

Plasma ignition of solid fuels at thermal power plants. Part 1. Mathematical modeling of plasma-fuel system *

V.E. Messerle¹⁻³, A.B. Ustimenko^{1,3,4}, and A.K. Tastanbekov³

¹*Institute of Combustion Problems, Almaty, Kazakhstan*

²*Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia*

³*Al-Farabi Kazakh National University, Almaty, Kazakhstan*

⁴*LLP SDTC "Zhalyn", Almaty, Kazakhstan*

E-mail: ust@physics.kz

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One of the promising ignition technologies is the plasma thermochemical preparation of pulverized coal for combustion using plasma-fuel systems (PFS). This technology allows increasing the efficiency of fuel application and improving the environmental performance of thermal power plants, as well as eliminating fuel oil, used traditionally to ignite boilers and stabilize combustion of a pulverized coal flame. This paper presents the numerical results on ignition of a pulverized coal flame in a PFS. The plasma-fuel system is designed for oil-free start-up of boilers and stabilization of flame combustion and this is a pulverized coal burner equipped with a plasma torch. In addition to plasma torch electric power and ash content in coal, one of the main operating parameters of PTS, which ensures fuel ignition, is concentration of coal dust in the aeromixture, which can be varied over a wide range. The conditions of fuel mixture ignition in the PFS were determined for three above-mentioned operating parameters of PFS using the PlasmaKinTherm program, which combines kinetic and thermodynamic methods for calculating the processes of motion, heating, and thermochemical transformations. The calculations were performed for a cylindrical PFS with a diameter of 0.2 m and a length of 2 m. The coal consumption was 1000 kg/h. The conditions of fuel mixture ignition in the PFS were studied depending on the plasma-torch power (20–100 kW), coal concentration in the fuel mixture in the range from 0.4 to 1.8 kg of coal per 1 kg of air, and also for three different values of coal ash content (20, 40, and 70 %). The main regularities of the process of plasma thermochemical preparation of fuel for combustion have been revealed.

Keywords: coal, aeromixture, plasma-fuel system, ignition, numerical experiment.

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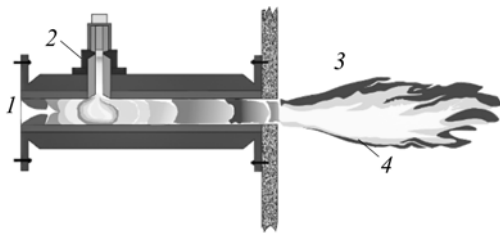
Introduction

In recent years, a steady increase in consumption of electrical and thermal energy is observed all over the world. According to the BP Statistical Review of World Energy for 2020 [1], over the past 10 years, the global increase in electricity generation has amounted to 25 %. Despite the rapid development of renewable energy sources, their share in the global energy balance remains about 10 %, and the bulk of energy (62.8 %) is generated at thermal power plants that burn fossil fuels. By 2035, the share of solid fuel in the production of electricity will remain quite high (28 %) [2, 3]. The high share of using solid fuels in the energy sector, especially due to the gas crisis of 2021, requires the development of more efficient and environmentally friendly technologies for their combustion.

In addition to traditional burners and technologies of fuel combustion activation [4, 5], the plasma technologies for fuel processing are known [6–13]. One of the promising ignition technologies is plasma thermochemical preparation of pulverized coal fuel for combustion (PTPC) [14–16] using plasma fuel systems (PFS). The scheme of the most common PFS is shown in Fig. 1. The PTPC technology allows an increase in the efficiency of solid fuel combustion and improvement of the environmental performance of thermal power plants (TPPs), as well as complete avoidance of application of additional highly reactive fuel (fuel oil or gas), traditionally used to light boilers and to stabilize the combustion of a pulverized coal flame. The PTPC technology consists in heating an aeromixture of coal dust and air by electric arc plasma to the temperature of coal devolatilization and partial gasification of the coke residue. Thus, in PFS, a highly reactive two-component fuel (HRTCF) of given composition (combustible gas and coke residue) is obtained from original coal. Being mixed with air in the boiler furnace, HRTCF ignites and burns steadily without the use of additional highly reactive fuel.

In contrast to well-known studies on thermochemical preparation of solid fuels for combustion [17, 18] and plasma ignition of solid fuels in a boiler furnace [8, 9], the PTPC technology is carried out in the PFS volume using a plasma torch with a temperature of 5000–6000 K, affecting the aeromixture directly [19–21]. The use of a plasma source allows significant acceleration of the processes of thermochemical transformation of solid fuel and oxidizer into HRTCF. To design a PFS, it is necessary to use physical and mathematical models of heat and mass transfer processes and thermochemical transformations of fuel and oxidizer in PFS. This paper presents the first part of results of long-term research aimed at solving the actual problem of using the PTPC technology at thermal power plants, numerical simulation of PTPC processes and choosing the optimal PFS operating parameters. The second part will present the results of 3D modeling of a 300 MW pulverized coal furnace equipped with PFS and compare them with experimental data.

1. Application of PTPC technology at TPPs



The developed PTPC technology and PFS for its implementation were successfully

Fig. 1. Scheme of direct-flow PFS.

