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The use of a new "clean" technology for burning low-grade coal in on boilers of Kazakhstan TPPs

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The combustion of low-grade coals is associated with the difficulties of their inflammation and burn-out, an increase of harmful dusty and gaseous emissions (ash, nitrogen and sulphur oxides). The use of low-grade coals leads to an increase in the fuel oil and natural gas expenses for the furnace kindling, capturing and stabilization of the pulverized coal torch combustion, and the environmental situation worsens. In this work the research on the torch combustion of the coal dust prepared by a plasma-thermochemical treatment for combustion have been done using the method of three-dimensional simulation. The authors have obtained that the plasma preparation of coal for combustion enables one to optimize the process, improve the conditions for inflammation and combustion and minimize the emissions of harmful substances.

Keywords: Combustion, plasma preparation, simulation, harmful substances, plasma-fuel system

INTRODUCTION

At present, in Kazakhstan, it is necessary to increase energy production processes efficiency in strict compliance with emission standards harmful substances and effective utilization of the equipment.

A promising solution in this area is the new effective technology of combustion processes during the thermal activation of low-grade coal to create efficient methods of "clean" energy production in real combustion chambers of Kazakhstan TPP [1-2]. This is a technology of preliminary preparation for the burning of low-grade coal (high-ash content), which use the plasma-fuel system (PFS). As follows from the very definition of the system, the PFS generally represents a burner device with a plasmatorch. The processes of the plasma thermochemical preparation of solid fuels for combustion are realized in the PFS.

This technology recommended itself quite well on powerful energy units in a number of foreign countries, and has a high economic and ecological potential.

At the use of a plasma activation of the pulverized coal flow the input parameters employed in computations differ from those existing in practice at a conventional arrangement of the pulverized coal torch combustion. A torch of the reacting fuel mixture enters the combustor, which causes an alteration of the main parameters of the combustion process.

In this connection, a complex investigation of the work process of the furnace chamber with allowance for the influence of the fuel thermochemical preparation, including the numerical simulation of processes occurring within the combustor volume, becomes especially urgent.

The relevance and importance of these researches is that this technology may be implemented on all coal-fired thermal power plants of Kazakhstan.

PLASMA TECHNOLOGY OF LOW-GRADE COAL COMBUSTION

The essence of solid fuel preparation using a plasma technology is that the low-reaction high-ash coal is converted into a high-reaction fuel, heated to the ignition temperature in the volume of burners. The resulting highly reactive fuel by mixing with the secondary air in the combustion chamber intensively ignites and burns rapidly without the "backlight" of the fuel oil (Fig.1).

The plasma thermochemical preparation of coal for combustion consists of the heating by a plasmatorch at an oxygen deficiency in the pulverized coal flow in a special chamber up to a

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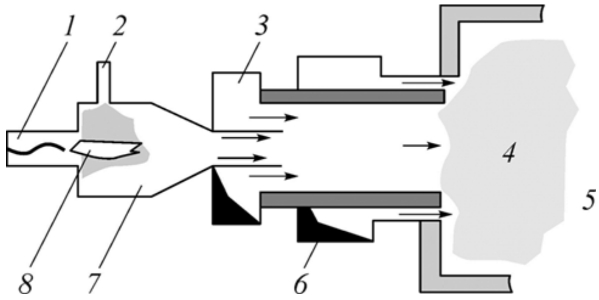
temperature exceeding the temperature of the self-inflammation of a given coal.

As a result, the obtained fuel mixture or the highly reactive two-component fuel (HRTF) consisting of the combustible gas and coke rest ignites at its mixing with a secondary air and stably burns without using a pulverized coal torch for stabilization even in a cold furnace of the backup high-reaction fuel (mazut or natural gas).



