MODELLING OF PLASMA SUPPORTED COAL COMBUSTION IN FULL-SCALE BOILER

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Abstract Plasma activation promotes more effective and environmental friendly low-rank coal combustion. This work presents numerical modelling results of plasma thermochemical preparation of pulverized coal for ignition and combustion in the furnace of a utility boiler. Two kinetic mathematical models were used in the investigation of the processes of air-fuel mixture plasma activation, ignition and combustion. A 1D kinetic code, PLASMA-COAL, calculates the concentrations of species, temperatures and velocities of treated coal-air mixtures in a burner incorporating a plasma source. It gives initial data for 3D-modeling of power boilers furnaces by the code FLOREAN. A comprehensive image of plasma activated coal combustion processes in a furnace of pulverised coal fired boiler was obtained. The advantages of the plasma technology are clearly demonstrated.

Keywords: Coal combustion, thermo chemical preparation, plasma-fuel system, modelling

INTRODUCTION

The conventional combustion of solid fuels accounts for higher pollutant levels than emitted by liquid and gas fuels. The increase in the solid fuels fraction in the worldwide fuel balance demands new, more effective, and ecologically acceptable technologies. One possible solution is ‘pulverised fuel thermo chemical preparation’ of the coal using plasma [1]. Plasma activation promotes more effective and environmental friendly power coals combustion. The technology utilises air-fuel mixture arc plasma to heat the coal fuel to the temperature of volatile release and char carbon partial gasification. In this manner, from an air-coal mixture a highly reactive two-component fuel is obtained, regardless of whether the initial coal is of a high or low rank. When mixed with the secondary air in the furnace it can be ignited and caused to burn stably without the need for supplementary fuels (fuel oil or natural gas) traditionally used for start-up the boilers and for flame stabilisation when the coal is out of design quality.

Fig. 1 presents a schematic of the plasmatron and its mounting onto a pulverised coal burner. The plasmatron is the main element of the plasma-fuel system (PFS). It is a low-temperature plasma generator with the plasma gas being formed from air blown through the electrodes.

Fig. 1. Schematic of the plasmatron and its mounting onto a pulverised coal burner (Plasma-Fuel System)
Effective development of a new technology is impossible without prior and accompanying process modelling and numerical investigations. Two fluid dynamics kinetic mathematical models are considered herein. Numerical simulations of plasma thermochemical preparation of fuel for ignition and combustion of a pulverized coal in utility boilers are performed. Comparison of the calculated results with experimental data obtained under fullscale industrial conditions are effected.

1. ONE-DIMENSIONAL MODELLING OF PULVERIZED COAL PLASMA ACTIVATION IN A PLASMA-FUEL SYSTEM

The calculations of the coal thermochemical plasma preparation processes in the PFS are performed with the help of a specially constructed mathematical model of the flow, heat transfer and thermochemical transformation of coal-dust fuel in the plasma device (Fig. 1) [2]. The model describes two-phase (coal particles and gas-oxidiser), chemically reacting flow, with an internal heat source (electric arc, plasma torch or chemical reactions). Gas and coal particles are assumed to enter the PFS with equal temperatures. There is particle-to-particle, gas-to-particle and gas-to-electric arc heat and mass exchange. Heat and momentum exchange between the flow and the wall of the PFS is accounted for. Also, some fuel chemical transformations are considered. They are the formation of primary volatile products, conversion of evolved volatile products in the gas phase and the char carbon gasification reactions. An entrained flow reactor is considered and plug flow is assumed. The resulting set of ordinary differential equations includes equations for species concentrations (chemical kinetics equations) in conjunction with equations for gas and particles velocities and temperatures, respectively. The model is described in detail in [2-4].

The model is distinguished by its detailed description of the kinetics of the chemical reactions whose general scheme, along with the reactions of the evolution of primary products, takes into account the reactions of their further gas phase transformations and char carbon gasification (Table 1). The temperature dependence of rate constants is governed by the Arrhenius equation:

\[ k_j = A_j \cdot \exp \left( -\frac{E_j}{RT} \right) \cdot T^n. \]

The coal composition is represented in the model by its organic and mineral parts. The organic mass of coal is specified by the set of the functional groups (CO, CO₂, CH₄, H₂O, tar), fuel nitrogen, sulphur and carbon, and the mineral part is represented as ash with appropriate thermo physical properties.

According to the assumed scheme, the first chemical stage of the process is coal thermal destruction (reaction 1-11 in Table 1). The coal particles generate volatile and tar components. They are benzol (C₆H₆), pyridine (C₅H₅N) and pyrrole (C₄H₅N), thiophene (CH₉S₂) and mercaptan (C₄H₄S) .

