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Processes of heat and mass transfer in furnace chambers with combustion of thermochemically activated fuel*

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The paper presents the results of numerical studies of the influence of thermochemical activation of pulverized coal flows on the processes of heat and mass transfer occurring in the areas of real geometry (furnaces) with burning power fuel. The aerodynamic flow pattern, velocity, temperature, and concentration fields were obtained, the analysis of which allows the conclusion that plasma activation of fuel increases the efficiency of its combustion and reduces emissions of harmful substances into the atmosphere.

Keywords: numerical modeling; heat and mass transfer; velocity, temperature and concentration fields; plasma-fuel systems; thermochemical activation.

At present, there is an increased interest in studying the processes of heat and mass transfer in high-temperature media with combustion. Such processes are widespread. They occur under conditions of considerably non-isothermal and turbulent flows, multiphase medium, significant influence of nonlinear effects of thermal radiation, interfacial interaction, and multi-stage chemical reactions.

In connection with the adopted concept of “energy security of Kazakhstan” and development of “clean” technologies of fuel combustion, the study of heat and mass transfer processes occurring in the furnaces of thermal power plants (TPPs) on pulverized coal, which form

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the basis of the energy sector of the Republic of Kazakhstan, is of particular relevance. Expensive experiments carried out on available firing models do not allow strict fulfillment of all conditions that correspond to the real process of fuel combustion. The methods of numerical simulation and computational experiments provide the opportunity to achieve geometric and physical similarity of the studied objects, compliance with all the basic parameters and operating conditions, which are adequate to the technological scheme of combustion adopted at a real energy facility.

At the present stage of development of the energy sector of the Republic of Kazakhstan, the question of increasing the efficiency of processes associated with energy production arises in terms of minimizing dust and gas emissions and economical use of equipment and fuel. Recently, in our country and abroad, there is reorientation in the use of energy resources, which should lead to a significant reduction in oil and natural gas consumption in the energy sector and to energotechnological use of liquid fuels. In this regard, it is necessary to optimize the processes of combustion of traditional energy fuels (such as high-ash Kazakhstan coal), develop and implement «clean» technologies for energy production in order to protect the environment from harmful dust and gas emissions and ensure the efficiency of power plants.

An effective solution to the above problem is the use of technology of plasma gasification of low-grade solid fuels [1]. A distinctive feature of the plasma-chemical processing of organic raw materials is their high selectivity: obtaining the target products (synthesis gas, hydrogen), which is accompanied by only a slight formation of by-products and impurities. The technology of using plasma-fuel systems (PFS) consists in heating the aerosol with the help of a plasma torch to the temperature of devolatization and partial gasification of carbon coke residue. As a result, regardless of the quality of feed coal, highly reactive two-component fuel (combustible gas and coke residue) is obtained from the aerosol mixture, and further it is mixed with secondary air in the boiler furnace. At that, it ignites intensely and burns stably without the use of additional fuel oil or natural gas, traditionally burned to kindle the boilers from a cold state and stabilize the burning of a torch of low-grade power-generating coal.

This paper presents the results of applying the modern technology for plasma ignition and stabilization of pulverized coal at Kazakhstan thermal power plants using three-dimensional modeling, which allows optimization of the processes accompanying combustion of Kazakhstan high-ash power-generating fuel and reduction of harmful dust and gas emissions into the atmosphere (carbon oxides, nitrogen oxides, etc.) and creates a way to get «clean» energy.

The pulverized coal fuel is thermochemically prepared for combustion by installing plasmatorch [2–5] on the lined air mixture channel of the burner, which is thereby converted into a PFS (Fig. 1). To carry out numerical experiments, we selected the furnaces of boilers at the functioning Kazakhstan TPPs: BKZ-420 of Almaty TPP-2 and BKZ-160 of Almaty TPP-3. These boilers differ from each other in power, furnace geometry, its size, method of fuel and oxidizer supply, layout of the burners and type of PFS [6–12]. The BKZ-420 boiler with a steam capacity of 420 t/h on the frontal wall of the furnace is equipped with six vortex dust-coal burners located in two levels with three burners per tier (Fig. 2). The extreme burners in the tier are turned to the center of the furnace by 8 degrees. The consumption of Ekibastuz coal per one burner is 12 t/h. To carry out thermochemical activation of fuel, three PFSs were installed instead of two burners of the first tier and one burner of the second tier. The BKZ-160 boiler with a steam capacity of 160 t/h is equipped with burners with tangential fuel supply.

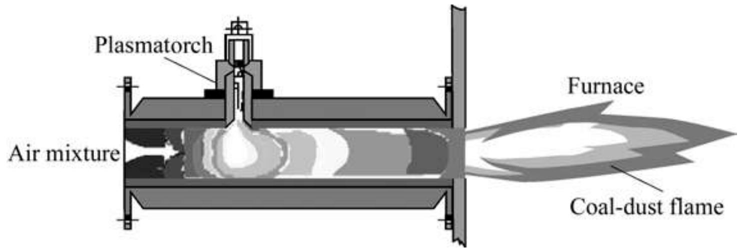

Fig. 1. Plasmatorch and scheme of its installation on the straight-flow burner.

On the sides of the furnace, there are four blocks of straight-flow slit burners directed tangentially to a circle with a diameter of 0.78 m (Fig. 3). Each burner has one air mixture channel and two secondary air channels located above and below the air mixture channel and separated by the lined walls.

