

# Plasma Thermochemical Preparation for Combustion of Pulverized Coal

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**Abstract**—A plasma model of thermochemical preparation for the combustion of pulverized coal implemented through the PlasmaKinTherm program for the calculation of plasma-fuel systems has been described. Such systems are used at nonfuel-oil start-up of boilers and the stabilization of the combustion of a pulverized coal torch. The model combines kinetic and thermodynamic methods describing the process of the thermochemical preparation of fuel in the volume of the system. The numerical study of the regime parameters of the plasma-fuel system as a function of plasmatron power providing the ignition of the high-ash coal air-petrol mixture is carried out. Distributions of temperatures and velocities of gas and coal particles and concentrations of products of the thermochemical preparation over the length of the system are obtained. The main regularities of the process of the plasma ignition of fuel are revealed consisting in the displacement of the maxima of temperatures and velocities of products of thermochemical preparation upstream (in the direction of the plasmatron), and the independence of plasmatron power maximal values of temperatures and velocities. The results of calculations are compared with experimental data confirming the validity of assumptions accepted at the development of the model.

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## INTRODUCTION

In connection with the forecast increase in the share of solid fuels in the world production of electrical energy in the next 20 years (28% in 2035 [1]) and the observed deficit of electrical and thermal energy, considerable attention is paid to the increase in the efficiency and ecological safety of processes of combustion of solid fuels at pulverized coal thermal power plants producing 40.6% of electrical and thermal energy [2]. At the same time, the global trend of lowering the quality of thermal coals is clearly seen, leading to the increase in the usage of nonproject fuels, i.e., coals with heat engineering characteristics differing from project. In this connection the technical-economical and ecological job performance of boiler units worsens. For this reason, of special urgency are the creation and application of new technologies favoring the effective combustion of solid fuels independent of their quality.

New technologies of processing organic compounds are known, in particular local fuel-energy resources [3], including plasma technologies of processing using a plasmatron [4]. One promising technology is plasma thermochemical preparation for the combustion of pulverized coal (PTPC) [5–8] using plasma-fuel systems (PFS), the most common scheme of

which is given in Fig. 1. This technology makes it possible to increase the efficiency of using fuel and ecological performance of a thermal power station (TPS), and also to completely eliminate the usage of furnace fuel oil conventionally applied for lighting boilers and the stabilization of the combustion of the pulverized coal torch. However, conducting field tests of PFS as complex thermal-electrotechnical systems is specified by the high cost and labor costs in spite of their apparent simplicity [7, 8]. The PTPC technology consists in heating the air-petrol mixture (coal dust + air) by electric arc plasma to the exit temperature of volatile coal and the partial gasification of the coke residue. Thus the highly reactive two-component fuel (combustible gas + coke residue) of the given composition is prepared from initial coal in the PFS. The two-component fuel is ignited at its mixing with air in the boiler furnace and steadily burns without the additional highly reactive fuel (fuel oil or gas) conventionally used for lighting boilers and the stabilization of the combustion of the pulverized coal torch.

Unlike the known studies of the plasma ignition of coals in the furnace volume [9, 10] and the thermochemical preparation of solid fuels for combustion [11–13], PTPC is performed in the PFS volume at the direct impact on the air-petrol mixture (a mixture of

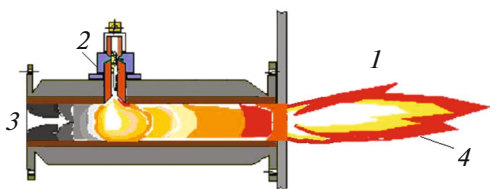


Fig. 1. Scheme of the uniflow PFS: 1—boiler furnace, 2—plasmatron, 3—air-petrol mixture, 4—torch of the highly reactive two-component fuel.

coal particles and air) of the plasma flame at 5000–6000°C [14, 15]. This makes it possible to accelerate many times processes of thermochemical transformations of the solid fuel and oxidizer.

This work is devoted to solving a topical problem of the numerical simulation of PTPC processes for selecting the optimal PFS regime parameters, and also the numerical study of the uniflow PFS using the PlasmaKinTherm program, developed based on the Plasma-Coal and TERRA [16, 17] programs, and combining the kinetics of the release of volatile compounds and oxidation of the carbon coke residue with the thermodynamic approach to the calculation of plasma thermochemical transformations in the gas phase of products of the primary destruction of coal.

#### THE PTPC MODEL (PLASMAKINTHERM)

At present a series of mathematical models is known, which, along with the experiment can be used for obtaining characteristics of fuel ignition and combustion processes [16–20]. All of them are characterized by an extremely simplified model of the initial interaction of a cold air-petrol mixture flow ( $T = 20\text{--}30^\circ\text{C}$ , primary air + coal particles) with a plasma flame. Mathematical models proposed in a series of works [16, 17, 20] lead to qualitatively and quantitatively reliable results owing to the corresponding selection of parameters of processes but they are too laborious for performing the parametric numerical analysis necessary during the design of specific furnace devices. The calculation models, as a rule, include the following:

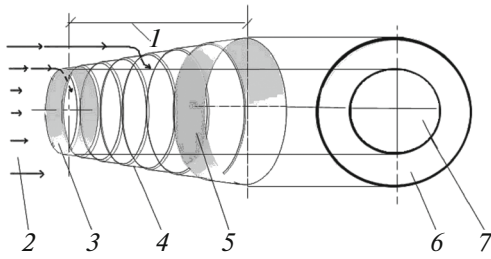
- equations of heat and mass transfer between the gas phase and coal particles;
- the Arrhenius equation for the calculation of volatile compounds exit from coal particles;
- equations of the thermochemical interaction of released compounds in the gas flow.