1 — aeromixture, 2 — plasma torch,
3 — boiler furnace, 4 — flame of high-reactive
two-component fuel.

tested in 1989 at the Ust-Kamenogorsk CHPP (Kazakhstan) and the Mironovskaya State District Power Plant (Ukraine); in 1995, they were tested at the Baodiyskaya TPP (China); in 1996, the tests were carried out at the Alma-Ata CHPP-3 (Kazakhstan), and in 2011, they were performed at the Alma-Ata CHPP-2 (Kazakhstan) [22–25]. In 1995, works on the development and implementation of PFS got a powerful boost in Russia; they began to be used at the Gusinozerskaya State District Power Plant (Gusinozersk) [22–24]. In total, during the period

Table 1
Industrial testing of plasma-fuel systems at thermal power plants

Country	No.	TPP location	Type and amount of boilers with PFS	Steam capacity of one boiler, t/h	Number of PFSs installed at TPPs, pcs.
Russian Federation	1	Gusinozersk SDPP (Gusinozersk, 1994–1995)	TRE-215 — 2 boilers BKZ-640 — 2 boilers	670 640	8 7
	2	Cherepetskaya SDPP (Suvorov, 1997)	TP-240 — 1 boiler	240	4
	3	Neryungri SDPP (Neryungri, 1997)	Water boiler KVTH-100 — 1 boiler	Heat rating 116 MW	2
	4	Partizansk SDPP (Partizansk, 1998)	TP-170 — 1 boiler	170	2
	5	Ulan-Ude CHPP-2 (Ulan-Ude, 1997)	TPE-185 — 1 boiler	160	2
	6	Khabarovsk CHPP-3 (Khabarovsk, 1998)	TPE-216 — 1 boiler	670	4
Ukraine	7	Kurakhovo TPP (Kurakhovo, 1998–1999)	TP-109 — 1 boiler	670	4
	8	Mironovskaya SDPP (Mironovo, 1989)	TP-230 — 1 boiler	230	2
Kazakhstan	9	Almatinskaya SDPP (Alma-Ata, 1996)	BKZ-160 — 1 boiler	160	2
	10	Ust-Kamenogorsk CHPP (Ust-Kamenogorsk, 1989)	TsKTI-75 — 2 boilers	75	4
	11	Almaty CHPP-2 (Almaty, 2011)	BKZ-420 — 1 boiler	420	6
Mongolia	12	Ulaanbaatar CHPP-4 (Ulaanbaatar, 1994)	BKZ-420 — 8 boilers	420	16
	13	Erdenet CHPP (Erdenet, 1995)	BKZ-75 — 1 boiler	75	1
China	14	Baoji TPP (Baoji, 1995)	Ch-200 — 1 boiler	200	3
	15	Shaoguan TPP (Shaoguan, 1999–2001)	F-220/100-W — 1 boiler, K-75 — 1 boiler	230 75	4 1
	16	TPP golden mountain (Shenyang, 2007)	BG-75/39-M — 1 boiler	75	2
	17	Ganshun TPP (Shansi, 2009)	BG-950/150 — 1 boiler	950	4
North Korea	18	Eastern Pyongyang TPP (Pyongyang, 1993)	E-210 — 1 boiler	210	3
Slovakia	19	Voyany TPP (Velki Kapushany, 2000)	TAVICI — 1 boiler	350	2
Serbia	20	Nikola Tesla Beograd TPP (Obrenovac, 2007)	TP-210 — 1 boiler	650	16

under consideration, PFSs were installed and tested in Russia, Kazakhstan, Ukraine, Korea, China, Slovakia, Serbia, and Mongolia on 31 boilers with a steam capacity from 75 to 950 t/h, equipped with various coal dust preparation systems (direct blow and with intermediate bunker) and various types of pulverized coal burners (direct-flow, muffle and vortex ones) (see

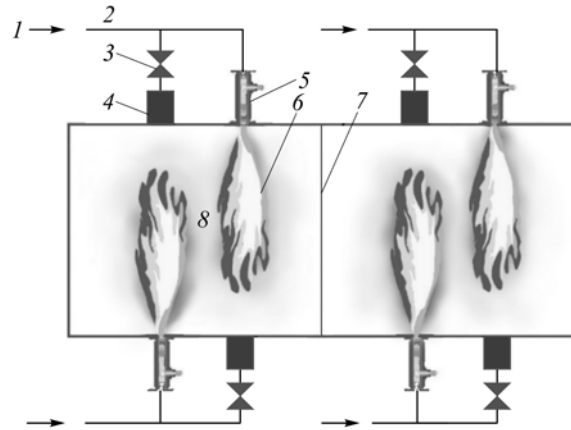


Fig. 2. Diagram of the TPE-215 boiler equipped with four PFSs (top view):
 1 — aeromixture, 2 — dust pipe, 3 — shut-off gate, 4 — main direct-flow pulverized coal burner, 5 — PFS,
 6 — flame of high-reactive two-component fuel, 7 — division wall, 8 — boiler half-furnace.

Table 1). When testing PFS, all types of thermal coals were burned: brown, black, anthracite and their mixtures with a volatile content from 4 to 50 %, an ash content from 15 to 56 % and a calorific value from 1600 to 6200 kcal/kg.

The most powerful in Russia TPE-215 boilers equipped with PFS at Gusinoozerskaya SDPP (Table 1) are still operating in the regime of boiler starting from any thermal state. The scheme of the furnace of these boilers is shown in Fig. 2. It can be seen that four main burners have been replaced by PFS. The combustion chamber of the boiler is divided by a division wall into two half-furnaces. The boiler burns Tugnui coal with an ash content of 14.3 % with a calorific value of 22 500 kJ/kg. Since 1995, 120 000 tons of fuel oil have been saved on boiler starting with PFS. This resulted in a reduction in emissions of nitrogen oxides (NO_x) and sulfur (SO_x), carbon monoxide (CO) and vanadium pentoxide (V_2O_5) by a total of 325 000 tons.

An example of implementation of PFS in Kazakhstan at the Almaty TPP-2 (Table 1) is presented in Fig. 2 [25]. During testing, the temperature of PFS flames was 1050–1070 °C (Fig. 3). It was recorded that the rate of an increase in the hot air temperature in the regime of boiler starting from a cold state corresponded to the rate of a temperature increase during fuel oil starting of the boiler unit (1.5 degrees per minute).

