Plasma Preparation of Coal to Combustion in Power Boilers

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This paper presents plasma technology for solid fuel ignition and combustion promoting more effective and environmentally friendly low-rank coal incineration. To realise this technology at coal-fired power plants plasma-fuel systems (PFS) were developed. PFS is pulverized coal burner equipped with plasmatron. The base of the technology is plasma thermo-chemical preparation of coal for burning. It consists of heating of the pulverized coal and air mixture by arc plasma up to temperature of coal volatiles release and char carbon partial gasification. In the PFS carbon is oxidised mainly to carbon monoxide. As a result, at the PFS exit a high reactivity mixture is formed of combustible gases and partially burned char particles, together with the products of combustion, while the temperature of the products is around 1300 K. Further mixing with air promotes intensive ignition and complete combustion of the prepared fuel.

Combustion of pulverized coal flame was numerically simulated. The results of calculations of the processes of conventional and plasma activated combustion of coal in experimental and full-scale furnaces are discussed. Influence of plasma activation of combustion onto thermotechnical characteristics of the flame, decrease of unburned carbon and nitrogen oxides concentrations at the furnace exit was discovered.

I. Introduction

Reorientation of the fuel balance of thermal power plants (TPP) from gaseous and liquid fuels to the solid ones is a worldwide tendency. Pulverized coal TPP share in the electricity production is growing up permanently and now it is about 60 % in the USA and Germany, 85 % in Kazakhstan and 87% in China[1]. That is why increase of solid fuels use efficiency is one of the actual issues of modern thermal physics. But it is unachievable without detail study of the pulverized coal flame combustion in furnaces of TPP.

To increase efficiency of solid fuels utilization, to decrease fuel oil and natural gas flow rate, and dangerous emissions at TPP plasma technology of coal ignition was developed. It is based on electro- thermo-chemical preparation of fuel to burning (ETCPF)[2]. ETCPF is realized in zone I of the plasma-fuel system (PFS) (Fig. 1). In this technology pulverized coal is replaced traditionally used for the boiler start up and pulverized coal flame stabilization fuel oil or natural gas. Part of the coal/air mixture is fed into the PFS where the plasma-flame, having a locally high concentration of energy, induces gasification of the coal and partial oxidation of the char carbon. The resulting coal/air mixture is deficient in oxygen, the carbon being mainly oxidized to carbon monoxide. As a result, a highly reactive fuel (HRF) composed of mixture of combustible gases (at a temperature of about 1300 K) and partially oxidized char particles is obtained at the exit of the burner. On entry to the furnace, this combustible mixture is easily ignited. This allows prompt ignition and much enhanced flame stability of the main portion of the coal flame which is not directly treated by the plasma.

Detailed mathematical modeling is required for enhancement and dissemination of the plasma technology of coal ignition. Lack of detailed experimental data on plasma ignition of coals and their combined burning with the highly reactive two-component fuel complicates the development of mathematical and physical models. To develop such models knowledge of the main characteristics of ETCPF and combustion processes, temperature fields, velocities and concentrations of gaseous and condensed components, is required.

To understand physical mechanism of the ETCPF and combustion more completely, and to verify the software code CINAR ICE, investigations of coal incineration in the equipped with PFS experimental furnace of 3 MW thermal power have been fulfilled. Two computer codes were used for that. The first one was 1D code PLASMA-COAL[2,3]. It

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describes a two-phase chemically reactive flow in a plasma-chamber with an internal source of heat (plasma flame). The second is 3D code CINAR ICE. It operates with real geometry of a furnace. PLASMA-COAL code has been verified using experimental data on plasma gasification and ETCPF [3-6]. It was used for plasma-fuel system computation, and data to enable a 3D numerical simulation of coal combustion in a furnace equipped with PFS were collected. CINAR ICE code was used for computation of coal co-combustion with highly reactive two-component fuel in the furnace. The code has been verified for 3D simulation of traditional furnace processes [7-9]. However, to use this code for computation of the equipped with PFS furnaces verification was required.

On the software code CINAR ICE verification numerical comparative simulation of ETCPF and coal combustion in a furnace of the full-scale boiler was fulfilled.

