Plasma-assisted ignition and combustion of pulverized coal at thermal power plants of Kazakhstan

V. E. Messerle, A. B. Ustimenko, and O. A. Lavrichshev

***Abstract*—**Application of direct-flow and vortex plasma-fuel systems (PFS) for coal-fired boilers of thermal power plants (TPP) at Ust-Kamenogorsk, Shakhtinsk, and Almaty (TPP-2 and TPP-3) (Kazakhstan) is discussed. In the plasma technology coal replaces traditionally used for the boiler start up and pulverized coal flame stabilization fuel oil or natural gas. Part of coal/air mixture is fed into the PFS where the plasma-flame from plasma torch induces gasification of the coal and partial oxidation of the char carbon. As 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 and partially oxidized char particles is obtained at the exit of the PFS. On entry to the furnace, this HRF is easily ignited.

Simulation and testing of PFS at existing pulverized coal-fired boilers of TPP confirmed the technical feasibility, environmental and energy efficiency of no-fuel oil boilers start-up and pulverized coal flame stabilization using PFS.

***Keywords*—**Coal, plasma torch, ignition, combustion, furnace, efficiency, environment.

I. Introduction

THE technology of plasma ignition of coal and its realizing plasma-fuel systems (PFS) is electro- thermo-chemical preparation of fuel to burning (ETCPF) [1] – [6]. 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 from plasma torch, having a locally high concentration of energy, induces gasification of the coal and partial oxidation of the char carbon. As 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 PFS. On entry to the furnace, this HRF is easily ignited.

II. Boilers Plasma Start up

75 ton steam productivity boiler (Fig. 1) of Ust-Kamenogorsk TPP has three main pulverized coal turbulent burners and two kindling muffle burners. The last two were transformed to PFS. Kuznetsk bituminous coal of 17.7 % ash content and 4878 kcal/kg calorific value was incinerated in the boiler. During the PFS tests at this boiler the pulverized coal flow through each PFS was 1.5 t/h and the primary air - 2.6 t/h. The pulverized coal flow through the main burners was 11.5 t/h. Plasma torch power was varied from 60 to 70 kW and its heat efficiency was 85-86 %. HRF flame temperature at the PFS exit was in interval 1040-1240^{O}C. Plasma torch's relative power consumptions were 0.5 – 0.7 % of the muffle burner heat power. NO_x concentration on the PFS exit was not more than 20 mg/Nm^3 and synthesis gas ($CO+H_2$) yield exceeded 60 %. In 35 minutes of the PFS start stationary heat regime of the muffle burner was achieved, plasma torches were turned off and heated muffles went on stabilizing the flame combustion. The flames from muffle burners were 3 m in length. The boiler oil-free start-up lasted 3.25 h after which the boiler was linked up with the main steam pipeline of the TPP.

75 ton steam productivity boiler of Shakhtinsk TPP has four burners (Fig. 2), two on the front and rear in one layer. Bituminous coal of 30% ash content with the flow through the burner (or PFS) 3200 kg/h is incinerated in the boiler. Primary air flow through the burner is 6400 kg/h, plasma torch power is 200 kW and PFS length is 2.3 m (Fig. 3). Numerical modeling of the ETCPF in PFS is performed using a one-dimensional mathematical model Plasma-Coal. The calculation results allowed defining the geometric dimensions of PFS, the required power of plasma torch, temperature, velocity and composition of the products of ETCPF. These results can be used as initial conditions for numerical simulation of HRF combustion in the boiler furnace using Cinar ICE code. 3D modeling results showed that when operating PFS ignition of pulverized coal flame starts earlier, the combustion front moves to the installation location of the PFS on the boiler, resulting in lower temperature of the exhaust gases, the

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concentration of nitrogen oxides in them and unburned carbon, compared with the traditional mode of coal incineration without plasma activation in PFS.

