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STEAM BOILERS, POWER PLANT FUEL, BURNER ARRANGEMENTS, AND AUXILIARY EQUIPMENT OF BOILERS

Modeling and Full-Scale Tests of Vortex Plasma–Fuel Systems for Igniting High-Ash Power Plant Coal

V. E. Messerle[a, b, c], A. B. Ustimenko[c], Yu. E. Karpenko[d], M. Yu. Chernetskii[a, b], A. A. Dekterev[a, b], and S. A. Filimonov[a]

[a] *Siberian Federal University, ul. Kirenskogo 26, Krasnoyarsk, 660074 Russia*
[b] *Institute of Thermal Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent'eva 1, Novosibirsk, 630090 Russia*
[c] *Research Institute of Experimental and Theoretical Physics, ul. Tole Bi 96a, Almaty, 050010 Kazakhstan*
[d] *Sectoral Center of Plasma–Energy Technologies of RAO UES of Russia, ul. Pushkina 33, Gusinoozersk, Selenga Region, Buryat Republic, 671160 Russia*
e-mail: ust@physics.kz

Abstract—The processes of supplying pulverized-coal fuel into a boiler equipped with plasma–fuel systems and its combustion in the furnace of this boiler are investigated. The results obtained from 3D modeling of conventional coal combustion processes and its firing with plasma-assisted activation of combustion in the furnace space are presented. The plasma–fuel system with air mixture supplied through a scroll is numerically investigated. The dependence of the swirled air mixture flow trajectory in the vortex plasma–fuel system on the scroll rotation angle is revealed, and the optimal rotation angle at which stable plasma-assisted ignition of pulverized coal flame is achieved is determined.

Keywords: combustion, pulverized-coal fuel, thermochemical treatment, plasma, boiler furnace, numerical modeling

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Natural gas or furnace fuel oil is commonly used in thermal power facilities around the world for starting pulverized-coal boilers and stabilizing the pulverized coal flame combustion process. More than 50 million t of fuel oil a year is spent for these purposes. More than 5000000 t of fuel oil is fired every year at coal-fired thermal power plants (TPPs) in Russia. The general tendency toward worsening the quality of power plant coals (with a growing content of ash and moisture, and decreasing yield of volatiles) generates the need for larger consumption of furnace fuel oil at TPPs.

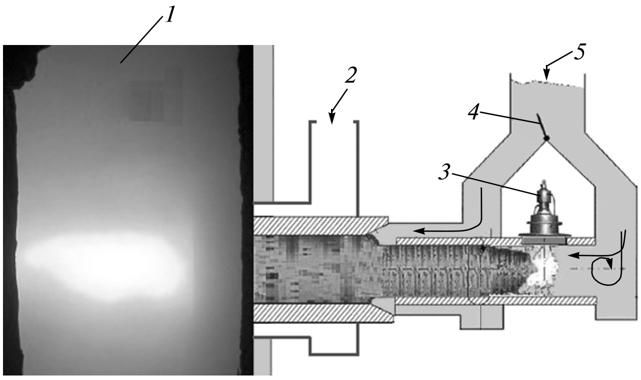

Fig. 1. Vortex plasma fuel system. (*1*) Furnace, (*2*) overfire air, (*3*) plasmatron, (*4*) gate, and (*5*) air mixture.

Plasma-assisted ignition of coals [1, 2] is the only known technology for oil-free starting of boilers and for picking up and stabilizing the combustion of a pulverized-coal flame that has been elaborated in real coal-fired boilers. For implementing this technology, plasma-fuel systems (PFSs) comprising pulverized-coal burners fitted with an electric-arc plasmatron have been developed (Fig. 1). The PFS operating principle is as follows. Cold air mixture (a mixture of pulverized coal with air) is heated in the zone of plasma flame, as a result of which a high-reaction two-component fuel (HTF) is obtained from low-grade coal. This fuel complies with the modern environmental and economic requirements and consists of combustible gas and coke residue, which are readily ignited as they are mixed with secondary (overfire) air in the boiler furnace and burn in a stable manner without the need to fire additional high-reaction fuel (fuel oil or gas). It has been shown by numerical modeling and by measurements carried out at the experimental furnace outlet that the use of PFSs in coal-fired boilers results in more efficient combustion of power plant coals due to a smaller fraction of unburned carbon with simultaneous decrease of nitrogen oxide emissions [3, 4].

