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Application of Numerical Methods for Calculating the Burning Problems of Coal-Dust Flame in Real Scale

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Abstract
The burning of low-grade coals in coal-dust boilers presents considerable difficulties because poor quality fuels adversely affects to the performance of the ignition process, stabilization of the burning torch and process of burning out of fuel, in addition, significantly reduces to the environmental and economic indicators of thermal power plants, as a result of emission of harmful gases (NO, SO, CO) and fly ash. This article presents the numerical methods for calculating the burning problems of coal-dust flame. The increase in moisture of fuel leads to the reduction of average values of temperature and concentration of carbon dioxide in the combustion chamber, and also to the reduction of concentration of carbon monoxide CO and nitrogen oxides NO in the field of combustion.

Keywords: Combustion, heat power plant, heat and mass transfer, moisture of coal, coal-dust torch.

Introduction

It is known, fuel moisture is the ballast that substantially reduces the effectiveness of its combustion. However, the studies on burning of coals of various moisture carried out by groups of scientists[1, 2, 3] showed the need for a more complete investigation.

Today, numerical modeling is rather effective method for predicting the behavior of systems difficult for analytical research, among them is the burning of low-grade coal in the combustion chambers of boilers on power plants. Computer simulation allows obtaining of qualitative and quantitative characteristics of the process and also the response of the system to the change of its parameters and initial conditions[4-7].

The main stages of process of modeling are: 1) the stage of subject modeling consisting of the formulation of basic laws, rules and approximations; 2) stage of mathematical modeling – the description of the main equations; 3) the stage of computer modeling including mathematical calculations and graphic interpretation of the obtained data.

Numerical modeling was carried out with FLOREAN[8, 9] software on the basis of the three-dimensional equations convective warm and a mass transfer for a prediction of influence of moisture content of coal for the general operation of the fire chamber and formation of products of combustion[1, 7].This software package was used for a basis of numerical researches and added by us the new GEOM software, which is always written in the selection of a new object of study (the combustion chamber), taking into account the geometry, sizes of burners, their shape and location in the space of the combustion chamber[10-15]. In this program all the characteristics of complex real physical and chemical processes in the object of research also the boundary conditions for the solution of the chosen research problem which are adequately reflecting this process are set[16, 17].

As the object of study was chosen real industrial steam boiler PK-39, mounted on the Aksu power plant (Kazakhstan) with dimensions7, 762x10, 76x29, 985m. Seven steam boilers PK-39 with rated capacity of 300 MW and steam production capacity of 475 t/h work at Aksu power plant. The combustion chamber of the boiler is equipped with 12 vortex coal-dust torches located on two tiers. The sizes of the burners: lower layer – d=1.2 m and upper layer – d=1.05 m The scheme of the combustion chamber of the boiler and its breakdown on control volumes is submitted in Fig.1.

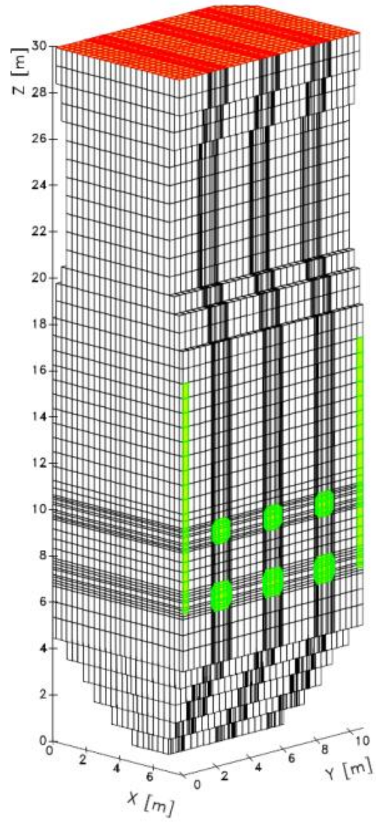

Figure 1: PK-39 boiler combustion chamber

Mathematical Formulation of the Problem

A mathematical model describing the processes of turbulent heat and mass transfer in this case is as follows[8-11]:

a) Continuity equation: $\frac{\partial \rho}{\partial t} = -\frac{\partial \ \rho u_j}{\partial x_j}$, (1)

ρ – density; u – flow velocity.

b) Equation of motion:

$$\frac{\partial \ \rho u_j}{\partial t} = -\frac{\partial \ \rho u_i u_j}{\partial x_j} + \frac{\partial \tau_{i,j}}{\partial x_j} - \frac{\partial p}{\partial x_j} + \rho f_i, \qquad (2)$$

p – pressure; $\tau_{i,j}$ – tensor of viscous tension; f_i – volume forces.

