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6.1 CFD modeling of microjet combustion processes with asymmetric fuel supply

The development needs of fuel combustion technologies necessitate in-depth studies of combustion processes in power devices. Among the different methods of organizing fuel combustion in these devices, microjet combustion is distinguished, which is achieved by crushing the flame into separate microfoci. Such combustion can be implemented, in particular, by forming a torch behind a system of flame stabilizers [353-365]. Corresponding microjet burners are characterized by a number of advantages, such as a high degree of homogenization of the combustion zone, improved stabilization properties, low toxicity of combustion products, etc.

Microjet combustion of fuel in a flame stabilizer system as an object of physical research is a complex of intricate processes (flows, mixture formation of fuel and oxidizer, fuel burnout, formation of temperature regimes of the combustion zone, etc.). However, at present, there is no necessary complexity and completeness of studies of various aspects of this combustion method. This primarily applies to studies related to new modifications of devices that implement this combustion [355, 357-361, 363-365]. Thus, one of the promising modifications of such devices used in operation under conditions of relatively high excess air ratios are stabilizer-type devices with asymmetric fuel supply (see, for example, [360, 361, 365]).

According to current trends, the analysis of the possibility of providing improved energy-ecological characteristics of these devices is one of the important areas of research on the processes of microjet combustion of fuel in new burner devices.

In recent decades, computer simulation has become an increasingly important tool for studying combustion processes and designing burners for various purposes. This is mainly due to the use of more and more advanced models that take into account a large number of complicating factors [362-365].

In this paper, using computer simulation, we study the processes of microjet combustion in a burner with an asymmetric fuel supply. On this basis, the conditions for the rational organization of work processes in stabilizer type burners are analyzed, which ensures their high energy and environmental efficiency. The scheme of the module of the considered burner device is shown in fig. 1.

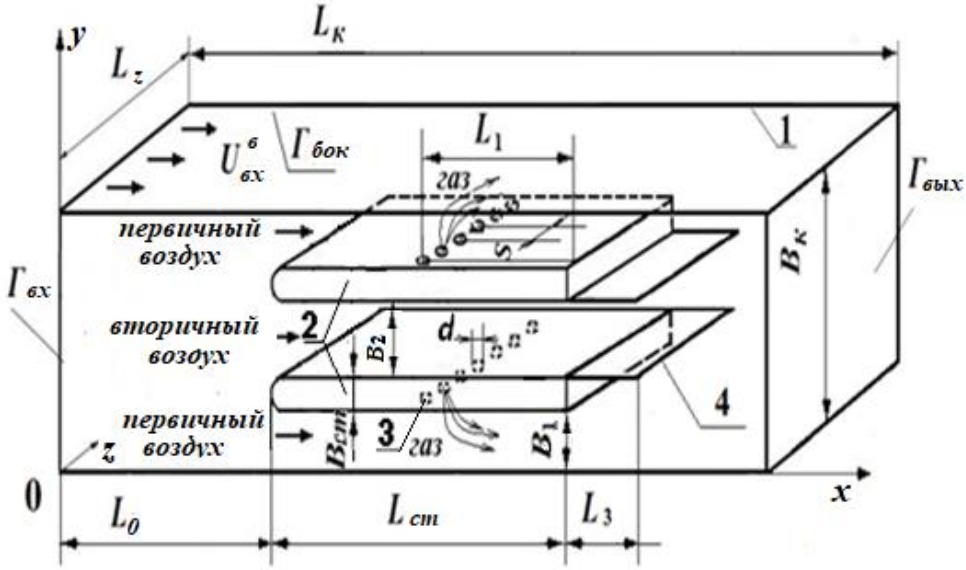


Fig. 1. Scheme of the stabilizer-type microjet burner module with asymmetric fuel supply: 1 – flat channel; 2 - flame stabilizers; 3 - gas supply hole; 4 - flap

As can be seen, the module of this device consists of two flat flame stabilizers 2 located in channel 1 at some distance from each other. The jet supply of fuel in each of the stabilizers is carried out through a system of round holes 3 located on one of its side surfaces. Flame stabilizers are equipped with flat flaps 4 mounted on their end surfaces. The main functions of these flaps are as follows. Firstly, in facilitating the formation of stable zones of reverse currents in the aft regions of the stabilizers, which are responsible for stabilizing the flame. Secondly, in the implementation of two-stage combustion, the first stage of which is carried out in the area corresponding to the location of the flap. Such a two-stage combustion scheme is designed to increase the temperature levels at the first stage of combustion and, as a result, reduce the chemical underburning of the fuel.