1 – plasmatron; 2 – a smaller part of the air mixture; 3 – the main part of the air mixture; 4 – the flame of plasma thermochemical preparation products of an air mixture; 5 – furnace space; 6 – secondary air; 7 - the chamber of electrothermochemical preparation of fuel to burning; 8 – plasma flame

Fig.1. Plasmatron in a cylindrical vortex burner [3]

In this case, there occurs a practically complete emission of volatiles and a partial combustion and/or gasification of the coal carbon. The use of various types of burners does not cause the differences in the mechanisms of the process of the plasma thermochemical treatment of coal for combustion. The use of plasma fuel systems enables one to eliminate from the TPS fuel balance the mazut, which is conventionally used for the lighting of boilers.

The method of thermochemical plasma preparation of coal for combustion has been tested successfully on several thermal power stations, which confirms its efficiency. However, one needs the development of special techniques for computing the burner devices for a wide introduction of plasma technology of the coals fuel oil-free inflammation, which will make it possible to estimate prior to experiment the main parameters of the processes occurring in the volume of a burner supplied with a plasmatorch, obtain the fuel mixture composition at the furnace inlet, and compute the characteristics of the heat and mass transfer within the combustor of the TPS boiler. The use of new computer technologies for simulation has enabled one to carry out the computations of these processes [4−12, 25].

OBJECT OF RESEARCH

The present paper deals with the numerical investigation of the plasma source influence on thermochemical conversions of the aeromixture and its combustion by the example of the combustion of the high-ash coal in the furnace of the BKZ-420 boiler of the Almaty TPS-2. Thus, the investigation task included the computation of combustion processes in the furnace of a boiler supplied with the conventional pulverized coal burners with a fuel oil sprayer and the PFS. Three regimes of the boiler operation: 1) the conventional (using six pulverized coal burners); 2-3) plasma activation of combustion (with a replacement of three and six pulverized coal burners with the PFS’s) were chosen for numerical investigations.

When carrying out computational experiments for plasma activation of combustion, the authors used the program FLOREAN, which accounts for the furnace actual configuration and the kinetics of the process of the combustion of coal particles by a simplified kinetic scheme. The same code was used also for the computations of the conventional regime of coal combustion in the furnace of boiler BKZ-420.

While replacing the design burners with the vortex PFS’s (Fig.1) with a chamber for electrothermochemical fuel preparation 0.73 m in diameter one employs a plasmatorch with 100 kW power. The chamber wall temperature was assumed equal to 700 K. The mean-mass diameter of coal particles was 60 μm (R_{90} = 14.3 %), the original aeromixture temperature at the PFS inlet remained the same as at the inlets of the main burners and was equal to 423 K, the coal consumption via the PFS was 7.3 t/h. The thermal efficiency of the PFS based on experimental data was taken to equal 90 %. The results of the PFS numerical simulation are summarized in Tab.1. These data taken for the PFS outlet section have been used as the input data for the three-dimensional simulation of the furnace of the power boiler BKZ-420 of the Almaty TPS-2, three and six burners of which were virtually reequipped into the PFS’s [13−15].

Table 1. The results of the PFS numerical simulation

<table>
<tr><td>CO</td><td>H₂</td><td>CH₄</td><td>CO₂</td><td>H₂O</td><td>N₂</td><td>O₂</td></tr>
<tr><td colspan="7">Volumetric, %</td></tr>
<tr><td>11.04</td><td>2.17</td><td>0.22</td><td>13.53</td><td>1.93</td><td>70.55</td><td>0.13</td></tr>
<tr><td colspan="2">NO, mg/m^{3*}</td><td>X_C, %</td><td>V_g, m/s</td><td colspan="2">T_g, K</td><td>τ_g, s</td></tr>
<tr><td colspan="2">7.5</td><td>67.6</td><td>42.1</td><td colspan="2">1076</td><td>0.016</td></tr>
</table>

The table contains the following values:

[*] Normal cubic meter (under normal conditions: P = 101325 Pa, T = 298 K);

X_C – coal gasification degree;

V_g – the flow velocity;

T_g – the temperature of the highly reactive two-component fuel flow;

τ_g – the time of fuel residence in the plasma-fuel system.