Recently, China, Turkey, Korea, India, and Kazakhstan demonstrate significant interest

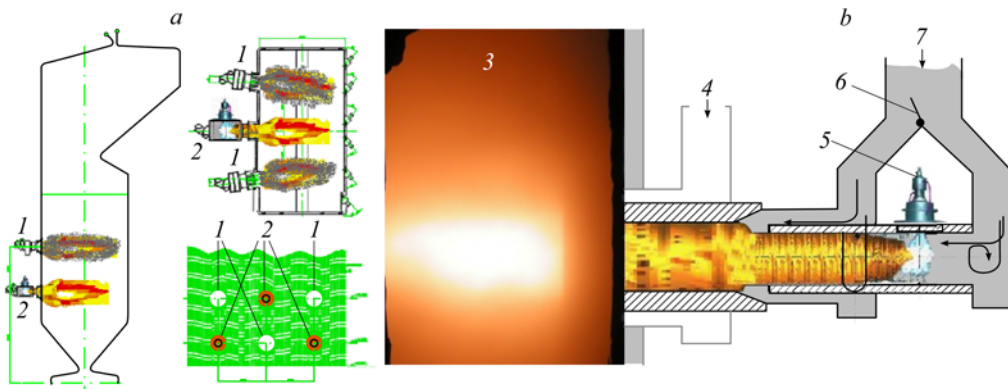
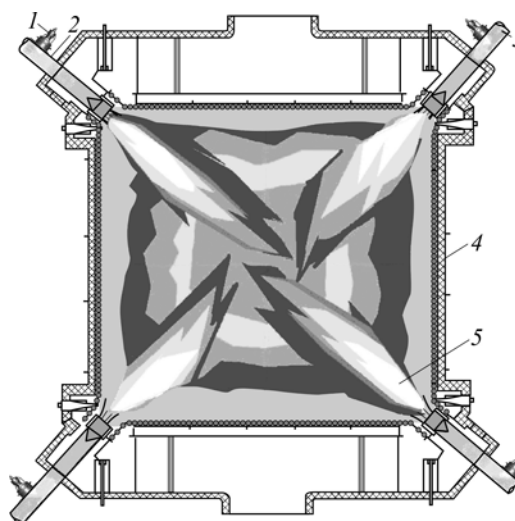


Fig. 3. PFS and scheme of their arrangement on BKZ-420 boiler of Almaty CHPP-2.
 1 — standard vortex double-flow pulverized coal burner, 2 — PFS, 3 — burner,
 4 — secondary air, 5 — plasma torch, 6 — gate, 7 — aeromixture.

Fig. 4. Layout chart of PFS on BKZ-160, Ch-200, F-220/100-W, BG-75/39-M, and BG-950/150 boilers (Table 1):

1 — plasma torch, 2 — PFS, 3 — aeromixture, 4 — boiler furnace, 5 — flame of high-reactive two-component fuel (HRTCF).



in the use of PFS at pulverized coal thermal power plants: in these countries, the share of pulverized coal thermal power plants in the energy sector is 87, 47, 50, 70, and 85 %, respectively, [22–24].

In China, plasma technology for starting boilers and stabilizing combustion of a pulverized coal flame is at the stage of large-scale industrial application on pulverized coal boilers with electric power from 200 to 1000 MW. For the first time in China, PFSs (with a combined plasma torch designed by the Kazakh Research Institute of Energy and the Institute of Thermophysics SB RAS) were tested at the Ch-200 boiler of the Baodiy TPP (Table 1) [23]. The Yantai Longyuan Electric Power Technology Co., Ltd (China), which is part of China Guodian Corporation, having upgraded these PFSs, placed them on more than 850 pulverized coal-fired boilers in China with installed capacity of more than 400 million kW [25–28]. The total savings in heating oil at pulverized coal-fired power plants through the use of PFS reached 6 million tons worth 25 billion yuans. In China, more than 20 oil-free thermal power plants using plasma starting technology have already been successfully implemented. The layout of corner PFS arrangement in pulverized coal-fired boilers at TPPs, widely used in both Kazakhstan and China, is presented in Fig. 4.

The use of PFS at pulverized coal-fired power plants increases the efficiency of ignition and combustion of power-generating coal, eliminates the use of scarce fuel oil for starting and lighting the boiler, reduces unburned carbon loss, and also provides ample opportunities for automating the process of starting boilers, stabilizing the combustion of a pulverized coal flame, and reducing harmful emissions. Thus, the main element of implementing the PTPC technology is PFS, the study of which is of paramount importance. Given the laboriousness of full-scale tests of plasma technology, numerical simulation of PTPC processes is of particular relevance for choosing the optimal PFS parameters and predicting the efficiency of their use at pulverized coal thermal power plants.

2. Verification of PlasmaKinTherm program and numerical investigation of PFS

Numerical study of PFS is of independent scientific importance, and the obtained output parameters of PFS can be used as input data for three-dimensional modeling of boiler furnaces equipped with PFS.

Numerical studies of a direct-flow PFS were carried out using the PlasmaKinTherm program [29]. The PlasmaKinTherm program was developed based on the Plasma-Coal and TERRA computer programs [30, 31]. It combines the kinetics of volatile emission and oxidation of coke residue carbon with the thermodynamic approach to the calculation of plasma thermochemical transformations of products of primary destruction of coal in the gas phase. The proposed model describes a two-phase (coal particles and air) chemically reacting flow propagating in a channel with an internal heat source (electric arc). Pre-mixed particles and gas enter the PFS, which is a cylindrical channel with a plasma torch. In accordance with

the kinetic mechanism of the process, gas and solid coal particles are heated by plasma to the temperature of devolatilization into the gas phase [30]. The model is based on the assumption of quasi-stationary and one-dimensional character of the process, coal particles are considered to be isothermal, and ash (mineral mass) is an inert component. It is also assumed that particles do not interact with each other. The composition of coal in the model is represented by its organic and mineral matter. The organic matter of coal is determined by combination of volatile substances (CH_4 , C_6H_6 , CO , H_2 , H_2O , CO_2) and carbon. The process of devolatilization is limited by the kinetics of coal particle heating. Volatile substances released into the gas phase mix and react with the plasma torch. The local thermodynamic equilibrium model implemented using the TERRA software [21] is used to calculate reactions in the gas phase. This approach allows combining the kinetics of volatile emission and oxidation of coke residue carbon with the thermodynamic method for calculating plasma thermochemical transformations of primary products of coal destruction in the gas phase. The PlasmaKinTherm has been verified for PFS engineering calculations [29, 32].