Computer simulation of combustion processes was carried out for three different consumption ratios of primary and secondary air. These ratios correspond to the following widths of the near-wall $2B_1$ and interstabilizer B_2 channels: $\beta = 2B_1/B_2$ = 34,0/11,0 ≈ 3,1; 27,0/18,0 = 1,5; 20/25 = 0,8. The flap length was set equal to 0.06 m, and the distance L_1 from the gas supply holes to the blunt rear edge of the flame stabilizer was 0.02 m. The studies were performed for different values of the excess air coefficient $2.0 \le \alpha \le 4.0$. In the course of computer simulation, the variation of α was provided by changing the flow rate of natural gas at a fixed air flow rate.

Figure 2 illustrates the results of computer simulation to determine the coefficient of fuel burnup completeness η_z for α = 3.0 at different values of the ratio β. (Here and below, x^* is the longitudinal coordinate measured from the flame stabilizer end downstream).

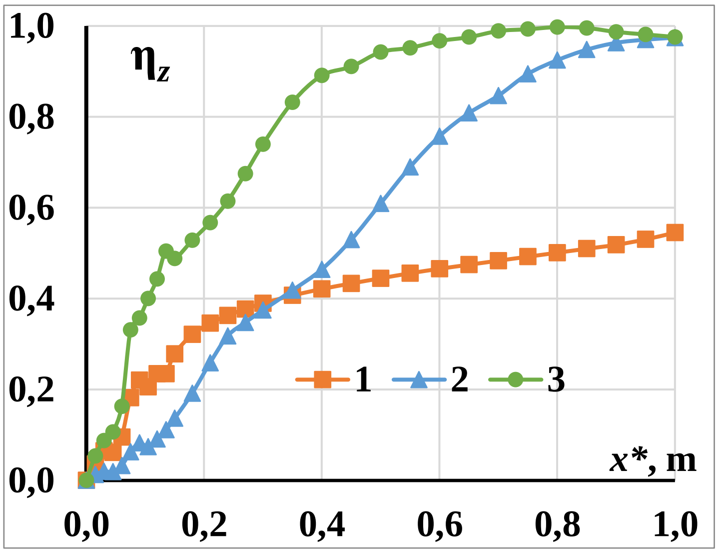


Fig. 2. Change in the coefficient of fuel burnup completeness along the length of the channel at α = 3.0 for different values of the ratio β: 1 – β = 3,1; 2 - 1,5; 3 – 0,8.

In Table 1 for conditions corresponding to Fig. 2, the composition of gases in the combustion products, the coefficient η_z and the coefficient of non-uniformity of the temperature field γ in the outlet section of the channel are shown ($\gamma = \frac{T_{max} - \bar{T}}{\bar{T} - T_{in}}$, T_{max}, $\bar{T}$ – are the maximum and average mass temperatures in a this cross section of the channel x^* = const; T_{in} is the air temperature at the inlet to the channel).

Table 1. The composition of gases in the combustion products and the values of the coefficient of fuel burnup completeness and the coefficient of relative non-uniformity of the temperature field at the outlet of the channel at α = 3.0 for different values of β

The results obtained indicate that in the studied range of variation of the ratio β, the flow structure, the temperature regime of the combustion zone, and the

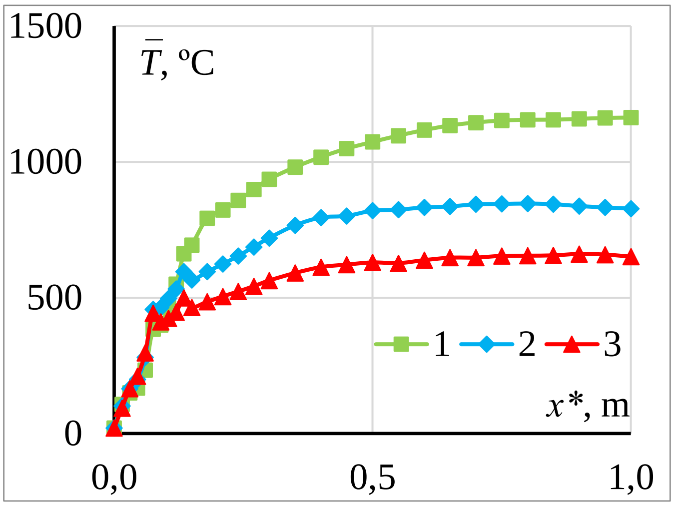
β	Indicators				
	Carbon monoxide CO, % vol.	Hydrogen H_2, % vol.	Nitrogen oxides NO_x, mg/m^3	γ	η_z
3,1	0,379	0,326	51,2	1,74	0,545
1,5	0,032	0,009	95	0,18	0,974
0,8	0,005	0,002	77,9	0,29	0,995