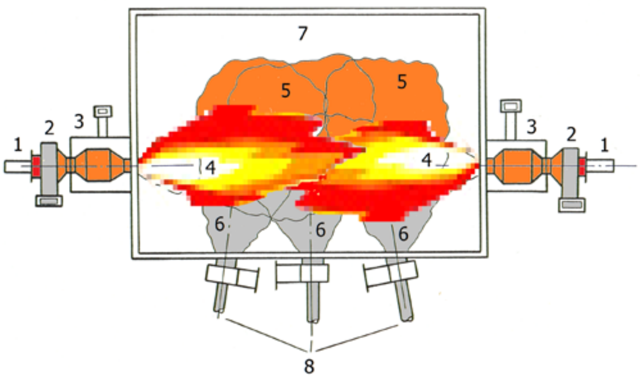

Fig. 1. PFS layout at a boiler of 75 ton steam productivity of Ust-Kamenogorsk TPP (cross-section view of the furnace with PFS): 1) plasmatron, 2) chamber for plasma assisted incineration, 3) muffle burner, 4) flame of high reactive two component fuel from PFS, 5) pulverised coal flame, 6) air-coal mixture from the main burners, 7) furnace, 8) the main pf burners

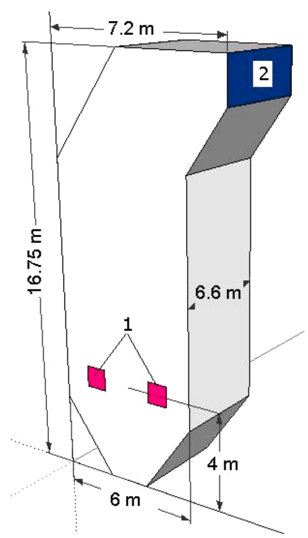

Fig. 2. Layout of the furnace of BKZ-75 power boiler: 1) burner throat, 2) section of the swiveling chamber of the boiler

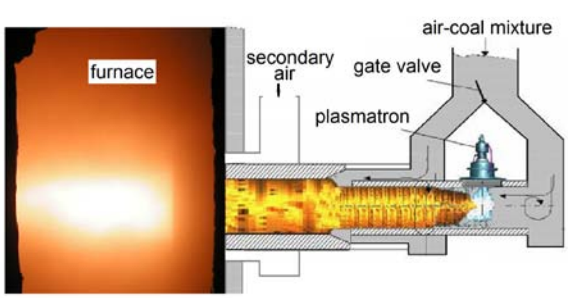

Fig. 3. Sketch of the PFS for replacement of the traditional burners of the boiler BKZ-75

Almaty TPP-3 boiler of 160 t/h steam productivity (Fig. 4) has four coal-fired blocks of two-layer slot burners (Fig. 5). Consumption of 45 % ash content and 3800 kcal/kg calorific value Ekibastuz bituminous coal was 4 t/h through each burner. Two PFS were installed in the lower layer of the burners diagonally. Plasma torches were running on the power of 120-140 kW (350-450 A current, and 300-350 V voltage). Ignition of the flames in the furnace was observed in 2-3 seconds after submitting of pulverized coal at a rate of up to 3 t/h through each PFS. Coal-dust flame temperature at the exit of the PFS reaches 1200-1300^{O}C, and is 5-6 m in length. Using these parameters, the formation of the bright yellow core flame in the center of the furnace was observed. In 3.5 hours from the kindling start parameters of the boiler reached operating values, and it was connected to the steam main, after which air/coal mixture was filed to all the burners. According to the rule one start-up of the boiler consumes 12 tons of fuel oil that by calorific value is equivalent to 30 tons of the coal. Instead, one start-up on average consumed about 16.5 tons of coal that confirms ETCPF energy efficiency. The specific power consumptions for plasma torches were 1.2-1.4% of the heat capacity of pulverized coal burners.