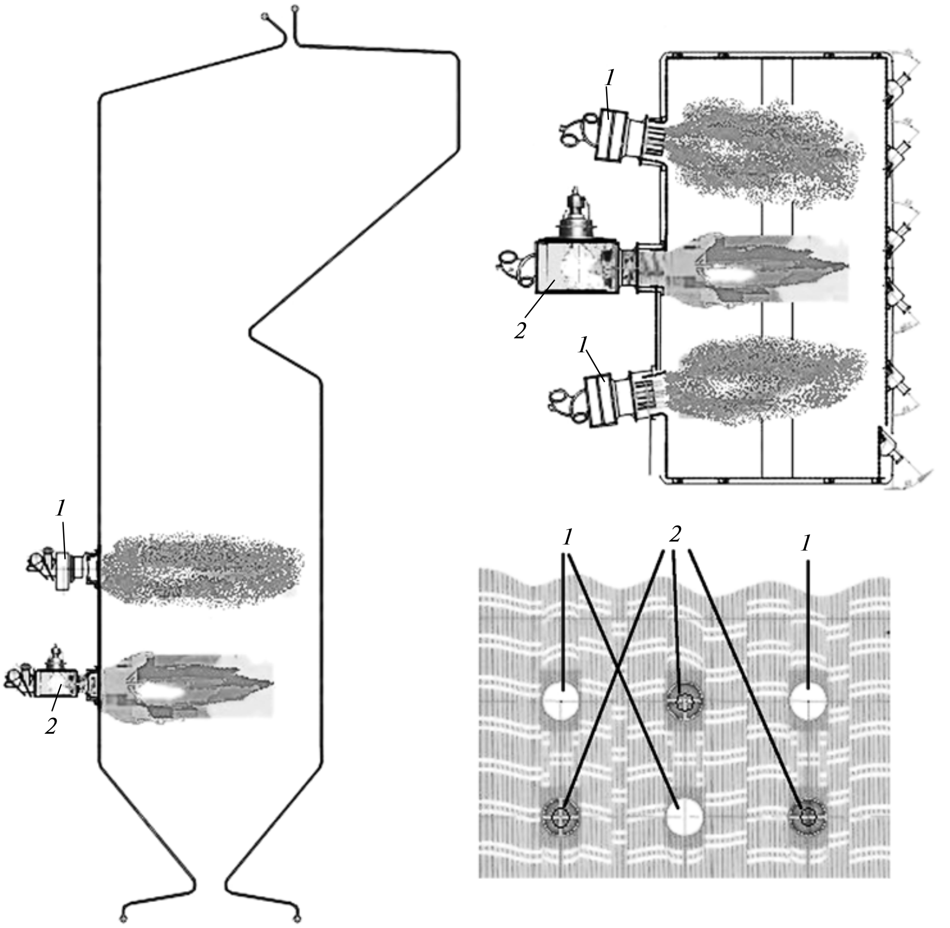

Fig. 2. Schematic layout of the PFS and main pulverized-coal burners in the BKZ-420 boiler at the Almaty CHP-2. (*1*) Standard vortex two-flow pulverized-coal burner and (*2*) PFS.

MODELING AND TESTING THE PFS IN THE BKZ-420 BOILER AT THE ALMATY CHP-2

In this work, the results obtained from modeling and tests of the PFS used in the BKZ-420 boiler at the Almaty combined heat and power plant No. 2 (CHP-2) (Fig. 2) are presented. The plasma-fuel systems for the BKZ-420 boiler have been constructed on the basis of three main burners: two extreme burners in the lower tier and the middle burner in the upper tier; the PFSs are installed in the burners instead of the primary air mixture channel. With such a solution, it became possible to leave the secondary air mixture pulverized-coal conduit (the air mixture external channel) and overfire air conduit unchanged.

The plasma-fuel system consists of two parts: a water-cooled plasmatron unit and muffled channels for preparing coal to combustion by subjecting it to thermochemical processing. The plasma–fuel system was developed and designed using two computer programs: the 1D Plazma-Ugol' (Plasma-Coal) computer program, which takes into account the detailed kinetics of thermochemical transformations of fuel in a two-phase flow containing a plasma source, and the 3D CFD Cinar ICE computer program, which takes into account the furnace geometry, turbulence of medium, radiative heat transfer, and coal particles combustion process according to the fast kinetics model [3].

Two boiler operating modes were selected for carrying out numerical investigations: the conventional one (with the use of six pulverized-coal burners) and with plasma-activated combustion (with three pulverized-coal boilers replaced by the PFSs). The parameters of the HTF obtained in the PFS from air mixture were calculated using the Plazma-Ugol' computer program. They served as the initial parameters for 3D calculation of the BKZ-420 boiler furnace equipped with a PFS, which was carried out using the Cinar ICE computer program. The same program was used for calculating the conventional coal combustion

Composition of HTF at the PFS outlet

Gas phase, vol %								Ash, kg/h	C, kg/h
H_2	CO	CH_4	C_6H_6	CO_2	H_2O	N_2	O_2		
1.05	7.75	0.3	0.77	15.6	3.55	70.84	0.15	1518	261

mode in the BKZ-420 boiler furnace fitted with the standard vortex pulverized-coal burners.

The boiler fires high-ash Ekibastuz black coal with the ash content equal to 40%, yield of volatiles equal to 24%, moisture content equal to 5%, and heating value equal to 16?760 kJ/kg. The coal milling fineness is $R_{90} = 15\%$. The initial data for calculating the PFS using the Plazma-Ugol' computer program are as follows:

Plasmatron power capacity, kW	200
Initial air mixture temperature, K	362
Coal flow rate through the burner or PFS, kg/h	6000
Primary air flow rate, kg/h	8955
PFS length, m	3.687

Coal is modeled as the sum of four components, wt %: fixed carbon C = 46.18, volatiles (H_2 = 2.63, H_2O = 1.84, CO = 3.95, CO_2 = 1.4, and CH_4 = 0.55), ash = 40, and tar represented by benzene C_6H_6 = 3.45. The following parameters of the HTF plasma-assisted formation process have been obtained from the calculation: the distribution of temperatures and velocities of gas and particles, the concentrations of gas phase components, and the gasification ratio and the carbon concentration in coke residue. At the PFS outlet, thermal equilibrium between the gas and particles is achieved at the temperature of gas and particles equal to 1025 K, and the gas flow velocity is equal to 49 m/s, exceeding the velocity of particles by 1 m/s. It should be pointed out that the flow velocity at the PFS outlet is significantly higher than the velocity of air mixture at the outlet from conventional pulverized-coal burners. The concentration of oxidizers (CO_2, H_2O, and O_2) at the PFS outlet is equal to 19.2%, and the coal gasification ratio at the outlet reaches 48%, which is quite sufficient for obtaining HTF.

The integral characteristics obtained at the PFS outlet (see the table) were used as initial parameters in carrying out 3D numerical modeling of HTF combustion in the furnace of the BKZ-420 power-generating boiler using the Cinar ICE computer program.

The following results were obtained from calculations of the parameters at the furnace outlet in the conventional and plasma-assisted operating modes:

	Conventional mode	Plasma-assisted mode
Temperature, °C	950	798
Concentration of:		
O_2, %	2	1
CO_2, %	16	18
NO_x, ppm	80.6	59.5
Content of carbon in ash, %	1.1	0.9

It follows from the data presented above that the concentration of residual carbon—the parameter characterizing the completeness of coal burnout—obtained at the outlet from the furnace equipped with three PFSs is by 16% lower than it is in the case of conventional combustion. The use of the plasma–fuel system improves the environmental indicators of the solid fuel combustion process due to decreasing the amount of nitrogen oxide emissions by more than 33%. Obviously, the fact that the use of PFSs results in smaller concentrations of residual carbon and nitrogen oxides NO_x at the boiler furnace outlet means improvement in the environmental and economic indicators of the TPP.