The processes of plasma ignition of solid fuel in PFS are described using the system of ordinary differential equations given below.

The equation of gas phase momentum conservation is as follows:

$$u \frac{d(\rho u)}{dx} = \sum_{l=1}^L F_l, \quad (1)$$

where $F_l = C_{Dl} \frac{\rho(u-u_l)^2}{2} \pi R_l^2 N_l$ is the force of aerodynamic drag of a particle with size fraction l , C_{Dl} is the particle drag coefficient, ρ and u are density and velocity of the flow gas phase, R_l is the radius of coal particles, N_l is the number of particles of fraction l per a mass unit.

The equation of momentum conservation of coal particles of a certain fraction is:

$$m_l u \frac{du_l}{dx} = F_l, \quad (2)$$

where u_l is the velocity of particles of fraction l .

The equation of gas phase energy conservation is:

$$\rho u \frac{dl}{dx} = \sum_{i=1}^L \rho u \frac{dn_i}{dx} I_i - \sum_{l=1}^L \Delta Q_l + \Delta Q_p + \Delta Q_r, \quad (3)$$

here the term $\Delta Q_l = \alpha_l (T_g - T_l) 4\pi R_l^2 N_l$ describes heat transfer between gas and particles, ΔQ_p is contribution of plasma torch thermal energy, ΔQ_r is the thermal effect of coal devolatilization reactions, I and T_g are gas phase enthalpy and temperature, respectively, n_i and I_i are concentration and enthalpy of the i th component of the gas phase, α_l is the heat transfer coefficient of particles.

The equation of conservation of coal particle energy:

$$\rho u \frac{dI_l}{dx} = \Delta Q_l + \Delta Q_C. \quad (4)$$

where ΔQ_C is the thermal effect of carbon combustion reaction.

The drag coefficient for particle movement under the Stokes force influence is calculated depending on the Reynolds number (Re) for the velocity of relative movement using

the following expression:

$$C_{Dl} = \begin{cases} \frac{24}{Re_l} (1 + 0.15 Re_l^{0.687}), & Re_l = \frac{2(u - u_l)R_l}{\nu} < 1000, \\ 0.44, & Re_l \geq 1000. \end{cases}$$

The heat transfer coefficient α_l is determined using the criterial heat transfer equation, valid for the laminar flow around a sphere:

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

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

The equation for the flow rates of aeromixture and plasma-forming gas is as follows:

$$\frac{dm_{air}}{dt} + \frac{dm_{plasma}}{dt} = \frac{\rho u \pi d_c^2}{4}, \quad (5)$$

where $\frac{dm_{air}}{dt}$ and $\frac{dm_{plasma}}{dt}$ flow rates of aeromixture (primary air + coal) and plasma-forming gas (air), respectively, d_c is the channel diameter.

The energy contribution to the process of heating the aeromixture gas phase due to combustion of coal volatile components is determined by the step-by-step calculation of the equilibrium composition of combustion products and the added mass of coal volatile components.

The equations of kinetics of coal devolatilization are determined by dependence of the rate constant of the j th reaction of coal devolatilization on temperature, which is described by the Arrhenius equation of the first order:

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

where A_j is the preexponential factor, E_{ij} is the activation energy, T_l is the temperature of a particle, R is the gas constant. Numerical values of parameters of the Arrhenius equation used in the PlasmaKinTherm model to describe coal devolatilization are presented in Table 2. Carbon burn-out is also calculated using the Arrhenius equations. It is assumed that all carbon is oxidized to CO_2 by the reaction $C + O_2 = CO_2 + \Delta Q_C$. Oxygen present in the ash elements does not participate in coal ignition and combustion.

The system of ordinary differential equations (1)–(6) was solved numerically by the Euler method. The initial conditions are the temperatures of air and coal dust particles at the PFS inlet. The initial gas flow velocity u^* is determined from the equation of aeromixture and plasma-forming gas flow rates (5). It is assumed that the shape of particles is spherical and they are of the same size within one fraction.

Table 2

Kinetic parameters of reactions of coal devolatilization [30, 31]

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

The results of rig and pilot tests of plasma ignition of Ekibastuz coal [10, 14–16, 33] with calculation results are compared in Table 3. The same initial data for calculation and experiment (coal consumption, plasma-torch power, and dust concentration in the aeromixture) were chosen as the comparison criteria. The following designations are used in the Table: G is coal consumption, P is the plasma-torch power, μ is coal dust concentration in the aeromixture, T_f is the flame temperature at the PFS outlet, C_i is concentration of gaseous components at the channel outlet. An experimental PFS with a length of 2.5 m and an inner diameter of 0.2 m is shown in Fig. 5. The PFS is equipped with a DC electric arc plasma torch with adjustable power from 80 to 200 kW. The distance from the plasma torch to the PFS outlet is 2 m. The coal consumption through the PFS varies from 500 to 2000 kg/h. In experiments, the temperatures were measured in the core of the flame from the PFS using a digital pyrometer, and samples for the gas analysis were taken with a ceramic probe at the PFS outlet. An Ircon Ultrimax Plus UX10P pyrometer with a resolution of 1 °C was used to measure temperatures from 600 to 3000°C (873–3273 K). The measurement error depends on the temperature range and makes up $\pm 0.5\%$ of the measured value for the temperatures of up to 1500 °C (1773 K), it is $\pm 1\%$ for the temperatures of 1500–2000 °C (1773–2273 K), and it increases to $\pm 2\%$ for the temperatures above 2000 °C (2273 K). The composition of gases at the PFS outlet was determined using a Khromatek-Gazokhrom-2000 gas chromatograph. The absolute error in measuring concentration of gaseous products was 10^{-2} vol. %. The electrical parameters of the plasma torch (current and voltage) were measured with an M-381 ammeter and a M-381 voltmeter with measurement ranges of 0–1500 A and 0–600 V, respectively. The division value of the ammeter scale was 25 A, and the voltmeter scale was 20 V. The accuracy class of the instruments was 1.5. The relative error in measuring the plasma-torch power did not exceed 2.5 %.