A two-phase (coal particles + air) chemically reacting flow propagating in a channel with the internal source of heat (in the general case the source of heat of any kind, e.g., the electric arc plasmatron flame, electric arc, (microwave) plasmatron flame), or without it, is considered in this model. Particles and gas, uniformly mixed, arrive in a cylindrical flow channel PFS with a plasmatron. Gas is heated from the plasma source of heat and heats particles. When particles

reach the temperature of the release of volatiles, their exit into the gas phase begins in accordance with the kinetic mechanism of this process [16]. This model is based on assumptions about the quasi-stationary course of the process and its one-dimensionality, the coal particles are considered isothermal, and ash (mineral mass), the inert component. It is also assumed that particles do not interact. The interaction between the pulverized coal mixture and plasma is considered the heating of the pulverized coal flow by hot gas. The composition of coal is presented in the model by its organic and mineral masses. The organic mass of coal is given by a set of coal volatiles ( $\text{CH}_4$ ,  $\text{C}_6\text{H}_6$ ,  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{CO}_2$ ) and carbon. The process of the release of volatiles from the organic mass of coal is limited by the kinetics of heating of coal particles. Volatiles released into the gas phase are mixed and react with the plasma flame. The model of the local thermodynamic equilibrium, which was implemented using the TERRA program complex, is used for the calculation of reactions in the gas phase [17]. Such an approach made it possible to combine the kinetics of the release of volatiles and oxidation of carbon of the coke residue with the thermodynamic method of the calculation of plasma thermochemical transformations in the gas phase of products from the primary destruction of coal.

To approximate the phenomena of the large-scale mixing of gas flows occurring in the real PFS due to large temperature gradients, the notion of physical mixing is introduced in model [21]. Since the plasma flame volume is much less than the PFS volume, a certain spatial mixing law of the air-petrol mixture along the PFS axis passing through the region occupied by the plasma flame is given. The essence of the mixing law is the consideration of the phenomenon of mixing of flows with different chemical compositions and different temperatures inside the PFS over its radius, while the one-dimensional model is used. The empiric spatial law of the propagation of the reaction zone is given on the assumption of data obtained in a series of experiments [22]. The simulation of the mixing effect leads to the necessity of the consideration of the separation of coal particles into fractions not only over the size but also over the temperature. Usually five representative size fractions of coal particles and an infinite amount of the temperature (the temperatures of particles on the cut of the PFS channel differ: particles are hotter in central regions than on the periphery) are considered during calculations. In [23], it was shown that the amount of fractions with sufficient accuracy describes the granulometric size distribution of coal particles of industrial grinding. The amount of temperature fractions is determined by the given mixing law and the number of stages of channel partitioning into calculation stages.

All space inside the cylindrical PFS is split into cylinders with a certain step and with a diameter increasing according to a certain law (Fig. 2). Each of them



**Fig. 2.** Principle mixing scheme: 1—length of the mixing zone, 2—flow of the air-petrol mixture, 3—first cylinder of partitioning, 4—mixing law, 5—mixing final zone.

contains coal particles of the given number of size fractions, the temperatures of which differ. Cold portions of the air-petrol mixture are captured at an increase in the cylinder diameter, and the reaction zone expands. It is considered that, at each step, the gas temperature inside the ring is equalized, and the temperature of particles is not. Therefore, e.g., in the zone 7 of the cylinder 5 (Fig. 2), the temperatures of particles of any fraction in the case of the occurrence of combustion reactions will be higher than the temperatures of the same fraction in the zone 6, later “captured” by the expanding reaction zone and reacted later.

Figure 2 illustrates the principle of physical mixing. It is seen that the mixing length  $I$  corresponds to the PFS length, at which the expansion of the reaction zone occurs in the radial direction. The first partitioning cylinder 3 is the beginning of the mixing zone, and the mixing law 4 characterizes the expansion of the reaction zone according to a certain law, in this case, according to the linear.

These assumptions made it possible to describe the considered processes using the system of ordinary differential equations (ODEs) that considerably simplified the calculation of hydrodynamics of the process at the presence of the thermochemical transformations of coal and oxidizer initiated by plasma.

*Equations of the Mathematical Model*

The adopted model is described using the differential equations for conservation of mass, momentum and energy over the length of cylindrical channel of the constant cross-section.

Equation for conservation of momentum of the gas phase

$$u \frac{d(\rho u)}{dx} = - \sum_{i=1}^L F_i, \tag{1}$$

where  $F_i = C_{Di} \frac{\rho(u - u_i)^2}{2} \pi R_i^2 N_i$ . Here,  $\rho$ ,  $u$  are the density and velocity of the gas phase of the flow;  $F_i$  is the aerodynamic drag force of the particle the size fraction  $i$ ;  $C_{Di}$  is the drag coefficient of the particle;  $R_i$

is the radius of the coal particle; and  $N_i$  is the number of particles of the fraction  $i$  in the unit of mass.