characteristics of fuel burnup differ significantly with varying the value of this ratio. So, according to the data shown in Fig. 2, combustion of fuel gas at β = 3.1 is characterized by significant chemical underburning. Namely, at the exit from the channel, the completeness factor of fuel burnup η_z is only 0.545. At β = 1.5, the coefficient η_z increases to a value of 0.974. The highest intensity of fuel burn-up takes place at a ratio of β equal to 0.8.

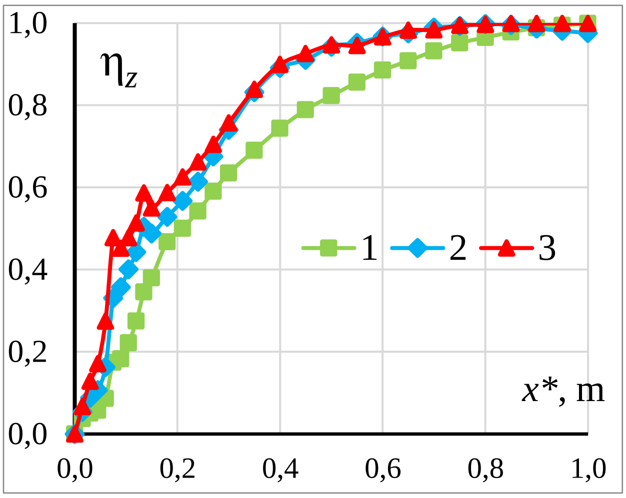
According to the data presented in table. 1, at β = 0.8, the concentration of nitrogen oxides at the outlet of the channel is relatively small and amounts to 77.9 mg/m^3. Thus, for the value of the excess air coefficient α = 3.0, the ratio of primary and secondary air flow rates, at which high fuel combustion efficiency and low NO_x emission values are realized, corresponds to the value β = 0.8. As can be seen from Table. 1, at β = 1.5 there are also relatively low values of NO_x and relatively high values of η_z at the channel outlet. However, the growth rate η_z along the channel length for β = 0.8 in a significant initial section is significantly higher.

The results of the performed studies on the selection for different values of α of the ratios of primary and secondary air consumption, corresponding to a high rate of fuel burnup and low emissions of toxic substances, showed the following. Under the conditions under consideration, these ratios are the same for all values of α in the range (2.0 ≤ α ≤ 4.0) and correspond to the value of β equal to 0.8. As can be seen from Table. 2 and fig. 3,*b* for a this value of β at α = 2.0; 3.0 and 4.0, the factor of fuel burnup completeness η_z at the outlet of the channel approaches unity. At the same time, the concentration of nitrogen oxides does not exceed 112.4 mg/m^3.

On Figure 3 shows the change temperature and the fuel burnup efficiency η_z along the length of the channel at different values of α for the β = 0.8, which corresponds to high fuel combustion efficiency and low NO_x emission values.



a)



b)

Fig. 3. Distribution along the length of the channel of the average mass temperature and the coefficient of fuel burn-up completeness η_z at β = 0.8 for various values of the excess air coefficient α: 1 – α = 2.0; 2 – α = 3.0; 3 – α = 4.0; *a*) temperature $\bar{T}$; *b*) coefficient η_z.

According to the research data, at β = 0.8 and different values of α, the characteristics of the combustion process can differ markedly. Thus, for different values of α, there are significant divergences in the values of average mass temperatures (Fig. 3, *a*). At the outlet of the channel, the temperature is 651.2 ºC; 828.0 ºC; and 1163 ºC, respectively, for α = 4.0; 3.0 and 2.0.

Figure 4 illustrates the corresponding temperature fields in the channel cross section. In table. 2 for the parameters corresponding to Fig. 3 - 5, data are presented on a number of energy-ecological characteristics of combustion in the outlet section of the channel.

