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Simulation of Coal Plasma Ignition and Combustion in a Furnace Chamber

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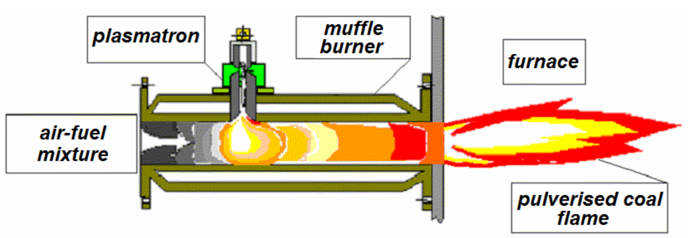
Traditional technologies of solid fuels incineration account for higher level of pollutant in comparison with incineration of liquid and gas fuels. However the fraction of heat and electric power generated at coal fired thermal power plants will increase and by 2020 will have exceeded 50%. Plasma activation promotes more effective and environmental friendly power coals incineration [1]. Effective development of a new coal technology is impossible without its modeling and numerical investigation. This paper presents numerical simulation results of plasma thermochemical activation of coal for ignition and combustion and comparative analysis of traditional and plasma activated coal combustion at a furnace chamber.

Two mathematical models were used for investigation of pulverised coal plasma activation and combustion processes. 1D code PLASMA-COAL with an emphasis on detail chemistry calculates concentrations of species, temperatures and velocities of treated coal-air mixture along the chamber with plasmatron. As a result of 1D model the initial data for 3D numerical simulation of coal combustion in a furnace chamber was obtained. 3D numerical experiments were performed for a furnace of the boiler having 475 t/h steam productivity. The furnace is equipped with 12 swirl three-channel burners; it is considered four of them were equipped with plasmatrons in the furnace corners. Burners are mounted in two layers, by 6 ones in every layer. The furnace grid of 25x47x58 size, this comprises 68150 control volumes, was used for numerical simulation. Figure 1 shows plasmatron and scheme of its mounting onto pulverized coal burner. Plasmatron is the main element of the plasma-fuel system (PFS). Plasma forming gas is air blown through the electrodes. Temperature of plasma flame reaches 5000 K on the outlet of plasmatron. Besides, Fig. 1 shows a scheme of the furnace dividing onto finite volumes.



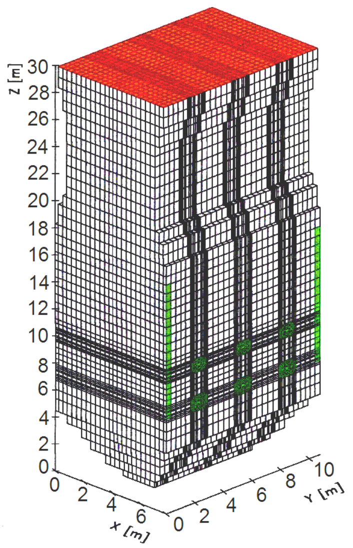


Fig. 1. Plasmatron and scheme of its mounting onto direct flow pulverized coal burner (plasma-fuel system) and the furnace chamber dividing for finite volumes scheme.

The calculations of the process of coal plasma thermochemical preparation at the plasma fuel systems for incineration are performed with the help of 1D mathematical model of flow, heat transfer and thermo-chemical transformation of pulverised coal in the plasma devices [2]. The model describes two-phase (coal particles and gas-oxidiser), chemically reacting flow, with an internal heat source (electric arc, plasma flame or chemical reactions). Entrained flow reactor is considered and plug flow is assumed. The gas and coal particles are assumed to enter the chamber with equal temperatures. Particle-to-particle, gas-to-particle and gas-to-plasma heat and mass exchange is considered. Heat and momentum exchange between the flow and the wall of the chamber is accounted. Besides considering plasma source, the model is distinguished by its detailed description of the kinetics of concurrent chemical reactions those general scheme, along with the reactions of evolution of primary products, takes into account the reactions of their further transformations. The temperature dependence of rate constants is governed by the Arrhenius equation. The list of the chemical reactions used in the model consists of 116 reactions [3]. The starting chemical stage of coal conversion in the plasma-chemical reactors is the evolution of volatile matter (CO, CO_2, CH_4, H_2, H_2O, C_6H_6, C_5H_5N, C_4H_5N, CH_3SH, C_4H_4S). After that there are two more stages. They are char carbon and nitrogen gasification (seven reactions with H_2O, CO_2, CO, O_2, NO, H_2S) and conversion of evolved volatile products in the gas phase. For NO formation a model of fuel NO, thermal NO and prompt NO was considered. The model comprises 36 chemical reactions. They are the reactions of C_5H_5N and C_4H_5N emission from coal, char-N oxidation and the following transformation of them through HCN and NH_3 to NO. In [4, 5] the model is shown in details. The set of the ordinary differential equations includes equations for species concentrations in conjunction with equations for gas and particles velocities and temperatures, respectively. The equations set was described in detail in [2, 6]. Experimental verification of the model was performed for different coal–oxygen ratios, power of plasma source and processes (steam gasification, combustion and air gasification) and showed satisfied results [2, 7].