The discrepancy between the experimental and calculated values of the process temperature depends on the plasma-torch power and is in the range of 17–22 % for the plasma torch power of 80–200 kW. The discrepancy between the experimental and calculated

Table 3

Comparison of experimental and calculated values of PTPC parameters of Ekibastuz coal

No.	G , kg/h	μ , kg/kg	P , kW	Experiment					Calculation				
				T_f , C	C_i , vol. %				T_f , °C	C_i , vol. %			
					CO	H ₂	CO ₂	N ₂		CO	H ₂	CO ₂	N ₂
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

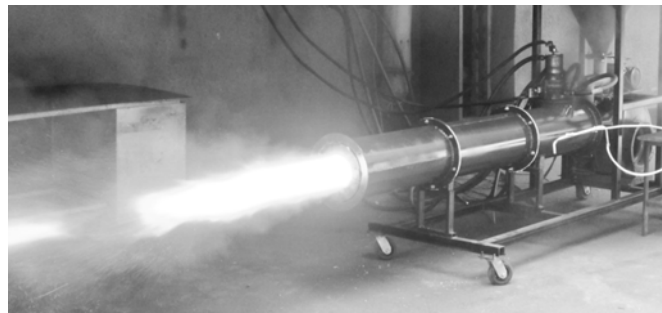


Fig. 5. Experimental PFS in operation.
Coal consumption of up to 2000 kg/h.

concentrations of combustible components (CO + H₂) also depends on the plasma-torch power and is in the range of 16–28 %. We should note that according to calculated data presented in Table 3, 100 % gas composition is not observed, which is explained by the presence of steam with concentration of 3–7 % in the products. During the gas analysis, steam condenses in the sampler and is not detected by the gas analyzer. It follows from the Table that the discrepancy between experimental and calculated values of the main parameters of the PTPC process decreases with an increase in the plasma-torch power. Taking into account that the temperature and composition of the gas phase are calculated in the PlasmaKinTherm program by the method that combines kinetics of coal devolatilization and thermodynamic approach to determining the composition of the gas phase, we can conclude that the discrepancy between the calculation and experiment is associated with a deviation from the thermodynamic equilibrium in the PFS. Thus, the discrepancy between calculation results and experimental data observed under these conditions, which does not exceed 22 % for the synthesis gas temperature and 28 % for its concentration, can be considered acceptable. The results of comparison confirm the validity of assumptions made in the development of the model and allow the application of the model and the PlasmaKinTherm program for calculation and design of PFS, successfully tested on pulverized coal TPP.

The calculations carried out using the PlasmaKinTherm program are aimed at the study of the process of coal plasma ignition in PFS, as well as at the study of the effect of the plasma-torch power, ash content of coal, and concentration of coal dust in the aeromixture on the temperature and composition of the resulting PTPS products. An indicator of stable aeromixture combustion at the PFS outlet is the high content of combustible gases (CO, H₂) exceeding 15 %, as well as gas heating to a self-ignition temperature (> 800 °C) when interacting with air in the boiler furnace.

To calculate numerically the process of plasma ignition of coal, high-ash Ekibastuz coal, which is the main energy fuel at thermal power plants in Kazakhstan and the adjacent part of Russia, was chosen. The chemical composition of coal is presented in Table 4. Ekibastuz coal with an ash content of 40 %, a volatile yield of 24 %, and a moisture content of 5.8 % has a specific calorific value of 4000 kcal/kg. The aeromixture flow rate was 2667 kg/h (coal dust flow rate was 1000 kg/h and air flow rate was 1667 kg/h), the initial temperature of aeromixture was 27 °C, the inner diameter of the PFS was 0.2 m, and the PFS length was 3 m. The average size of coal particles was taken as 60 μm, which corresponded to the average particle size of industrial grinding at thermal power plants.

The effect of plasma-torch power on the temperature, velocity, and composition of the PTPS products was studied. Calculations of solid fuel ignition and combustion were performed for the following values of the plasma-torch power: 20, 40, 60, 80, and 100 kW.

As can be seen from Fig. 6, ignition of coal particles in the PFS is ensured within the plasma-torch power range of 40–100 kW (curves 2–5, respectively), while at the plasma-torch power of 20 kW, the gas temperature along the channel length does not change, remaining at the level of 110 °C, which is clearly not enough to ignite solid fuel. The effect

Table 4

Chemical composition of Ekibastuz coal, mass. %

A ^c , %	C	O ₂	H ₂	N ₂	S	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O
40	48.86	6.56	3.05	0.8	0.73	23.09	13.8	2.15	0.34	0.31	0.16	0.15

A^c — ash content per dry weight of coal. High heat value of coal per dry weight —16740 kJ/kg, moisture content of coal —5.8 %, volatiles yield —24 %.

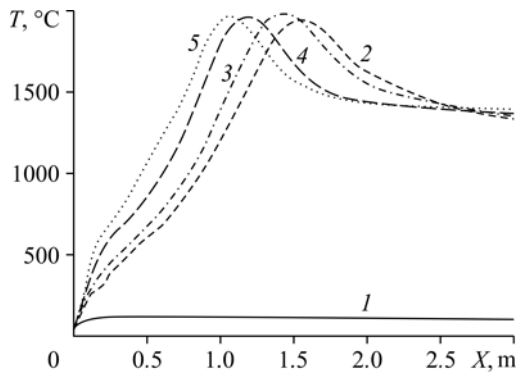


Fig. 6. A change in the gas phase temperature along PFS with power variation from 20 to 100 kW.