The interactions between the char carbon and water vapour, oxygen, carbon dioxide, nitrogen oxide and hydrogen sulphide (reactions 12-17) are the rate-limiting stages of the process. Each of the above reactions is a complex process, and includes elementary stages: reagent adsorption on the particle surface, dissociation, reactions in the gaseous phase, desorption etc. The detailed mechanism of these reactions was not taken into account in the model. Only the whole transformation, in accordance with the gross reactions 12-17, was considered.

For nitrogen oxide (NO) formation, a model embodying fuel NO, thermal NO and prompt NO was considered [5, 6]. The model comprises 36 chemical reactions (Table 1). Among them there are the reactions of C₅H₅N and C₄H₅N emission from coal, char nitrogen (N) oxidation, the following conversion of them through hydrogen cyanide (HCN) and ammonia (NH₃) to NO.

Conversions of the components containing sulphur are described by reactions 91-116. Note, kinetic scheme takes into account sulphur oxides (SOₓ) formation both in the gas phase (reactions 100-106) and from gaseous species interaction with components of coal mineral mass (reactions 107-116).
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<th>$E$</th>
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51 \( \text{C}_2\text{H}+\text{H}_2\text{O}=\text{CH}_3+\text{CO} \quad 9.08 \ 0 \ 0.5 \ | \ 109\text{H}_2\text{S}+\text{O}=\text{OH}+\text{HS} \quad 8.2 \ 0 \ 1.5 \)
52 \( \text{C}_6\text{H}_6=\text{C}_2\text{H}_2+\text{C}_2\text{H}_2+\text{C}_2\text{H}_2 \quad 12.0 \ 0 \ 85.0 \ | \ 110\text{H}_2\text{S}+\text{O}=\text{SO}+\text{H} \quad 11.0 \ 0 \ 0.0 \)
53 \( \text{OH}+\text{OH}=\text{H}_2\text{O}+\text{O} \quad 9.5 \ 0 \ 1.1 \ | \ 111\text{H}_2\text{O}+\text{O}_2=\text{SO}+\text{OH} \quad 7.8 \ 0 \ 0.0 \)
54 \( \text{H}+\text{OH}+\text{M}=\text{H}_2+\text{M} \quad 10.56 \ 0 \ 0.0 \ | \ 112\text{H}_2\text{O}+\text{O}_2=\text{SO}_2+\text{H} \quad 8.54 \ 0 \ 6.5 \)
55 \( \text{H}+\text{H}+\text{M}=\text{H}_2+\text{M} \quad 9.56 \ 0 \ 0.0 \ | \ 113\text{SO}_2+\text{O}_2=\text{SO}_2+\text{M} \quad 10.8 \ 0 \ 0.0 \)
56 \( \text{CH}_2\text{O}+\text{OH}+\text{H}_2\text{O} \quad 10.5 \ 0 \ 1.5 \ | \ 114\text{SO}_2+\text{O}_2=\text{SO}_2+\text{H} \quad 11.5 \ 0 \ 0.0 \)
57 \( \text{H}+\text{OH}+\text{M}=\text{H}_2O+\text{H} \quad 9.84 \ 0 \ 7.04 \ | \ 115\text{SO}_2+\text{O}_2=\text{SO}_2+\text{H} \quad 9.1 \ 0 \ 0.0 \)
58 \( \text{H}_2+\text{OH}=\text{H}_2\text{O}+\text{H} \quad 11.4 \ 0 \ 10.0 \ | \ 116\text{SO}_2+\text{O}_2=\text{SO}_2+\text{H} \quad 11.38 \ 0 \ 2.5 \)

\( a\) Equations 1-6 are the devolatilization reactions.  
\( b\) Dimensions of \( A_j \) are \([\text{s}^{-1}]\) for the first-order reactions and \([\text{litre} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}]\) for the second-order reactions.

The model is realised by the computer code: ‘PLASMA-COAL’ which uses Gear’s method for the solution of stiff systems of chemical kinetics equations.

Experimental validation of the one-dimensional model was performed for different coal – oxygen flow ratios, plasma source power levels and processes (steam gasification, combustion and air gasification) Satisfactory results were achieved [4, 7].

