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Application of 3D modelling for solving the problem of combustion coal-dust flame

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This article presents the results of numerical simulations on research of influence of moisture of the burned Ekibastuz coal in the combustion chamber of Kazakhstan Aksu power plant on processes of heat and mass transfer. Graphs of distribution of such characteristics as temperature, concentration of carbon oxides and nitrogen oxide are attached. It is shown that 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 to the reduction of concentration of carbon monoxide CO and nitrogen oxides NO in the field of active combustion.

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

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 [1-3] showed the need for a more complete investigation.

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

Numerical modelling 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 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 model all the characteristics of complex real physical and chemical processes in the object of research chosen by us also the boundary conditions for the solution of the chosen research problem which are adequately reflecting this process are set [16, 17].

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EXPERIMENTAL

Mathematical and physical 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:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial(\rho u_j)}{\partial x_j}, \tag{1}$$

b) Equation of motion:

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

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

c) Energy equation:

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

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

d) Conservation law for substance components:

$$\frac{\partial}{\partial t}(\rho c_n)+\frac{\partial}{\partial x_i}(\rho u_i c_n)=\frac{\partial}{\partial x_i}\left[\rho D_{c_n}\frac{\partial c_n}{\partial x_i}\right]+S_{c_n}, \quad (4)$$

S_{Cn} – 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:

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

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

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

and the equation for the turbulent kinetic energy dissipation ε:

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

$\bar{\rho}\,\varepsilon$ – the conversion of kinetic energy pulsating movement in the internal energy (dissipation).

Empirical constants are defined and equal to the following values:

c_μ=0,09; σ_k=1,00; σ_ε=1,30; $C_{\varepsilon1}$=1,44; $C_{\varepsilon2}$=1,92.

By consideration of the heat transfer processes in technical reacting flows in combustion chambers heat transfer by radiation makes the largest contribution to the total heat transfer. In a zone of a flame, the contribution of radiant heat exchange makes up to 90 % and even more.

Physical quantity, which describes heat transfer by radiation, is the spectral intensity I_ν. In general terms, the radiation energy balance equation has the form:

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t}+\frac{\partial I_\nu}{\partial s}=-(K_{abs,\nu}+K_{sca,\nu})I_\nu+K_{abs,\nu}I_\nu+ +\frac{K_{sca,\nu}}{4\pi}\int_{4\pi}\left(P(\Omega_i\to\Omega)\cdot I_\nu(\Omega_i)\right)d\Omega_i. \quad (8)$$

To describe the radiant heat exchange the six-line model in Cartesian coordinates, proposed by de Marco and Lockwood. In this model, the distribution of radiation energy flux at appropriate sites is approximated using power series and spherical functions.

The intensity distribution in various directions is approximated using a Taylor power series over the solid angle:

$$I=A_i(\vec{n_i}\cdot\Omega)+B_i(\vec{n_i}\cdot\Omega)^2, \quad (9)$$

where A_i, B_i – the coefficients in the Taylor series expansion – functions of intensity of radiation.

Integrating all six directions with a constant angle of integration Ω*i*=2π and infinitely small angles in the positive and negative directions of coordinates we obtain a system of differential equations of six-line model:

$$\frac{\partial}{\partial x_j}\left[\frac{1}{K_{abs}}\frac{\partial(B_i b_{ij})}{\partial x_j}\right]=K_{abs}B_j-K_{abs}\frac{\sigma}{\pi}T^4, \quad (10)$$

where σ=5,67*10^{-8} W/m^2·K^4 – Stefan-Boltzmann constant; b_{ij} is the matrix coefficient and is defined as

$$b_{ij}=\frac{1}{2}\cdot\begin{pmatrix}1+x_i^{//2} & \frac{1-x_i^{//2}}{2} & \frac{1-x_i^{//2}}{2}\\ \frac{1-x_i^{//2}}{2} & 1+x_i^{//2} & \frac{1-x_i^{//2}}{2}\\ \frac{1-x_i^{//2}}{2} & \frac{1-x_i^{//2}}{2} & 1+x_i^{//2}\end{pmatrix} \quad (11)$$

Parameters $x_i^{//}$ depend on intensity of directing radiation and are defined by

$$x_i^{//}=\gamma_{Sca}\cdot\frac{B_i}{\sqrt{B_1^2+B_2^2+B_3^2}}. \quad (12)$$

The value of the constant γ_{Sca} is defined in [18] and equals 0.1. Source term associated with radiant heat transfer in the energy equation is obtained by integrating the total intensity over the solid angle Ω=4π. Thus, we have

$$S_{h,Sca}=\frac{4\pi}{3}K_{abs}(B_1+B_2+B_3)-4K_{abs}\sigma T^4. \quad (13)$$

As the object of study was chosen real industrial steam boiler PK-39, mounted on the Aksu power plant (Kazakhstan) with dimensions 7,762 x 10,76 x 29,985 m. The combustion chamber of the boiler is equipped with 12 vortex coal-dust torches located on two tiers. The scheme of the combustion chamber of the boiler and its breakdown on control volumes is submitted in Fig.1.

