THE 3-D MODELLING OF HEAT AND MASS TRANSFER DURING COMBUSTION OF LOW-GRADE COAL

by

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Using numerical methods, the basic characteristics of heat and mass transfer processes in the furnace chamber of the BKZ-75 boiler of the Shakhtinskaya TPP (Kazakhstan) were studied during a forced partial stop of the supply of coal dust through the burners. Two modes of fuel supply were studied; a direct-flow method of supplying air mixtures, when two direct-flow burners are working and two are in emergency mode and vortex method of supplying air mixtures - two vortex burners with a swirl angle of the air mixture flow and their inclination the center of symmetry of the boiler by 30° and two are in emergency mode. The computational experiments allowed to obtain the distributions of the total velocity vector, temperature fields, concentration fields of CO, NO_2 throughout the entire volume of the combustion chamber and conduct a comparative analysis for the two investigated emergency mode (direct-flow and vortex). Based on the results, it can be concluded that in the case of a forced partial stop of the supply of coal dust, the use of the vortex method of supplying air mixtures improves heat and mass transfer processes and allows minimizing emissions of harmful substances.

Key words: *combustion, numerical modelling, thermal power station, off-design performance, emergency mode, harmful emission*

Introduction

Kazakhstan is one of the countries with huge hydrocarbon reserves, which have a significant impact on the formation and condition of the global energy market; in particular, in the republic there are deposits of about 33.600 millionns of coal (3.8% of the world's coal reserves), 30000 million barrels of oil (1.8% of world reserves), and 1.5 trillion cubic meters of natural gas (0.8% of world reserves) [1]. As a result, in our country, up to 85% of all electricity generation is produced by burning fossil fuels, mainly local coal; in particular, about 80% of the energy supply is provided through the production of electricity at 69 power plants, the main source of which is Kazakh coal in the Ekibastuz, Karaganda, and Turgai coal basins.

Coal in Kazakhstan has several advantages: low sulphur content, high volatile content, on a dry ash less mass [2, 3] and low price, because the coal is mined in open cast mainly. However, it is characterized by its low rating due to the high ash content in its composition

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(more than 40%). As a result, the use of such fuel in the power system leads to problems in flame stabilization and combustion in general, in slagging of convective heating surfaces (furnace walls) and air pollution from fly ash, CO, NO_x, and SO_x, hydrocarbons (C_nH_m), and other combustion products. Using low-grade coals increases the consumption of fuel oil or natural gas used to melt the boiler, pick up and stabilize the burning of the dust torch, and the environmental situation worsens [4-10].

Another problem is that any energy company needs a periodic shutdown of the boiler room, which is divided into three types: scheduled shutdown, short-term shutdown, emergency shutdown. The scheduled shutdown of the boiler is carried out according to the schedule; a short shutdown of the boiler unit can be caused by a violation of its normal operation due to equipment malfunction or for other reasons that can cause an accident. The emergency shutdown of the boiler can be in the following cases: when the steam pressure in the boiler rises above the permissible one; due to malfunction of the pressure gauge and all water indicating devices; the presence of significant damage to the elements of the boiler; detection of abnormalities in the operation of the boiler [11].

In this work, a computer package of applications of Florean applied programs was used as a basis for the conduct of computational experiments on thermal transfer processes using 3-D modelling in the combustion chamber of the thermal power plant [12-17]. Studies have been conducted to determine the effect of swirling pulverized coal flow during a forced partial stop of the supply of coal dust through the burners (hereinafter we will call it *emergency mode*) on the main characteristics of the combustion chamber of the BKZ-75 boiler of the Shakhtinskaya TPP [18, 19].

Technical characteristics and initial data for computational experiments

The combustion chamber of the BKZ-75 boiler of the Shakhtinskaya TPP (Kazakhstan) was chosen as the object of the study. The steam boiler of factory mark BKZ-75 is a vertical-water pipe, with a productivity of 75 tonne per hour (59.84 MJ/s). The boiler is equipped with four pulverized coal burners which installed in two on the front and back walls in one tier [20-28]. The boiler burns the dust of Karaganda ordinary (KR-200) coal, with an ash content of 35.1%, a yield of volatile 22%, a moisture content of 10.6%, and a calorific value of 18.55 MJ/kg. For carrying out of computing experiments the geometry of investigated object according to the real scheme, fig. 1(a), and its finite-difference grid was compiled for numerical modelling of solid fuel combustion in the furnace chamber of the BKZ-75 boiler, fig. 1(b). The finite difference grid has steps along the *X*-, *Y*-, and *Z*-axes of: 59 × 32 × 67, which is 138355 control volumes. In the area of location of the burners a finer mesh is used, which in turn allows us to provide an adequate picture of the process of burning pulverized coal at any point in the combustion chamber.