II. Calculation Method and the Comparison of Numerical and Experimental Data

CINAR ICE code (Cinar Integrated CFD Environment)[2,7-9] was designed to provide computational solutions of industrial problems, especially those related to two-phase combustion. It solves the governing time-averaged Eulerian equations for the gas phase mixture combined with Lagrangian tracking of the particles[7, 12-14] and simulates devolatilisation, volatiles combustion (fast diffusion combustion), char combustion and the turbulence (k-ε model). "Fast chemistry kinetics" model of chemical reactions is used in the code. The kinetic model is based on the conception of multi-fraction mixtures burning[12]. Radiative heat transfer is represented by six-flow model of particles radiation and reemission[13]. The Control Volume method is used for discretization of the initial equations. SIMPLE[12] algorithm is used for calculation of pressure field.

To verify CINAR ICE code two regimes of experimental furnace were selected. The first one was conventional coal combustion and the second regime was combustion plasma activated coal. Plasma activation to coal combustion was provided with the plasma flame of 36 kW power. The parameters of two-component high reactive fuel produced in PFS (Fig. 1) were calculated using PLASMA-COAL computer code. These parameters were used as initial data for 3D simulation of the experimental furnace equipped with PFS.

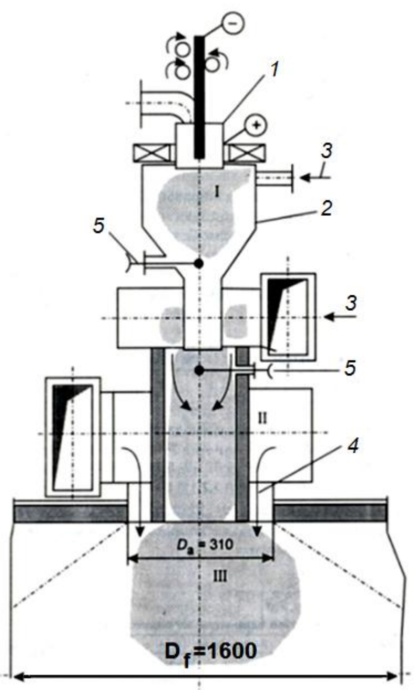
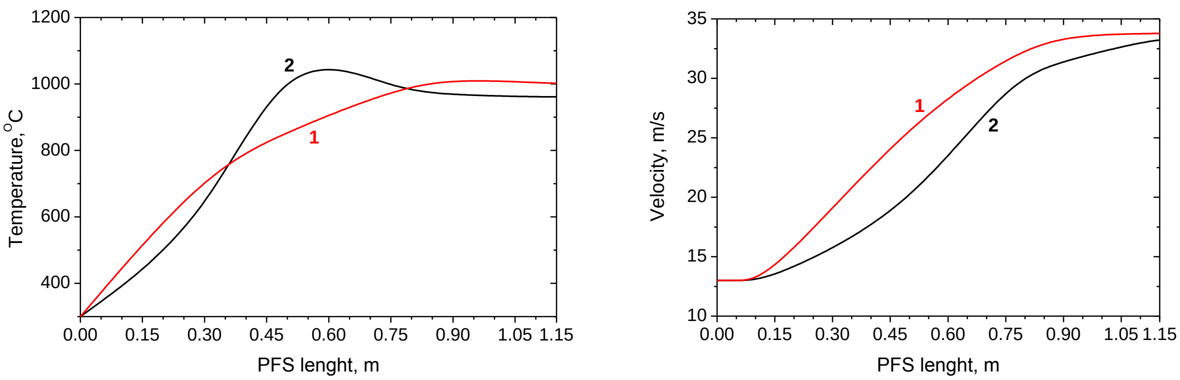


Figure 1. Layout drawing of plasma-fuel system and experimental furnace: 1 – plasmatron; 2 – chamber of electro- thermo-chemical preparation of fuel; 3 – pulverised coal; 4 – secondary air; 5 – slot for measuring; I – zone of air/coal mixture interaction with plasma flame and HRF forming; II – zone of HRF interaction with the main air/coal mixture; III – zone of the fuel self-ignition.

