Thermophysics and Aeromechanics, 2019, Vol. 26, No. 2

DOI: 10.1134/S0869864319020124

3D modeling of the aerodynamics and heat transfer in the combustion chamber of the BKZ-75 boiler of the Shakhtinsk cogeneration plant*

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(*Received February 24, 2016*; *revised October 8, 2018*; *accepted for publication December 11, 2018*)

The processes of heat and mass transfer occurring in real furnaces of the industrial TPS's have been investigated with the aid of advanced methods of the three-dimensional computer modeling. The computational experiments have been done on the study of the aerodynamics of high-temperature flows and heat transfer characteristics at a combustion of a low-grade Karaganda coal of the KR200 brand in the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS. As a result of the execution of numerical experiments, the aerodynamic pattern of high-temperature flows as well as the temperature distribution in the main cross sections of the furnace chamber and along its height have been obtained. The radiation heat flux on the combustion chamber walls has been computed by the methods of numerical modeling, which has enabled the determination of the regions of its maximum action on furnace shields. The obtained pattern of the distribution in the furnace space of the heat release intensity at combustion determines the regions of the maximum interaction of the fuel and oxidizer.

Key words: aerodynamics, turbulence, heat and mass transfer, numerical modeling, numerical experiment, combustion chamber.

At present, an increased interest is observed in the investigation of the heat and mass transfer processes in high-temperature media in the presence of combustion therein. These processes occur under the conditions of a strongly non-isothermal and turbulent flow, many phases of the medium, significant influence of nonlinear effects of thermal radiation, interphase interaction and many stages of occurring chemical reactions. Such phenomena are prevalent, play an important role in thermophysical processes, and their investigation is a topical problem of the advanced thermophysics.

The investigations of heat and mass transfer processes in turbulent high-temperature and chemically reacting media are urgent in the light of applied possibilities and for technological

* The work was carried out within the framework of projects financially supported by the Ministry of Education and Science of the Kazakhstan Republic (grants Nos. AP05133590, AP05132988, and BR05236730).

applications and may be used at the development of new physical and chemical technologies, at the design of aviation and rocket technology, at the development of new furnace devices, gas turbines and internal combustion engines [1–3]. Under the conditions of the natural power resource depletion and the ambient medium pollution, the development of the heat and mass transfer theory and the development of technological processes with a reasonable use of the power-plant fuel, the solution of the questions of an economical use of power-plant facilities, increase in the power production efficiency and the solution of environmental problems are the topical and most important tasks for many thermophysical investigations in this direction [3–5].

It is to be noted that over 80 % of the entire produced in the world is obtained at the expense of the organic fuel combustion. The other energy sources to which the nuclear power engineering, hydro-electric engineering, solar and wind power plants, cannot compete during the nearest decades with the conventional techniques of its obtaining [4]. The coal as the power-plant fuel is, at the background of relatively higher prices for oil and natural gas and the abundance of its deposits, is a reliable and economically efficient fuel kind in the countries of Eurasia, including Kazakhstan. According to the data of the annual report of the statistical overview of the world power engineering [6], about 70 % of the world established resources of the coal are located on the territory of USA, China and CIS countries, including Russia and Kazakhstan (Fig. 1). A thorough understanding of the processes occurring at the combustion of the fossil fuel, for example, coal gives the possibility of increasing the efficiency of heat-and-power engineering units. The improvement of thermal characteristics of furnace processes may affect significantly the solution of environmental problems of heat-and-power engineering.

At present, the method of three-dimensional (3D) modeling using the advanced computer technology and the program package accounting for the most phenomena and factors affecting real processes is the most efficient means in the realization of a complex study of the processes of the combustion of coal-dust fuel in furnace chambers of the boilers of industrial objects (thermoelectric power stations (TPS), cogeneration plants, etc.). Besides, the proposed technique ensures high accuracy of predicting the behavior of these factors at computations [7–9].

The combustion is one of the most complex processes for the mathematical modeling because it includes in itself concurrently the processes of three-dimensional two-phase dynamics of liquid and gas, turbulent mixing, fuel evaporation, radiation and convection heat transfer and chemical kinetics [9, 10]. To model the process of fuel combustion based on the fundamental laws of physics it is necessary to use a model accounting for all these factors. A considerable progress was achieved in this direction in a detailed modeling of combustion systems, but the main problems such as turbulence and multi-phase character of reacting flows, the formation and destruction of interaction products, etc., remain unsolved [11, 12].