The model presented in to the numerical simulation of BKZ-420 combustion chamber. Its steam capacity equal to 420 t/h. Boiler equipped with six vortex dust burner, arranged in two levels with three burners on the front wall of the boiler as shown in Fig.2.

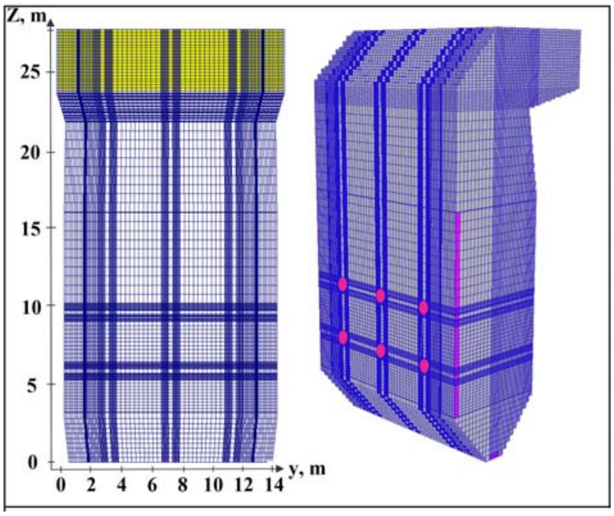


Fig.2. Geometry and finite-difference grid of the boiler furnace BKZ-420 of Almaty TPS-2

Low-grade high-ash coal dust from Ekibastuz has burnt in the boiler, it has ash content of 40 %, volatile – 24 %, moisture content – 5 % and the highest calorific value 16700 kJ/kg. The fineness of coal milling is equal to R_{90}= 15 %. All numerical calculations were performed on above characteristics. The initial parameters required for the three-dimensional calculation of the BKZ-420 boiler of Almaty TPS-2, equipped with plasma-fuel systems, are shown in Tab.2.

Table 2. The initial data of coal and BKZ-420 combustion chamber for numerical calculation

Characteristic	Quantity
Coal type	Ekibstuz
Density of particles, kg/m^3	1300
C_{daf}, %	82.0
H_{daf}, %	5.0
N_{daf}, %	1.5
O_{daf}, %	11.5
Ash, %	40
Humidity, %	5
Volatile, %	24
Coal consumption by the boiler, kg/h	72 000
Coal consumption by the burner, kg/h	12 000
Primary air consumption by the boiler, kg/h	107 035
Secondary air consumption by the boiler, kg/h	402 656
Secondary air temperature, °C	280
Temperature of aeromixture, °C	90
Average particle size of coal, m	60×10^{-6}
The lower heating value of coal, kJ/kg	16 750
The amount of computation (control volume)	$1\ 150 \times 10^3$

METHODOLOGY OF THE RESEARCH

Basic equation

Among the methods of modelling the combustion of pulverized fuel most widely used method based on the Euler, an approach to describe the motion and heat transfer of the gas phase. This method uses the spatial balance equations for mass, momentum, the concentrations of gaseous components and energies for the gas mixture. To describe the motion of single particles and heat mass transfer of fuel along their trajectories used Lagrange approach. Turbulent flow structure is described by a two-parameter of k-ε model of turbulence, where k – the kinetic energy of turbulence, ε – turbulent energy of dissipation [16].

The mathematical description of physical and chemical processes based on the solution of balance equations. In general, these equations contain four terms describing:

- Change in the value of time;
- Convective transfer;
- Diffusive transfer;
- External and internal sources.