Equation for conservation of momentum of coal particles the fraction  $i$

$$m_i u \frac{du_i}{dx} = F_i, \tag{2}$$

where  $u_i$  is the velocity of the motion particles the fraction  $i$ .

Equation for conservation of energy of the gas phase

$$\rho u \frac{dI}{dx} = \sum_{i=1}^k \rho u \frac{dn_i}{dx} I_i - \sum_{l=1}^L \Delta Q_l + \Delta Q_r + \Delta Q_p. \tag{3}$$

Here, the term  $\Delta Q_l = \alpha_l (T_g - T_l) 4\pi R_l^2 N_l$  describes the heat transfer between the gas and particles;  $\Delta Q_p$  is the contribution of the thermal energy from the plasmatron;  $\Delta Q_r$  is the thermal effect of reactions of the release of volatiles from coal;  $I$ ,  $T_g$  are the enthalpy and temperature of the gas phase, respectively;  $n_i$ ,  $I_i$  are the concentration and enthalpy of the  $i$ -th component of the gas phase; and  $\alpha_l$  is the coefficient of the heat transfer of the particle.

Equation for conservation of energy of the coal particles

$$\rho u \frac{dI_l}{dx} = \Delta Q_l + \Delta Q_c, \tag{4}$$

where  $\Delta Q_c$  is the thermal effect of the combustion reaction of carbon.

The drag coefficient of the motion of particles under the impact of the Stokes force is calculated as a function of the Reynolds number for the velocity of the relative motion using the known expression:

$$C_{Di} = \begin{cases} \frac{24}{Re_i} (1 + 0.15 Re_i^{0.687}), \\ Re_i = \frac{2(u - u_i)R_i}{\nu} < 1000, \\ 0.44, & Re_i \geq 1000. \end{cases}$$

The heat transfer coefficient,  $\alpha_l$ , is determined using the criterion equation of the heat transfer fair for the flow around the sphere by the laminar flow:

$$\alpha_l = \frac{Nu_l \lambda}{2R_l}; \quad Nu_l = 2 + 0.03 Pr^{0.33} Re_l^{0.54} + 0.35 Pr^{0.35} Re_l^{0.58},$$

where  $Nu_l$  is the Nusselt number for the particle of the fraction  $l$ , and  $Pr$  is the Prandtl number.

Equation of consumption of the air-petrol mixture and the plasma-forming gas

$$\frac{dm_{aer}}{dt} + \frac{dm_{plasma}}{dt} = \frac{\rho u \pi d^2}{4}, \tag{5}$$

where  $\frac{dm_{\text{aer}}}{dt}$ ,  $\frac{dm_{\text{plasma}}}{dt}$  are the consumption of the air-petrol mixture (primary air + coal) and the plasma-forming gas (air), respectively;  $d$  is the channel diameter.

The initial conditions are the values of temperatures of air and coal dust particles at the input in the PFS. The velocity of the gas flow  $u^*$  at the initial time is determined from equations of the consumption of the air-petrol mixture and plasma-forming gas (5). It is assumed that, in any coal fraction, all particles have the same size and spherical shape.

The energy contribution to the process of heating of the gas phase of the air-petrol mixture caused by burning of coal volatiles is determined by the step-by-step calculation of the equilibrium composition of combustion products and the added mass of coal volatiles. The usage of methods of equilibrium thermodynamics in this case is justified, since the rate of gas-phase reactions by the orders of magnitude exceeds (at characteristic temperatures in the reaction zone) the rate of heterogeneous reactions on the surface of particles (reactions of the release of volatiles from particles and combustion of carbon on the surface) [24]. In this connection, it is possible to consider that, on each calculation step, local thermodynamic equilibrium is established in the system. The lawful use of the equilibrium approximation is justified by the high level of concentration of energy in the considered volumes and, consequently, the high rates of the course of processes of thermochemical transformations instantly leading the reaction medium to the state of local thermodynamic equilibrium. The principle of local thermodynamic equilibrium used for the description of plasma-chemical reactions of the transformation of fuels is rather wide in the practice of mathematical simulation [8, 12, 17, 21, 25]. This assumption makes it possible to apply, for the calculation of the composition of the gas phase at transformations and associated thermal effects in reacting gas mixtures, the universal thermodynamic methods using the principle of the entropy maximum [17], and to abandon the consideration of simultaneously occurring hundreds of chemical reactions and reduce sharply the time of calculations that, in turn, makes possible the performing parametric calculations necessary for designing specific PFS.

Equations of release of coal volatiles

The temperature dependence of the rate constant of the  $j$ -th reaction is described by the first-order Arrhenius equation

$$K_j = A_j \exp[-E_{ij}/RT_l], \tag{6}$$

where  $A_j$  is the preexponential factor,  $E_{ij}$  is the activation energy,  $T_l$  is the temperature of the particle, and  $R$  is the gas constant.