Power: 20 (1), 40 (2), 60 (3), 80 (4), 100 (5) kW.

of an increase in the plasma-torch power on the gas temperature is demonstrated by a shift of the temperature maximum to the plasma source located at the beginning of the PFS channel ($X = 0$ m). It should be noted that a change in the temperature of particles is qualitatively similar to a change

in the gas phase temperature.

According to Fig. 7, the gas velocity curves are characterized by extrema in the range of plasma-torch power of 40–100 kW (curves 2–5, respectively), while at the plasma-torch power of 20 kW, the gas phase velocity along the PFS length almost does not change and amounts to 11 m/s, which relates to a low temperature level at this plasma-torch power (Fig. 6). The influence of the plasma-torch power on the gas velocity (Fig. 7) consists in the displacement of the velocity maximum towards the plasma source located at the beginning of the PFS channel ($X = 0$ m). We should note that the maximum values of gas phase velocity vary in a narrow range and amount to 66.3–67.9 m/s. The behavior of the velocity curves is similar to the behavior of the temperature curves (Fig. 6).

A change in the gas phase composition along the PFS length at the plasma-torch power of 60 kW is shown in Fig. 8. At the plasma-torch power of 100 kW, the behavior of concentrations of PTPC products is qualitatively similar. The obtained values of PTPC product concentrations at the PFS outlet indicate the formation of HRTCF and its stable ignition. With a temperature increase in the PFS, concentrations of combustible components increase, reaching 30.9 and 43.7 % at the PFS output at the plasma-torch power of 60 and 100 kW, respectively. With the plasma-torch power of 20 kW, ignition of the fuel mixture does not occur. Concentrations of oxygen and nitrogen correspond to their contents in the source air along the entire length of the PFS, and concentrations of resulting carbon dioxide (CO_2) and steam (H_2O) do not exceed 0.3 %.

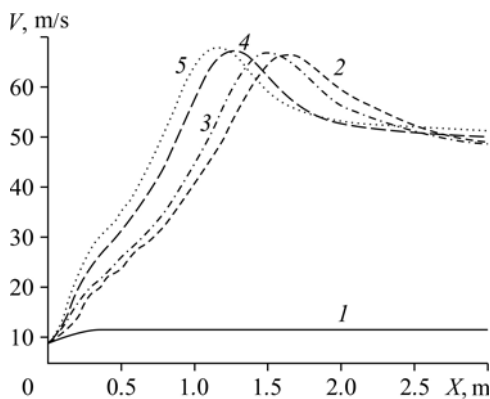


Fig. 7. A change in gas phase velocity along PFS depending on plasma-torch power.

Power: 20 (1), 40 (2), 60 (3), 80 (4), 100 kW (5).

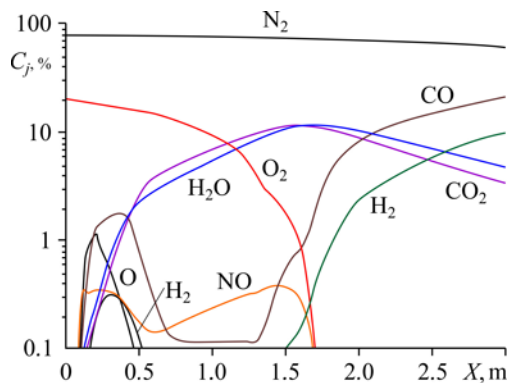


Fig. 8. A change in gas phase composition along PFS for plasma-torch power of 60 kW.

The numerical studies on determination of PFS characteristics depending on the plasma-torch power allow us to determine changes in temperatures, gas and coal particle velocities, as well as concentrations of PTPC products along the PFS length. Calculations have shown that in the range of plasma-torch power of 40–100 kW at an aeromixture flow rate of 2667 kg/h, stable ignition of high-ash coal is achieved. In addition, the ignition process is confirmed by high temperatures and concentrations of combustible components at the PFS outlet. As the power of the plasma torch increases, the maximum temperatures and velocities of PTPC products shift along the PFS length (towards the plasma torch). The maximum values of temperature and velocity vary in a narrow range and almost do not depend on the plasma-torch power.

The effect of the ash content of coal on temperature, velocity, and composition of PTPC products was studied for the plasma-torch power of 60 kW. Calculations on ignition and combustion of solid fuels were performed for the following coal ash contents: 20, 40, 60, and 70 %. Changes in the temperature and velocity of PTPC gas phase products along the PFS length are shown in Figs. 9 and 10. It can be seen from Fig. 9 that the gas phase temperature increases along the entire length of the PFS, reaching a maximum in its central part (1.5–1.7 m). At that, the maximum temperatures with coal ash contents of 60, 40, and 20 % are 2180, 1935, and 1845 °C, respectively. When the ash content of coal is 70 %, the gas temperature reaches 710 °C, which indicates that coal does not ignite. At the PFS outlet with coal ash content of 20, 40, and 60 %, the gas temperature reaches high values: 1260, 1332, and 1589 °C, respectively, which contributes to intense self-ignition of PTPC products (see Table 5) when mixed with secondary air in the boiler furnace. The calculations revealed also an increase in the gas phase temperature with an increase in the ash content of coal. This relates to the fixed concentration of coal dust in the aeromixture in all versions of calculations ($1000/1667 = 0.6$ kg/kg), which leads to an increase in oxygen concentration at a high ash content of coal and its decrease at a low ash content of coal. An increase in oxygen concentration leads to the development of carbon combustion processes and a corresponding increase in the gas phase temperature. With an ash content of coal of 70 %, there is no ignition because of a low content of combustible components in high-ash coal and relatively low heat release at their oxidation in the gas phase as compared to the above versions.