The initial data for performing numerical experiments on fuel combustion in the furnaces of BKZ-420 at Almaty TPP-2 and BKZ-160 at Almaty TPP-3, as well as all required parameters of furnaces and coal dust (before and after plasma treatment) are presented in Tables 1–3.

The results of three-dimensional modeling of the effect of thermochemical activation of coal-dust flows on the process of combustion of a pulverized coal torch in the furnaces of BKZ-420 and BKZ-160 boilers were obtained using the control volume method applied to solve numerically the differential equations describing heat and mass transfer in a furnace and presented in detail in [13–27]. The control volume method is based on dividing the furnace of the examined boiler into small volumes, used for integration of the differential equations of the mathematical model. The number of control volumes depends on the furnace geometry, its size, location of the burner, and plasma devices.

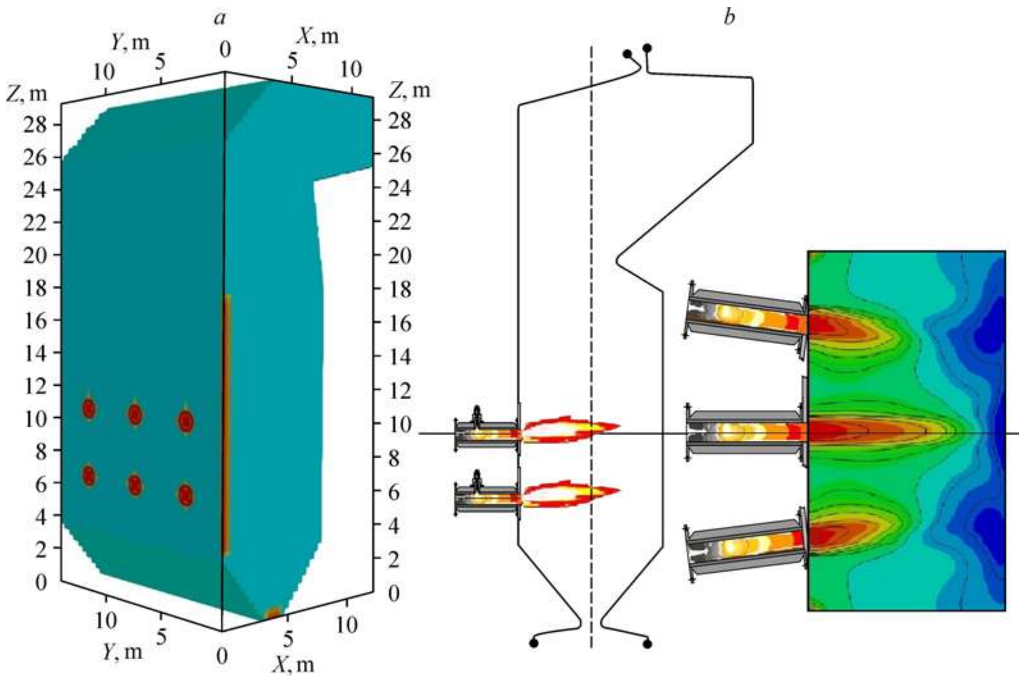

Fig. 2. Geometry (*a*) and burner arrangement (*b*) of the BKZ-420 boiler at Almaty TPP-2.

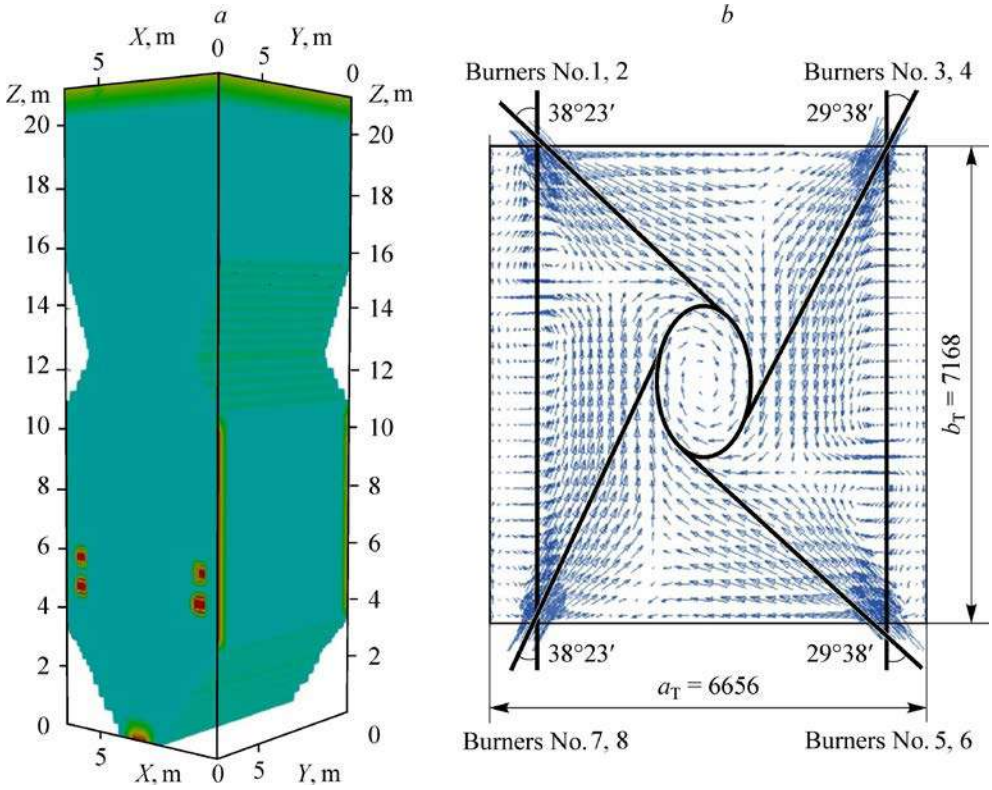

Fig. 3. Geometry (*a*) and burner arrangement (*b*) of the BKZ-1600 boiler at Almaty TPP-3.