The performed studies also showed that, under the above conditions, there are noticeable differences in the nature of the temperature fields of the combustion zone. As follows from the data presented in Fig. 4, at α = 2.0, there is a significant shift of the high-temperature zone to the near-wall region of the channel. This is primarily due to the greater range of gas jets at this value of α. For α = 3.0 and 4.0, there is no such obvious asymmetry in the location of the high-temperature zone relative to the axis of the flame stabilizer.

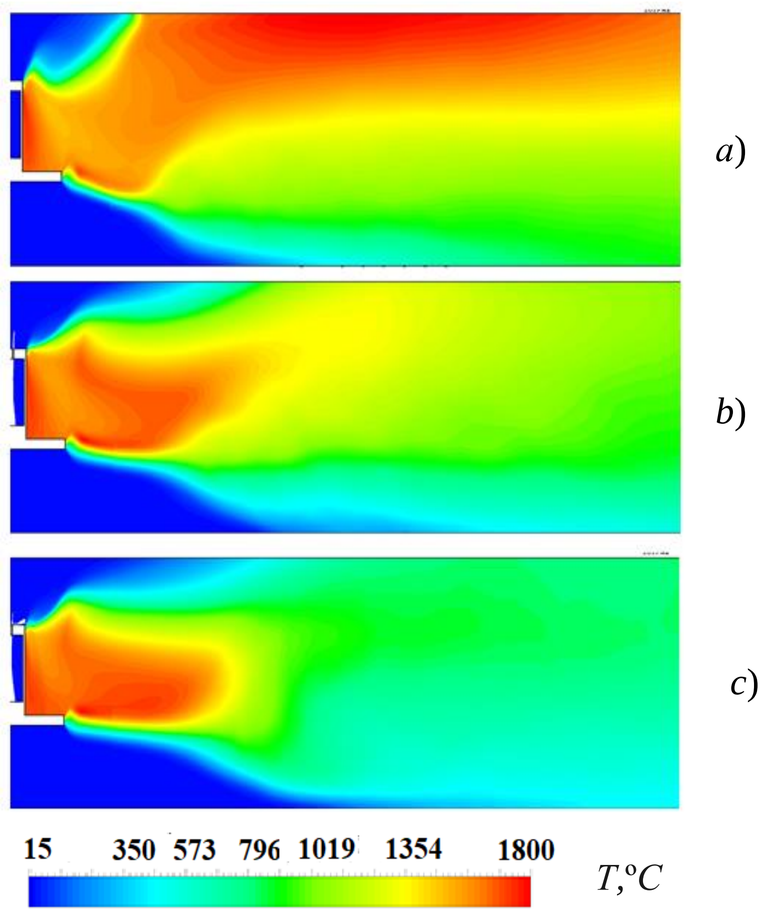


Fig. 4. Temperature field in the longitudinal section passing through the axis of the gas supply holes, at β = 0.8 for different values of the air excess coefficient α: *a*) α = 2,0; *b*) α = 3,0; *c*) α = 4,0.

Table 2. The composition of gases in combustion products and the values of the coefficient of fuel burnup completeness and the coefficient of relative non-uniformity of the temperature field at the outlet of the channel at β = 0.8 for various values of the excess air coefficient α

Excess air coefficient, α	Indicators				
	Carbon monoxide CO, % vol.	Hydrogen H_2, % vol.	Nitrogen oxides NO_x, mg/m^3	γ	η_z
2,0	0,125	0,067	112,4	0,42	0,999
3,0	0,005	0,002	77,90	0,29	0,995
4,0	0,015	0,002	70,78	0,27	0,999

The place of secondary air supply was regulated by changing the length of the flap L_f installed on the end surface of the flame stabilizer. When conducting research, the flap length varied within $0.045 \le L_f \le 0.09$ m. The upper limit of this range was determined from considerations of the structural strength of the burner.