To calculate the gas flow solid-phase with the input of all transport quantities in the control volume are determined by the generalized Eq.(1):

$$\frac{\partial(\rho\phi)}{\partial t} = -\frac{\partial(\rho u_1\phi)}{\partial x_1} - \frac{\partial(\rho u_2\phi)}{\partial x_2} - \frac{\partial(\rho u_3\phi)}{\partial x_3} + \\ + \frac{\partial}{\partial x_1}\left[\Gamma_\phi \frac{\partial\phi}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[\Gamma_\phi \frac{\partial\phi}{\partial x_2}\right] + \\ + \frac{\partial}{\partial x_3}\left[\Gamma_\phi \frac{\partial\phi}{\partial x_3}\right] + S_\phi \qquad (1)$$

In this equation *t* – time, ρ – density, $u_1..u_3$ – velocity vector components, $x_1..x_3$ – spatial coordinates, Γ_ϕ – turbulent exchange coefficient, S_ϕ – describes external and internal sources for the quantity ϕ, other terms describes the variation of ϕ:

$\dfrac{\partial(\rho\phi)}{\partial t}$ – Time component;

$\dfrac{\partial(\rho u_j \phi)}{\partial x_j}$ – Convective transfer;

$\dfrac{\partial}{\partial x_1}\left[\Gamma_\phi \dfrac{\partial \phi}{\partial x_1}\right]$ – Molecular transfer.

In mathematical model of gas, flow or liquids used equations of conservation of mass and momentum:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial(\rho u_j)}{\partial x_j},$$

here: $\phi=1$, $\Gamma_\phi=0$, $S_\phi=0$;

$$\frac{\partial(\rho u_i)}{\partial t} = -\frac{\partial(\rho u_i u_j)}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial p}{\partial x_i} + \rho g_i,$$

here: $\phi = u_i;\ \ \Gamma_\phi = \mu;$

$$S_\phi = -\frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}\left(\mu \cdot \left(\frac{\partial u_j}{\partial x_i} - \frac{2}{3}\cdot \delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right).$$

For flows in which taken place processes of heat transfer, as well as for compressible media we have to solve the equation of energy conservation:

$$\frac{\partial(\rho h)}{\partial t} = -\frac{\partial(\rho u_i h)}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\frac{\mu}{\Pr}\cdot\frac{\partial h}{\partial x_i}\right) + S_h,$$

here: $\phi=h$, $\Gamma_\phi= \dfrac{\mu}{\Pr}$, $S_\phi=S_h$, were μ – dynamic viscosity coefficient, Pr – Prandtl number, S_h - source term due to radiant heat transfer.

The six-flow model of De Marco and Lockwood in Cartesian coordinates is used to describe the radiant heat exchange in this work. In this model the distribution of radiant energy flow in corresponding regions is approximated by power series and spherical functions. The distribution of intensity in different directions is approximated by Taylor power series by solid angle.

Source term due to radiant heat transfer in the equation of energy balance is obtained by integration of total intensity along solid angle Ω =4π.

Thus, we have following:

$$S_h = \frac{4\pi}{3}\cdot K_{abs}(B_1 + B_2 + B_3) - 4\cdot K_{abs}\cdot\sigma\cdot T^4,$$

here: K_{abs} – integral absorption factor, σ – Stefan-Boltzmann constant.

In flows with the processes of mixing of different components, with the reactions of combustion, etc. must be added the equation of conservation of the mixture components or the conservation equation for mixture fraction and its changes:

$$\frac{\partial(\rho c_\beta)}{\partial t} = -\frac{\partial(\rho c_\beta u_i)}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\rho\cdot D_{c_\beta}\cdot\frac{\partial c_\beta}{\partial x_i}\right) + S_\beta,$$

here: $\phi=c_\beta$, $\Gamma_\phi=\rho\cdot D_{c\beta}$, $S_\phi=S_\beta$, were $D_{c\beta}$ – diffusion coefficient, S_β – the formation and decomposition of the components of β as a result of chemical reactions.

For turbulent flow the system of equations is complemented by transport equations for turbulent characteristics.

RESULTS OF COMPUTATIONAL EXPERIMENTS

The present paper provides an overview of the current capabilities of the CFD-computer code FLOREAN (acronym for FLOw and REActioN) developed at the Institute for Fuel and Heat Technology in Technical University of Braunschweig (Germany) [16-23].