c) Energy equation:

$$\frac{\partial}{\partial t}(\rho h) = -\frac{\partial}{\partial x_i}(\rho u_i h) - \frac{\partial q_i^{res}}{\partial x_j} + \frac{\partial p}{\partial t} + u_i \frac{\partial p}{\partial x_i} + \tau_{i,j} \frac{\partial u_j}{\partial x_i} + S_q, \qquad (3)$$

h – enthalpy; q_i^{res} – energy flux density due to molecular heat transfer, S_q – a source of energy.

d) Conservation law for substance components:

$$\frac{\partial}{\partial t} \ \rho c_n \ + \frac{\partial}{\partial x_i} \ \rho u_i c_n \ = \frac{\partial}{\partial x_i}\left[\frac{\mu_{eff}}{\sigma_{c_{n,eff}}} \frac{\partial c_n}{\partial x_i}\right] + S_{c_n}, \qquad (4)$$

$c_n = \frac{\rho_n}{\rho}$ – mass concentration substance components; ρ_n – partial density – the mass of the components of n in the considered control volume; $\mu_{eff} = \mu_{lam} + \mu_{turb}$ – effective viscosity; $\sigma_{c_{n,eff}}$ – empirical constant; S_{c_n} – the source term taking into account the contribution of the chemical reactions in the change in the concentration of components.

e) Standard k-ε turbulence model:

$$\frac{\partial\left(\bar{\rho} k\right)}{\partial t} = -\frac{\partial\left(\bar{\rho}\ \bar{u}_j k\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_k} \frac{\partial k}{\partial x_j}\right] + P - \bar{\rho}\varepsilon, \qquad (5)$$

k – kinetic energy of turbulence; P – the production of turbulent kinetic energy, which is determined by the following equation:

$$P = \left[\mu_{turb}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right]\frac{\partial \bar{u}_i}{\partial x_j} - \left[\frac{2}{3}\rho k \delta_{ij}\right]\frac{\partial \bar{u}_i}{\partial x_j} \qquad (6)$$

and the equation for the turbulent kinetic energy dissipation ε:

$$\frac{\partial \ \bar{\rho}\varepsilon}{\partial t} = -\frac{\partial\left(\overline{\rho u_j}\varepsilon\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon} \frac{\varepsilon}{k} P - C_{2\varepsilon} \frac{\varepsilon^2}{k} \bar{\rho}, \qquad (7)$$

$C_{1\varepsilon}$, $C_{2\varepsilon}$ – empirical constants; $\bar{\rho}\varepsilon$ – the conversion of kinetic energy pulsating movement in the internal energy (dissipation):

$$\bar{\rho}\varepsilon = \overline{\mu_{turb} \cdot \frac{\partial u'_i}{\partial x_j} \cdot \left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i}\right)}. \qquad (8)$$

For obtaining characteristics of turbulent flow Reynolds's method was used (transport variables are presented as the the sum of an average and the pulsation values): $u = \bar{u} + u'$ and $\rho = \bar{\rho} + \rho'$.

In these equations using the appropriate turbulent Prandtl numbers σ_k, σ_ε, which are empirical constants for modeling of turbulent processes of energy exchange.

Results

Figures 2-5 shows the results of modeling experiments of the study of heat and mass transfer taking into account various value of moisture content in fuel. As it is possible to notice, qualitatively provided characteristics don't change depending on moisture, however, it is possible to notice that curves in these drawings differ in a quantitative sense.

Along with the results of modeling experiments, Fig. 2 shows the results of a natural experiment on the power plant[18] for coal with a moisture content equal to 7%. We see that the behavior of the experimental and calculated (numerical simulation) curves coincide. It is possible to see the existence of a minimum curves in areas of an arrangement of a line of torches that is connected with the low temperature of the aero mix (150 °C) given through these torches. Temperature reaches the maximum values in the central part of the combustion chamber where there is a torch core. In process of advance to an exit from the combustion chamber, the field of temperature is leveled, and the values are reduced.

The greatest differences between the calculated and experimental data (Fig. 2.) are observed when ignited coal torch. This can be explained by the instability of the combustion process in this area and, accordingly, the difference between the actual physical conditions of the dust mixture and ignition of a mathematical model that describes the process of combustion of solid fuels in this area.