The mathematical model of ETCPF describes the two-phase (coal particles and gas-oxidiser) chemical reacting flow with an internal heat source (electric arc or flame). Generally coal particles and gas are admitted into the PFS at ambient temperatures. Particle-to-particle, gas-to-particle transfer and gas-to-plasma heat-mass transfers are considered. Heat and momentum transfer between the flow and the PFS wall have been calculated. The average size of the coal particles was taken as a constant and equal to the particle mineral skeleton size. In other words the particle was not resized at conversion. The particles were spherical and the temperature gradients within the particle are negligible. Also, some chemical transformations of fuel were considered. They are as follows: formation of primary volatile products from coal, conversion of evolved volatile products in the gas phase and the char carbon gasification reactions. The coal composition was presented in the model by its organic and mineral parts. The organic mass of coal was specified by the set of the functional groups (CO, CO_2, CH_4, H_2O, C_6H_6) and carbon. An entrained flow reactor was considered and the plug flow was assumed. The resulting set of ordinary differential equations includes equations for species concentrations (chemical kinetics equations) in conjunction with the equations for gas and particle velocities and temperatures, respectively. The energy contribution from the plasmas had been found empirically [3] and included into the energy equation as a distribution of internal heat source. Also the model was distinguished by its detailed description of the kinetics of the chemical reactions mentioned above [10]. Kinetic scheme consists of 116 chemical reactions. The temperature dependence of rate constants is governed by the Arrhenius equation. In Ref. 2, 3 and 5 the model was presented in detail.

The swirl burner was mounted axial on the furnace top (Fig. 1). Ekibastuz bituminous coal of 45.2 % ash content, 14.7 % devolatilization, 1.3 % humidity and 15960 kJ/kg heat value was incinerated in the experimental furnace [4,11]. Grinding of coal gave the average particle size of 60 microns. PLASMA-COAL computer code has been used for calculation of ETCPF in the volume of PFS of 1.15 m length. The following initial parameters were used for calculations: plasmatron power was 36 kW, initial temperature of pulverized coal (coal/air mixture) was 300^{O}C, coal and air consumption through PFS were 410 and 600 kg/h correspondingly. The air is composed of nitrogen (79 vol. %) and oxygen (21 vol. %) and neither carbon dioxide nor noble gas were taken in consideration.

As a result of calculations temperature distribution (Fig. 2 a), gas and particles velocities (Fig. 2 b), gas-phase components concentrations (Fig. 3 a), gasification degree and carbon concentrations in coke residue (Fig. 3 b) were found. Gas and coal particles temperatures (Fig. 2 a) increase along the PFS. The heat exchange between plasma source and gas-phase is prevailing at the initial section ($0< X < 0.35$ m). Coal particles are heated from gas and their temperature increase up to 1121^{O}C at the section $0.35 \leq X<0.8$ m due to carbon oxidation and corresponding out of heat. It exceeds the gas temperature by 264^{O}C. As a result of that inversion of temperature curves is observed at the section. Gas temperature reaches maximum at 1015^{O}C (X=0.9 m) and goes down to the outlet of PFS (T=1002^{O}C). Gas temperature is 41 degrees higher than particles temperature, that is related to heat-emission from the particles to the wall of PFS.



a **b**

Figure 2. Gas (1) and particles (2) temperatures (a) and velocities (b) along the PFS.

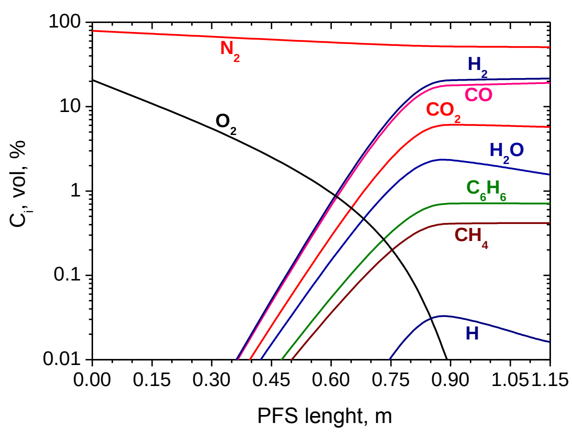


Figure 3. Gas phase components concentrations along the PFS.