Table 1

Initial data for modeling the combustion chamber of BKZ-420 at Almaty TPP-2

Characteristics	Nomenclature	Measurement units	Value
Steam capacity	D	t/h	280–450
Boiler heat productivity	Q_b	Gcal/h	160–255
Fuel consumption per boiler	B_c	t/h	48–72
Number of burners on the boiler (dual flow)	n_b	pcs	6
Fuel consumption per one flow of burner	B_b	t/h	4–6
Diameter of dust pipe to burner	$\varnothing_{dp}$	m	0.53
Air mixture temperature	t_a	°C	90–130
Hot air temperature	T_{ha}	°C	280–340

Table 2

Initial data for modeling the combustion chamber of BKZ-160 at Almaty TPP-3

Characteristics	Nomenclature	Measurement units	Value
Fuel consumption per boiler	B_c	t/h	30.296
Fuel consumption per burner	B_b	t/h	3.787
Air mixture temperature	t_a	°C	250
Number of burners	N_b	pcs	8
Number of tiers	N	pcs	2

Table 3

Initial characteristics of Ekibastuz coal before and after plasma treatment

Composition of initial coal dust, mas. %		Composition of products of plasma activation of coal-dust flow				
		Gas phase composition	vol. %	Kg/h	Gas phase composition, mas. %	
W^{P*}	7.0	H_2O	1.84	232.9	A^{C*}	85.78
A^P	40.9	CO_2	13.9	4295	C^C	14.22
S^P	0.8	CO	10.63	2097		
C^P	41.1	CH_4	0.22	24.83		
H^P	2.8	C_6H_6	0.43	235.5		
O^P	6.6	H_2	2.01	28.39		
N^P	0.8	N_2	70.86	13980		
Air mixture temperature, K	423	O_2	0.15	33.44		
		Gas temperature, K	1074			
Flow velocity, m/s	15.0	Particle temperature, K	1077			
		Flow velocity, m/s	41.9			

* The indices P and C mean that the composition of initial gas dust is calculated per the working and dry masses, respectively.

A general view of the furnaces of BKZ-420 and BKZ-160 boilers equipped with PFS and their division into control volumes are presented in Fig. 4. The calculation area depends on the furnace size and for BKZ-420 this area includes 261008 control volumes (72x139x126), and for BKZ-160, it includes 177472 control volumes (59×32×94). For the BKZ-420 boiler (Fig. 4*a*), three regimes of furnace operation were investigated: the first regime is traditional combustion, when the furnace operates with standard coal-dust burners; in the second regime, three plasmatorches are installed and they act on the flow of pulverized coal in three burners: in two extreme burners of the lower tier and in the central burner of the upper tier; in the third regime, the plasmatorches are installed in all six burners of two tiers (Fig. 5). As applied to the furnace chamber of the BKZ-160 boiler (Fig. 4*b*), two cases were investigated: traditional combustion of pulverized coal and combustion of coal with PFSs installed in two opposite

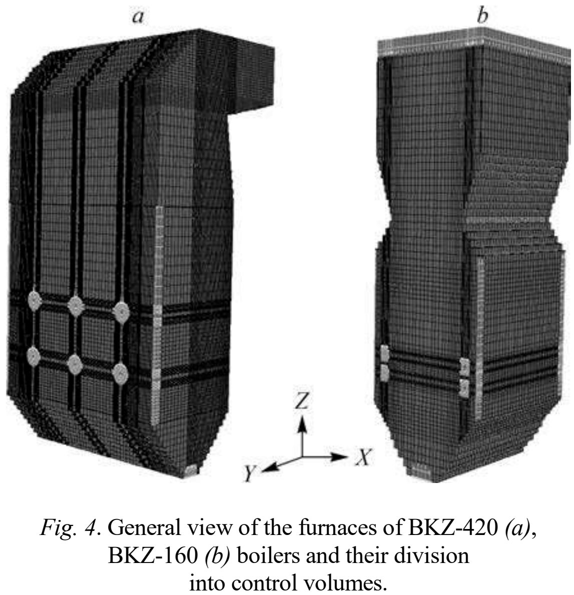

Fig. 4. General view of the furnaces of BKZ-420 *(a)*, BKZ-160 *(b)* boilers and their division into control volumes.