A continuous and stable development of computer technologies has changed the approaches to the engineering design and execution of the investigations in the area of heat and mass transfer. If the technological solutions at the design and analysis previously relied during

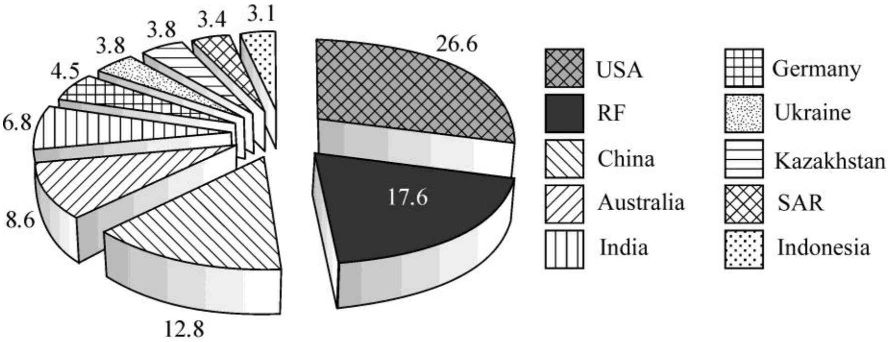

Fig. 1. Shares of the world coal deposits (%).

a long time upon the theory and experiment, then there emerged the third approach in the form of numerical modeling [13]. The results of the physical and mathematical modeling, experimental and industrial investigations are the basis for the choice of design and regime parameters at the development of industrial boilers. This concerns, first of all, the geometric sizes of furnace chambers of power boilers, temperature levels, velocities, toxic emissions, mixing intensity, thermal stresses inside the combustion chamber and other characteristics [14, 15].

The heat and mass transfer processes in the boiler combustion chamber are mainly influenced by the flow aerodynamics, the technique of the supply of air mixture, its velocity and temperature, the location of burner devices, the polydisperse character of fuel particles, and many other factors. At the derivation of a chemical model of the process of the coal-dust torch combustion, it is necessary to account for such stages as the heating of coal particles, the emission and combustion of volatiles, the char burnout, as well as the process of the formation and destruction of the products of chemical interaction [16].

Mathematical model of the turbulent heat and mass transfer

In the present work, the physical, mathematical, and chemical models have been used for investigating the heat and mass transfer in high-temperature media. These models include the system of three-dimensional Navier–Stokes equations and the heat and mass transfer equations with allowance for source terms, which are determined by the process chemical kinetics, nonlinear effects of thermal radiation, interphase interaction as well as by many stages of chemical reactions. Let us write the governing equations employed for the solution of the posed problem:

— the mass conservation law (the continuity equation)

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=S_m, \tag{1}$$

where S_m is the source term determining the mass added to the continuous phase from the disperse phase;

— the momentum conservation law (the Navier–Stokes equation)

$$\frac{\partial}{\partial t}\left(\rho u_i\right)=-\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)+\frac{\partial \tau_{ij}}{\partial x_j}-\frac{\partial P}{\partial x_i}+F_i, \tag{2}$$

where ρ is the density, u_i, u_j, is the velocity in the direction of i, j; x_i and x_j are the Cartesian coordinates, $\tau_{i,j}$ is the tensor of viscous stresses, P is the pressure, F_i are the forces of the interphase interaction;

— the energy conservation law (the first law of thermodynamics)

$$\frac{\partial}{\partial t}\left(\rho h\right)=\frac{-\partial}{\partial x_i}\left(\rho u_i h\right)-\frac{\partial q_i^{\mathrm{res}}}{\partial x_i}+\frac{\partial P}{\partial t}+\tau_{ij}\frac{\partial u_j}{\partial x_i}+S_h, \tag{3}$$

where h is the specific enthalpy, q_i^{res} is related to the energy transfer at the expense of thermal conductivity of the substance flux and diffusion, S_h is the energy source at the expense of chemical reactions and heat exchange by radiation and at the expense of interphase heat exchange;

— the conservation law for the mixture components

$$\frac{\partial}{\partial t}\left(\rho C_\beta\right)=-\frac{\partial}{\partial x_i}\left(\rho C_\beta u_i\right)+\frac{\partial j_i}{\partial x_i}+S_\beta, \tag{4}$$

where C_β are the mass fractions of components β; j_i is the mass-averaged flux in the ith direction, S_β is the source term of the component β.

The Reynolds-averaged Navier–Stokes equations are used for a theoretical analysis of vortex flows, which occur in combustion chambers of industrial boilers, as well as in most engineering applications. These equations may be written in the form [1]

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j)=\frac{\partial}{\partial x_j}\left(\mu\left[\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right]\right)-$$
$$-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}(-\rho\overline{u_i' u_j'})+F_i, \qquad (5)$$

where $-\rho\overline{u_i' u_j'}$ represents the Reynolds stresses τ_{ij} and they can be modeled with the aid of the Boussinesq hypothesis, which is used in most turbulence models [17] in the form

$$-\rho\overline{u_i' u_j'}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_l}{\partial x_l}\right)\delta_{ij},$$

where μ_t is the turbulent viscosity. To close the time-mean system of partial differential equations the authors have used the standard k-ε model, where k is the turbulence kinetic energy and ε is its dissipation [18].