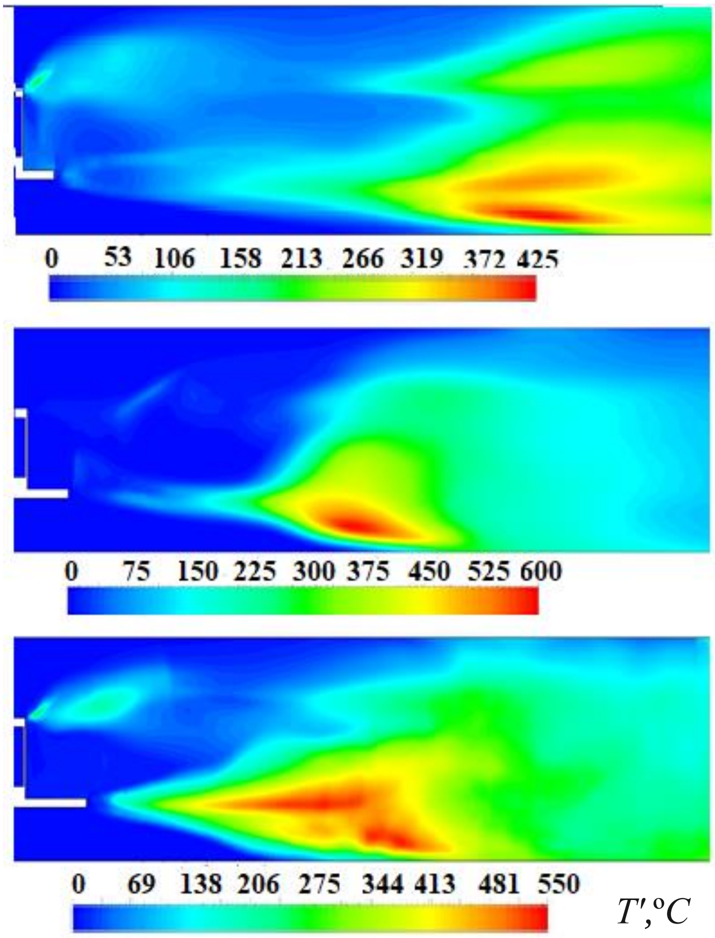
In Table. 3 and in fig. 5., as an example, are the results of studies that correspond to α = 3.0 and β = 1.5.

Table 3. Composition of gases in combustion products and values of fuel burnup completeness coefficient and coefficient of relative non-uniformity of the temperature field at β = 1.5 and α = 3.0 for different values of L_f.

Length of the flap L_f, 10^{-3} m	Indicators				
	Carbon monoxide CO, % vol.	Hydrogen H_2, % vol.	Nitrogen oxides NO_x, mg/m^3	γ	η_z
45	0,215	0,147	70,1	0,39	0,896
60	0,032	0,009	95	0,18	0,974
90	0,069	0,047	79,6	0,16	0,983

Figure 5 illustrates the fields of temperature fluctuations in the longitudinal section passing through the axis of the gas supply holes for different values of the flap length L_f.

According to the results of the studies performed, it was found that the length of the flap L_f, which determines the place of supply of secondary air to the flame, has a significant influence on the characteristics of the flow, the temperature regime of the combustion zone, the composition of combustion products, etc. in the astern areas of the flame stabilizers. Namely, with an increase in L_f from 0.045 m to 0.06 m, there is a noticeable increase in the length of the zone of reverse currents in this area - from 0.024 m to 0.059 m. A further increase in the length of the flap L_f to 0.09 m, on the contrary, leads to a significant reduction of the length of this zone - up to 0.023 m.



a)

b)

c)

Fig. 5. Fields of temperature fluctuations *T'* in the longitudinal section passing through the axis of the gas supply holes, at β = 1.5 and α = 3.0 for different values of the flap length, L_f : *a*) L_3 = 0,045м; *b*) L_f = 0,06 м; *c*) L_f = 0,09 м.

A number of characteristics of the heat state of the combustion zone also turn out to be qualitatively different for distinct values of L_f. As can be seen from fig. 5, for the L_f values under consideration, the patterns of the fields of root-mean-square temperature fluctuations differ significantly. With an increase in L_f, the zones of increased values of temperature fluctuations approach the end surface of the flame stabilizer, which corresponds to an earlier homogenization of the combustion zone along the flow.