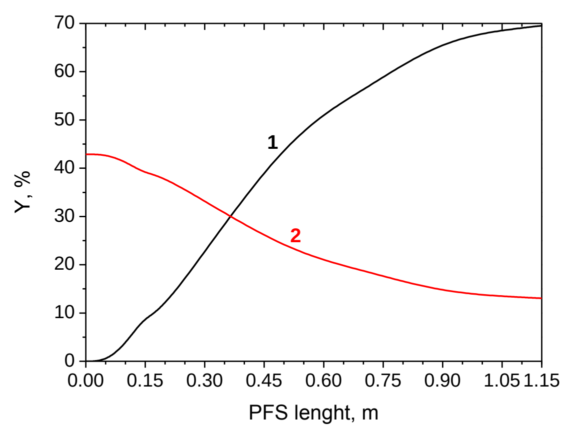


Figure 4. Gasification degree (1) and carbon concentration (2) in coke residue along the PFS.

Equal at the PFS inlet velocities of gas and particles (Fig. 2 b) increase with the length achieving their maxima of 33.8 and 33.2 m/s at the PFS exit accordingly. Meanwhile gas velocity is higher one of particles along the full PFS. Note velocity of the flow at the exit of PFS is considerably higher than one for traditional pulverized coal burner.

With coal particles heating it is observed devolatilization and carbon gasification (Figs. 3 and 4). Concentration of combustible components (CO, H_2, H, CH_4, C_6H_6) increases along the PFS and reaches its maximum of 41.8 % at the PFS outlet. Oxidants concentration (CO_2, H_2O, O_2) does not exceed 7.3 % at the PFS outlet. The nitrogen concentration

(N_2) decreases along the PFS from 79 % to 50.8 % at the outlet. The carbon concentration in the coke residue decreases, and carbon gasification degree (Fig. 5) increases along the PFS and achieves 69.5 % at the outlet. The two-component fuel with aforesaid characteristics is intensively ignited mixing with the secondary air flow in the furnace volume. Calorific value of the coke residue was amounted to 7200 kJ/kg.

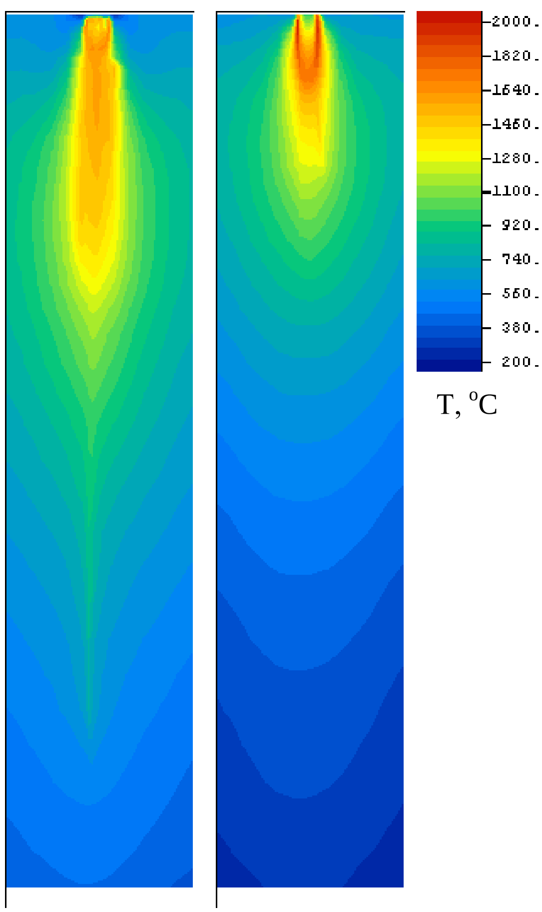
Integral characteristics of ETCPF at the PFS exit are gathered in Table 1. It the table T_{gas}, T_{solid} and V_{HRF} are temperatures of gas and particles and velocity of the HRF correspondingly. They were taken as initial data for numerical simulation of ETCPF combustion in the experimental furnace using CINAR ICE software code. Secondary air flow rate was 2322 kg/h. The furnace height was 7.5 m. Computing origin was the furnace top. The x, y, z grid size was, respectively: 56 x 56 x 60.

Table 1. Characteristics of ETCPF at the PFS exit.