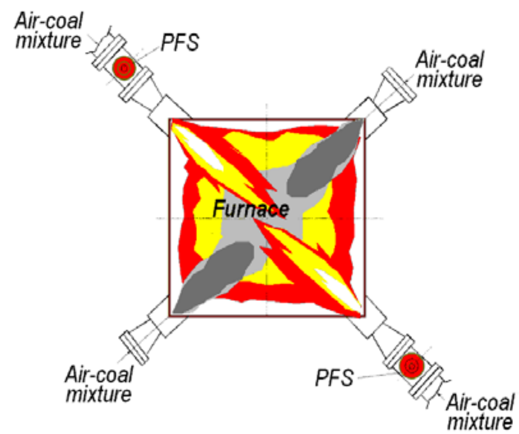

Fig. 4. BKZ-160 boiler furnace of 160 ton steam productivity (Almaty TPP-3) equipped with two PFS (top view)

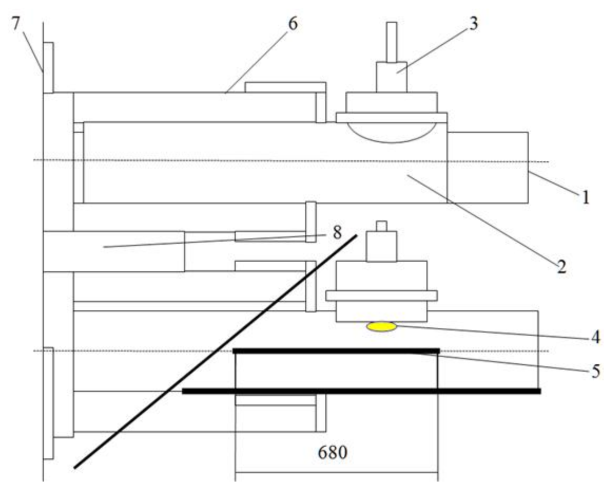

Fig. 5. Sketch of direct flow PFS – burner assembly with plasma torches: 1) dust flue, 2) chamber of plasma ignition, 3) plasma torch, 4) plasma flame, 5) partition plate, 6) secondary air duct, 7) furnace border, 8) oil fuel nozzle channel

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III. COMPUTATION OF PFS AND FULL-SCALE INDUSTRIAL BOILER'S FURNACE

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. 2) 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. 3), 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: plasma torch 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.

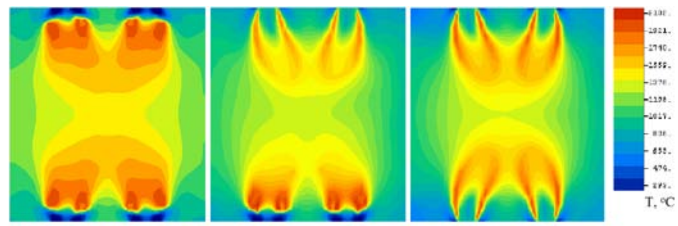
The results of numerical simulation by the PLASMA-COAL code are summarized in Table I. Heat value of the coke residue was 8580 kJ/kg. These data were taken as initial parameters for 3-D computation of the furnace of the power-generating boiler equipped with PFS. This computation was performed using CINAR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

Table I. Characteristics of ETCPF at the PFS exit

Content of gas phase, vol.% & kg/h							
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
88.5	1599.0	14.0	133.8	931.2	162.8	4911	31.0
Ash, kg/h	Char carbon, kg/h		T_{HRF}, ^{O}C		V_{HRF}, m/s		
1123.2	435.0		997		189		

Initial parameters for calculations of the furnace (Fig. 2) 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).