Simulation tool FLOREAN allows getting detailed information about furnace performance including velocities, temperature, thermal radiation and concentration distributions, etc. within the furnace and along the walls. The efficient combustion of solid fuel in combustion chambers and the efficient heat transfer to water and steam in steam generators are essential for the economical operation of power plants. This information is useful to evaluate the combustion process and to design optimal furnaces. FLOREAN will also be very useful in improving combustion process of different fuels in industrial boilers, optimizing operation and minimizing pollutant emission [24].

Fig.3 show the full velocity vectors in the combustor cross section for the conventional coal combustion in the burners location plane.

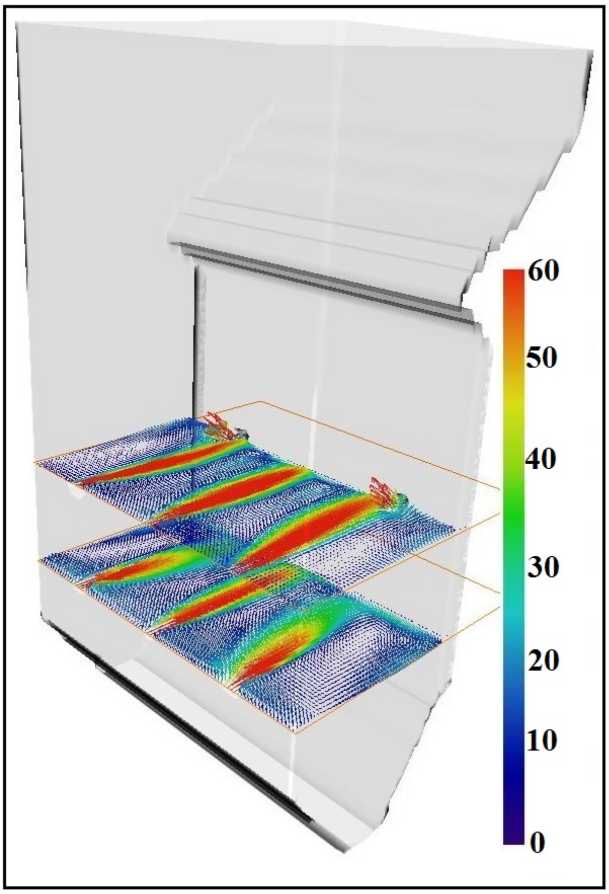


Fig.3. Full velocity vector fields in the combustor cross section at a conventional coal combustion

Fig.4a show the case of a combustor with the same cross section of which is supplied with three PFS's, and Fig.4b show the case of a furnace chamber supplied with all six PFS's.

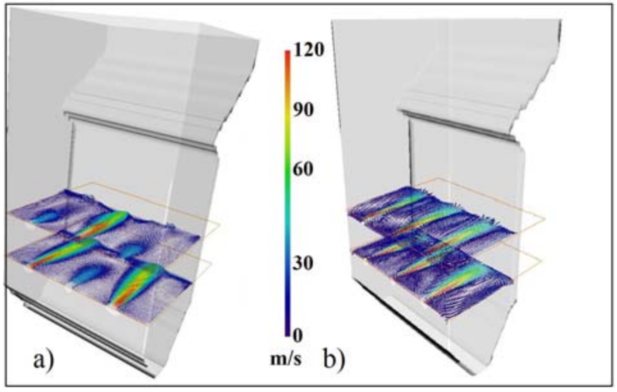
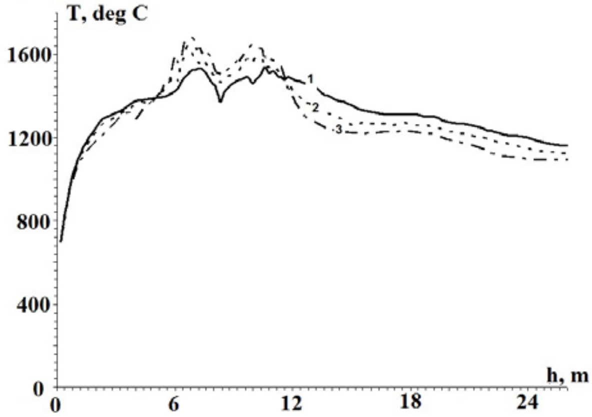


Fig.4. Full velocity vector fields in the combustor cross section at the combustion of a coal activated at three PFS's (a) and at six PFS's (b)

An analysis of the obtained velocity fields has shown that the pulverized coal flow activation affects significantly the flow field, namely the reacting jet propagation in the furnace volume, the admixing processes in the jet, the sizes and shape of torches. One observes a substantial difference in the distribution of pulverized coal flows entering the furnace through the conventional burners and through the PFS.