The plasma thermo chemical preparation of coal for combustion is a complex thermal process which occurs in several stages. The plasma flame initially 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 a cylindrical through flow PFS equipped with a plasmatron of 100 kW power. The diameter of the PFS is 0.73 m, its wall temperature is assumed to be 700 K. The PFS thermal efficiency was taken as 90 %. The mean diameter of the coal particles is 60 \( \mu \)m. The temperature of the air-coal mixture at the inlet of the PFS is 423 K. The PFS coal consumption rate was 7.3 t/h. The chemical analysis of the coal, Ekibastuzski (Kazakhstan), is given in Table 2.

The results of the numerical simulations are presented in Figs. 2 and 3. The gas species concentrations (Fig. 2 on the left) at the PFS outlet comprise combustible gas (CO+H2+CH4+C6H6) of 39.2 %, oxidants (CO2+H2O) of 3.9 % and nitrogen (N2) of 56.8 %. Fig. 2 (on the right) shows the variation of the degree of coal gasification along the PFS. The degree of gasification rises monotonically, attaining 81 % by the end of the PFS.

Table 2. Chemical Analysis of the Bituminous Coal (% dry mass basis)

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<tr>
<td>44</td>
<td>44.47</td>
<td>6.97</td>
<td>3.03</td>
<td>0.72</td>
<td>0.81</td>
<td>28.51</td>
<td>13.59</td>
<td>1.20</td>
<td>0.33</td>
<td>0.37</td>
</tr>
</tbody>
</table>

The coal moisture content is 7 %; volatile matter is 24 %; lower calorific value is 16750 kJ/kg

Fig. 3 displays the gas phase temperature and gas and solids velocity variation along the PFS. By the end of the PFS, the gas reaches a temperature of 1328 K. The difference between gas and solids temperatures is negligibly small. The velocities of the gas and particles increase and are little different, the gas velocity exceeding that of the solids by less than 10 %. By the end of the PFS (inlet to the furnace) they are in equilibrium.

It is evident that the gaseous products at the above temperatures will self ignite on mixing with the secondary air in a furnace. Note that the char carbon heated to such high temperatures (circa 1300 K) will also ignite. This two-component highly reactive fuel will enhance ignition and combustion of the main pulverised coal in a furnace and will allow start-up of the boiler without the need for supplementary natural gas or fuel oil.

It is seen from the table that the NO concentration is quite low. This is due to the known mechanism of fuel nitrogen oxides suppression in PFS [1]. Inside the PTS, fuel nitrogen evolves to the gas phase together with the volatile matter of the coal. At this location, there is a deficit of oxygen for
complete combustion of the coal, so the fuel nitrogen transforms to its molecular form. The temperature inside the PFS is not enough (Fig. 3) for significant thermal NOx formation. As regards sulphur oxides, their concentration at the PFS outlet is determined mainly by the sulphur content of the coal (Table 2).

![Diagram](image1)

**Fig. 2.** Species concentrations (on the left) and Coal Gasification Degree (on the right) Variation along the PFS

![Diagram](image2)

**Fig. 3.** Gas temperature (on the left) and Gas and Solids Velocity (on the right) Variation along the PFS

Table 3 presents the calculated results at the PFS outlet (x=2 m).

<table>
<thead>
<tr>
<th>CO</th>
<th>H₂</th>
<th>CH₄</th>
<th>C₆H₆</th>
<th>CO₂</th>
<th>H₂O</th>
<th>N₂</th>
<th>O₂</th>
<th>NO</th>
<th>SOₓ</th>
<th>X_c</th>
<th>V_g</th>
<th>T_g</th>
<th>t_g</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.3</td>
<td>13.3</td>
<td>0.3</td>
<td>0.3</td>
<td>3.8</td>
<td>0.1</td>
<td>56.8</td>
<td>0</td>
<td>7.5</td>
<td>2126.6</td>
<td>81.5</td>
<td>55.4</td>
<td>1328</td>
<td>0.023</td>
</tr>
</tbody>
</table>

The data (Table 3) were taken as initial conditions for the 3D simulations of the furnace equipped with a plasma-fuel system.

### 2. THREE-DIMENSIONAL MODELLING OF PLASMA ACTIVATED COAL COMBUSTION IN A FURNACE

The computer simulation was performed with the help of the computer code FLOREAN [8, 9] applicable to coal-fired furnaces. This code is based on the solution of the conservative equations of the flue gas mixture by the finite volume method. It includes a submodel of momentum and energy balances, the SIMPLE-method for pressure corrections, a k-ε turbulence model, the six-flux model for radiation heat transfer and a balance equation for the components of substance. This computer code allows to extraction of the velocity components {u,v,w}, the temperature T, the pressure P, the concentration of combustion products and other characteristics of the process. Pulverised coal homogenous model was used. By the model solids velocities are in dynamic equilibrium with gas.
solid phase influence to the turbulent transfer was accounted for with the help of a ratio for the
turbulent viscosity from [10] \( \mu_{\text{eff}} = \mu_{G,\text{eff}} \left(1 + \rho_p/\rho_G \right)^{1/2} \).