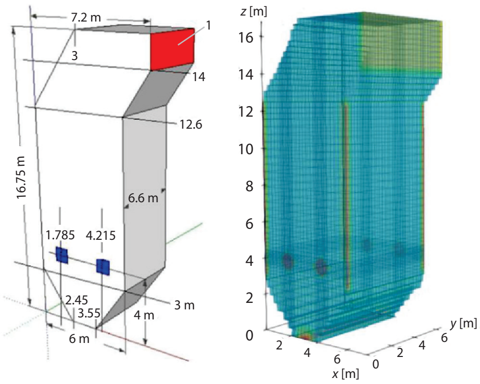

Figure 1. General view and finite-difference grid of the combustion chamber of the boiler BKZ-75 of the Shakhtinskaya TPP

Figure 2 shows the design of the burners of the furnace chamber of the boiler BKZ-75 in *emergency mode* (off burners are marked in red – 1).

Two modes of fuel supply were investigated: a direct-flow method of supplying air mixture, when two direct – flow burners are working, two are in *emergency mode* and a vortex method of supplying the air mixture – two vortex burners with a swirl angle of the air mixture and their inclination the center of symmetry of the boiler by 30°, and two are in *emergency mode*.

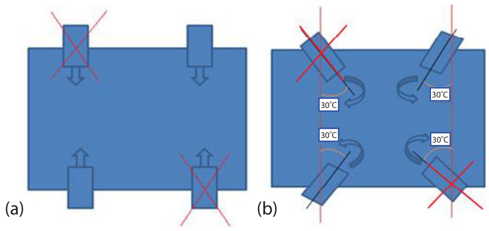

Figure 2. Designs of the burners of the furnace chamber of the BKZ-75 boiler in emergency mode; (a) direct-flow method of supplying air mixture, (b) vortex method of supplying air mixture

Modelling of coal combustion

The mathematical model that describes the flow of gases or liquids is based on the equations of conservation of mass and momentum. For flows in which heat transfer processes occur, as well as for compressed environments, it is necessary to additionally solve the energy conservation equation. In flows with mixing processes of various components, with combustion reactions, *etc.*, it is necessary to add the equation of conservation of the mixture components. For turbulent flows, the system of equations is supplemented by transport equations for turbulent characteristics. For rotating flows of fuel and air, in the general case, the solution of a complex 3-D problem is required. This work contains the physical-mathematical and chemical models used to study the heat and mass transfer in high temperature environments. These models include a system of 3-D Navier-Stokes equations and heat and mass transfer equations considering the source terms determined by the chemical kinetics of the process, non-linear effects of thermal radiation, interfacial interaction, as well as multi-stage chemical reactions [27-34]. The basic equations used in this work can be written in generalized form:

$$\frac{\partial \rho \phi}{\partial t} = -\frac{\partial \rho u_i \phi}{\partial x_i}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_i} + S_\phi\right) \tag{1}$$

where ϕ is the generalized transport variable, Γ_ϕ – the generalized coefficient of exchange, and S_ϕ – the source term, which is determined by the chemical kinetics of the process, non-linear effects of thermal radiation, interfacial interaction, as well as multi-stage chemical reactions.

The values included in the eq. (1) are given in the tab. 1.