Plasma thermo-chemical preparation of coal for combustion is complex thermal process occurring in several stages. First the plasma flame heats the air-coal mixture followed by ignition and then by spontaneous combustion and gasification of the coal in the primary air of the mixture. Calculations were performed for the cylindrical through flow chamber equipped with plasmatron of 100 kWe power. The diameter of the chamber was 0.73 m, wall temperature was accepted as 700 K. Mean diameter of coal particles was 60 μm. Chemical analysis of the coal is given in table 1. Temperature of the air-coal particles mixture on the inlet of the chamber was 423 K. Coal consumption through the chamber was 7.3 t/h. Coal concentration 0.4 kg/kg in air-coal mixture was used for the calculations. It is equal 0.44 of air theoretically necessary for complete combustion of the coal. Plasma chamber thermal efficiency was taken as 90%.

Table 1. Chemical analysis of the black coal, mass %.

A^d	C	O	H	N	S	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
44	44.47	6.97	3.03	0.72	0.81	28.51	13.59	1.20	0.33	0.37

The results of the numerical simulations are presented in Fig. 2. Figure 2 (*a, b*) displays gas and solid phase temperature and velocity variation along the PFS correspondingly. By the outlet of the PFS gas and solid particles reach equilibrium at the temperature 1076 K. The velocities of gas and particles increase and are little different; the gas velocity exceeds the solid one by less then 10%. By the PFS outlet to the furnace chamber, gas and particles velocities are in equilibrium. Figure 2 (*c*) shows variation of the degree of coal gasification along the PFS. It rises monotonously and by the PFS outlet it attains 70%. Table 2 gives the main data on the outlet of PFS. The data can be used for PFS design and here they were taken as initial parameters for 3D simulation of the furnace equipped with four PFS.

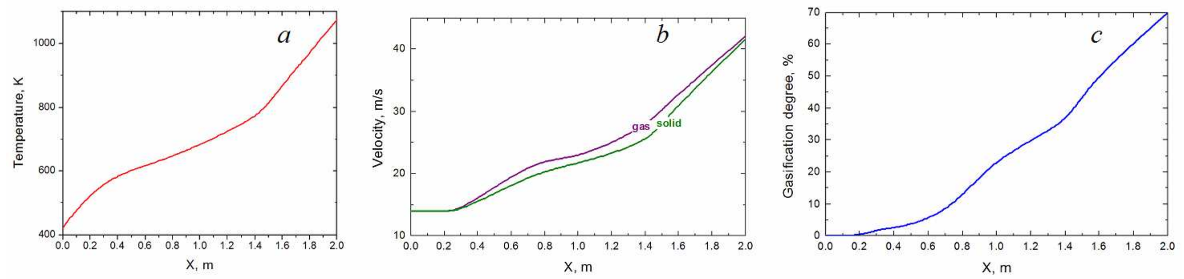


Fig. 2 Temperature of the products along the PFS (a); velocity of the products along the PFS (b); coal gasification degree variation along the PFS (c).

Table 2. The 1D simulation results.