During the tests of three PFSs installed in the BKZ-420 boiler, ignition of the pulverized-coal flame in the cold boiler furnace at the PFS outlet was observed on reaching the necessary concentration of pulverized coal in the air mixture equal to 0.6–0.7 kg/kg. Flame temperature measurements carried out by means of a digital pyrometer through inspection 1
holes showed that the temperature immediately after ignition was equal to 700–800°C and then increased to the required level equal to 1050–1070°C, which is consistent with the results of modeling the BKZ-420 boiler furnace fitted with PFSs. At the beginning of the ignition process, pulsations of flames burning in the furnace were observed, which became stabilized as the furnace was heated up and as overfiring air was supplied (in an amount of 30–40%) through the burners

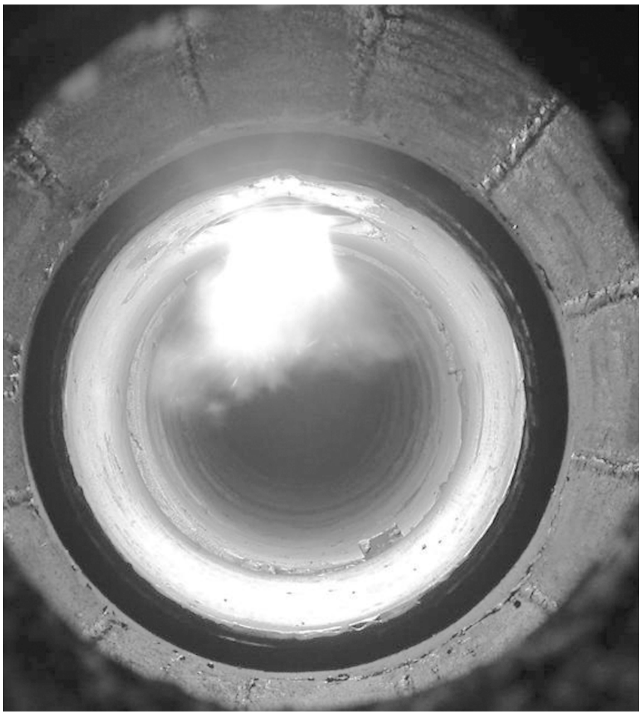

Fig. 3. Plasma flame in the PFS prior to supplying air mixture.

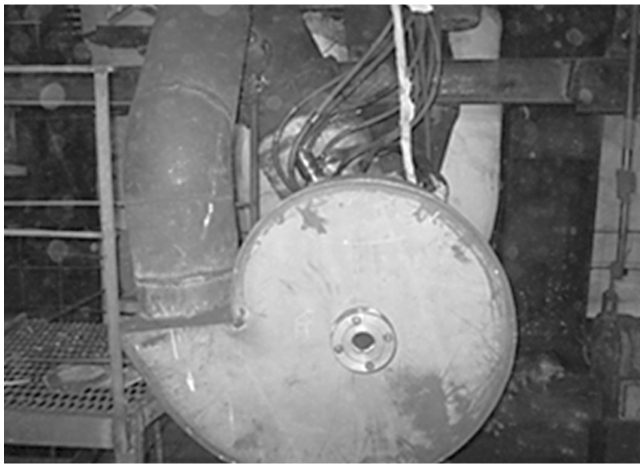

Fig. 4. General view of the vortex PFS with a scroll for the BKZ-420 boiler at the Almaty CHP-2.

fitted with the PFSs. It was recorded during the tests that the rate at which the hot air temperature increased after stabilizing the flames was equal to that in starting the boiler on fuel oil [4–6].

However, our attempts to obtain a stable pulverized-coal flame in the design operating mode of the pulverized coal system with direct injection necessary for oil-free starting of the boiler were not met with success because it was not possible to stabilize the pulverized coal concentration in air mixture at a level of 0.6–0.7 kg/kg, and because the swirl flow of air mixture did not come in sufficiently active interaction with the compact air plasma flame in the PFS (Fig. 3). It can be seen from the figure that with the relatively small degree to which the plasma flame covers the PFS cross section, the main portion of air mixture flow does not come in contact with this flame, which results in unstable ignition of the spray of pulverized high-ash Ekibastuz coal. In this connection, it is necessary to determine the trajectory of swirl air mixture flow in the vortex PFS for setting up its intense interaction with the compact plasma flame. For solving this problem, numerical investigations of a vortex PFS with air mixture supplied through a scroll (Fig. 4) were carried out. The aim of the calculations was to determine the intersection region between the air mixture flow and the plasma flame outlet region from the plasmatron, which is determined by the throat for installing the plasmatron as a function of the scroll rotation angle.

CALCULATED INVESTIGATION OF THE VORTEX PFS WITH A SCROLL

The calculations were carried out using the FLUENT 14 CFD software package [7]. The PFS analysis diagram is shown in Fig. 5. The PFS receives air mixture with the flow rates of pulverized coal and primary air equal to 5 t/h and 6230 m^3/h. The pulverized coal has the following disperse composition:

Particle diameter, μm	Fraction in the flow, %
10	19
47	45
80	21
150	15

The calculation was carried out on a polyhedral mesh with a size of 206?200 cells (Fig. 6). For performing the analysis, we used the Euler model with granular medium, in which the carrying flow and particles are represented as continuous interacting media. This model has found wide use for calculating the flows in process devices with a high concentration of the dispersed phase. For describing the interaction of particles with one another and their influence on the gas flow, a number of empirical correlations and parameters are introduced into the model, which depend on the dispersed phase concentration. In this work, the forms of correlations and the values of empirical quantities, as well as the set of equations for describing the motion of granular medium, were taken from [8–11].