Table 1. The system of equations of heat and mass transfer for reacting flows

Name	Value, ϕ	Exchange ratio, Γ_ϕ	A source, S_ϕ
Weight	1	0	0
Impulse	u	μ_{eff}	$-(\partial p/\partial x_i)+ S_{imP}$
Energy	h	$\mu_{\text{eff}}/\sigma_h$	$S_{Str} + S_{\text{chem}}$
Components β (O_2, CO_2, H_2O, CO, C, C_xH_y, NO, NO_2, NH_3, HCN, *etc.*)	C_β	$\mu_{\text{eff}}/\sigma_\xi$	S_ξ
The energy of turbulence	k	$\mu_{\text{eff}}/\sigma_k$	$S_k + \rho\varepsilon$
Turbulent dissipation	ε	$\mu_{\text{eff}}/\sigma_\varepsilon$	$(\varepsilon/k)(C_1)$
	$S_{imP} = \left[\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial u_j}\right) - \frac{2}{3}\rho k \delta_{ij}\right]\frac{\partial u_i}{\partial x_j}$		

The aforementioned system of eq. (1) is solved numerically using the control volume method, which is described in detail in [27, 35-42] and later it was used when conducting computational experiments on the burning of high-ash coal at Kazakhstan's thermal power plants.

When solving the problem, the mathematical model should include specific initial and boundary conditions for the desired functions (velocity, temperature, concentration of the mixture components*, etc.*) corresponding to the geometry of the selected combustion chamber and the actual technological process of fuel combustion at TPP.

To solve the problem, the following boundary conditions for the velocity were chosen:
– input: u – input velocity
– exit:

$$-\left.\frac{\partial u_i}{\partial x_i}\right|_{\infty} = 0$$

– symmetry plane:

$$\left.u_i\right|_{no} = 0,\ \left.\frac{\partial u_i}{\partial x_i}\right|_{\infty} = 0$$

– hard surface:

$$\left.u_i\right|_{no} = 0,\ \left.\frac{\partial u_i}{\partial x_i}\right|_{\infty} = 0,\ \left.\frac{\partial u_i}{\partial x_i}\right|_{no} = 0,\ \left.u_i\right|_{ta} = 0$$

The following relation was used for the friction stress on the wall:

$$\tau_W = \frac{\rho C_\mu^{0.25} k_{WP}^{0.5} k}{ln\left[EE_{y_*}\right]} u_{i,WP|_{ta}} \tag{2}$$

To solve the energy equation, we chose the following boundary conditions:
– input: $h = C_p T$ – inlet flow temperature is set
– exit:

$$\left.\frac{\partial h}{\partial x_i}\right|_{no} = 0$$

– symmetry plane:

$$\left.\frac{\partial h}{\partial x_i}\right|_{no} = 0,\ \left.\frac{\partial h}{\partial x_i}\right|_{ta} = 0$$

On solid walls, various types of boundary conditions for temperature can be specified. For adiabatic walls, the heat flux q_w is equal to zero, in this case, boundary conditions are used as in the plane of symmetry. In the case of heat exchange between the wall and the liquid, you can set the wall temperature or heat flux. If the convective heat transfer coefficient a is experimentally or analytically determined, then we can use the condition:

$$q_W = \alpha\left(T_{WP} - T_W\right) \tag{3}$$

For the equation for the transfer of the concentration of components, the following boundary conditions can be specified:
– input: C_p – component concentration value,
– exit:

$$\left.\frac{\partial c_\beta}{\partial x_i}\right|_{no} = 0$$

– symmetry plane:

$$\left.\frac{\partial c_\beta}{\partial x_i}\right|_{no} = 0$$

– hard surface:

$$\left.\frac{\partial c_\beta}{\partial x_i}\right|_{no} = 0$$

Results and discussion

Figures 3-9 show the results of computational experiments on the distribution of the full-velocity vector, temperature fields, concentration fields of CO and NO_2 in the furnace chamber of the BKZ-75 boiler of the Shakhtinskaya TPP during a forced partial stop of the supply of coal dust through burners.

Two modes of supply of fuel have been investigated:
– direct-flow method of supplying air mixture, when two direct-flow burners are working and two direct-flow burners are in *emergency mode* and
– vortex method of supplying air mixture - two vortex burners with a swirl angle of the air mixture flow and their inclination the boiler center of symmetry by 30°; two vortex burners are in *emergency mode*.

