 1,3; 1,5.

As for the noted increase in the value of $\overline{C}_m$ with an increase in α, it turns out to be the more significant the larger the number of the fuel supply rows. With an increase in α from 1.1 to 1.5, the concentration of methane $\overline{C}_m$ in the reverse current zone increases by 1.6 times for the first row, 2.2 times for the second, and 2.4 times for the third row of fuel gas supply.

For all the considered values of α, as already noted, with an increase in the number of the row N_R, (i.e., when distancing the gas supply from the stall edge of the flame stabilizer), the length of the zone of reverse currents L_z and the average concentration of methane $\overline{C}_m$ decrease. In this case, the relative decrease in L_z when fuel is supplied through the first, second, and third row of gas supply holes is close in value for all considered values of α. As for the corresponding relative decrease in the value of $\overline{C}_m$, it can differ markedly at different values of the coefficients of excess air. Namely, this decrease is the largest for α=1.1, slightly smaller at α=1.3, and the smallest at α=1.5. Thus, the relative drop in methane concentration $\overline{C}_m$ when fuel gas is supplied to the first and third row of gas supply holes is 2.2 times, 1.8 and 1.4 for α=1.1; 1.3; and 1.5 (Table 1).

The solution of the problem of determining the rational design parameters of the fuel supply of the proposed burners was specified as follows. For each of the three fuel supply sections, the relative pitch S/d of the location of the gas supply holes meeting such conditions were to be found. When fuel is supplied through one of the sections – the first, second, or third, the burner device must be operated, respectively, at α=1.1; 1.3; and 1.5. At the same time, as already noted, favorable conditions for mixture formation in the aft region of the flame stabilizer should be ensured. As such favorable conditions, it is assumed that in the zone of reverse currents behind the stabilizer, the average value of the methane concentration $\overline{C}_m$ is equal, with a given accuracy, to the average value between the upper and lower concentration limits of ignition $C_m^e = 5.9\,\%$.

As can be seen from the data obtained (Table 2), the recommended relative pitch of the location of gas supply holes increases from the first N_R=1 to the third N_R=3 rows of fuel supply and is 5.4; 5.6; and 5.8, respectively, for the first, second, and third row. With regard to the diameter of the gas supply holes d for different sections of fuel gas supply, with a fixed value of the distance between the holes $S=14{\cdot}10^{-3}$ m, the recommended values of these diameters for the first row are 2.6 10^{-3} m, for the second row $2.5{\cdot}10^{-3}$ m, and $2.4{\cdot}10^{-3}$ m for the third row.

An alternative to the proposed burner devices with a three-row supply of fuel gas are burners with its single-row supply [9]. In such alternative burners, it is not possible to ensure the required composition of the fuel mixture in the flame stabilization zone at operating modes that meet different values of α. In contrast, in the proposed burner devices, due to the three-row fuel supply system, it is possible to adjust the specified composition for various values of the excess air coefficient. This allows for effective combustion of fuel at fire facilities operated under conditions of variable values of α.

In our work, the study is limited to considering only the structure of the flow and mixture formation of fuel and oxidizer in the proposed burner devices. Further research should be aimed at studying such elements of the working process of the burners under consideration as the formation of temperature fields in the active combustion zone, fuel burnout, etc.

The scope of application of the research results are fire objects operated at different values of the coefficient of excess air. The found rational values of the geometric parameters of the proposed burners will be used in their design.

7. Conclusions

1. CFD data on modeling the processes of flow and mixture formation in micro jet burner devices with a three-row system of jet fuel gas supply are obtained with a value of the coefficient of excess air of 1.1≤α≤1.5. The basic regularities of the course of these processes in burners of the type under consideration are established. It is shown that the structure of flow and mixture formation has common features when supplying fuel to different rows of gas supply holes. In particular, the velocity pulsation fields are similar, characterized by the highest values at the initial stage of development of fuel jets and the lowest values in the subjet region and the central part of the reverse current zone behind the flame stabilizer. Particular attention is paid to the consideration of the characteristics of the flow and mixture formation in the aft region of the flame stabilizer, where vortex structures responsible for stabilizing the torch are formed. It is established that in this area there is a favorable pattern of a stable circulation flow in the absence of spontaneous violation of the symmetry of the flow. It is also shown that in the zone of reverse currents behind the flame stabilizer, the required nature of the methane concentration field necessary for the process of stable combustion is realized.

2. The regularities of influence on the aerodynamics and mixture formation of fuel and oxidizer in burners of the considered type of factors such as the number of the rows of jet fuel supply, the relative pitch of the location of gas supply holes, and the coefficient of excess air are revealed. It is shown that the characteristics of flow and mixture formation differ markedly when fuel is supplied to the first, second, or third row of fuel supply holes. In particular, it was found that with an increase in the row number, that is, when distancing the fuel supply from the stall edge of the flame stabilizer, the length of the reverse current zone L_z behind it and the average methane concentration $\overline{C}_m$ in this zone decrease. Based on the results of CFD modeling, it was revealed that when the relative pitch of the location of the gas supply holes S/d varies from 4.0 to 5.6, both the flow structure and the pattern of mixture formation of fuel and oxidizer undergo significant changes. It is also shown that the nature of the influence of the coefficient of excess air in the range of its change from 1.1 to 1.5 is qualitatively the same when supplying fuel gas to different rows of gas supply holes. Although there are noticeable quantitative differences.

3. Rational design parameters of the fuel supply system of the burner devices under consideration have been determined. For each of the three fuel supply sections, the relative pitch of the gas supply holes S/d are established, at which favorable conditions for mixture formation in the aft region of the flame stabilizer are ensured. It is shown that the rational values of S/d are 5.4; 5.6; and 5.8 for the first, second; and third fuel sections with an excess air coefficient of 1.1; 1.3; and 1.5, respectively.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The manuscript has no related data.

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