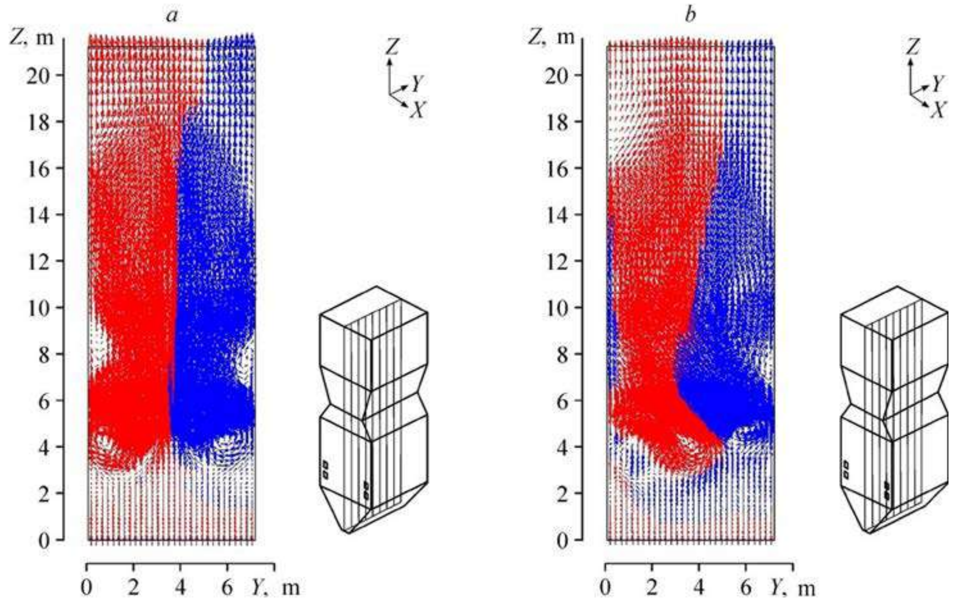

Fig. 5. The field of full velocity vector in longitudinal cross section $I = 33$ ($X = 3.16$ m) of the furnace chamber of BKZ-160 boiler at Almaty TPP-3.

a — traditional combustion of fuel, *b* — 2 plasma-fuel systems.

burners of the lower tier. As a result of numerical experiments, we obtained aerodynamic flow pattern (distribution of the full velocity vector), temperature and concentration fields of carbon CO and nitrogen NO oxides over the entire volume of the furnace chambers of BKZ-420 and BKZ-160 boilers.

According to analysis of Figs. 5–7, where the field of the full velocity vector is presented for each boiler, activation of the coal-dust flow has a significant effect on the flow field: propagation of the reactive jet in the furnace, mixing processes in the jet, and size and shape of the torch. In the volume of BKZ-420 boiler furnace, two-component flows high-reactive fuel

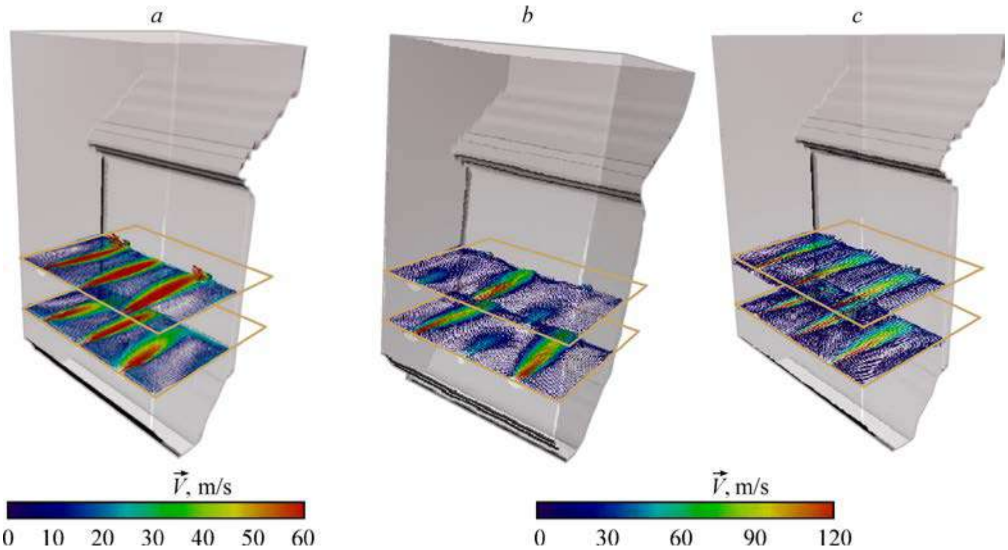

Fig. 6. Field of full velocity vector in the zone of the burners of the furnace chamber of BKZ-420 boiler at Almaty TPP-2.

a — traditional combustion, *b* — 2 plasma-fuel systems, *c* — 6 plasma-fuel systems.