Figure 3 shows the distribution of the field of the full velocity vector in the longitudinal section of the furnace chamber of the BKZ-75 boiler operating in *emergency mode* (forced partial stop of the supply of coal dust through 2 burners). An analysis of fig. 3(a), shows that in the burners with a direct-flow method of supplying the air mixture, two oncoming flows directed from the burners collide in the center of the combustion chamber, dissecting into six vortices. With the vortex method of supplying the air mixture, fig. 3(b), it is seen that the flows opposite to each other at an angle of 30° form a *vortex* flow in the center of the combustion chamber. After the collision, the flows are additionally dissected into two vertical vortices above the burner installation area, closer to the center of the com-

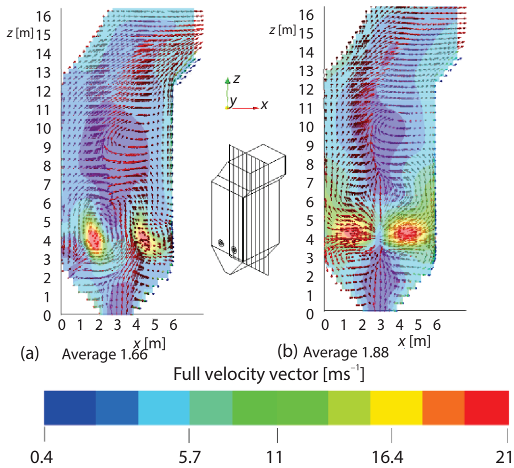

Figure 3. Distribution of the full velocity vector in the central longitudinal section (*y* = 3.3) of the combustion chamber of the boiler BKZ-75 in *emergency mode*; (a) direct-flow method of supplying air mixture, (b) vortex method of supplying air mixture

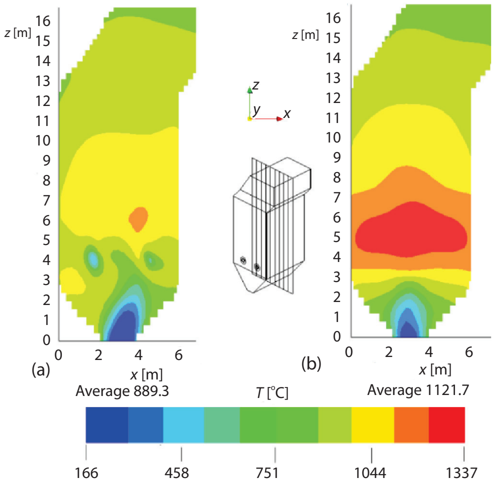

Figure 4. Distribution of the temperature in the central longitudinal section (y = 3.3) of the combustion chamber of the boiler BKZ-75 in *emergency mode*; (a) direct-flow method of supplying air mixture, (b) vortex method of supplying air mixture

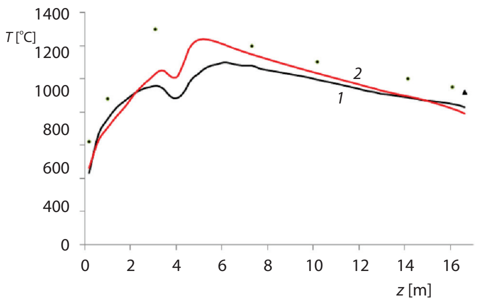

Figure 5. Distribution of the temperature along the height of the combustion chamber of the BKZ-75 boiler in *emergency mode*:
1– direct-flow method of supplying air mixture, 2 – vortex method of supplying air mixture, • – experimental data at TPP [42], ▲ – is theoretical values obtained by the method of thermal calculation (*Central Boiler-and-Turbine Institute*) *[43]*

bustion chamber, which favourably affects the mixing of fuel and oxidizer and, accordingly, the completeness of combustion pulverized coal dust. The main advantage of the vortex method of supplying air mixture in the case of both basic and *emergency modes* is the provision of intensive heat and mass transfer in the reacting two-phase mixture due to the stable highly turbulent vortex flow [43, 44].

Figure 4 show 3-D temperature distributions characterizing the thermal behaviour of the pulverized-coal flow in the combustion chamber for the two studied modes of supply of air mixture (direct-flow and vortex). Compared to using the direct-flow method of supplying the air mixture, the average temperature of the combustion chamber of the BKZ-75 boiler during the vortex method of supplying the air mixture in the central longitudinal section 1121.7 °C, fig. 4(b). This is due to the vortex nature of the flow, providing maximum convective transport and an increase in the residence time of coal particles in the combustion chamber of the BKZ-75 boiler.