The calculations results are shown in Figs. 6 - 10. Fig. 6 visualizes the difference between temperature fields in three regimes of coal incineration. In the traditional regime (Fig. 6 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. 6 b two PFS are on top. The PFS impact appears as increase of temperature maximum up to 2102^{O}C and transformation of HRF flame shape, it becomes narrow and longer. When the furnace operates with four PFS (Fig. 6 c) the flames length increases but maximal temperature decreases to 1930^{O}C.



a b c

Fig. 6. 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

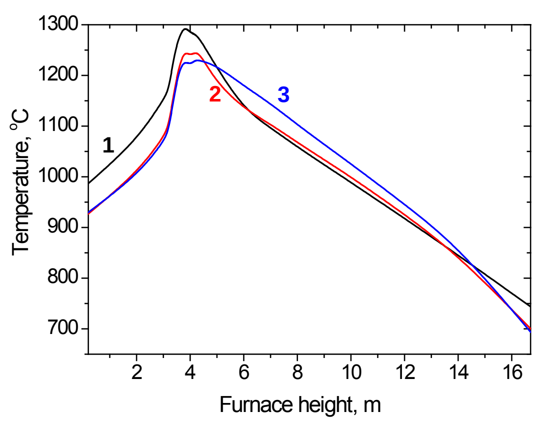


Fig. 7. Furnace height distribution of mass average temperature: 1) standard operational regime, 2) regime with two PFS, 3) regime with four PFS

Average characteristics of the boiler are compared in Figs. 7 - 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. 7). 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

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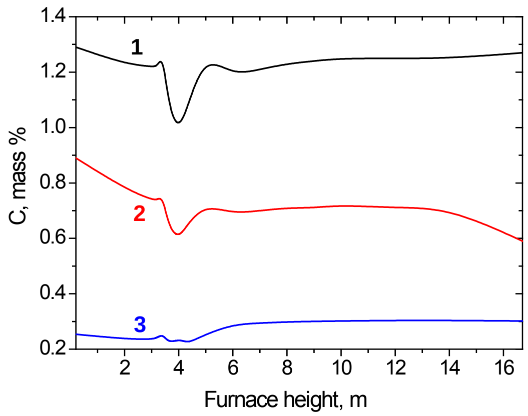

Fig. 8. Furnace height distribution of carbon mean concentrations: 1) standard operational regime, 2) regime with two PFS, 3) regime with four PFS

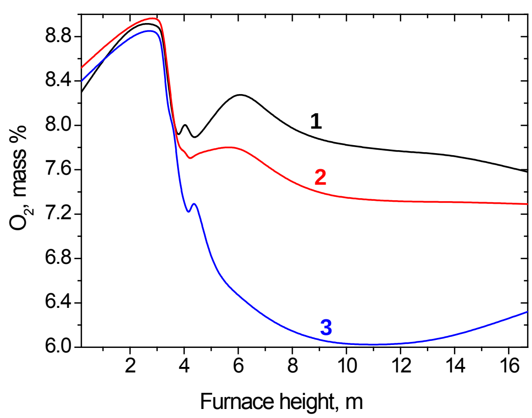

Fig. 9. Furnace height distribution of carbon mean concentrations: 1) standard operational regime, 2) regime with two PFS, 3) regime with four PFS

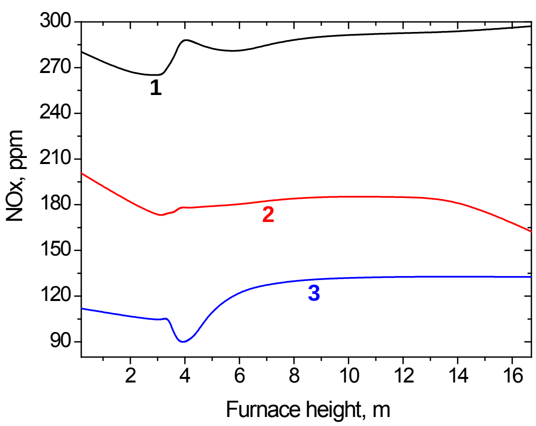

Fig. 10. Furnace height distribution of NOx mean concentration: 1) standard operational regime, 2) regime with two PFS, 3) regime with four PFS

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. 8) by ETCPF confirmed by decreased oxygen concentration in the furnace at the same location (Fig. 9). 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).