For the description of the chemistry, simplified models were used. They account only for the
chemical reactions of the main components and the overall reactions of the fuel components oxidizing
to their stable end-products Intermediate reactions, and also the formation of unstable intermediate
products, are not taken into consideration.

The model from [12], which demands minimal computational expense, was used. Moreover, this
model has been tested for a large number of laboratory experiments and in large combustion chambers.
This model takes into account the reactions of devolatilization (water steam, hydrogen, carbon oxides,
methane) and also the transformation reactions of the initial volatiles released from the coal as gaseous
final products (CO, CO2, H2O, H2, O, H). The reactions and their kinetic data are given in [8, 12].

The formation of nitrogen oxides from the nitrogen-containing species of fuel is calculated by a
simplified scheme. According to this scheme the nitrogen-containing species are decomposed during
the combustion of the volatile matter to active atomic nitrogen, which partially recombines into
molecular nitrogen (N+N→N2) and partially oxidises to a mixture of nitrogen oxides
(mN+O2→mNOx). For NOx formation, a global mechanism is used. The NOx-model considers 31
elementary reactions with account of 15 species. Zeldovich mechanism is used for thermal NO
formation description. The mechanism of fuel NO formation is taken from [15]. The model involves
NH3, HCN, NO and N2 as nitrogen-containing species. The first reaction step is the conversion of HCN
to NH3 by an attack of an oxidizing agent. The NH3 forms and destructs NO within a pair of
competitive parallel reactions. And the recycling of NO back to HCN through hydrocarbons is
accounted [10]. The concentration of resulting molecular nitrogen and mixture of nitric oxides during
gas combustion is found by the solution of the equation of homogeneous kinetics [11].

The code FLOREAN has been validated in details for a lot of experiments in laboratory and
industrial furnaces [8, 9, 13, 14]. The computer simulation experiments were conducted for low-rank
Ekibastuz bituminous coal (see Table 2) supplied to a boiler with a steam productivity of 475 tonnes
per hour. The boiler is installed at the Ermakov Thermal Power Plant in Kazakhstan. The furnace size
is as follows: 30 m height, 10 m in width and 7 m depth. There are twelve swirl burners. They are
placed at two layers, six per layer facing each other. A computational grid of 27x61x60 was used for
the numerical simulation. The calculations were carried out for four, six and twelve burners replaced
with PFS. In the case of the four PFS they are placed in the furnace corners at the lower layer. Next
variant is six PFS placed in the lower layer. And the last variant is twelve PFS instead of all main
burners.

The model predictions are presented in the following figures which show results for plasma
activated coal combustion compared with conventional coal combustion.

Fig. 4 shows temperatures and NO concentrations along the furnace with and without plasmatron
assistance. One can see that in general the temperatures along the furnace for plasma-activated coal
combustion with four and six plasma systems are less than those for conventional coal combustion.
However, a zone exists in the lower part of the furnace where the temperature of coal combustion with
plasma activation is more than that without it. It extends to the level of the upper tier of burners. It can
be explained by the influence of the plasma-fuel systems. They cause earlier heating and ignition of the
air mixture and subsequent displacement of the combustion front to the zone of plasma-fuel systems.
The observed temperature decrease in the upper part of the furnace indicates earlier completion of the
combustion process. Concerning NO formation along the furnace we can see a decrease of NO
concentration for the plasma activated combustion of mean, maximal and minimal concentrations along
the full height of the furnace. Increasing the number of plasma-fuel systems the decreases in the
temperature and NO concentrations becomes more pronounced. When the coal combustion process is
initiated by four plasma-fuel systems the difference between the temperatures for plasma activated and conventional combustion are noticeably less than is the case for six plasma-fuel systems.

Fig. 5 illustrates the oxygen and carbon dioxide concentration distributions along the furnace height. The mean level of oxygen along the full height of the furnace is lower for plasma activated combustion, but as consequence the mean values of carbon dioxide are higher. These data confirm more complete combustion and unburned carbon decrease when the PFS are deployed.

Figs. 6 and 7 visually demonstrates the difference between conventional and plasma activated coal combustion in the furnace by way of the temperature field and NO formation.