Figure 5 shows a comparative analysis of the distribution of the average temperature along the height of the combustion chamber for the two studied modes of air mixture supply (direct-flow and vortex). We observe an increase in the zone of maximum temperatures (Curve 1) with the vortex method of supplying the air mixture (Curve 2). At the same time, the temperature at the outlet of the combustion chamber in this case is less than with the direct-flow method of supplying the air mixture and its value is 836 °C *vs.* 847 °C. The temperature at the outlet of the combustion chamber (base version) is confirmed by experimental data at TPP and theoretical value calculated by the method of Central Boiler-and-Turbine Institute for direct-flow supplying of air mixture [42, 43].

Figures 6 and 7 illustrate the distribution of concentrations CO in different sections of the combustion chamber of the BKZ-75 boiler. With a direct-flow method of supplying the mixture, the average concentration of CO in the burner zone (z = 4.0 m) of the furnace chamber of the BKZ-75 boiler is 0.003 kg/kg, fig. 6(a), and when the mixture is swirling, the average value increases and amounts to 0.004 kg/kg, fig. 6(b). The vortex method of supplying the mixture allows to optimize the combustion of high-ash coal, due to the circulation movement, the residence time of the fuel particles in the combustion chamber increases, there is an increase in temperature in the flame core and its decrease at the exit of the combustion chamber, which has a significant effect on the chemical processes of the formation of combustion products.

Despite the fact the maximum values of the concentration CO are observed in the region where the burners are located, and at the outlet from the combustion chamber its concentration decreases. The concentration CO at the outlet of the combustion chamber is $5.2 \cdot 10^{-4}$ kg/kg for direct-flow method of supplying air mixture, and $3.4 \cdot 10^{-4}$ kg/kg for the vortex method of supplying the mixture. This is confirmed by fig. 7, which shows the curves of the distribution of concentration CO over the height of the combustion chamber of the BKZ-75 boiler for the two studied cases.

The concentration distributions of NO_2 in the burner sections of the combustion chamber are shown in fig. 8. An analysis of these figure shows that the main gas formation of NO_2 occurs in the area of propagation of flows from the burners. Intensive mixing of fuel and oxidizing agent created by turbulent flows of injected aerosol mixtures near the burners, as well as the high temperature in the torch core, create favourable conditions for the formation of NO_2. In this area, the concentration of NO_2 reaches its average values is equal to 824.05 mg/nm^3, fig. 8(a) with a direct-flow method of supplying air mixture, and 1216.31 mg/nm^3, fig. 8(b) with a vortex method of delivering an air mixture.

Figure 9 shows a graph of the distribution of the average values of the concentration of NO_2 over the height of the combustion chamber of the BKZ-75 boiler for the two studied modes of supply of air mixture (direct-flow and vortex). We see that the use of the vortex method of supplying air mixture leads to a decrease in the total concentration of NO_2 at the exit from the furnace space and amounts to 636.58 mg/Nm^3, fig. 9, Curve 1, and for the direct-flow method of

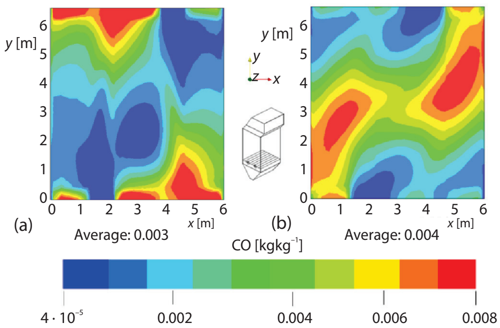

Figure 6. Distribution of CO in the burner section (z = 4) of the combustion chamber of the boiler BKZ-75 in *emergency mode*;
(a) direct-flow method of supplying air mixture, (b) vortex method of supplying air mixture