The main reason for the alteration in the distribution of velocities in the furnace space is an increase in the velocity of the fuel mixture supplied to the combustor (the two-component high-reaction fuel). With increasing number of the PFS's that is of the thermochemically activated fuel flows, the torch core shifts to the symmetry centre of the furnace chamber, and one observes a clearer pattern of the motion of vortex flows from the PFS.

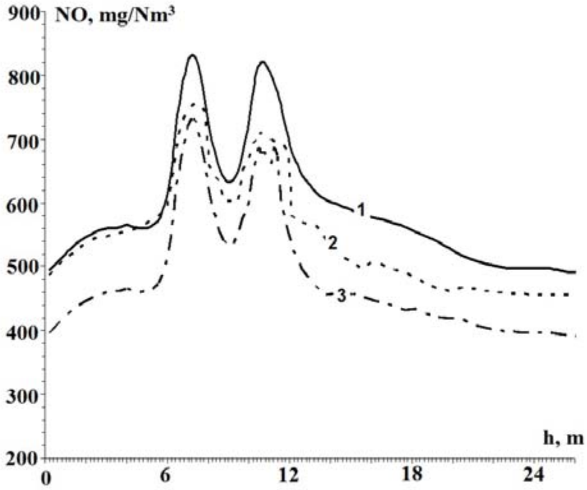
The mass and heat exchange intensify at a collision of counter torches and tubulisation of flows, and the resulting enhancement of the mixture formation and heating speed up the combustion process. An increase in the velocity along the torch axis increases the intensity of admixing high temperature furnace gases, which in turn leads to a speed-up of the growth of particles temperature and, consequently, to an improvement of the pulverized coal torch inflammation from the burners, which are not supplied with plasma torches. An intense supply of hot furnace gases to the torch root is ensured due to aerodynamic peculiarities of thermochemically activated flows owing to an external and internal recirculation.



1 - Conventional regime of coal combustion; 2 - Combustion regime of the coal with its plasma activation in three PFS's; 3 - Combustion regime of the coal with its plasma activation in six PFS's

Fig.5. Variation of temperatures over the combustor height

Figs.(5, 6) show the variations of the temperatures and NO concentrations over the combustor height, which were computed for two versions of coal combustion with a preliminary plasma activation of the coal in a PFS and with a conventional one. It is seen that the temperatures over the combustor height, which were computed for the coal combustion activated by plasma (Fig.5, curves 2 and 3) are mainly below the temperatures calculated for the conventional regime of the coal combustion (Fig.5, curve 1). There is, however, a zone (the combustor lower part up to the level of the upper row of burners), in which the combustion temperature of the coal with plasma activation is above the coal combustion temperature in the conventional regime. This phenomenon may be explained by the PFS influence, which cause an earlier inflammation of the mixture saturated with air and the corresponding shift of the flame front towards the PFS mouth.