IV. Computation of 420 t/h Steam Productivity Boiler's Furnace Equipped with PFS

The boiler of 420 t/h steam productivity (Fig. 11) is equipped with 6 swirl burners arranged in two layers, three burners each, on faced wall of the furnace. As it is seen from the figure three PFS (Fig. 12) are installed instead of two burners of the lower layer and one of the upper layer. Low-rank Ekibastuz bituminous coal of 40 % ash content, 24 % devolatilization, 5 % humidity and 16700 kJ/kg heat value was incinerated in the furnace. The coal grinding fineness is R_{90}=15 %. All the calculations were performed in accordance to the aforecited technique.

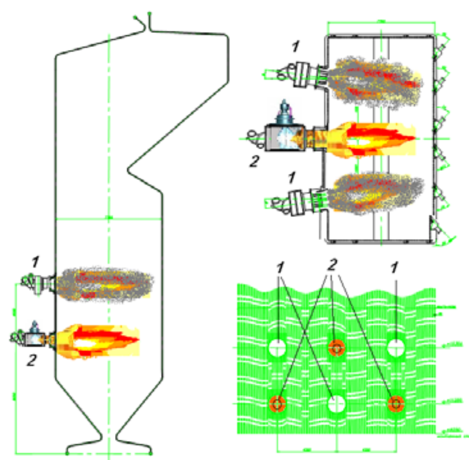

Fig. 11. Scheme of industrial 420 t/h steam productivity boiler in Almaty TPP-2 (Kazakhstan) retrofitted with PFS: 1) standard pulverized coal swirl burner, 2) PFS

PLASMA-COAL computer code has been used for calculation of ETCPF in the volume of PFS of 3.687 m length. The following initial parameters were used for calculations: plasma torch power was 200 kW, initial temperature of pulverized coal (coal/air mixture) was 90^{O}C, coal and air consumptions through PFS were 6000 and 8955 kg/h correspondingly.

The results of numerical simulation by the PLASMA-COAL code are summarized in Table II. Heat value of the coke residue was 6165 kJ/kg.These data obtained for the PFS exit were taken as initial parameters for 3-D computation of the furnace of a power-generating boiler equipped with PFS. This computation was performed using CINAR ICE code to demonstrate advantages of plasma aided coal combustion technology.

Table II. Characteristics of ETCPF at the PFS exit

Content of gas phase, vol.% & kg/h							
H_2	CO	CH_4	C_6H_6	CO_2	H_2O	N_2	O_2
1.05	7.75	0.3	0.77	15.6	3.55	70.84	0.15
7.272	751.4	16.75	207	2378	220.5	6870	16.49
Ash, kg/h		Char carbon, kg/h		T_{HRF}, ^{O}C		V_{HRF}, m/s	
1518		261		1025		48.2	

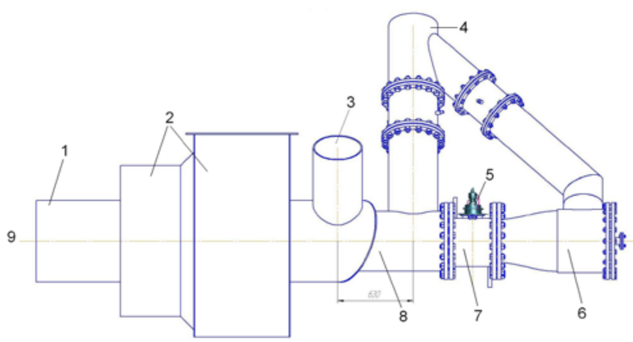

Fig. 12. Layout of the PFS for the boiler of Almaty TPP-2: 1) channel of the external flow of pf, 2) secondary air duct, 3) inlet of pf external flow, 4) inlet of pf internal flow, 5) plasmatron, 6) chamber for pf flow turning, 7) chamber for plasma chemical preparation of fuel for combustion, 8) chamber for mixing and thermochemical preparation of fuel, 9) furnace

Initial parameters for calculations of the furnace (Fig. 11) in different operational regimes were the following: temperature of the secondary air was 280^{O}C, coal productivity of the burner was 12000 kg/h and primary air flow rate through the burner was 17900 kg/h. Secondary air flow rate to the boiler was 446412 kg/h. Averaged size of the coal particles was 60 micron. The furnace size is as follows: 27 m height, 7.7 m depth and 14.5 m width. The x, y, z grid size was, respectively: 106 x 38 x 104.