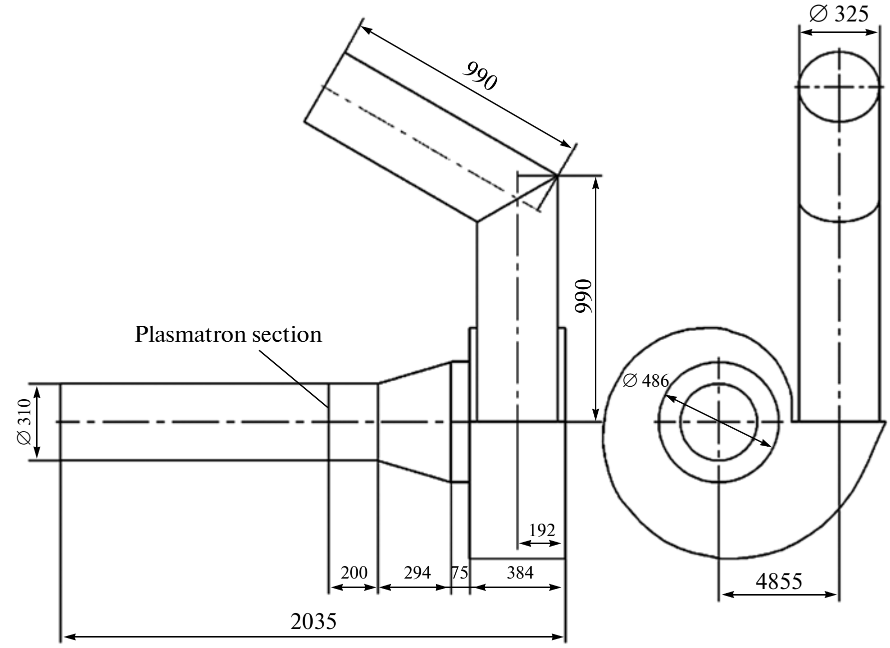

Fig. 5. PFS analysis diagram.

The mass conservation equation for the gas and dispersed phases is given by

$$\nabla(\alpha_i \rho_i \vec{v}_i) = 0,$$

where α is the phase volume fraction, ρ is the phase density, $\vec{v}$ is the velocity vector, and i is the phase subscript.

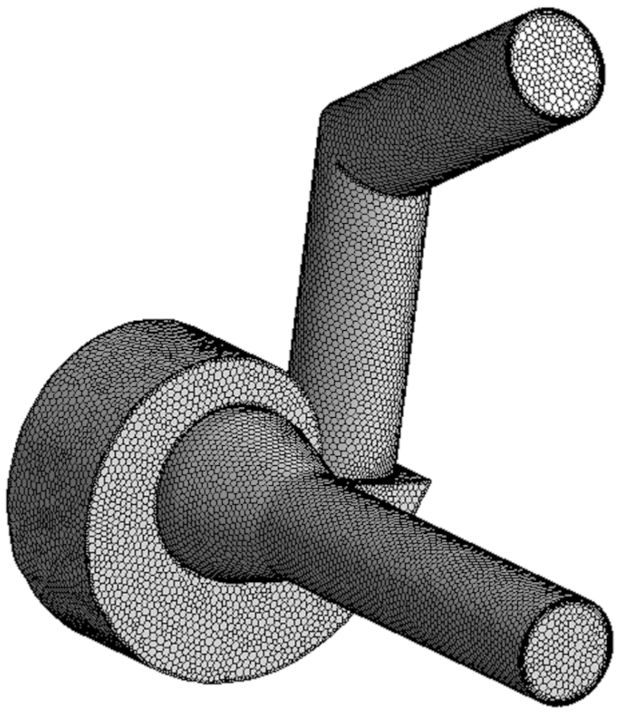

Fig. 6. Scroll computation mesh.

The momentum conservation equations are given by for air

$$\nabla(\alpha_L \rho_L \vec{v}_L \vec{v}_L) = -\alpha_L \nabla p + \nabla \hat{\tau}_L + \alpha_L \rho_L \vec{g} + \sum_{s=1}^{N_s} K_{L,s}(\vec{v}_L - \vec{v}_s) - \sum_{s=1}^{N_s} \vec{F}_{lift,s};$$

for dispersed phases

$$\nabla(\alpha_s \rho_s \vec{v}_s \vec{v}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla \hat{\tau}_s + \alpha_s \rho_s \vec{g} + \sum_{k=1}^{N_s} K_{k,s}(\vec{v}_s - \vec{v}_k) - K_{L,s}(\vec{v}_L - \vec{v}_s) + \vec{F}_{lift,s},$$

where p is the total pressure of all phases, p_s is the pressure caused by chaotic motion of particles, $\hat{\tau}_s$ is the tensor of stresses, $K_{L,s}$ is the coefficient of interaction between the liquid and dispersed phases, $K_{k,s}$ is the coefficient of interaction between the dispersed phases, N_s is the number of solid phases, $\vec{F}_{lift,s}$ is the lift, s and k are the dispersed phase subscripts ($s \neq k$), L is the liquid phase subscript, and $\vec{g}$ is the acceleration of gravity.

The pressure p_s is given by the following expression:

$$p_s = 2\rho_s(1 + e_{ss})\alpha_s^2 g_0 \Theta_s,$$

where e_{ss} is the particle interaction restoration coefficient (its value in the calculations was taken equal to 0.9), g_0 is the radial distribution function describing the particle collision probability, Θ_s is the granular