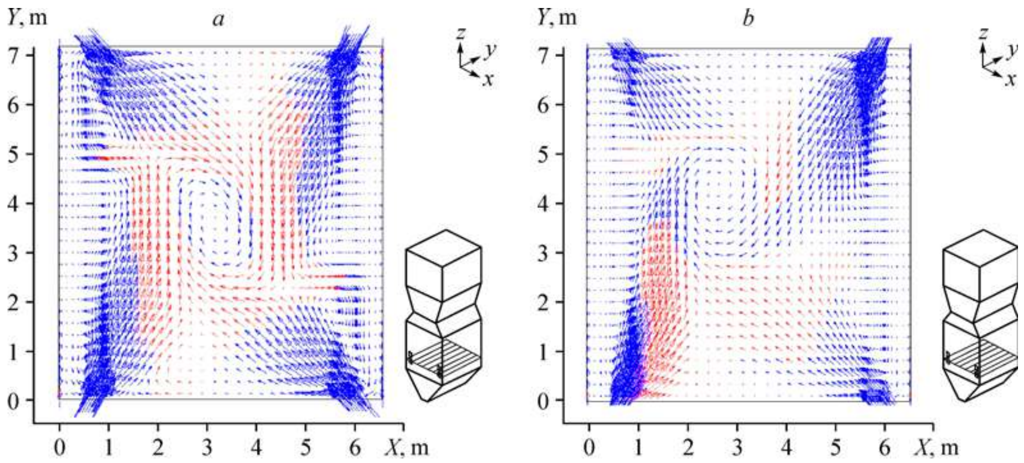

Fig. 7. Distribution of the full velocity vector in the zone of the burners of the furnace chamber of BKZ-160 boiler (cross section $K = 32$ ($Z = 4.81$ m)) at Almaty TPP.
a — traditional combustion of fuel, *b* — 2 plasma-fuel systems.

obtained with the use of plasma activation (Figs. 6*b*, 6*c*) propagate in accordance with aerodynamic laws and they are the thermal sources for the air mixture fed through the burners without systems of plasma ignition. Thus, for the same coal dust in the furnace volume, there are two types of fuel: traditional air mixture and air mixture, thermochemically prepared for intensive combustion. With an increase in the number of plasma burners for the BKZ-420 boiler, a sharper boundary of movement of thermochemically activated flows from burners, equipped with plasmatorches, is observed (Figs. 6*b*, 6*c*). Under the action of plasma activation of coal-dust fuel, turbulization of flows increases and mass and heat transfer accelerates significantly, and mixture formation and heating, intensified during this process, intensify the combustion process.

The field of the full velocity vector in the longitudinal section of the furnace chamber of the BKZ-160 boiler is presented in Fig. 5, and this field in the area of the burners is shown in Fig. 7. Traditionally, the flows of pulverized coal, secondary and tertiary air entering the furnace space create a swirling volumetric flow at the center of the chamber, which undoubtedly improves the process of mixture formation and increases the intensity of heat and mass transfer. This, in turn, leads to an increase in the time of coal particle stay in the furnace chamber and a decrease in chemical and mechanical underburning due to their more complete burnout. The counter dust and gas flows from the opposite burners, hitting the walls of the furnace chamber, create a return flow, and some part of the flow goes down to the funnel, forming two symmetric vortices below the burners (Fig. 5*a*). The indicated character of the flow leads to the fact that the most intense combustion occurs in the central zone of the furnace, in the region of the burner location. Just here all thermophysical and concentration characteristics of the process occurring in the furnace chamber reach their extreme values, as indicated by the analysis of the temperature and concentration fields presented below.

When using plasma-fuel systems (Figs. 5*b* and 7*b*) in two opposite burners of the lower tier of the furnace chamber of the BKZ-160 boiler, an increase in the flow rate of air mixture and thermochemically gasified fuel in the entire volume of the furnace is observed. This leads to significant turbulization of the flow (especially in the central part of the furnace), which causes mixing and ignition of the flows coming from conventional burners. Analysis of these figures allows the conclusion that due to an increase in velocity along the PFS, the length

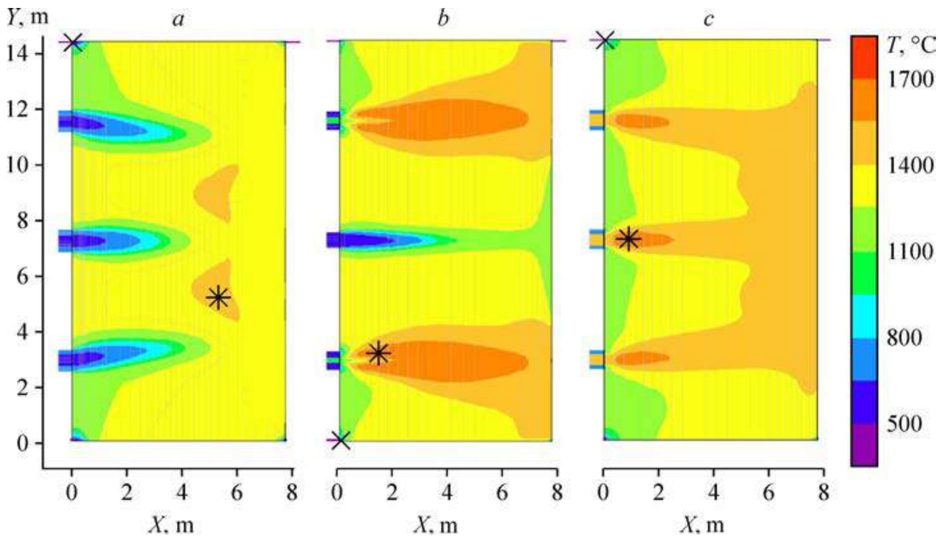

Fig. 8. The temperature field in the plane of cross section $K = 32$ ($Z = 4.81$ m) for the burners of the lower tier of the furnace of BKZ-420 boiler at TPP-2.

a — traditional combustion, *b* — 3 plasma-fuel systems, *c* — 6 plasma-fuel systems.

of the torch increases markedly and the main vortex flow caused by the tangential supply of the air mixture, secondary and tertiary air, is displaced, which undoubtedly affects the shape of the torch core (further see Fig. 9*b*). Thus, analysis of Figs. 5 and 7 indicates a significant difference in velocity distributions for two studied situations (traditional fuel combustion (without PFS) and combustion with two PFSs); further this affected the temperature and concentration fields.