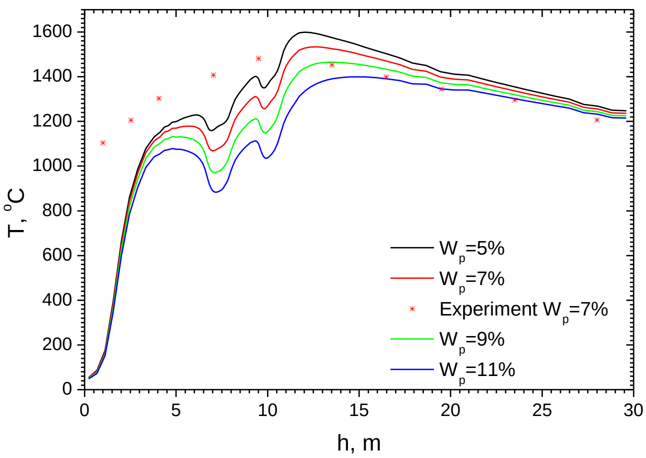

Figure 2: The temperature distribution in height of the combustion chamber during combustion of coal of varying moisture in the combustion chamber of the boiler PK-39 Aksu power plant

By analyzing the curves of Fig. 2, it should be noted that an increase in fuel moisture results in a decrease in average temperature in the combustion chamber. This can be explained by the fact that moisture of fuel reduces its thermal value, as transformation of 1 kg of water into steam takes 2, 5 MJ of heat. The greatest distinctions between temperature curves for coal of different moisture can be noticed in the combustion chamber in the field of a line of torches. At the exit from the combustion chamber differences in values of temperature for coals which moisture changes from 5% to 11%, decrease and makes no more than 35 °C.

As a result of modeling experiments on burning Ekibastuz coal concentration fields of harmful dust and gas products of combustion were calculated. In figures 3-5 schedules of distribution of concentration of CO and CO_2 carbon oxides and NO nitrogen oxide are submitted. The analysis of Fig. 3 shows that formation of carbon monoxide occurs mainly in the main body of the torch, where its average temperature reaches its maximum value. Moreover, with decreasing of moisture content in coal, maximum of CO concentration increases and moves to the region of the burners. In process of advance to an exit from a fire chamber, concentration of carbon monoxide decreases.

Thus, increasing the fuel moisture reduces the concentration of carbon monoxide CO in the active combustion, which coincides with the experimental data given in works[1, 18]. It can be explained to that at low temperatures fuel carbon reaction with air oxygen with formation of carbon dioxide prevails, however at temperature increase reaction between coal and the formed carbon dioxide starts proceeding.

Fig.4 shows the distribution of average values of the CO_2 concentration in each section of the height of the combustion chamber. It can be seen that increasing moisture leads to reduction of concentration of carbon dioxide that is connected with temperature conditions of process.

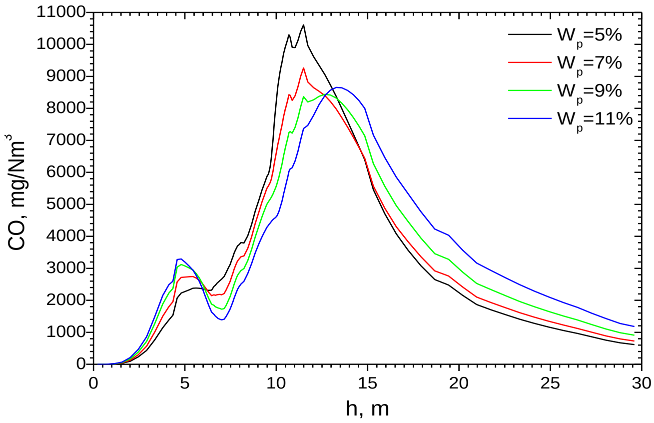

Figure 3: The distribution of the CO concentration at the height of the combustion chamber of the boiler PK-39 Aksu power plant coal combustion varying moisture

This in turn creates worse conditions for the reaction connected with afterburning of CO to CO_2. Consequently, the concentration of carbon dioxide CO_2 at the outlet of the fire chamber with increasing fuel moisture is reduced.

Fig. 4 shows the results of an experiment conducted directly at the power plant[18]. We see that the greatest distinctions in results of modeling and natural experiments are observed in the field of ignition of gas mixture that is connected with instability of burning and distinction between the modeled and experimental conditions for aero mix ignition.