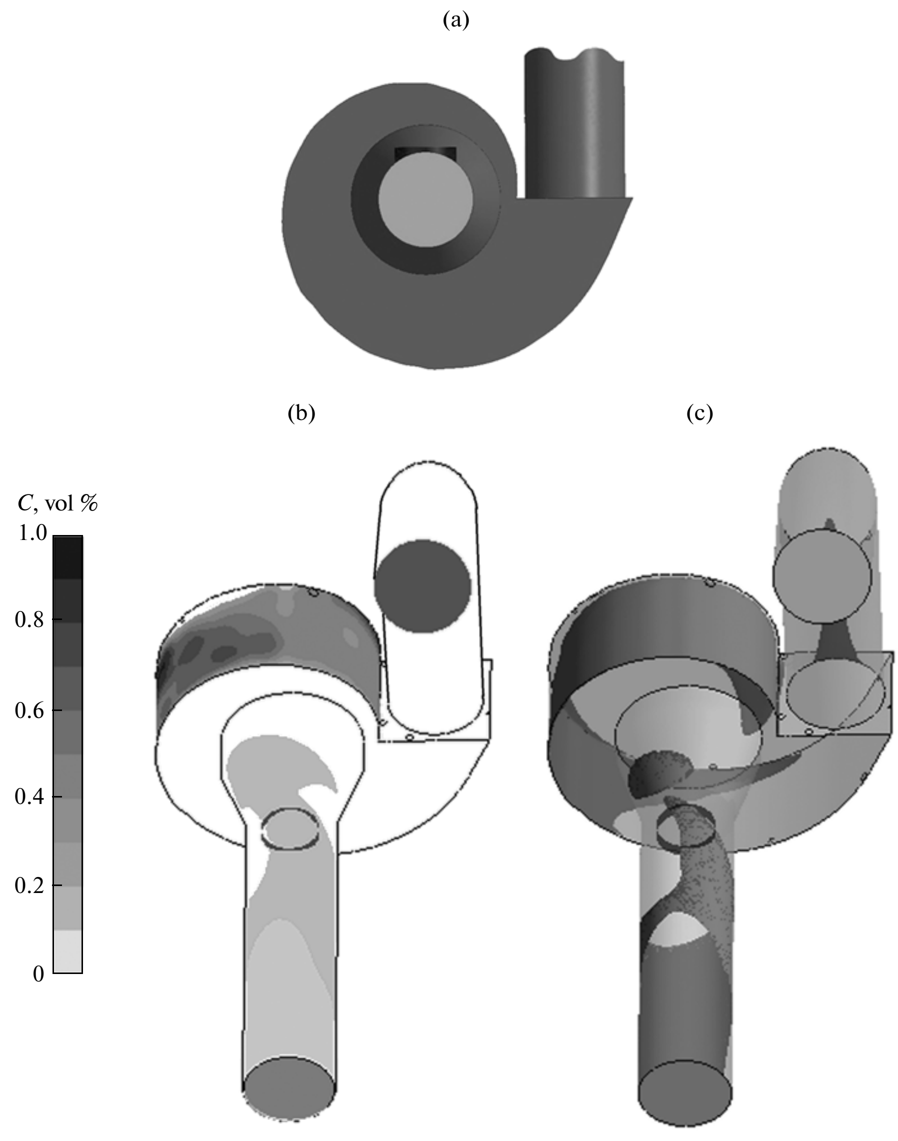

Fig. 7. Results from air mixture flow calculation at the scroll rotation angle equal to 0°. (a) Installation position, (b) dispersed phase volume concentration near the inner surface of the scroll and the air mixture plasma ignition, and (c) isosurface of dispersed phase volume concentration $f = 7\%$.

temperature (its value is proportional to the particle chaotic motion kinetic energy), for which the equation of transfer has the following form:

$$\frac{3}{2}\nabla\left(\alpha_s\rho_s\vec{v}_s\Theta_s\right)$$
$$= \left(-p_s\hat{I} + \hat{\tau}_s\right) : \nabla\vec{v}_s + \nabla\left(k_{\Theta_s}\nabla\Theta_s\right) - \gamma_{\Theta_s} + \varphi_{k,s},$$

where the polynomial $\left(-p_s\hat{I} + \hat{\tau}_s\right) : \nabla\vec{v}_s$ determines the generation of energy connected with viscous stress, the colon denotes the trace from the product of two tensors, $\nabla\left(k_{\Theta_s}\nabla\Theta_s\right)$ is the diffusion transfer of granular temperature, k_{Θ_s} is the diffusion coefficient, $\hat{I}$ is the unit tensor, γ_{Θ_s} is the energy of interaction between the particles of one phase, and $\varphi_{k,s}$ is the energy of interaction between the particles of different phases.

The turbulence of mixture is described by a standard k–ε model; i.e., its velocity and density are used. The empirical constants in the equations for turbulent characteristics are specified as for the k–ε model of single-phase medium:

$$\nabla\left(\rho_m\vec{v}_m k\right) = \nabla\left(\frac{\mu_{t,m}}{\sigma_k}\nabla k\right) + G_{k,m} - \rho_m\varepsilon;$$

$$\nabla\left(\rho_m\vec{v}_m\varepsilon\right) = \nabla\left(\frac{\mu_{t,m}}{\sigma_\varepsilon}\nabla\varepsilon\right) + \frac{\varepsilon}{k}\left(C_{1\varepsilon}G_{k,m} - C_{2\varepsilon}\rho_m\varepsilon\right),$$