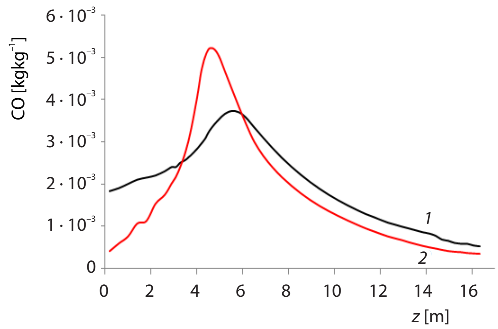

Figure 7. Distribution of concentration CO along the height of the combustion chamber of the BKZ-75 boiler in *emergency mode*:
1 – direct-flow method of supplying air mixture,
2 – vortex method of supplying air mixture

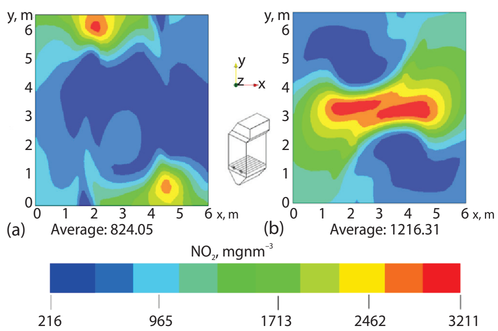

Figure 8. Distribution of NO_2 in the burner section (z = 4) of the combustion chamber of the boiler BKZ-75 in *emergency mode*; (a) direct-flow method of supplying air mixture, (b) vortex method of supplying air mixture

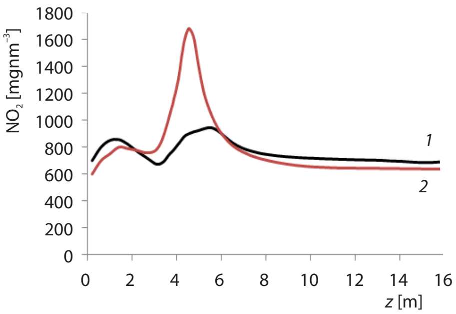

Figure 9. Distribution of NO_2 concentration along the height of the combustion chamber of the BKZ-75 boiler in emergency mode: *1 – direct-flow method of supplying air mixture, 2 – vortex method of supplying air mixture*

supplying air mixture 688.50 mg/Nm^3, fig. 9, Curve 2.

At the outlet CO and NO_2 concentrations are less than the maximum permissible concentration accepted in Kazakhstan. Thus, we can conclude that the vortex method of supplying air mixtures in the combustion chambers of energy boilers significantly improves the environmental performance of thermal power plants.

Conclusions

Using numerical methods, a study was carried out of the main characteristics of heat and mass transfer processes in the furnace chamber of the BKZ-75 boiler of the Shakhtinskaya TPP (Kazakhstan) during a forced partial stop (*emergency mode*) of coal dust supply through burners. Based on the results of studies of the influence of the vortex method of fuel supply during operation of the furnace chamber of the BKZ-75 boiler in *emergency mode*, the following conclusions can be drawn as follows.

- Comparison of the characteristics of the combustion processes in emergency mode for two cases is a direct-flow method of feeding the mixture, when two direct-flow burners and two burners are in emergency mode and the vortex method of feeding the mixture is two vortex burners with a swirl angle of the mixture and tilting them to the center of symmetry of the boiler 30° working and two burners are in emergency mode.
- Aerodynamics of the flow in the combustion chamber for the two studied modes of supply of the air mixture (straight-through and vortex) in the area of the burners is significantly different. In the vortex method, after collisions, the flows are dissected into two vertical vortices above the burner installation area, closer to the center of the combustion chamber, which favourably affects the mixing of fuel and oxidizer and, accordingly, the completeness of combustion of pulverized coal.
- The vortex method of supplying air mixture into the burners of the combustion chamber leads to a decrease in temperature, *T*, the concentration of CO and NO_2 at the outlet of the combustion chamber.
- The use of vortex burners in the combustion chambers of coal-fired TPP can significantly optimize the combustion process of low-grade high-ash coals and significantly reduce emissions of harmful substances (NO_2 and CO) into the environment.
- The obtained results of 3-D modelling of heat and mass transfer processes in the furnace chambers of the BKZ-75 boiler operating in emergency mode, confirms the prospects of using the vortex method of feeding air mixtures in order to achieve the requirements of energy-efficient and environmentally friendly burning of solid fuels.

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