Content of gas phase, vol.% & kg/h							Ash, kg/h	Char carbon, kg/h	T_{gas}, °C	T_{solid}, °C	V_{HRF}, m/s
H_2	CO	CH_4	C_6H_6	CO_2	H_2O	N_2					
21.6	19.2	0.4	0.7	5.8	1.6	50.8	185.3	68.4	1002	961	33
14.0	174.2	2.2	18.0	82.2	9.1	462.0					

The calculations results are shown in Figs. 5 and 6. Figure 5 visualizes the difference between temperatures fields for the furnace two operational regimes. The traditional mode flame, with maximum temperature of 1580 °C, generates the common flame body with the temperature 1300-1580°C. The PFS impact appears as transformation of high reactive two-component flame shape, decrease of the flame length and increase of temperature maximum up to 2015°C. That can be explained by earlier ignition and more complete burning-out of ETCPF.

Experimental and numerical temperatures dependences on the furnace height (Fig. 6) are similar. The curves have typical maxima at the distance of 0.5 m from the top of the furnace. The maximal temperature level for conventional mode of the furnace operation at the distance H<0.13 m is higher than one for plasma activated fuel combustion. This difference is up to 164 degrees (0.025<H<0.13 м). It can be explained by more intensive radiation from coal particles having higher concentration and total surface when the furnace operation is in conventional mode in comparison with plasma activated regime of coal combustion. When PFS operates electro-thermochemically prepared fuel (two component high reactive



a b

Figure 5. Temperature fields along the furnace height in the central section for conventional (a) and plasma supported (b) regimes.

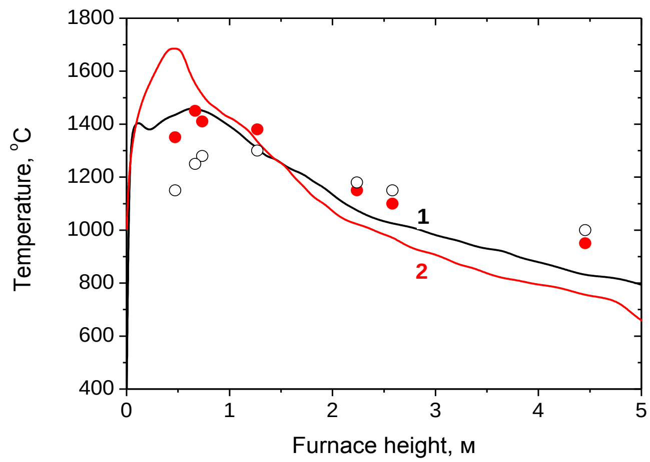


Figure 6. Furnace height distribution of the combustion products maximal temperature: 1 – conventional incineration of coal; 2 – incineration of coal in the furnace with PFS; ●, ○ – experimental data on coal incineration in the furnace with PFS and without PFS correspondingly.

fuel) is gone from it to the furnace. The fuel contains combustible gas and particles of coke residue which mass do not exceed 30 % of the initial coal mass. That brings to triple decrease of radiative particles total surface. In section $0.13 \leq H < 0.6$ m temperature at plasma activated regime is higher than one for conventional mode of the furnace operation. The maximum difference reaches 260 degrees at height 0.4 m. The maximum combustion temperature of plasma activated fuel at the experiment was 200 degrees higher one for conventional mode. Experimental temperature maximum was at the furnace height of 0.67 m. Higher temperature of the flame of plasma activated fuel can be explained by more complete burnout of the fuel.

Table 2. Characteristics of ETCPF at the PFS exit.

Content of gas phase, vol.% & kg/h								Ash, kg/h	Char carbon, kg/h	T_{HRF}, ^{O}C	V_{HRF}, m/s
H_2	CO	CH_4	C_6H_6	CO_2	H_2O	N_2	O_2				
14.2	18.4	0.3	0.6	6.8	2.9	56.4	0.3	1123.2	435.0	997	189
88.5	1599.0	14.0	133.8	931.2	162.8	4911	31.0				

Thus, the experimental data [4,11] were used for verification of CINAR ICE computer code. Figure 6 confirms the qualitative agreement between calculated and experimental data. Divergence of experimental and calculated values of temperature of combustion products does not exceed 20 % along the full height of the furnace. The divergence explains by imperfection of the "fast chemistry" scheme of fuel combustion used by CINAR ICE program. The concentration of unburned carbon was measured at the exit of the experimental furnace. Also divergence of the experimental and calculated values does not exceed 20 %. In experiments unburned carbon was found as 3.1 and 1.8 % for traditional and plasma activated mode correspondingly. Computed figures were 3.72 and 1.42 % accordingly for these two modes. Concentration of nitrogen oxides at the furnace exit is significantly lower for ETCPF combustion (244.5 ppm) than for conventional mode of coal combustion (537.9 ppm). Calculated values of NOx concentrations for these two modes were 122.1 and 228.1 ppm. However, essential quantitative difference of experimental and calculated values of NOx concentrations shows that CINAR ICE kinetic scheme of NOx formation is in need of revision.