The model predictions are presented in Figs. 13 - 17 which show results for the plasma-activated coal combustion in comparison with conventional coal combustion. Figs. 13 and 14 show temperature fields along the furnace height in the mean cross-sectional plane for two regimes of the furnace operation, traditional (Fig. 13) and plasma activated coal combustion (Fig. 14). The figures visually demonstrate the difference between the temperature fields for the two modes of coal combustion. When the coal combustion is in conventional

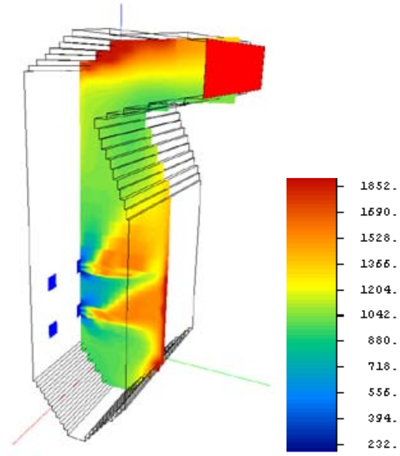

Fig. 13. Temperature field (^{o}C) along the furnace height in the mean cross-sectional plane of the furnace when it works in conventional mode of coal combustion

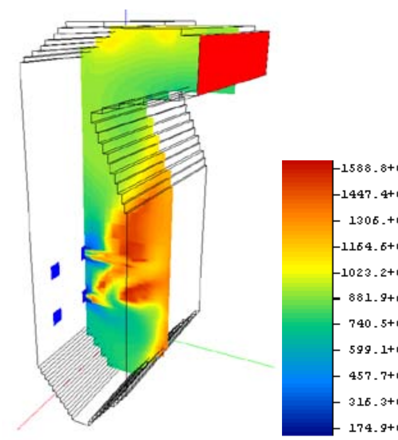

Fig. 14. Temperature field (^{o}C) along the furnace height in the mean cross-sectional plane of the furnace when it works in plasma-assisted mode of coal combustion using 3 PFS

mode, six symmetric pulverized coal flames are formed. Maximum temperature of these flames is 1852^{O}C. In Fig. 14 one can see influence of PFS on to the shape of the ETCPF flame and its maximal temperature. In the presented plane PFS is upwardly. High temperature body of the flame is moved closer to the PFS exit and upper in the furnace. Its maximal temperature is 1588^{O}C.

Averaged temperature curves (Fig. 15) have their maxima. The first one (H = 3 m) is generated by overheating of the furnace back wall by the pulverized fuel flame. The second maximum is above level of the burners of the upper layer due-to common forming of the flame body and observed moving as a result of natural convection. Averaged temperatures in the furnace operated in conventional mode are higher one for the furnace operated in plasma assisted regime using PFS. The difference achieves 350 degrees at the furnace exit. The reason of this is more intensive radiation of coal particles which have higher concentration and total reacting surface when the furnace operates in conventional mode in comparison with plasma assisted coal combustion. When PFS operates two component fuel of combustible gas and particles of coke

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residue enters the furnace. Mass of this fuel does not exceed 30 % of the initial coal mass. That decreases total surface of the radiative particles.