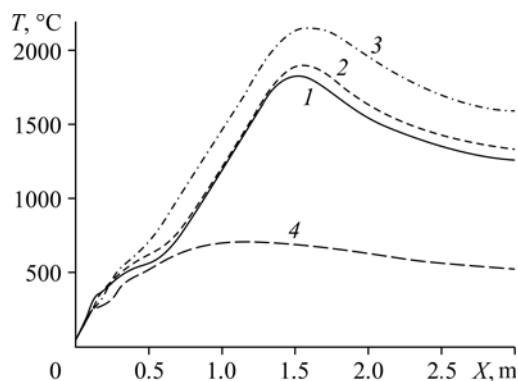


Fig. 9. A change in gas phase temperature along PFS depending on ash content of coal. Coal ash content: 20 (1), 40 (2), 60 (3), and 70 % (4).

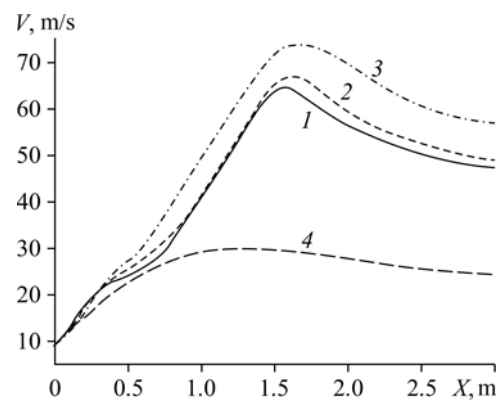


Fig. 10. A change in gas phase velocity along PFS depending on ash content of coal. Coal ash content: 20 (1), 40 (2), 60 (3), and 70 % (4).

Table 5

Integral characteristics of PTPC products at PFS outlet

Concentration, vol. %	Ash content, %			
	20	40	60	70
H ₂	15.31	9.82	4.29	0
CO	27.79	21.07	13.65	0
O ₂	1·10 ⁻⁶	1·10 ⁻⁶	5·10 ⁻⁶	13.27
CO ₂	0.62	3.31	6.55	3.78
H ₂ O	0.94	4.69	8.42	3.11
N ₂	55.36	61.1	67.09	79.83
T _f , °C	1260	1332	1589	515
X _C , %	12.5	28.6	96.4	42.9

A change in the gas phase velocity along the PFS length (see Fig. 10) is similar to a change in its temperature. The gas velocity increases with the PFS length, reaching its maximum in its central part (1.5–1.7 m). At the PFS outlet (3.0 m), the gas velocity is 47, 49, and 57 m/s with an ash content of coal of 20, 40, and 60 %, respectively. It should be noted that the primary air velocity in a traditional pulverized coal burner does not exceed 30 m/s.

Concentrations of gas phase components, temperature, and degree of coal carbon gasification at the PFS outlet are presented in Table 5. Here T_f is the flame temperature, C_i is the concentration of gaseous components, X_C is the degree of carbon conversion, which is determined from the residual carbon content in solid PTPC products and is calculated by the following formula:

$$X_C = (C_{in} - C_{fin}) / C_{in} \cdot 100 \%,$$

where C_{in} and C_{fin} are the initial and final contents of carbon in coal, respectively. According to the Table, concentrations of combustible components (H₂ and CO) decrease with an increase in the ash content in the almost complete absence of oxygen. At that, concentrations of oxidizing agents (CO₂ and H₂O) increase. With coal ash content of 70 %, no combustible components are formed even at significant concentrations of oxygen (13.27 %) and nitrogen (79.83 %) in the gas phase because of the low temperature (515 °C). The temperature of gaseous products at the PFS outlet increases with increasing ash content, which is a consequence of the heat release of exothermic reactions of carbon oxidation to CO₂. The degree of carbon conversion also increases with increasing ash content of coal. This is due to an increase in temperature and a decrease in initial concentration of carbon.

To identify the general patterns of changes in the main parameters of the PTPC process and to select the optimal PFS operation regime, it is necessary to study the effect of coal dust concentration in the aeromixture on the temperature and composition of PTPC products. The calculations were carried out for the following concentrations μ (kg/kg of air): 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8. The moisture content of coal was 5 %, the diameter of the cylindrical PFS was 0.2 m, the plasma-torch power was 60 kW, and the flow rate of coal dust was 1000 kg/h. Calculations were performed for three ash contents of coal: 20, 40, and 70 %.

Table 6 presents calculation results on the influence of coal dust concentration in the aeromixture on the main parameters of the PTPC process (the temperature and composition of PTPC products at the PFS outlet). It follows from the Table that the PTPC process at fixed values of the ash content of coal is initiated at various concentrations of dust in the aeromixture. With an increase in the ash content of coal, the aeromixture ignition is provided due to high dust concentration in the aeromixture. So, with an ash content of coal of 20 %, the ignition

of the aeromixture is observed at dust concentration of 0.6 kg/kg; with an ash content of coal of 40 %, it is observed at 0.8 kg/kg; and with an ash content of 70 %, we can observe it at 1.6 kg/kg. This follows from a considerable excess of total concentration of combustible components in the PTPC products (more than 15 %) and their temperature (more than 800 °C) at the PFS outlet. It should be noted that in the entire studied range of coal ash contents, the PTPC process proceeds in parallel with fuel combustion, as evidenced by significant concentrations of carbon dioxide at the PFS outlet.

The generalized dependence of total CO and H₂ concentrations on concentration of dust in the aeromixture for different coal ash contents is shown in Fig. 11. According to the figure, at ash contents of coal of 20 and 40 %, with an increase in concentration of dust in the aeromixture, concentration of synthesis gas (CO + H₂) passes through a maximum at dust concentration of 1.0 and 1.3 kg/kg, respectively. At an ash content of 70 %, the concentration of synthesis gas increases monotonically with an increase in concentration of dust in the aeromixture, reaching its maximum at 1.8 kg/kg.

The temperature dependence of PTPC gaseous products on dust concentration at ash contents of 20, 40, and 70 % is shown in Fig. 12. It follows from the figure that for the studied ash content of coal, the temperature curves pass through a maximum at dust concentrations of 0.6, 0.7, and 0.9 kg/kg, respectively.