Table 1 shows the numerical values of parameters of the Arrhenius equation used in the PlasmaKinTherm model. The system of Eqs. (1)–(6) was solved numerically by the Euler method.

**Table 1.** Kinetic parameters of reactions of the release of coal volatiles [16, 17]

Reaction	$\log A_j$	$E_{ij}$ , kcal/mol
$H_{2s} = H_2$	18.2	88.8
$H_2O_s = H_2O$	13.9	51.4
$CO_s = CO$	12.3	44.4
$CO_{2s} = CO_2$	11.3	32.6
$CH_{4s} = CH_4$	41.2	51.6
$C_6H_{6s} = C_6H_6$	11.9	37.4

RESULTS OF CALCULATIONS BY THE PLASMAKINTHERM PROGRAM

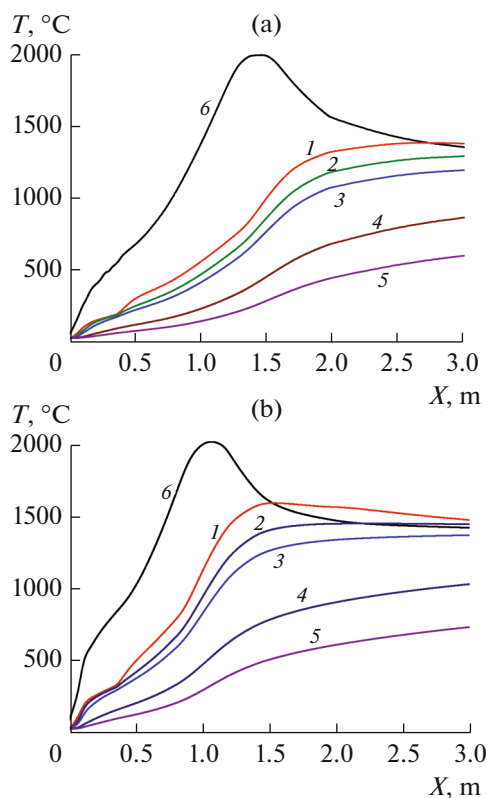
The above model was verified in [8, 21], then the numerical study of the plasma ignition of high-ash Ekibastuz black coal in the uniflow cylindrical PFS were performed (Fig. 1). Ekibastuz black coal with an ash content of 40%, volatile yield of 24%, and humidity of 5.8% has a specific heat of combustion at 4000 kcal/kg. The coal dust consumption is 1000 kg/h; its initial temperature, 27°C; internal PFS diameter, 0.2 m; and PFS length, 3 m. The chemical composition of coal is given in Table 2 [7]. The following model composition of Ekibastuz coal was used for calculations determined from data of Table 2, wt %: ash content, 40; C, 46.18; H<sub>2</sub>, 2.63; H<sub>2</sub>O, 1.84; CO, 3.95; CO<sub>2</sub>, 1.4; CH<sub>4</sub>, 0.55; and C<sub>6</sub>H<sub>6</sub>, 3.45. Concerning the material balance, the model composition of coal is equivalent to the composition of coal from Table 2 (40% mineral mass and 60% organic mass coal). The fractional composition of coal determined by sieve analysis of the coal dust is shown in Table 3 [8]. The mid-equivalent diameter of coal particles calculated from data of the table was 60 μm.

**Table 2.** Chemical composition of Ekibastuz coal, wt %

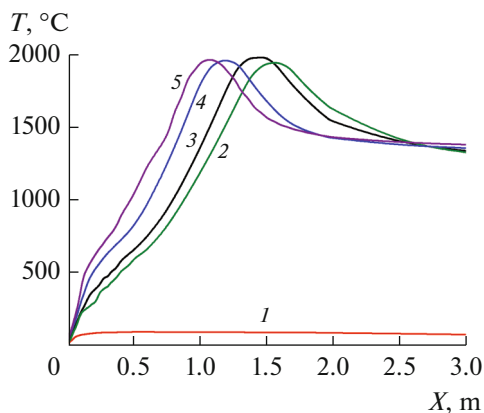
C	O	H	N	S	SiO <sub>2</sub>
48.86	6.56	3.05	0.8	0.73	23.09
Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O
13.8	2.15	0.34	0.31	0.16	0.15

**Table 3.** Fractional composition of coal dust

Fraction no.	Particle diameter, μm	Fraction mass fraction, %
1	10	10
2	30	20
3	60	40
4	100	20
5	120	10



**Fig. 3.** Change of temperature of coal fractions and the gas phase at the plasmatron power of 60 kW (a) and 100 kW (b) over the PFS length: 1–5—dimensional fractions of coal particles according to Table 3, 6—gas.