0, 4, 6, 12 – regimes of coal combustion: conventional, with four, six and twelve PFS;
1, 2, 3 – minimal, mean and maximal values correspondingly.

Examining the different regimes of plasmatrons installation, the temperature fields (Fig. 6) are noticeably different for the three considered cases. In furnace cross section at the lower burner level, it can be seen that the temperatures in the zone of plasma-fuel systems are higher. Considering the temperature field in section ZX, it is evident that implementation of the plasmatrons causes earlier heating and ignition of the air-mixture and initiation of combustion.

The PFS influence results in NOX (Fig. 7) formation in the wall region of the furnace at the outlet of the PFS. In contrast, for conventional coal combustion, NOX is formed in the central area of the furnace at the burner level. This is confirmed in the Fig. 4 by the presence of NO two peaks at the level of the burners. Comparison of the upper and lower panels reveals that the plasma-fuel systems influence the NOX distribution even at this level. Recall that the burners of the upper tier are not equipped with plasmatrons. These observations are confirmed by significant difference in mean NO concentrations for the calculated cases. The mean NO concentration in vicinity of the second tier of the burners is 1086.27 mg/Nm³ for the case of conventional coal combustion, 908.03 mg/Nm³ for coal
Conventional regime of coal combustion

Plasma-activated coal combustion with six plasma-fuel systems

Plasma-activated coal combustion with twelve plasma-fuel systems

Fig. 6. Temperature in Cross Section of the Furnace along the Furnace Height, on the Level of Lower Tiers of the Burners and on the Furnace Outlet (from left to right).
Conventional regime of coal combustion

Plasma-activated coal combustion with six plasma-fuel systems

Plasma-activated coal combustion with twelve plasma-fuel systems

Fig. 7. Nitrogen Oxide in Cross Sections along the Furnace Height, at the Level of Lower Tiers of the Burners and at the Furnace Outlet (from left to right).
combustion activated by the six plasma-fuel systems of the lower tier, and 615.20 mg/Nm$^3$ for coal combustion activated by twelve plasmatrons. The influence of the plasma-fuel systems on NO formation persists along the full height of the furnace as seen from the right upper and lower pictures of the figure. Interestingly, the plasma-fuel systems decrease the NO concentration even in the lower part of the furnace (below the level of PFS). This is explained by the phenomenon of suppression of fuel NO$_X$ formation inside PFS. Fuel nitrogen is released with the coal volatile matter inside the PFS. It forms molecular nitrogen due to a deficiency of oxygen in the air-fuel mixture treated by plasma, a fact confirmed by the low NO concentration (7.5 mg/Nm$^3$) at the outlet of the PFS (see Table 3). Fuel nitrogen is a main source of nitrogen oxide emission at coal combustion [5].

Table 4 gives a comparison of the two predicted cases, conventional and plasma activated coal combustion. Comparison of the numerical and experimental data for conventional coal combustion shows satisfactory agreement. The difference in experimental and calculated parameters is less than 17%. These results demonstrate the improvement of the main characteristics of the coal combustion process due to the use of plasma-fuel systems.

Table 4. Comparison of flue gas characteristics at the outlet of the furnace

<table>
<thead>
<tr>
<th></th>
<th>Conventional combustion (experiment)</th>
<th>Plasma activated combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Four PFS</td>
</tr>
<tr>
<td>T, °C</td>
<td>1219.40 (1180)</td>
<td>1166.30</td>
</tr>
<tr>
<td>NOX, mg/Nm$^3$</td>
<td>932.30</td>
<td>785.34</td>
</tr>
<tr>
<td>CO$_2$, kg/kg</td>
<td>0.185 (0.17)</td>
<td>0.186</td>
</tr>
<tr>
<td>O$_2$, kg/kg</td>
<td>$3.2 \times 10^{-2}$ (3.5 $\times 10^{-2}$)</td>
<td>$2.78 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Two fluid dynamics kinetic models have been used in this study. Computer simulations of pulverised coal combustion assisted by plasma-fuel systems have been performed throughout the furnace from the burner inlet locations to the furnace outlet. Comparison of the computed results with the experimental data has proved the reliability of the mathematical models and their potential for use in designing commercial plasma-fuel systems.

Analysis of the research reveals the ecological efficiency of the technology. The present plasma assisted combustion technology has been shown to increase the carbon burnout and reduce the emissions of nitrogen oxides. For still further enhanced environmental impact, plasma fuel systems should be fitted to all the burners of the power boiler.

REFERENCES