III. Computation of PFS and Full-Scale Industrial Boiler's Furnace

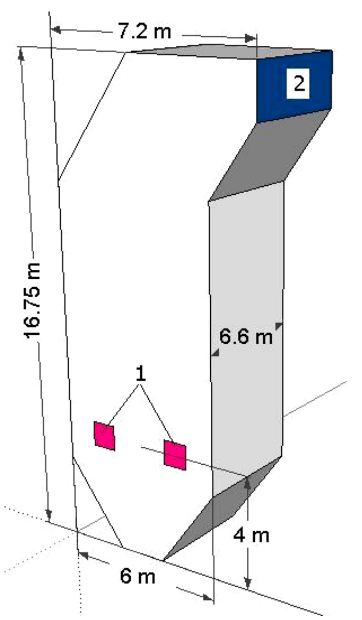


Figure 7. Layout of the furnace of BKZ-75 power boiler: 1–burner throat; 2–section of the swiveling chamber of the boiler.

The fulfilled verification of CINAR ICE code for plasma assisted coal combustion in the experimental furnace of 3 MW power confirmed legitimacy of the used codes complex (PLASMA-COAL and CINAR ICE) for simulation of the furnaces equipped with PFS. Thus in this part the numerical study was performed for a power-generating boiler with a steam productivity of 75 t/h. The boiler's furnace (Fig. 7) is equipped with four swirl burners arranged in one layers, by two burners, on the boiler front and backside. Low-rank bituminous coal of 35.1 % ash content, 22 % devolatilization and 18550 kJ/kg heat value was incinerated in the furnace. Averaged size of the coal particles was 75 micron. All the calculations were performed in accordance to the aforecited technique.

Three modes of the boiler operation were chosen for the numerical studies. The first one was traditional regime, using four pulverized coal burners, the second one was regime with plasma activation of combustion, using the replacement of two burners onto PFS (Fig. 8), and the third one was regime of the boiler operation using four PFS instead of all burners.

PLASMA-COAL computer code has been used for calculation of ETCPF in the volume of PFS of 2.3 m length. The following initial parameters were used for calculations: plasmatron power was 200 kW, initial temperature of pulverized coal (coal/air mixture) was 90 ^{O}C, coal and primary air consumptions through PFS were 3200 and 6400 kg/h correspondingly.

The results of numerical simulation by the PLASMA-COAL code are summarized in Table 2. Heat value of the coke residue was 8580 kJ/kg. These data were taken as initial parameters for 3-D computation of the furnace of the power-generating boiler equipped with PFS. This computation was performed using CINAR ICE code to demonstrate advantages of plasma aided coal combustion technology.

Initial parameters for calculations of the furnace (Fig. 7) in different operational regimes were the following: temperature of the secondary air was 290 ^{O}C, coal productivity of the burner was 3200 kg/h and primary air flow rate through the burner was 10260 kg/h. Secondary air flow rate to the boiler was 78160 kg/h. The grid is defined by 85 x 69 x 116 grid lines in three directions (x, y and z).

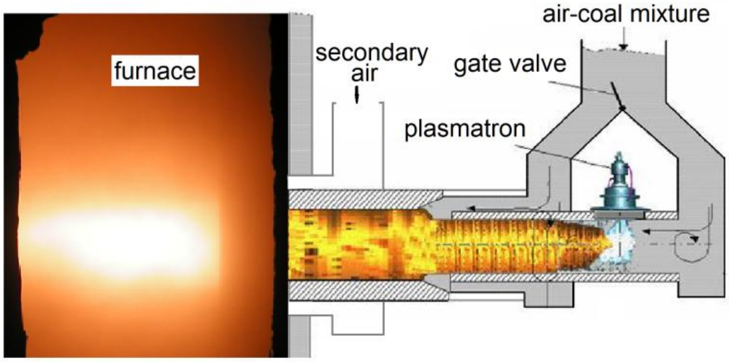


Figure 8. Sketch of the PFS for replacement of the traditional burners of the boiler BKZ-75.