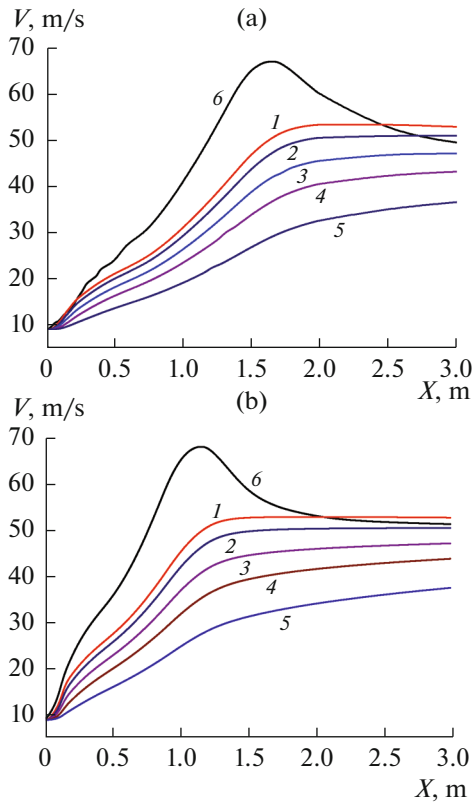
**Fig. 4.** Change of the temperature of the gas phase at the variation of power over the PFS length: 1—20 kW, 2—40, 3—60, 4—80, 5—100.

The effect of the plasmatron power on the temperature, velocity, and composition of PTPC products was studied. The calculation of ignition and combustion processes of coal was performed for the following values of the plasmatron power: 20, 40, 60, 80, and 100 kW. Results are shown in Figs. 3–7 and in Table 4. In the figures, the  $X$  axis is the distance over the PFS axis.

It follows from Fig. 3a that, at the plasmatron power of 60 kW, the maximal gas temperature ( $T_g = 1975^\circ\text{C}$ ) is sufficient for heating and ignition of coal particles in PFS. The temperature of gas and coal particles increases over the PFS length. The gas temperature goes through the maximum ( $T_g = 1975^\circ\text{C}$ ) at a length of 1.46 m, and temperatures of particles do not reach the maximum over the whole length of the channel ( $X = 3$  m), excluding the finest fraction with the size of  $10\ \mu\text{m}$ , the maximal temperature of which is reached at the length of 2.5 m ( $1381^\circ\text{C}$ ). The gas temperature in PFS is higher than the temperature of all coal fractions except for that for fraction 1, and the difference in temperatures of gas and particles at the output from the PFS is considerable, increasing with the size of coal fractions 2–5 (Table 3): 62, 157, 481, and  $742^\circ\text{C}$ , respectively. This difference is caused by the slower heating of large particles in comparison with the fine and the corresponding decreased heat from the reaction of oxidation of carbon of larger coal particles. At the output from PFS, the temperature of fraction 1 exceeds the gas temperature by the  $23^\circ\text{C}$  that is associated with the process of oxidation of carbon on the surface of particles. Thus, no thermal equilibrium of gas and particles at the considered PFS length (3 m) at the plasmatron power of 60 kW is observed, although the trend of the approach of temperatures of gas and particles is clearly seen. At the plasmatron power of 100 kW (Fig. 3b), the thermal equilibrium for gas and fractions 10 and  $30\ \mu\text{m}$  (curves 6, 1, 2 respectively) is established already at the output from PFS. For values of the plasmatron power of 40 and 80 kW, at which the temperature of the fuel ignition is achieved, the behavior of temperature curves qualitatively corresponds to that considered above.

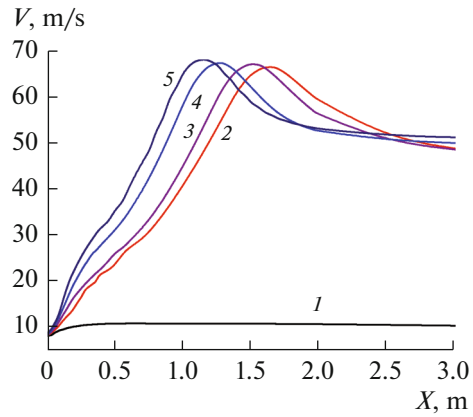
Figure 4 shows that the ignition of coal particles in PFS is provided at plasmatron powers of 40–100 kW (curves 2–5, respectively), while, at 20 kW, the gas temperature over the channel length almost does not increase, remaining on the  $110^\circ\text{C}$  level, which is clearly insufficient for fuel ignition. The ignition temperature of, e.g., coal, exceeds  $350^\circ\text{C}$  [26]. The effect of the increase in the plasmatron power on the gas temperature (Fig. 4) is manifested in the displacement of the temperature maximum of the plasma source located at the beginning of the PFS channel ( $X = 0$  m). We note that the maximal value of the gas temperature varies in a narrow interval of  $1940$ – $1975^\circ\text{C}$ . This is associated with the considerable excess of the heat from the reaction of oxidation of volatiles of coal particles and carbon over the thermal plasmatron power. In particular, the relative thermal plasmatron power at the ratio of the plasmatron power to the thermal power of obtained fuel released in the PFS volume varies from 5 to 13% for plasmatron powers of 40–100 kW, respectively.