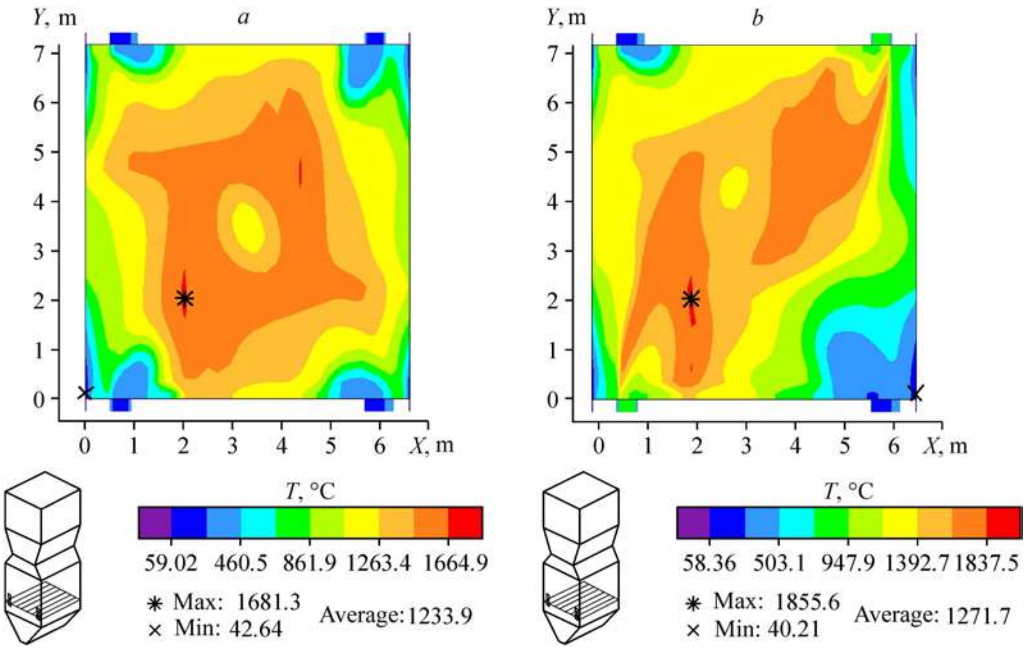

Fig. 9. Distribution of temperature in the region of burner location in the lower tier of the furnace of BKZ-160 boiler (cross section $K = 32$ ($Z = 4.81$ m) at Almaty TPP-3.

a — traditional combustion, *b* — 2 plasma-fuel systems.

Figures 8 and 9 illustrate the temperature fields in the region of location of the burners in the lower tier of BKZ-420 and BKZ-160 boilers. It can be noted that in comparison with the use of a conventional coal-dust flow, the average temperature in this area increases with the number of thermochemically activated flows and amounts to 1530°C for a BKZ-420 boiler without activation; with three activated flows, it is 1640°C; and with six activated flows, it is 1680°C. For the BKZ-160 boiler in the area of burner location, the average temperature for traditional combustion is 1234°C, and with two thermochemically activated flows, it is 1272°C. Thus, we can conclude that plasma activation leads to rapid heating and ignition of the air mixture and to a shift of the combustion front to the location of systems for plasma activation of coal flows. The region of high temperatures with an increase in the number of plasma-activated flows shifts towards the center of symmetry of the furnace, while the higher temperature level is also observed near the side surfaces. In addition, acceleration of heating and ignition of the fuel with an increase in the number of thermochemically activated flows leads to a more rapid stabilization of intense combustion processes.

A comparative analysis of distribution of the average temperature in the cross section along the height of combustion chamber is presented in Fig. 10 for two studied regimes: with supply of conventional fuel and fuel after thermochemical plasma preparation to the furnace. In the second case, there is a shift in the location of the torch core and an increase in the zone of maximum temperatures. An increase in the temperature in the torch core and its decrease at the outlet have a significant effect on the chemical processes of combustion product formation, since temperature is the main factor affecting the rate of combustion of the fuel mixture components.

Distribution of carbon monoxide (CO) concentration along the height of the furnaces of the BKZ-420 and BKZ-160 boilers and comparative analysis for the studied cases of the plasma-fuel system installation are presented in Fig. 11 (all results are reduced to normal conditions). Carbon monoxide is concentrated mainly in the zone of main distribution of the fuel flow from the burners, i.e., where carbon of fuel is available. With an increase in plasma-activated flows and, consequently, due to an increase in the CO content in the incoming highly reactive two-component flow, the maximum values of CO are observed in the plane of the burner cross section, and its concentration decreases at the outlet. So, CO concentration at the outlet for the BKZ-420 boiler at traditional combustion is 191 mg/m^3, for three activated