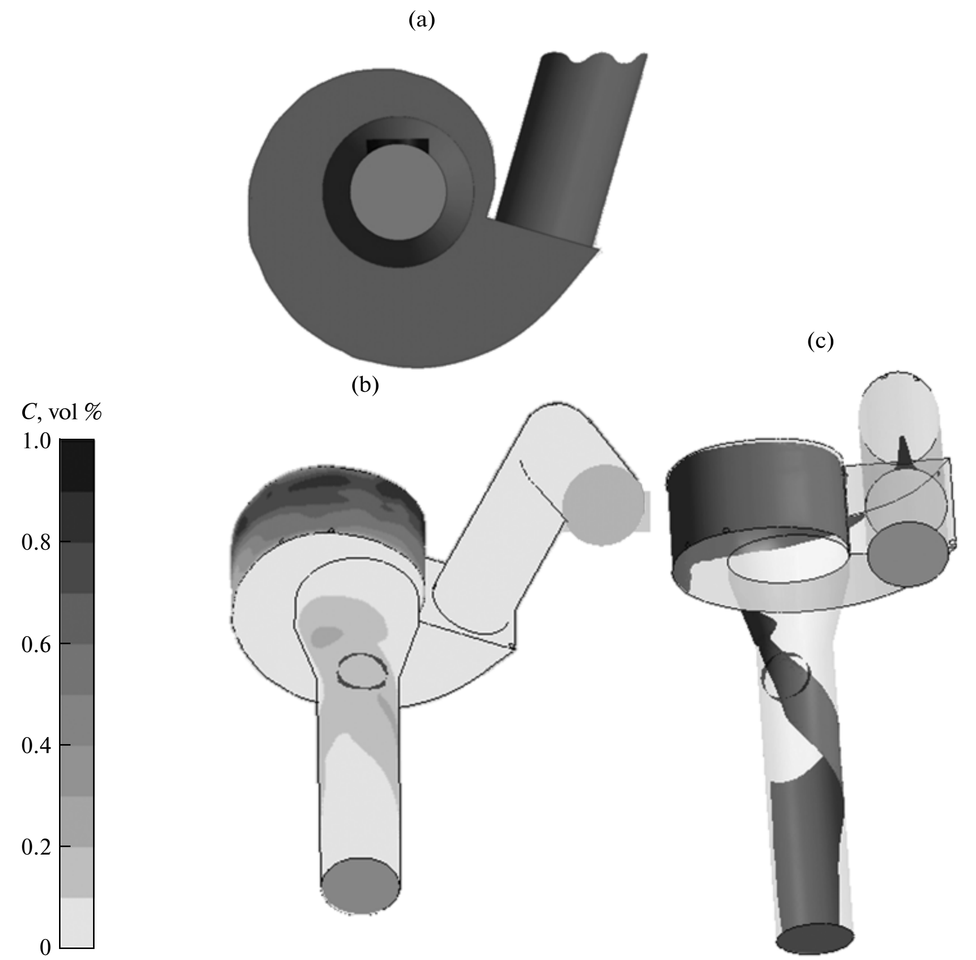

Fig. 8. Results from air mixture flow calculation at the scroll rotation angle equal to 15°. The meaning of (a) and (b) is the same as in Fig. 7, (c) $f = 10\%$.

where

$$\rho_m = \sum_{i=1}^{N} \alpha_i \rho_i; \text{ and}$$

$$\vec{v}_m = \frac{\sum_{i=1}^{N} \alpha_i \rho_i \vec{v}_i}{\sum_{i=1}^{N} \alpha_i \rho_i}$$ are the density and velocity of mixture,

$$\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon}$$ is the turbulent viscosity,

$G_{k,m} = \mu_{t,m}(\nabla \vec{v}_m + (\nabla \vec{v}_m)^T) : \nabla \vec{v}_m$ is the generation of turbulence energy, ε is the turbulence energy dissipation rate, k is the turbulence kinetic energy, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$, and C_μ are the closing constants, and T is the transposition operator.

A constant flow rate was specified for all phases at the calculation region inlet, and a constant pressure was specified at its outlet. The no-slip condition for the gas and dispersed phases was specified on the model's solid walls. The flow pulsation characteristics near the walls were determined using the wall function method.

Figures 7–10 show the results of calculations carried out for the versions with the scroll rotation angle for supplying air mixture $\varphi = 0–45°$ referred from the plasmatron axis.

The maximal concentration of pulverized coal is observed in the scroll, where circulation of pulverized coal takes place (see Fig. 7a). Interaction between coal particles becomes more intense as they accumulate in the scroll. With this interaction taken into account, it becomes possible to correctly describe the outflow of particles into the channel with the plasmatron. The scroll–convergent tube transition is the particle outflow main location. Owing to this design feature, a "cord" of particles is formed. The idea about the particle motion pattern can be gained from the distribu-

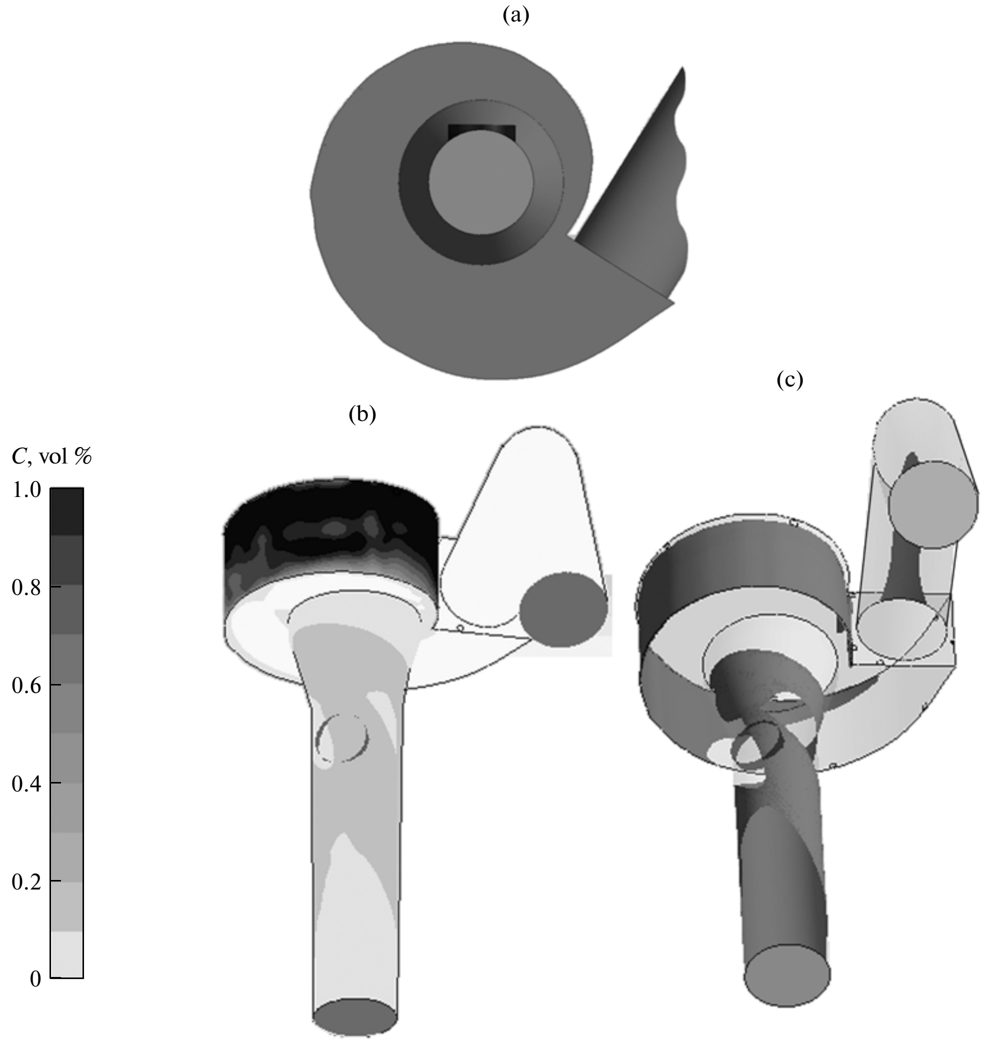

Fig. 9. Results from air mixture flow calculation at the scroll rotation angle equal to 30°. The meaning of (a) and (b) is the same as in Fig. 7, (c) $f = 6\%$.