Figure 5a shows that, at the plasmatron power of 60 kW, gas and coal particles accelerate over the PFS



**Fig. 5.** Change of the velocity of coal fractions and the gas phase at plasmatron power of 60 (a) and 100 kW (b) over the PFS length: 1–5—dimensional the fraction coal particles over Table 3, 6—gas.

length from 9 m/s to their maximal velocities. The maximal gas velocity reaches 66.3 m/s at the channel length of 1.7 m, decreasing to 48.8 m/s at the output from PFS. The curves of velocities of coal particles accelerated by gas have no extremum at the considered PFS length except for the velocity of fraction 1. The maximal velocity of coal particles of the fraction 1 reaches 52.8 m/s at the PFS length of 2.5 m. The maximum velocity of coal particles of other fractions at the output of PFS correspond to the values 50.4, 46.5, 42.7, and 36.2 m/s (curves 2–5). The velocities of gas and coal particles reached at the output from PFS, even for the largest fractions, considerably exceed the velocity of the air-petrol mixture at the output of exist-



**Fig. 6.** Change of the velocity of the gas phase at the variation of power over the PFS length: 1–20 kW, 2–40, 3–60, 4–80, 5–100.

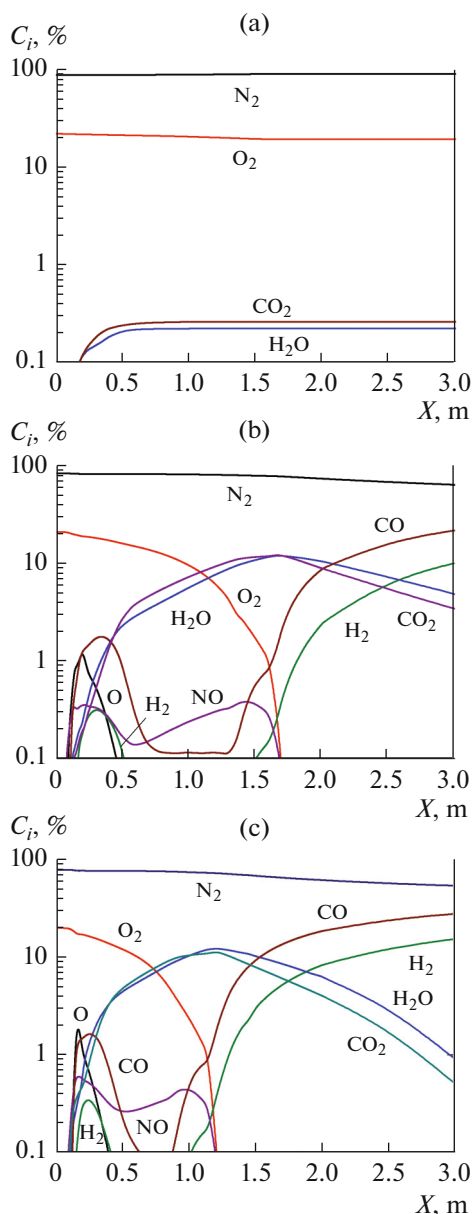
ing pulverized coal burners (as a rule, of 20–30 m/s). We note that no dynamic equilibrium between gas and coal particles at the considered PFS length (3 m) at the plasmatron power of 60 kW is achieved, though the trend of the convergence of velocities of gas and particles is seen clearly. At the plasmatron power of 100 kW (Fig. 5b) the dynamic equilibrium is observed for gas and fractions with sizes of 10 and 30  $\mu\text{m}$  (curves 6, 1 and 2, respectively) at the output from PFS. For the values of the plasmatron power of 40 and 80 kW, at which fuel ignition occurs, the behavior of velocity curves is qualitatively similar to that considered above.

Gas velocity curves are characterized by the extremum at plasmatron powers of 40–100 kW (curves 2–5, Fig. 6), while at 20 kW the gas velocity over the channel length almost does not increase remaining at the level of 11 m/s, which is associated with low temperature at this plasmatron power (Fig. 4). The effect of the increase in the plasmatron power on the gas velocity (Fig. 6) is manifested in the displacement of the velocity maximum to the plasma source. We note that the maximal value of the gas velocity changes in the narrow interval of 66.3–67.9 m/s. This is associated with the analogous behavior of temperature curves for these plasmatron powers (Fig. 4).

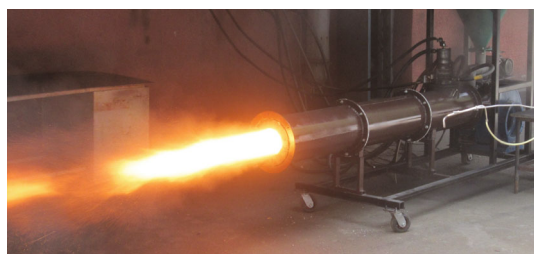
Figure 7 shows the comparison of compositions of the gas phase over the PFS length for different plasma-

**Table 4.** Comparison of experimental and calculation values of PTPC parameters of Ekibastuz coal

No.	G, kg/h	$\mu$ , kg/kg	P, kW	Experiment					Calculation				
				$T_f$ , °C	$C_i$ , vol %				$T_f$ , °C	$C_i$ , vol %			
					CO	H <sub>2</sub>	CO <sub>2</sub>	N <sub>2</sub>		CO	H <sub>2</sub>	CO <sub>2</sub>	N <sub>2</sub>
1	1000	0.6	80	1170	24.6	7.5	3.2	57.2	1429	16.3	6.8	5.1	64.6
2	1000	0.6	100	1180	27.8	9.3	2.2	55.4	1433	19.0	8.5	4.0	62.4
3	2000	0.6	200	1250	33.9	10.9	1.3	52.1	1469	24.8	12.7	1.7	57.7



**Fig. 7.** Change of the composition of the gas phase over the PFS length at plasmatron power of 20 (a), 60 (b), and 100 (c) kW.