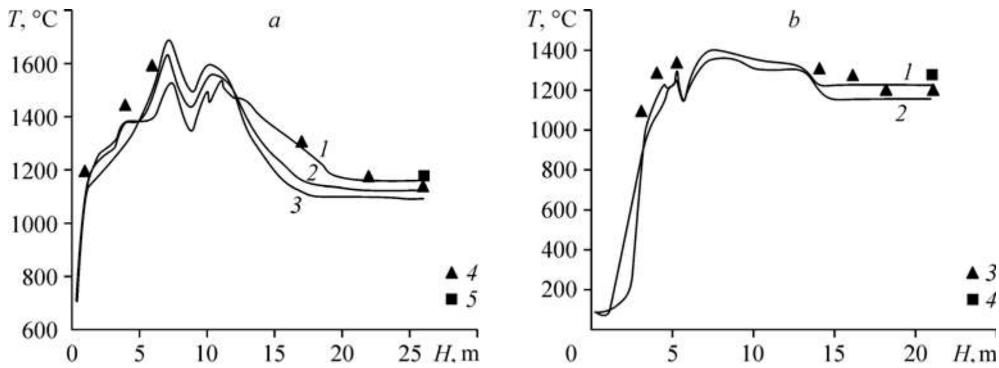

Fig. 10. Temperature distribution along the height of furnaces of BKZ-420 boiler at Almaty TPP-2 (*a*) and BKZ-160 boiler at Almaty TPP-3 (*b*).

a: *1* — traditional combustion of fuel, *2* — three plasma-fuel systems, *3* — six plasma-fuel systems, *4* — calculation results [11, 15, 20, 27], *5* — experimental data [28, 29];

b: *1* — traditional combustion of fuel, *2* — two plasma-fuel systems, *3* — calculation results [7, 30], *4* — experimental data [28, 29].

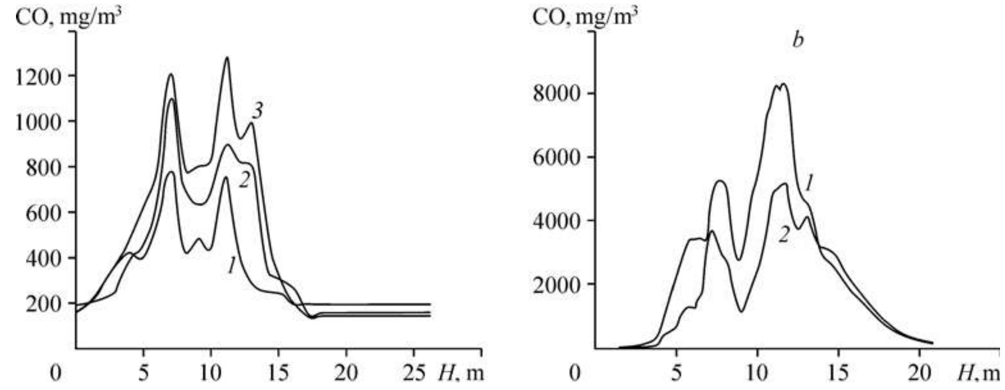

Fig. 11. Distribution of carbon oxide CO concentration along the height of furnaces of BKZ-420 boiler at Almaty TPP-2 (*a*) BKZ-160 boiler at Almaty TPP-3 (*b*).

a: *1* — traditional combustion of fuel, *2* — three plasma-fuel systems, *3* — six plasma-fuel systems;
b: *1* — traditional combustion of fuel, *2* — two plasma-fuel systems.

flows it is 156 mg/m^3, for six flows, it is 142 mg/m^3, and for the BKZ-160 boiler at traditional combustion, CO concentration is 225.81 mg/m^3 and for two plasma-activated flows, it is 187.88 mg/m^3.

The fields of nitrogen oxide (NO) concentration along the height of the furnaces of the BKZ-420 and BKZ-160 boilers are presented in Fig. 12. The main NO gas formation occurs in the area of distribution of flows from the burners. At that, the character of distribution of the curves in this region is ambiguous, which indicates a complex process of nitrogen oxide formation in this region [31–34] and the effect of plasma activation on NO formation. It can be seen that the use of plasma torches decreases total concentration of NO at the furnace space outlet, and for the BKZ-420 boiler with traditional combustion, it is 507 mg/m^3, and with 3 and 6 thermochemically activated flows, it is 456 mg/m^{3}and 407 mg/m^3, respectively. As for the BKZ-160 boiler, the average NO concentration during traditional combustion at the outlet is 522.8 mg/m^3, with two plasma-activated flows, it is 444.5 mg/m^3. This is confirmed by Fig. 13, which presents three-dimensional patterns of distributions of nitric oxide NO con-

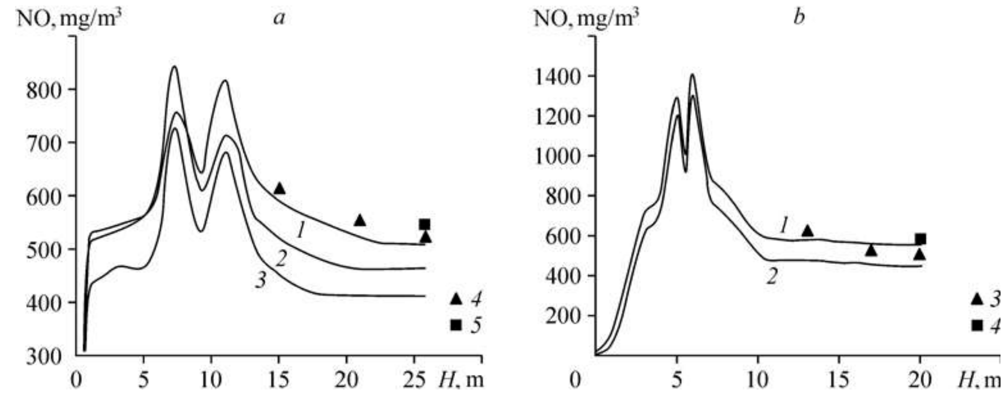

Fig. 12. Distribution of nitrogen oxide NO concentration along the height of furnaces of BKZ-420 boiler at Almaty TPP-2 (*a*) BKZ-160 boiler at Almaty TPP-3 (*b*) and comparison with experimental data.