tion of coal particle volume concentration near the inner surface of the scroll and the air mixture plasma ignition chamber (see Fig. 7b) and also from Fig. 7c, which shows the isosurface (the surface with the same concentration of the considered quantity) of coal particle volume concentration f.

After having entered into the channel, the particles move over a helical trajectory along its wall under the effect of inertial forces. The trajectories of coal particles depend on their sizes. Particles belonging to the finest fraction are distributed over the channel walls in a quite uniform manner. As the particles grow in size, the motion of pulverized-coal flow attains the form of a "cord".

A comparison of Figs. 7c–10c allows us to draw a conclusion that the pattern in which the bulk of pulverized coal moves in the pipe depends on the scroll rotation angle (Fig. 11). This is clearly seen from the distribution and isosurface of pulverized coal volume concentration shown in Figs. 7–10. It can be seen from Fig. 11 that the scroll rotation angle equal to 15° (Fig. 8), at which the pulverized coal fraction passing through the plasmatron cross section is equal to 19.5% of the total mass supplied to the scroll is the optimal version from the viewpoint of the "cord" hitting the flame outlet zone from the plasmatron.

Based on the results from numerical calculations, the scrolls of three PFS installed in the BKZ-420 boiler at the Almaty CHP-2 were turned by 15° with respect to the plasmatron axis for testing plasma-assisted ignition of high-ash Ekibastuz coal. During the tests, the plasmatrons operated at an average power of 190 kW each. The flow rate of pulverized coal passing through each PFS was equal to 2.5–3.1 t/h; the flow rate of primary air was equal to 2240–2640 m^3/h at standard temperature and pressure [12], and the flowrate of overfire air was equal to 40% of the nominal

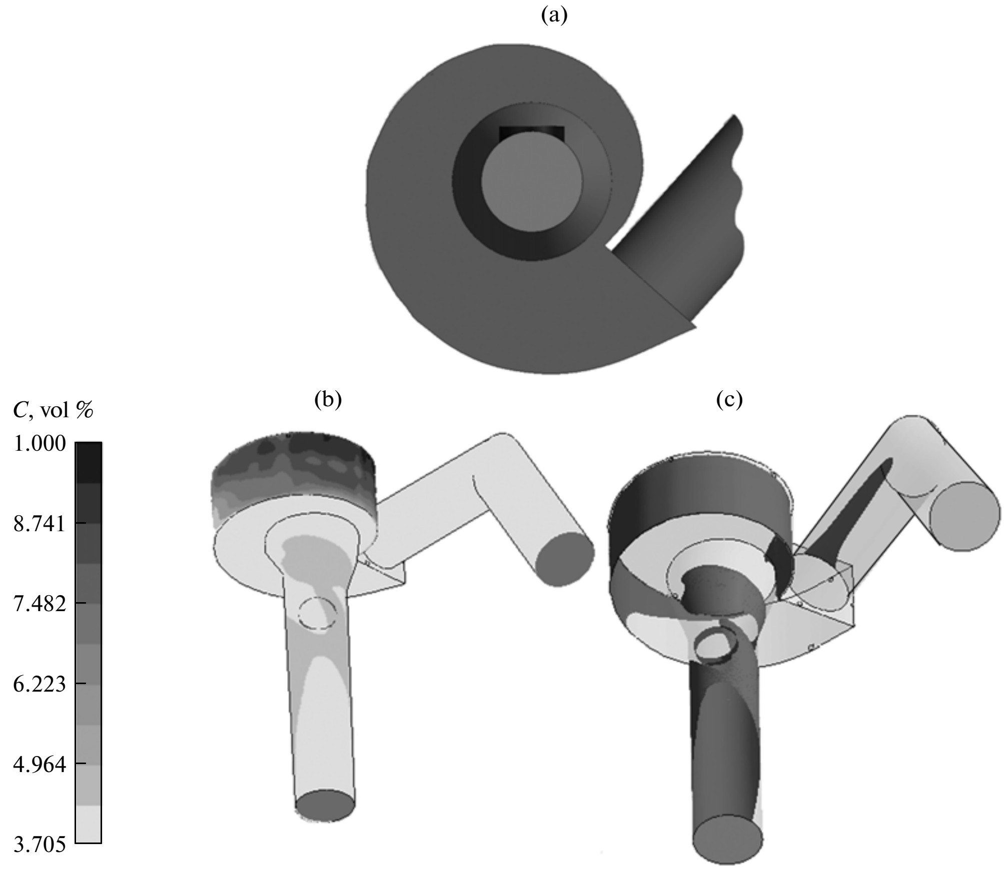

Fig. 10. Results from air mixture flow calculation at the scroll rotation angle equal to 45°. The meaning of (a) and (b) is the same as in Fig. 7, (c) $f = 6.5\%$.

value. The test results have shown that stable ignition of the pulverized coal flame is achieved at the optimal scroll rotation angle equal to 15° (Fig. 12). It can be seen from the figure that the flame luminosity has increased (the flame core temperature reached 1022°C), and the area of the flame luminous part has increased by approximately a factor of 1.5.