**Fig. 8.** Experimental PFS in action, coal consumption—to 2000 kg/h.

tron powers. It follows from Fig. 7a that, at the plasmatron power of 20 kW, the process of the air-petrol mixture ignition is not initiated. The oxygen and nitro-

gen concentration corresponds to their content in the initial air over the whole PFS length, and the concentration of formed carbon dioxide ( $\text{CO}_2$ ) and water vapor ( $\text{H}_2\text{O}$ ) does not exceed 0.3%.

Figures 7b and 7c indicate the ignition of the air-petrol mixture. The behavior of concentrations of PTPC is of products qualitatively similar for both plasmatron powers. Concentrations of flammable components ( $\text{CO}$  and  $\text{H}_2$ ) are characterized by the complicated dependence over the PFS length. At the initial channel region (0.2–0.5 m) slight extrema of concentration curves are observed: 0.2% ( $\text{H}_2$ ) and 1.8% ( $\text{CO}$ ). Extrema of atomic oxygen ( $\text{O}$ ) and nitrogen monoxide ( $\text{NO}$ ) concentrations can be seen in the same region. Since the separation of volatiles of coal is described by the Arrhenius equation (6), and their subsequent oxidation in the gas phase, by laws of chemical thermodynamics, extrema of these components in the initial region are associated with the following. The low level of temperatures in the initial channel region (Fig. 3) does not provide the termination of reactions of the oxidation of released volatiles. Further, at the increase in temperature in the channel, the concentrations of flammable components increase, reaching at the output from PFS in total 30.9 and 43.7% for plasmatron powers of 60 and 100 kW, respectively.

The comparison of results of bench studies and of test-and-production tests of processes of the plasma ignition of Ekibastuz coal [6, 7, 20, 22] with results of the calculation is given in Table 4. As criteria for the comparison, the same initial data were chosen for the calculation and experiment (the coal consumption, the plasmatron power, and the dust concentration in the air-petrol mixture). Here,  $G$  is the coal consumption,  $P$  is the plasmatron power,  $\mu$  is the dust concentration in the air-petrol mixture,  $T_f$  is the torch temperature at the output from PFS, and  $C_i$  is the concentration of gas-like components at the output from the channel. Figure 8 shows in action the experimental PFS with a length of 2.5 m and internal diameter of 0.2 m. The electric arc plasmatron of the constant current with the possibility for regulating the power from 80 to 200 kW was assembled on PFS. The distance from the plasmatron to the exit from PFS is 2 m. In experiments, the temperatures were measured using a digital pyrometer in the nucleus of the torch outcoming from PFS (Fig. 8), and probes for the gas analysis were collected by a ceramic probe at the output from PFS. The divergence between experimental and calculation temperature values of the process depends on the plasmatron power and is in the interval of 17–22% for plasmatron powers of 80–200 kW. The divergence between experimental and calculation values of concentrations of flammable components ( $\text{CO} + \text{H}_2$ ) also depends on the plasmatron power and is in the interval of 16–28%. It follows from the table that the divergence between experimental and calculation values of the main parameters of the PTPC process decreases with an increase in plas-

matron power. Thus, the divergence of the calculation with the experiment is observed relatively small for plasma processes not exceeding 22% for the temperature, and 28% for the synthesis-gas concentration. Results of the comparison confirm the validity of assumptions accepted at the development of the model and make it possible to use the model and PlasmaKinTherm program for designing plasma-fuel systems successfully tested on pulverized coal TPS [7].

## CONCLUSIONS

The model of the plasma thermochemical preparation to the combustion of pulverized coal and the PlasmaKinTherm program were intended for the calculation of plasma-fuel systems and the revelation of regularities of the interaction between air-petrol mixture with a plasma flame at different initial conditions of the process. Kinetic and thermodynamic methods in the model are combined, describing the PTPC process that makes it possible to obtain distributions of temperatures and velocities of gas and coal particles and concentrations of PTPC products over the PFS length.

The regime PFS parameters as a function of the plasmatron power were studied numerically. The changes of temperatures and velocities of gas and coal particles, and also concentrations of PTPC products over the PFS length were found. Calculations showed that the range of plasmatron powers of 40–100 kW reaches stable ignition of high-ash coal at an air-petrol mixture consumption of 1667 kg/h. This is confirmed by the high level of temperatures (to 1470°C) and concentrations of flammable components (to 44%) at the output from PFS.

At the increase in the plasmatron power, the maximum of temperatures and velocities of PTPC products are displaced upstream (in the direction of the plasma source). The maximal values of temperatures and velocities change in the narrow range and almost do not depend on the plasmatron power.

The comparison of the results of calculations with experimental data confirmed the validity of assumptions accepted at the development of the model that makes it possible to use the model and the PlasmaKinTherm program for designing of plasma-fuel systems.