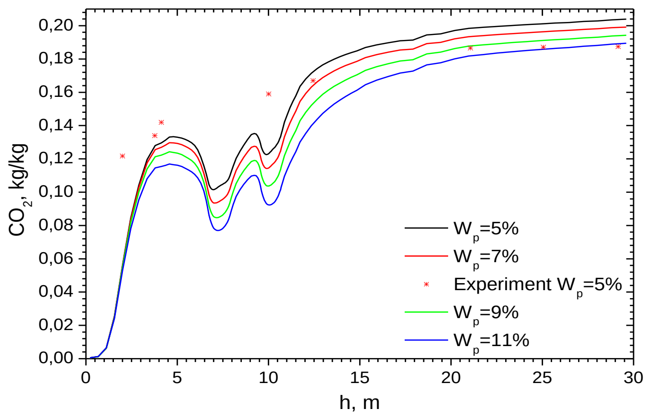

Figure 4: The distribution of the concentration of CO_2 in height of the combustion chamber of the boiler PK-39 Aksu power plant coal combustion varying moisture

Fig. 5 shows a field of concentration of NO nitrogen oxide on height of the combustion chamber of the boiler PK-39 Aksu power plant for different values of the moisture content of the fuel. From the figure we can see that the greatest distinctions in average concentration fall on the central part of the furnace where burners are located. Here the increase in moisture of coal leads to reduction of concentration of NO that is confirmed by the researches described in works[1, 3, 18]. However, it is possible to notice that to an exit from the fire chamber of a field of concentration of nitric oxide levels and differences in the concentrations shown in Table 1 in the order of 3-18 mg/Nm^3.

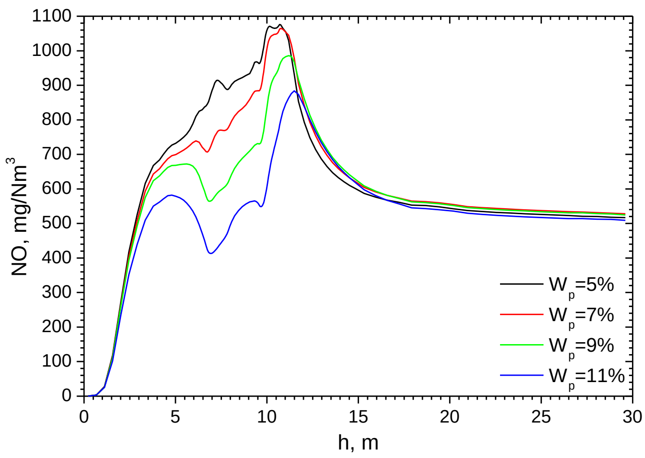

Figure 5: The distribution of the concentration of NO in height of the combustion chamber of the boiler PK-39 Aksu power plant coal combustion varying moisture

Table 1: The distribution of average values of the temperature, concentrations of CO, CO_2 and NO in section of the lower tier of burners for various values of fuel moisture.

Characteristics	Moisture, W_p			
	5%	7%	9%	11%
T, °C	1178, 86	1079, 82	976, 46	885, 72
CO, mg/Nm^3	2938, 94	2391, 9	1912, 79	1550, 57
CO_2, kg/kg	0, 104	0, 094	0, 085	0, 077
NO, mg/Nm^3	914, 58	766, 67	589, 49	431, 33

Table 2: The distribution of average values of the temperature, concentrations of CO, CO_2, and NO at the outlet of the combustion chamber for different fuel moisture.

Characteristics	Moisture, W_p			
	5%	7%	9%	11%
T, °C	1247, 9	1236, 1	1225, 0	1214, 6
CO, mg/Nm^3	614, 4	724, 5	907, 4	1183, 1
CO_2, kg/kg	0, 204	0, 199	0, 194	0, 189
NO, mg/Nm^3	516, 97	527, 79	524, 78	509, 25

Conclusions

The study has shown that an increase in moisture leads to a decrease in fuel temperature and the average concentration of carbon dioxide CO_2 in the combustion chamber, and to reduce the carbon monoxide concentration CO in the active burning. With reduction of moisture content in coal the maximum of concentration of CO increases and is displaced to area of an arrangement of burners. Out of the combustion chamber reduces the concentration of carbon monoxide. These researches are very important because Kazakhstan occupies the first place in the world in terms of specific greenhouse gas emissions per unit of GDP (3.38 kilograms per dollar). The greatest contribution to the volume of emissions of carbon dioxide is made by power engineering, in particular coal burning. In addition, emissions of carbon oxides adversely affect the environment and cause greenhouse effect.

It is also shown that the increase in moisture of coal leads to reduction of concentration of NO in the central part of the combustion chamber. The greatest differences in the results of modeling and physical experiments are observed in the inflaming of the combustible mixture. Concentrations of CO, CO_2, NO, which are the main substances polluting the atmosphere, at the outlet of the flue space does not exceed maximum permissible concentration norms adopted in the Republic of Kazakhstan.

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