The calculations results are shown in Figs. 9 and 10. Figure 9 visualizes the difference between temperature fields in three regimes of coal incineration. In the traditional regime (Fig. 9 a), with maximum temperature of 1852 ^{O}C, four symmetrical flames are generated. In central space of the furnace they form overall body of flame with the temperature about 1300 ^{O}C. In Fig. 9 b two PFS are on top. The PFS impact appears as transformation of HRF flame shape, it becomes narrow and longer, and increase of temperature maximum up to 2102 ^{O}C. When the furnace operates with four PFS (Fig. 9 c) the flames length increases but maximal temperature decreases to 1930 ^{O}C.

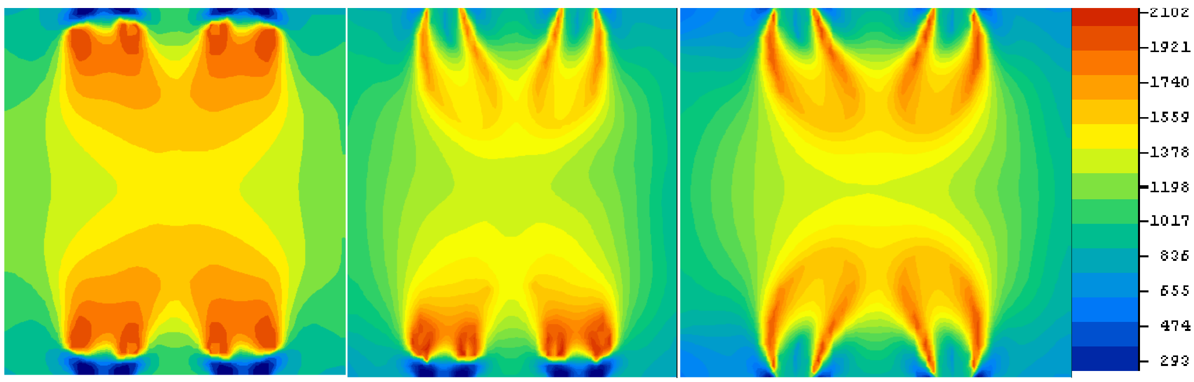
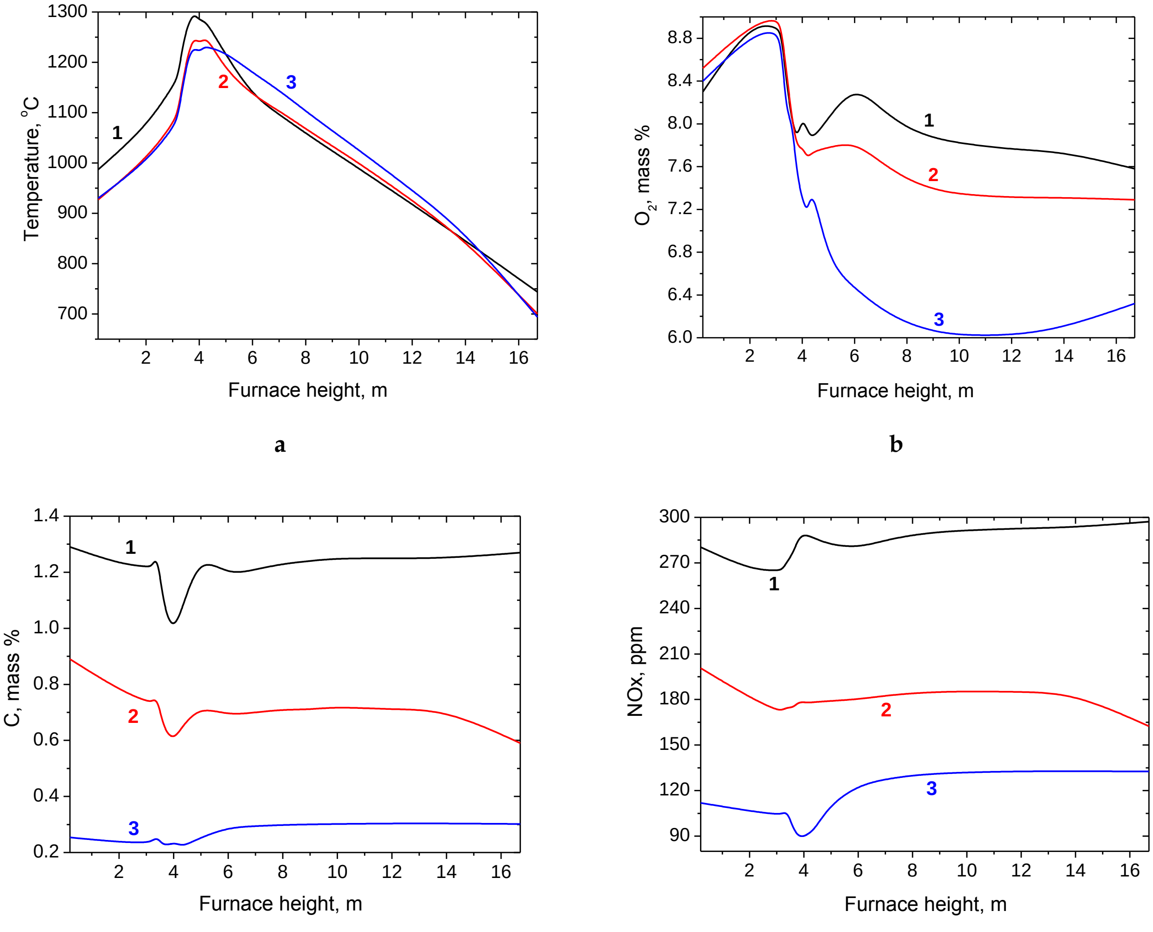