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## REFERENCES

1. BP Energy Outlook 2035, February 2015. <http://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2015/bp-energy-outlook-2035-booklet.pdf>
2. Key World Energy Statistics 2012: International Energy Agency. OECD/IEA, 2012. [www.iea.org](http://www.iea.org)
3. Antropov, A.P., Batenin, V.M., and Zaichenko, V.M., *High Temp.*, 2015, vol. 53, no. 1, p. 124.
4. Vasilieva, O.B., Kumkova, I.I., Kuznetsov, V.E., Rutberg, A.F., Safronov, A.A., and Shiryaev, V.N., *High Temp.*, 2015, vol. 53, no. 4, p. 470.
5. Messerle, V.E. and Ustimenko, A.B., Plasma-fuel systems for environment enhancement and processing efficiency increasing, in: *Computational Problems in Engineering. Lecture Notes in Electrical Engineering*, Mastorakis, N. and Mladenov, V., Eds., Interlaken, Switzerland: Springer, 2014, vol. 307, p. 271.
6. Messerle, V.E., Karpenko, E.I., Ustimenko, A.B., and Lavrichshev, O.A., *Fuel Process. Technol.*, 2013, vol. 107, p. 93.
7. Messerle, V.E., Karpenko, E.I., and Ustimenko, A.B., *Fuel*, 2014, vol. 126, p. 294.
8. <http://ljubljuknigi.ru/>
9. Drouet, M.G., *Rev. Gen. Electr.*, 1986, no. 1, p. 51.
10. Blackburn, P.R., *Energy*, 1980, vol. 4, no. 3, p. 98.
11. Bulat, A., Voloshyn, O., and Zhevzhik, O., in *Mining of Mineral Deposits*, Pivnyak, G., Bondarenko, V., Kovalyev'ska, I., and Illiashov, M., Eds., London: Taylor & Francis, 2013, ch. 8, p. 39.
12. Alcock, C.B., *Thermochemical Processes: Principles and Models*, Butterworth-Heinemann, 2000, p. 384.
13. Brown, R.C., *Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power*, San Francisco, CA: Wiley, 2011.
14. Zhukov, M.F. and Zasyepkin, I.M., *Thermal Plasma Torches: Design, Characteristics, Applications*, Cambridge: Cambridge Int. Sci., 2007.
15. *Plasma Assisted Combustion, Gasification, and Pollution Control*, vol. 1: *Methods of Plasma Generation for PAC*, Matveev, I.B., Ed., Denver, CO: Outskirts, 2013.
16. Kalinenko, R.A., Levitski, A.A., Messerle, V.E., Polak, L.S., Sakipov, Z.B., and Ustimenko, A.B., *Plasma Chem. Plasma Process.*, 1993, vol. 13, no. 1, p. 141.
17. Gorokhovski, M., Karpenko, E.I., Lockwood, F.C., Messerle, V.E., Trusov, B.G., and Ustimenko, A.B., *J. Energy Inst.*, 2005, vol. 78, no. 4, p. 157.
18. Askarova, A.S., Messerle, V.E., Ustimenko, A.B., Bolegenova, S.A., Maksimov, V.Yu., and Gabitova, Z.Kh., *High Temp.*, 2015, vol. 53, no. 3, p. 445.
19. Askarova, A.S., Bolegenova, S.A., Maksimov, V.Yu., Bekmukhamet, A., Beketaeva, M.T., Gabitova, Z.Kh., *High Temp.*, 2015, vol. 53, no. 5, p. 751.
20. Yankosky, Z., Lockwood, F.C., Messerle, V.E., Karpenko, E.I., and Ustimenko, A.B., *Thermophys. Aeromech.*, 2004, vol. 11, no. 3, p. 461.



21. Messerle, A.V., *High Energy Chem.*, 2004, vol. 38, no. 1, p. 35.
22. Karpenko, E.I., Zhukov, M.F., Messerle, V.E. Buyantuev, S.L., D'yakov, A.F., and Peregodov V.S., *Nauchno-tekhnicheskie osnovy i opyt ekspluatatsii sistem plazmennogo vosplamneniya uglei (bezmazutnaya ras-topka kotlov i stabilizatsiya gorennya pyleugol'nogo fakela)* (Scientific and Technical Foundations and Experience in the Operation of Plasma Ignition Systems for Coals (Oil-Free Firing of Boilers and Stabilization of Combustion of a Pulverized-Coal Torch)), Novosibirsk: Nauka, 1998.
23. Sakipov, Z.B., Messerle, V.E., and Ibraev, Sh.Sh., *Elektrotermokhimicheskaya podgotovka uglei k szhigan-iyu* (Electrothermochemical Preparation of Coals for Incineration), Almaty: Nauka, 1993.
24. Karpenko, E.I., Messerle, V.E., and Trusov, B.G., *Thermophys. Aeromech.*, 1995, vol. 2, no. 3, p. 245.
25. Matveev, I.B., Washcilenko, N.V., Serbin, S.I., and Goncharova, N.A., *IEEE Trans. Plasma Sci.*, 2013, vol. 41, no. 12, p. 3195.
26. Kiselev, N.A., *Kotel'nye ustanovki* (Boiler Installations), Moscow: Vysshaya Shkola, 1979.

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