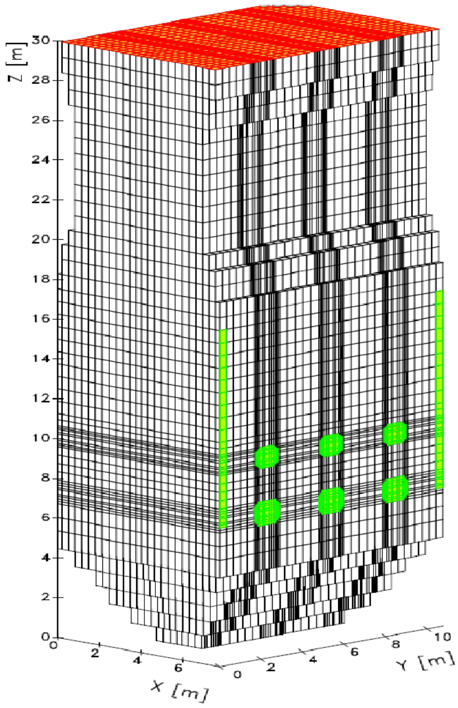

Fig.1. PK-39 boiler combustion chamber

RESULTS

Fig.2 to Fig.5 show the results of modelling experiments of the study of heat and mass transfer taking into account various value of moisture content in fuel in weight percent (wt%). 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 modelling experiments, Fig.2 shows the results of a natural experiment on the power plant [19] 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.

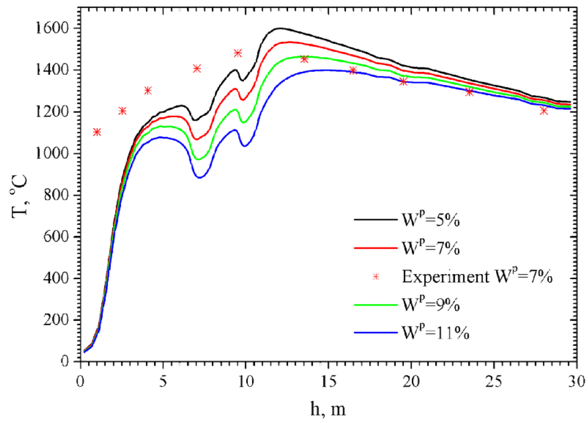

Fig.2. The temperature distribution along the height of the furnace chamber during combustion of varying moisture coal

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 (Table 1). 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 (Table 2).

As a result of modelling 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, 19]. 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.

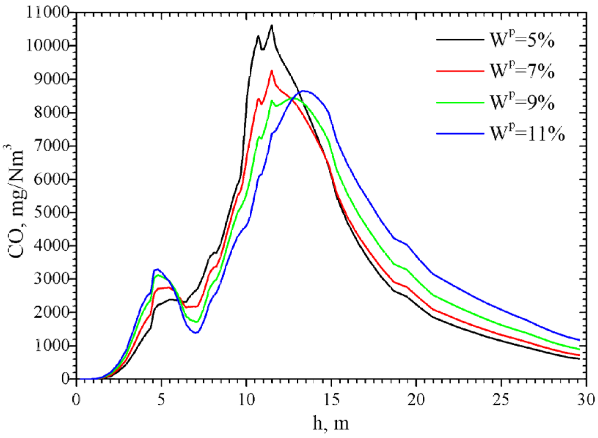

Fig.3. The distribution of the CO concentration along the height of the furnace chamber during combustion of varying moisture coal

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. 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.

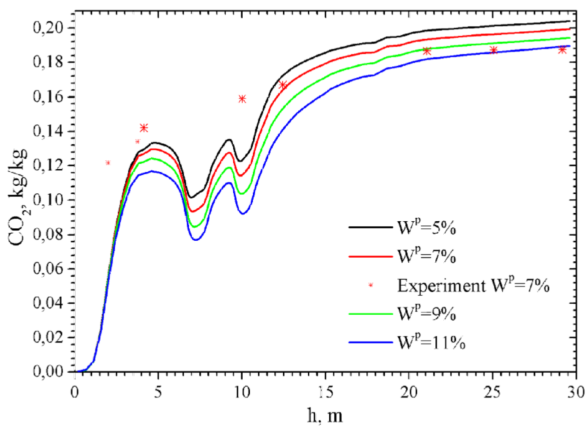

Fig.4. The distribution of the CO_2 concentration along the height of the furnace chamber during combustion of varying moisture coal

Fig.4 shows the results of an experiment conducted directly at the power plant [19]. We see that the greatest distinctions in results of modelling 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.