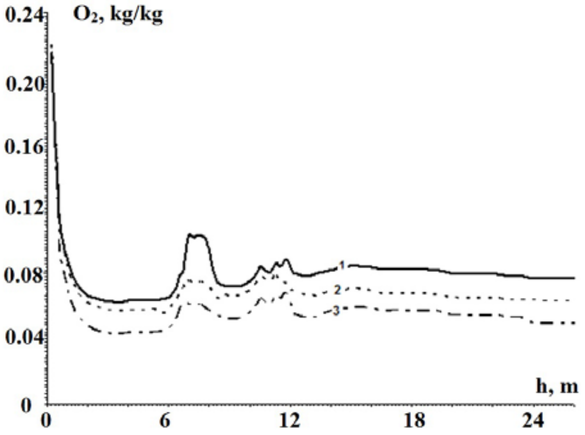


1 - Conventional regime of coal combustion; 2 - Combustion regime of the coal with its plasma activation in three PFS’s; 3 - Combustion regime of the coal with its plasma activation in six PFS’s

Fig.6. Variation of NO concentrations over the combustor height

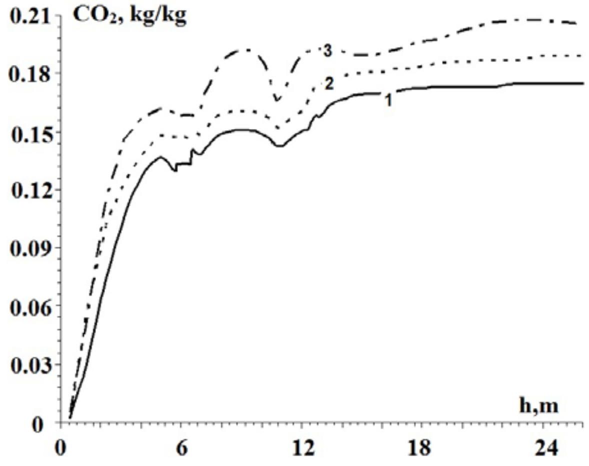
One observes also the PFS influence on the formation of NO (Fig.6) over the combustor height. Both the mean values of the NO concentration over the combustor height are much lower in the case of the combustion of the coal with its plasma activation. Note that the use of the PFS reduces the NO concentration (Fig.6, curves 2, and 3) even in the combustor lower part (below the PFS location level). This phenomenon is explained by a suppression of the formation of fuel nitrogen oxides inside the PFS. The fuel nitrogen is released into the gaseous phase at the coal heating together with the volatiles inside the PFS.

Figs.(7, 8) illustrate the distribution of the concentrations of oxygen and carbon dioxide over the combustor height. The mean values of oxygen concentrations (Fig.7, curves 2 and 3) over the entire combustor height below in the case of the combustion of a coal which has passed a preliminary thermochemical treatment in the PFS, and the mean values of the carbon dioxide concentrations (Fig.8, curves 2 and 3) are higher.



1 - Conventional regime of coal combustion; 2 - Combustion regime of the coal with its plasma activation in three PFS’s; 3 - Combustion regime of the coal with its plasma activation in six PFS’s

Fig.7. Variation of oxygen concentrations over the combustor height



1 - Conventional regime of coal combustion; 2 - Combustion regime of the coal with its plasma activation in three PFS’s; 3 - Combustion regime of the coal with its plasma activation in six PFS’s

Fig.8. Variation of carbon dioxide concentrations over the combustor height

These data confirm the fact that at the use of the PFS for coal combustion stabilization, one observes a more complete coal burn-out and a reduction of the mechanical underburning of the fuel [5].

CONCLUSIONS

A comparative numerical investigation of the conventional coal combustion and the coal combustion in a furnace supplied with a PFS, which has been conducted in the work, shows that the plasma thermochemical treatment of the coal prior to its combustion enables one to optimize the process, improve the inflammation and combustion conditions, minimize the emissions of harmful substances into atmosphere. The application of the PFS technology will enable a reduction of the equivalent fuel expense per 1 kWh of the generated energy by 10−15 gram of the equivalent fuel, which is equivalent to the 1.5−3 % fuel saving or to an increase in the efficiency of electricity generation by 0.5−1 %. A wide application of the PFS technology carries in itself an important social-economic effect and will make it possible not only to improve the environmental situation in regions near the TPS, optimize the process of the combustion of energy fuels, but also to raise the level of the culture of the TPS workers at the expense of the application of a more progressive and environmentally clean technology of the inflammation and combustion of solid fuels.

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