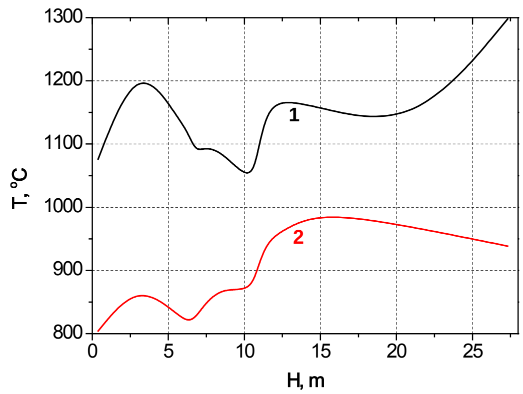

Fig. 15. Temperature (T) along the furnace height (H): 1) conventional incineration of coal, 2) incineration of coal when 3 PFS operate

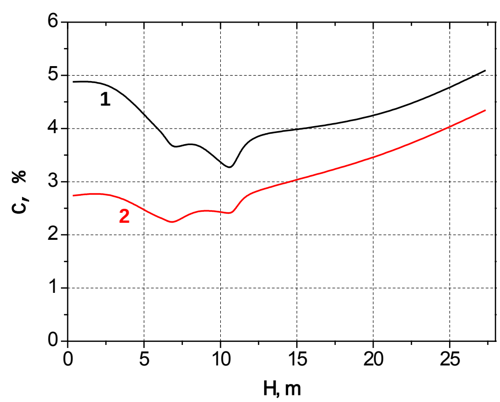

Fig. 16. Mean concentration of unburned carbon (C) along the furnace height: 1) conventional incineration of coal, 2) incineration of coal when 3 PFS operate

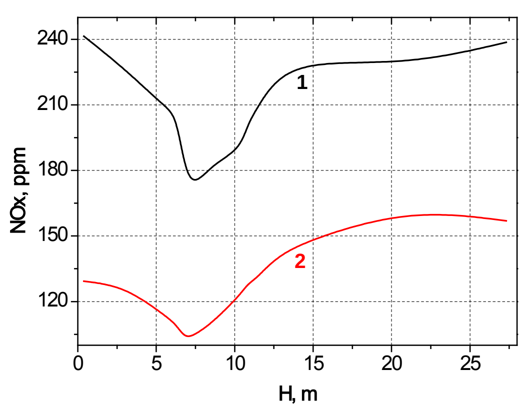

Fig. 17. NO_x mean concentration along the furnace height: 1) conventional incineration of coal, 2) incineration of coal when 3 PFS operate

At the furnace exit when three PFS operate concentration of unburned carbon (Fig. 16) is 16 % less one when the furnace works in traditional mode of coal combustion. Use of PFS improves ecological characteristics of the process of solid fuel combustion. Fig. 17 demonstrates more than 33 % decrease of nitrogen oxides concentration. Evidently decrease of unburned carbon and NOx concentrations at the furnace exit improves ecology-economic indexes of TPP.

V. Conclusion

Simulation and testing of PFS at existing coal-fired boilers of TPP confirmed the technical feasibility, environmental and energy efficiency of fuel oil free boilers start-up and pulverized coal flame stabilization using PFS.

PFS tests at the boilers BKZ-160 and BKZ-420 of Almaty Power System in the mode of the boilers start-up from cold confirmed possibility of high ash Ekibastuz coal ignition.

Inculcation of PFS gives economical effect, which depends on coal/fuel oil price ratio (Table III). Pay back period varies from 12 to 18 months. Economical effect for TPP of Kazakhstan is 400 mln. of US dollars a year.

Table 3. Economical comparison of the PFS technology with traditional one

Conventional technology	Plasma technology
1. Fuel Oil Rate for Russian TPP	
5.1 mln. t/year (cost is more than $ 2 billion)	0
2. Fuel Oil Rate for Kazakhstan TPP	
~1 mln. t/year (cost is about $ 400 mln.)	0
3. Investments for TPP	
100%	3-5%
4. Operating costs	
100%	28-30%
5. Electric power consumption for TPP auxiliary	
3-5%	0.5-1.0%

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