Currently distinguish 3 mechanism of formation of nitrogen oxides: thermal NOx and fast NOx formed from nitrogen of atmospheric air and fuel NOx formed from the fuel nitrogen. The greatest contribution to formation nitrogen oxides bring fuel and thermal NOx.

Thermal oxides – are formed by the oxidation of atmospheric nitrogen at high temperatures. Zel'dovich proposed the mechanism of their formation and proved that the formation of nitrogen oxides is not directly connected with the combustion reaction, and goes through the dissociation of molecular oxygen at high temperatures.

Fuel nitrogen oxides are formed as a result of transformation fuel the nitrogen which is contained in fuel oil and all types of solid fuel. Therefore, at combustion of coal dust the share of fuel NOx is very high. Considerable part (up to 80%) of NOx are formed on an initial site of a torch, in a zone of an exit and ignition of volatiles.

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.

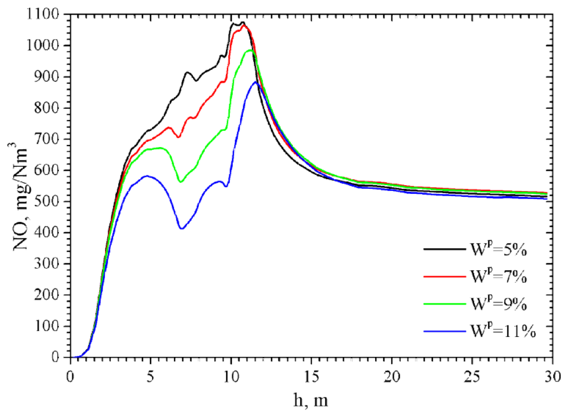

Fig.5. The distribution of the NO concentration along the height of the furnace chamber during combustion of varying moisture coal

Increasing the moisture of coal reduces the temperature (see. Fig.2) in a zone of active burning that conducts to reduction of concentration NO in this area. These results are confirmed by the researches described in works [1, 3, 19]. However, it is possible to notice that to an exit from the furnace chamber a field of concentration of nitric oxide NO are aligned and differences in the concentrations according to Table 1 in the order of 3-18 mg/Nm^3.

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

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CONCLUSION

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 also to reduce the carbon monoxide concentration CO in the active burning zone (Table 1). With reduction of moisture content in coal the maximum of concentration of CO increases and is displaced to area of an arrangement of torches. Out of the combustion chamber reduces the concentration of carbon monoxide (Table 2). It is also shown that the increase in moisture of coal leads to reduction of concentration of NO in the central part (Table 1) of the combustion chamber. The greatest differences in the results of modelling and physical experiments are observed in the ignition 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.

NOMENCLATURE LIST

u_i – components of the velocity, m/s;

t – time, s;

ρ – density, kg/m^3;

$\tau_{i,j}$ – tensor of viscous tension, N/m^2;

p – pressure, Pa;

f_i – volume forces, N;

h – enthalpy, kJ/kg;

q^{res} – energy flux density due to molecular heat transfer, kg/s^3;

S_h – a source of energy, kJ/m^3·s;

c_n – mass concentration of the components of the substance, kg/kg;

D_{c_n} – the diffusion coefficient of a component, m^2/s;

S_{c_n} – the source term taking into account the contribution of the chemical reactions in the change in the concentration of components, kg/ m^3·s;

k – turbulent kinetic energy per unit mass, m^2/s^2;

μ_{eff} – effective viscosity, kg/m·s;

σ_k, σ_ε – turbulent Prandtl numbers – empirical constants in turbulence model;

P – the production of turbulent kinetic energy, which is determined by the following equation, kg/m·s^3;

ε – dissipation rate of turbulent kinetic energy per unit mass, m^2/s^3;

δ_{ij} – Kronecker delta;

μ_{turb} – turbulent viscosity, kg/m·s;

$c_{\varepsilon 1}$, $c_{\varepsilon 2}$, c_μ – empirical constants;

I_ν – spectral intensity, kW/m^2·rad;

ν – frequency of radiant energy emitted from the element area, s^{-1};

ds – length of the infinitesimal element allocated in space, m;

K_{abs}, K_{sca} – optical absorption and scattering coefficients, m^{-1};

Ω – the solid angle, rad;

A_i, B_i – the coefficients in the Taylor series expansion – functions of intensity of radiation, kW/m^2·rad;

σ – Stefan-Boltzmann constant, W/m^2·K^4;

b_{ij} – the matrix coefficient.

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