CO	$\mathbf{H_2}$	$\mathbf{CH_4}$	$\mathbf{CO_2}$	$\mathbf{H_2O}$	$\mathbf{N_2}$	$\mathbf{O_2}$	$\mathbf{X_C}$	$\mathbf{V_g}$	$\mathbf{T_g}$	$\mathbf{t_g}$
Volume %							*%*	*m/s*	*K*	*s*
11.04	2.17	0.22	13.53	1.93	70.55	0.13	67.6	42.1	1076	0.016

The 3D simulation of coal fired furnaces was fulfilled with the help of the computer code FLOREAN [8]. This code is based on the solution of the conservative equations of the flue gas mixture by finite volume method. It includes a submodel of momentum and energy balances, SIMPLE-method for pressure corrections, k-ε turbulence model, six-flow model for radiation heat transfer calculations and balance equation for species. Two-fluid model is considered. Solid phase influence to the turbulent transfer was accounted with the help of ratio for turbulent viscosity taken from [9]. For description of chemistry simplified models were used. For NOx formation global mechanism was used. Zeldovich mechanism was used for thermal NO formation description. Mechanism of fuel NO formation is taken from [10]. The model involves NH_3, HCN, NO and N_2 as nitrogen containing species. The 1st reaction step is the conversion of HCN to NH_3 by an attack of an oxidizing agent. The NH_3 forms and destructs NO within a pair of competitive parallel reactions. And the recycling of NO back to HCN through hydrocarbons is accounted. The code FLOREAN has been validated in details for a lot of experiments in laboratory and industrial furnaces [8, 10].

Distributions of temperatures, velocities, species concentrations (CO, CO_2, N_2, NO_X, O_2, etc.) were determined for different sections of the furnace. Two variants were calculated. The first one is conventional coal combustion in the furnace and the second one is plasma activated coal combustion. As a result of it PFS advantages are clearly demonstrated. The temperatures along the furnace (see Figure 3) for plasma-activated coal combustion are less than ones for traditional incineration of coal. But there are few zones where the temperatures of coal combustion with plasma activation are more than ones without it. They are lower part of the furnace and zone on the level of the PFS's allocation. It can be explained by influence of PFS's. They cause earlier heating and ignition of air mixture and subsequent front of combustion displacement to the zone of plasma-fuel systems. Table 3 gives a comparison of the two calculated variants (traditional and plasma activated coal combustion). The numerical predictions are in satisfactory fit with experimental data. The difference in experimental and calculated parameters is within 15%. NOx concentration in the furnace outlet is ~16% smaller at plasma activation of coal incineration.

Analysis of the research showed ecological efficiency of the plasma technology. For more complete environmental effect it is most rationally to increase quantity of the plasma-fuel systems on the furnace and to mount them on to all burners. It will allow decreasing unburned carbon and nitrogen oxides to the maximum permissible concentration and even less.

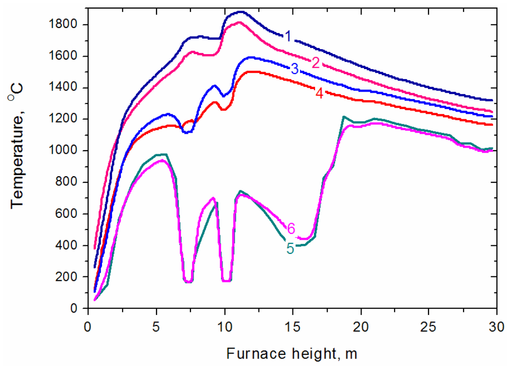


Fig. 3 Temperature variation along the furnace chamber.
1, 3, 5 – traditional regime of coal incineration, maximal, mean and minimal temperatures correspondingly; 2, 4, 6 – regime of coal incineration with four plasma-fuel systems, maximal, mean and minimal temperatures correspondingly.

Table 3. Comparison of flue gas characteristics on the outlet of the furnace chamber.

	Traditional incineration (experiment)	*Plasma activated incineration*
T, ^{O}C	1219 (1180)	1166
NO_X, mg/Nm^3	932	785
CO_2, kg/kg	0.20 (0.17)	0.21
O_2, kg/kg	$3.2\ 10^{-2}$ ($3.5\ 10^{-2}$)	$2.8\ 10^{-2}$

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