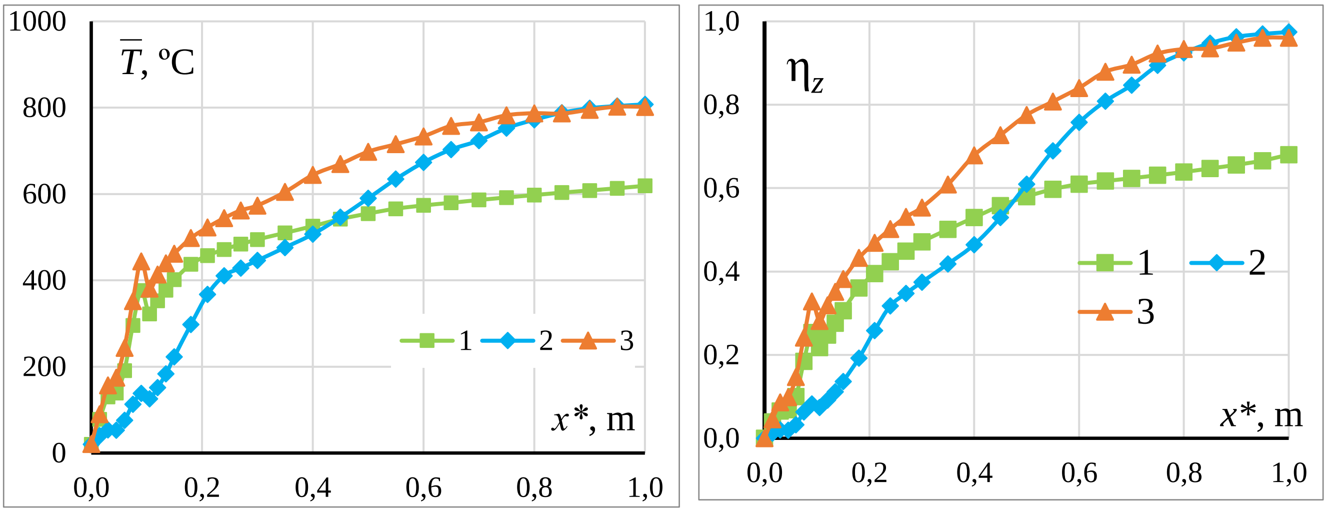
As for the process of fuel burnout, as can be seen from Table. 3, the coefficient η_z increases with the length of the flap L_f. Moreover, an increase in L_f from 0.045 m to 0.06 m leads to a noticeable increase in η_z at the channel outlet, from 0.896 to 0.947. As for the further increase in L_f from 0.06 m to 0.09 m, here the increase in η_z is insignificant - from 0.947 to 0.983. At the same time, for all considered values of L_f, NO_x emission does not exceed the limits of modern strict standards.

Thus, on the basis of the performed studies, it can be concluded that the coordinate of the place where secondary air is fed into the flame, which is controlled by the length of the flap L_f, must exceed a certain value. For the conditions under consideration, this value is 0.06 m.

Let us further consider the results of studies concerning the influence on the characteristics on the combustion characteristics of distance L_1 from the gas supply holes to the blunt rear edge of the flame stabilizer. In the framework of the studies performed, the value of distance L_1 varied from 0.01 to 0.03 m.

As an example, below are data for a situation that meets the following parameters: $\beta = 1.5$; $L_f = 0.06$ m; $\alpha = 3.0$.

In Figures 6, 7 and in Table 4 shows the characteristic results of the performed studies for the values $L_1 = 0.01$; 0.02 and 0.03 m.



a) *b*)

Fig. 6. Distribution along the length of the channel of the mass-average temperature and the coefficient of fuel burn-up completeness η_z at β = 1.5; L_f = 0,06 m and α = 3.0 for different values of distance L_1:1 – L_1 = 0,01 m; 2 – L_1 = 0,02 m; 3 – L_1 = 0,03 m; a) temperature $\overline{T}$: *b*) coefficient η_z.

Figure 6 illustrates the change along the length of the channel of the mass-average temperature $\overline{T}$ and the coefficient of fuel burn-up completeness η_z. On fig. 7 shows the velocity fields in a longitudinal section passing through the axes of the gas supply holes.

According to the data obtained, when the value of L_1 varies, the flow structure, the heat state of the combustion zone, the level of emission of nitrogen oxides, etc., undergo significant changes. As can be seen from the simulation results shown in Figs. 7, there is a noticeable difference in the velocity fields corresponding to different values of L_1. Significantly different in size are the zones with reduced values of velocity in the astern regions of the flame stabilizers. In high velocities zones located at some distance from the stabilizer, the speed levels are ranked as follows. The lowest velocities correspond to L_1= 0.01 m, the higher velocities correspond to L_1= 0.02 m, and the highest velocities correspond to L_1= 0.03 m.