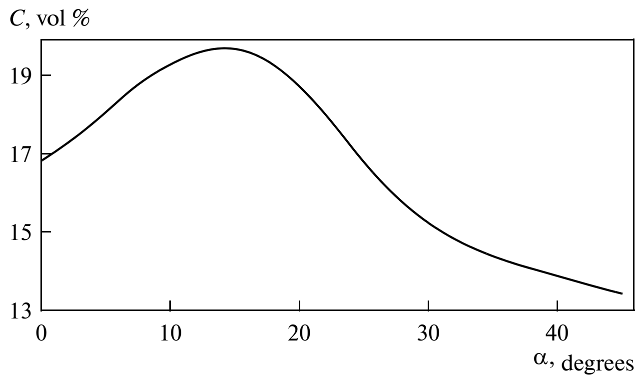

Fig. 11. Isosurface of pulverized coal volume concentration versus the scroll rotation angle.

CONCLUSIONS

(1) The use of PFS in pulverized-coal boilers makes it possible to achieve more efficient combustion of power plant coals with simultaneous reduction of harmful emissions.

(2) The results obtained from the tests of the PFSs installed in the BKZ-420 boiler at the Almaty CHP-2 in starting the boiler from its cold state have demonstrated the possibility to ignite high-ash Ekibastuz coals in the cold furnace without preheating of primary air.

(3) The results from numerical investigations of the vortex PFS with supplying air mixture through a scroll have shown that the distribution of pulverized coal volume concentration at the plasmatron installation place depends on the scroll rotation angle.

(4) The results of full-scale tests have confirmed that with the calculated optimal scroll rotation angle equal to 15° with respect to the plasmatron axis, stable plasma ignition of the pulverized coal flame in the BKZ-420 boiler furnace is achieved because the entire

Fig. 12. Pulverized-coal flame from the PFS at the initial moment (a) and in 5 min after starting coal supply (b). Temperature in the flame core, °C: (a) 835 and (b) 1022.

pulverized coal flow passes through the plasma flame outlet region from the plasmatron.

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REFERENCES

1. V. E. Messerle and A. B. Ustimenko, "Plasma-chemical fuel processing technologies," Izv. Vyssh. Uchebn. Zaved., Khim., Khimich. Tekhnol. **55** (4), 30–34 (2012).
2. V. E. Messerle, E. I. Karpenko, A. B. Ustimenko, S. S. Tyutebaev, Yu. E. Karpenko, and T. V. Eremina, "Modeling and tests of plasma–fuel systems in the BKZ-420 boiler at the Almaty CHP-2," Vestn. Vost. Sib. Gos. Univ. Tekhnol. Upr., No. 2 (37), 21–27 (2012).
3. V. E. Messerle, A. B. Ustimenko, A. S. Askarova, and A. O. Nagibin, "Pulverized coal torch combustion in a furnace with plasma-coal system," Thermophys. Aeromech. **17** (3), 435–444 (2010).
4. V. E. Messerle, E. I. Karpenko, and A. B. Ustimenko, "Plasma assisted power coal combustion in the furnace of utility boiler: numerical modelling and full-scale test," Fuel **126,** 294–300 (2014), DOI: http://dx.doi.org/10.1016/j.fuel.2014.02.047.
5. V. E. Messerle, A. B. Ustimenko, S. S. Tyutebaev, V. G. Lukiaschenko, V. N. Shevchenko, I. G. Stepanov, K. A. Umbetkaliev, A. O. Nagibin, V. N. Kozak, O. A. Lavrishchev, E. I. Karpenko, S. V. Lobitsin, and Yu. E. Karpenko, "Tests of plasma-fuel systems in Almaty TPP-2," in *Proceedings of the 7th International Scientific Conference "Modern Achievements in Physics and Physical Education," Almaty, Kazakhstan, October 3–5, 2011*, pp. 3–5.
6. V. E. Messerle, A. B. Ustimenko, V. G. Lukiaschenko, V. N. Shevchenko, I. G. Stepanov, K. A. Umbetkaliev, A. O. Nagibin, V. N. Kozak, E. I. Karpenko, S. V. Lobitsin, and Yu. E. Karpenko, "Application of plasma-fuel systems in Almaty TPP-2," in *Proceedings of the 6th International Symposium on Theoretical and Applied Plasmachemistry, September 3–9, 2011* (Ivanovo State Chemical-Engineering University, Ivanovo, 2011), pp. 392–395.
7. *ANSYS FLUENT User's Guide. Release 14.0* (ANSYS Inc., November 2011).
8. Yu-chun Zhang, Zhen-bo Wang, and Tou-hai Jin, "Simulation and experiment of gas-solid flow field in short-contact cyclone reactors," Chem. Eng. Res. Des. **91** (9), 1768–1776 (2013).
9. D. R. Kaushal, T. Thinglas, Yuji Tomita, Shigeru Kuchii, and Hiroshi Tsukamoto, "CFD modeling for pipeline flow of fine particles at high concentration," Int. J. Multiphase Flow **43,** 85–100 (2012).
10. Sonali Swain and Swati Mohanty, "A 3-dimensional Eulerian–Eulerian CFD simulation of a hydrocyclone," Applied Math. Model. **37,** 2921–2932 (2013).
11. Anders Darelius, Anders Rasmuson, Berend van Wachem, Ingela Niklasson Bjorn, and Staffan Folestad, "CFD simulation of the high shear mixing process using kinetic theory of granular flow and frictional stress models," Chem. Eng. Sci. **63,** 2188–2197 (2008).
12. V. E. Messerle, A. B. Ustimenko, V. G. Lukiashchenko, V. N. Shevchenko, I. G. Stepanov, K. A. Umbetkaliev, V. N. Kozak, A. L. Sindeev, S. V. Lobytsin, Yu. E. Karpenko, D. S. Saprykin, and R. D. Tokhtaev, "About the results of industrial tests of plasma–fuel systems (PFS) in the BKZ-420-140-7s pulverized-coal boiler station no. 3 at the Almaty TPP-2," in *Proceedings of the 7th International Symposium "Combustion and Plasmochemistry" (ISBN 978-601-04-0134-1), Al-Farabi KazNU, Almaty, 2013*, pp. 229–232.

Translated by V. Filatov

SPELL: 1. pyrometer