Figure 9. Temperature field within the combustion chamber at the level of the pulverized coal burners: a – standard operational regime; b – plasma operational regime with two PFS; c – plasma operational regime with four PFS.

Average characteristics of the boiler are compared in Fig. 10 for three modes of the boiler operation. The temperature curves have a characteristic maximum in the zone of the burners arrangement at a height of 4 m (Fig. 10 a). In the traditional mode of combustion level of the average temperature in the furnace at a height of up to 6 m higher than that for the boiler operating with PFS. The temperature difference reaches 75 degrees (height between 2 and 3 m), due to more intense radiation from the coal particles having a higher concentration and the total surface at the traditional combustion, compared to the operation mode with PFS. From the PFS HRF enters the combustion chamber, consisting of fuel gas and coke residue particles, whose mass does not exceed 30 % of the consumption of raw coal, which leads to a threefold reduction in the total surface of the radiating particles. Further, the section of the furnace from 4.5 to 16.75 m, the temperature in the regime with PFS higher than that for the traditional burning by 10 and 32 degrees in the case of 2 and 4 PFS respectively. This is due to more complete fuel burnout (Fig. 10 b) by ETCPF confirmed by decreased oxygen concentration in the furnace at the same location (Fig. 10 c). PFS improves the environmental characteristics of the combustion of solid fuels. Compared with the traditional mode of coal incineration use of four PFS reduces the unburned carbon at the outlet of the furnace (height of 16.75 m) 4 times, and nitrogen oxide emissions by more than 2.2-fold (Fig. 10 d).



c d

Figure 10. Furnace height distribution of mass average temperature (a), oxygen (b), carbon (c) and NOx (d) mean concentrations: 1–standard operational regime; 2-plasma operational regime with two PFS; 3-plasma operational regime with four PFS.

IV. Conclusion

To investigate the processes of coal combustion including plasma assisted one complex of two software codes (PLASMA-COAL and CINAR ICE) was used. The fulfilled verification of CINAR ICE code for plasma assisted coal combustion in the experimental furnace of 3 MW power confirmed legitimacy of the used codes complex for simulation of the furnaces equipped with PFS. These codes application allowed investigating the processes of coal plasma assisted combustion. Plasma activation of coal combustion increases efficiency of its incineration decreasing unburned carbon concentration and nitrogen oxides formation. Evidently decrease of unburned carbon and NOx concentrations at the furnace exit means improving of ecology-economic indexes of TPP. On the base of the presented numerical research renovation of the furnace of 75 t/h steam productivity boiler is scheduled.

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