Table 4. The composition of gases in the combustion products and the values of the coefficient of fuel burnup completeness and the coefficient of relative non-uniformity of the temperature field at the outlet of the channel at β = 1.5; L_f = 0,06 m and α = 3,0 for different value of L_1 .

Fuel distribution system parameter L_1, m	Indicators				
	Carbon monoxide CO, % vol.	Hydrogen H_2, % vol.	Nitrogen oxides NO_x, mg/m^3	γ	η_z
0,01	0,616	0,495	52,6	0,74	0,68
0,02	0,032	0,009	95	0,18	0,974
0,03	0,12	0,052	74,8	0,12	0,965

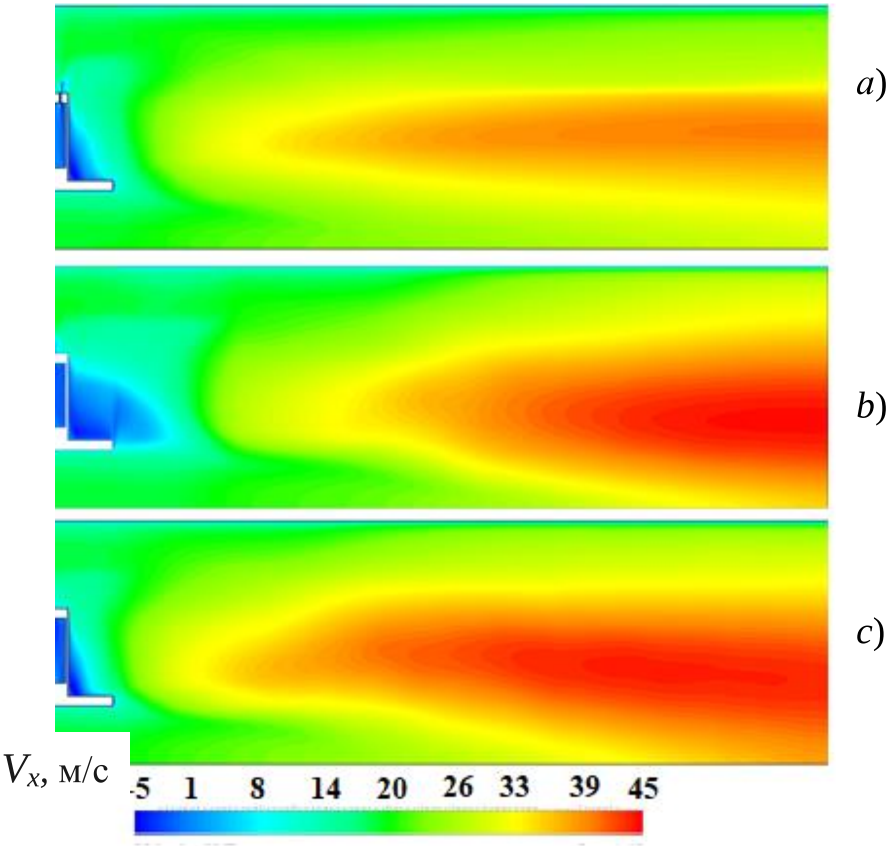


Fig. 7. Velocity fields in the longitudinal section passing through the axis of the gas supply holes, at β = 1.5; L_3 = 0,06 m and α = 3,0 or different values of the distance L_1 between the gas supply holes and the flame stabilizer stall edge: *a*) L_1 =0,01 m; *b*) L_1 =0,02 m; *c*) L_1 = 0,03 m.

As evidenced by the obtained data, there is also a noticeable difference in the patterns of change of the average mass temperature along the length of the channel at different values of L_1. At the same time, the fact of a pronounced correlation between the nature of the change in the average mass temperature and the coefficient of fuel burnup completeness η_z for different values of the distance L_1 attracts attention (compare the data in Fig. 6, *a* and Fig. 6, *b*).

It is also important to note that at L_1 = 0.01 m, the required level of completeness of fuel burnup is not observed. (The value of η_z at the channel exit is only 0.68). Increasing L_1 to 0.02 m and 0.03 m makes it possible to achieve the result of high values of η_z, which are 0.974 and 0.965, respectively (Table 4). At the same time, for two L_1 appointments, the levels of NO_x content appear very low (95.0 and 74.8 mg/m^3, respectively).

Thus, in order to achieve high energy-ecological efficiency of the burner devices, the geometric parameter of the fuel distribution system L_1 should be 0.02…0.03 m in the investigated range of change in the excess air coefficient α.