a: *1* — traditional combustion of fuel, *2* — three plasma-fuel systems, *3* — six plasma-fuel systems, *4* — calculation results [11, 5, 20, 27], *5* — experimental data [28, 29];
b: *1* — traditional combustion of fuel, *2* — 2 plasma-fuel systems, *3* — calculation results [7, 30], *4* — experimental data [28, 29].

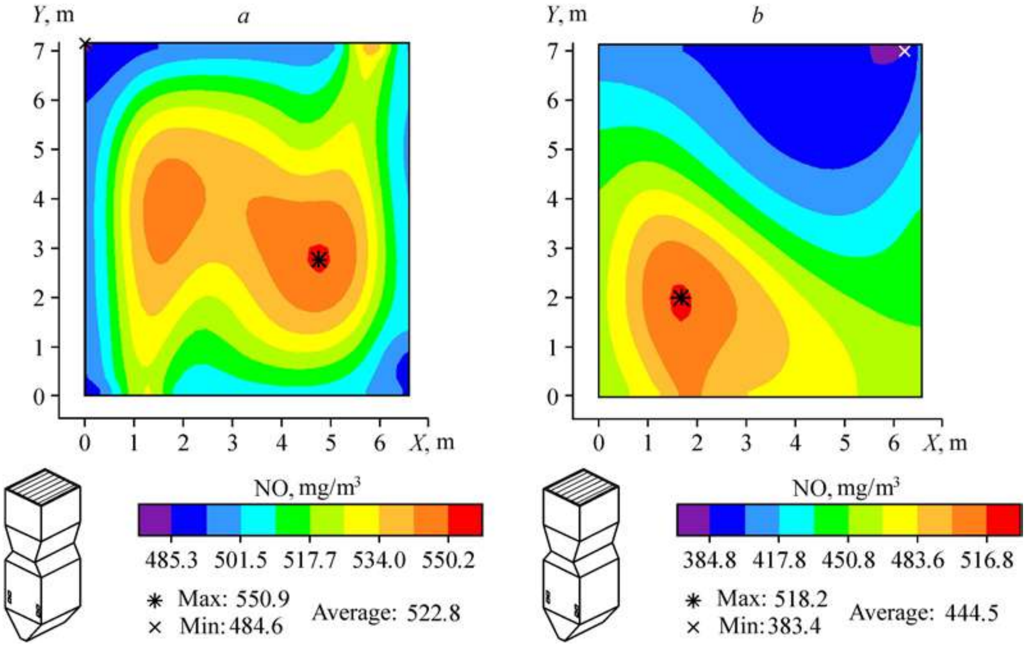

Fig. 13. Distribution of nitrogen oxide NO concentration at the outlet of furnace (h = 20.96 m) of BKZ-160 boiler in cross section K = 102 (Z = 20.96 m).
a — traditional fuel combustion, *b* — 2 plasma-fuel systems.

centration at the furnace outlet (K = 102, h = 20.96 m). In this area, the minimal value of concentration is NO_{min} = 484.6 mg/m^3 for traditional combustion and 383.4 mg/m^3 for two plasma-activated flows. The results obtained are in good agreement with the standards of NO emission for TPP. The maximum permissible concentration for nitrogen oxides NO, adopted in the Republic of Kazakhstan by 2016, is 850 mg/m^3. Thus, we can conclude that installation of the plasma-fuel systems in the furnaces of energy boilers improves significantly the environmental performance of thermal power plants.

Conclusions. The investigation results on the effect of thermochemical activation of coal-dust flows on heat and mass transfer processes occurring in the areas of real geometry (furnaces) with combustion of power fuel are presented. Numerical experiments were carried out using three-dimensional modeling methods. Comparative numerical studies of the processes of traditional coal combustion with plasma activation of its combustion in the furnace space showed satisfactory qualitative and quantitative agreement of experimental and calculated data in terms of the main parameters of coal combustion process (temperature, concentration of carbon and nitrogen oxides in the combustion products). The effect of plasma thermochemical processing of fuel on the main characteristics of combustion processes was investigated and it was found that the method of thermochemical activation of coal-dust flows can significantly optimize combustion of low-grade high-ash coal in the furnaces of thermal power plants and reduce significantly emissions of harmful substances (NO and CO) into the environment.

The obtained results of numerical modeling allow us to create highly economical technologies for burning low-grade fuels in the combustion chambers of operating TPPs; to offer the best design and layout solutions for implementation of plasma activation systems and to develop a number of recommendations on the use of preliminary thermochemical fuel preparation; to optimize the process of combustion of high-ash pulverized coal fuel in order to reduce emissions of harmful substances and create thermal power plants on the "clean" and efficient use of coal.

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