As follows from the comparison of Figs. 11 and 12, aeromixture ignition ($T > 800$ °C) at the ash content of 20 % is achieved at dust concentration of 0.6–1.0 kg/kg, while for the ash content of 40 %, this occurs at 0.7–1.4 kg /kg, and for the ash content of 70 %, this occurs at 1.5–1.8 kg/kg.

Table 6
Influence of coal dust concentration in the aeromixture on temperature and composition of PTPC products at PFS outlet

Ash content, %	μ , kg/kg	T , °C	Concentration, vol. %		
			CO	H ₂	CO ₂
20	0.4	187	–	–	0.5
	0.6	1537	14.0	5.6	5.7
	0.8	1056	16.3	8.3	5.7
	1.0	910	20.0	11.0	4.3
	1.2	779	19.4	11.8	4.9
	1.4	588	1.4	2.2	14.4
40	0.4	165	–	–	29.0
	0.6	1628	8.9	2.5	8.4
	0.8	1255	12.3	5.3	7.0
	1.0	1066	15.3	8.2	6.0
	1.2	938	18.2	10.8	4.9
	1.4	805	20.6	12.2	4.3
	1.6	709	3.0	4.2	11.7
70	0.6	626	–	–	3.5
	0.8	1749	2.7	0.5	12.4
	1.0	1450	4.9	1.3	11.0
	1.2	1335	7.2	2.5	9.6
	1.4	1217	9.5	4.1	8.4
	1.6	1081	11.2	5.8	7.8
	1.8	987	11.9	6.7	7.7

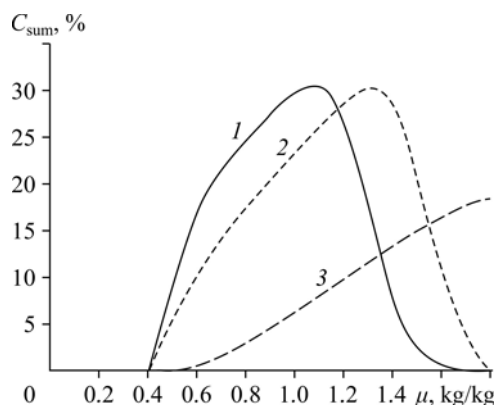


Fig. 11. The total yield of CO and H₂ at PFS outlet vs coal dust concentration at ash content of 20 % (1), 40 % (2), and 70 % (3).

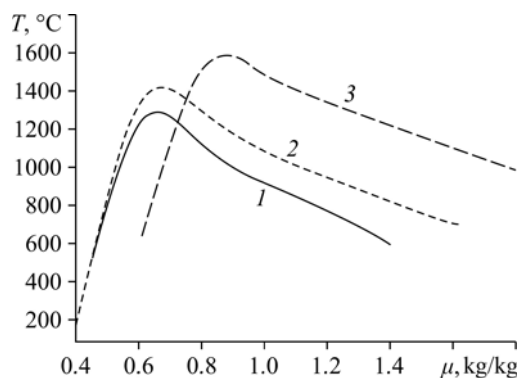


Fig. 12. The gas temperature at PFS outlet vs coal dust concentration at ash content of 20 % (1), 40 % (2), and 70 % (3).

The study of the influence of coal dust concentration in the aeromixture on the temperature and composition of PTPC products showed that in the entire studied range of ash contents (20–70 %), stable ignition of HRTCF is ensured at coal dust concentrations in the aeromixture in the range of 0.5–1.8 kg/kg.

The above PFS parameters and HRTCF characteristics can be used as input data for 3D modeling of pulverized coal-fired boilers equipped with PFS.

Conclusions

The basic principles for implementing the technology of plasma thermochemical preparation of pulverized coal for combustion, which underlies plasma ignition of solid fuels at thermal power plants, have been formulated. During the full-scale tests carried out at a number of thermal power plants, the advantages of using PFS have been shown.

To calculate numerically the characteristics of PFS depending on the plasma-torch power, ash content in coal, and concentration of coal dust in the aeromixture, the PlasmaKinTherm program was used, which combines kinetic and thermodynamic methods that describe the PTPC process in the PFS volume.

The results of comparing the calculations performed by the PlasmaKinTherm program with the experimental data showed their satisfactory agreement, allowed verification of the model and confirmed the validity of the assumptions made during its development, which indicates the possibility of using the program for calculating and designing PFS.

During the research, changes in temperatures and velocities of gas and coal particles, as well as concentrations of products of fuel plasma activation along the PFS length were determined. Stable ignition of high-ash coal is achieved in the range of plasma-torch power of 40–100 kW at the aeromixture flow rate of 2667 kg/h, high temperature of up to 1470 °C and concentration of combustible components of up to 44 % at the PFS outlet.

It was established that with an increase in the plasma-torch power, the temperature and velocity maxima of the PTPC products shift upstream in the direction of the plasma source (plasma torch). The maximum temperatures and velocities vary in a narrow range of values and almost do not depend on the plasmatron power.

It is shown that depending on the ash content of coal in the range of 20–70 % at the PFS outlet, the concentrations of combustible components (H₂ and CO) decrease with an increase in the ash content of coal and with an increase in the temperature of gaseous products. The degree of carbon conversion of coal reaches its maximum at an ash content of coal of 60 %.

The study of the effect of coal dust concentration in the aeromixture on the temperature and composition of PTPC products showed that in the entire studied range of ash content (20–70 %) in coal, used at coal fired power plants, stable ignition of the aeromixture is ensured at coal dust concentrations of 0.5–1.8 kg/kg. With an increase in the ash content of coal, the aeromixture ignites at higher concentration of coal dust in the aeromixture.

The performed numerical studies of the PTPC technology allowed the determination of the main patterns of heating and thermochemical transformations of solid fuel in the PFS, which provides an opportunity to use them as input data when designing PFS for oil-free start-up of boilers and the stabilization of combustion of a pulverized coal flame at TPPs, as well as for three-dimensional calculations of boiler furnaces equipped with PFS, increasing the efficiency of ignition and combustion of thermal coals.

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