Within the framework of the present work, the model of an instantaneous mixing is employed, which has no need in solving the additional transfer equation. The assumption on that the large-scale vortices characterized by the turbulence energy k speed up the macro mixing, and the turbulence energy dissipation ε speeds up the micro mixing underlies the given approximation. Consequently, one can associate the combustion rate of volatiles with the characteristics of the k-ε model. In addition, the choice of the standard k-ε turbulence model is caused by that it has shown itself fairly well at the conduction of investigations with the aid of the computational fluid dynamics methods, and its implementation requires relatively small computer resources. The correctness of the choice is also confirmed by the investigation results published in paper [19], where the authors have concluded: “Comparative analysis of the use of k-ε and k-ω SST turbulence models and Reynolds stress model for mathematical modeling of pulverized coal combustion in the swirl flow within the RANS-approach has shown their negligible effect on distribution of axial and tangential velocities, temperatures, and gas concentrations. When using any of the considered turbulence models, the processes associated with pulverized coal burning are well predicted. Taking into account that the k-ε turbulence model requires less computation, it is preferable for the solution of this problem. It was found that the choice of turbulence model has an impact on the value of pulsation velocity components, and this can affect some of the process characteristics. Formation of some harmful substances such as nitrogen oxides is one of the most significant potential consequences of this effect.” Thus, the application of the k-ε turbulence model in the present work is justified. One can write the employed governing equations in the generalized form as follows:

$$\frac{\partial(\rho\phi)}{\partial t}=-\frac{\partial(\rho u_1\phi)}{\partial x_1}-\frac{\partial(\rho u_2\phi)}{\partial x_2}-\frac{\partial(\rho u_3\phi)}{\partial x_3}+$$
$$+\frac{\partial}{\partial x_1}\left[\Gamma_\phi\frac{\partial\phi}{\partial x_1}\right]+\frac{\partial}{\partial x_2}\left[\Gamma_\phi\frac{\partial\phi}{\partial x_2}\right]+\frac{\partial}{\partial x_3}\left[\Gamma_\phi\frac{\partial\phi}{\partial x_3}\right]+S_\phi, \qquad (6)$$

where ϕ is the transport variable, S_ϕ is the source term determined by the chemical kinetics of the process, nonlinear effects of thermal radiation, interphase interaction as well as by the multi-stage character of chemical reactions.

The coal-dust torch represents a turbulent two-phase flow usually with a small volume fraction of the solid phase of particles. Consequently, outside the torch, the cloud of particles is approximated as a continuum, and the mean velocity of the particle is assumed to be approximately equal to the gaseous phase velocity. In the flows with a large amount of particles, the solid medium may have an inverse effect on the convective and diffusion transfer. Since the presence of solid substances in emitted gases is insignificant (except for a region near the burners), the authors of the present work accounted for the disperse phase only in the region of the fuel and oxidizer supply. Such a simplification was done to reduce the computer expenses.

In most cases, one considers at coal-dust combustion weakly loaded flows in which the maximum volume concentration of solid phase does not exceed 1 %, and the diameter of solid particles is less than 1000 microns, and the mean diameter of particles is within 100 microns in the entire volume. One can then present the process of the solid fuel combustion in furnace chambers as follows: the flame is a two-phase gas-disperse system and the solid phase influence on the flow aerodynamics is insignificant. The solid phase influence in the flame region on the turbulent exchange coefficients is taken into account with the aid of the following empirical relation entering equation (6):

$$\Gamma_\phi = \frac{\mu_\mathrm{p}}{\sigma_{\mathrm{p,turb}}} = \frac{\mu_\mathrm{t}}{\sigma_{\mathrm{p,turb}}}\left(1+\frac{\rho_\mathrm{p}}{\rho}\right)^{-1/2}, \qquad (7)$$

where μ_p is the turbulent viscosity accounting for solid particles, $\sigma_{\mathrm{p,turb}}$ is the Schmidt–Prandtl turbulent number accounting for particles, ρ_p is the particles density, ρ is the gaseous phase density. In this case, one can use the relation [20] for turbulent viscosity accounting for solid particles

$$\mu_\mathrm{p} = \mu_\mathrm{t}\left(1+\rho_\mathrm{p}/\rho\right)^{-1/2}, \qquad (8)$$

which shows that an increase in the partial density of solid particles leads to a reduction of turbulent exchange. The partial density of solid particles is determined from the ratio for the mass fraction of particles entering the torch: $Y_\mathrm{p} = \rho_\mathrm{p}/\rho$. The numerical value $\sigma_{\mathrm{p,turb}} = 0.7$ has been chosen for the turbulent Schmidt–Prandtl number with allowance for particles.

For the numerical modeling of the motion of the fuel polydisperse particles in the coal-dust torch, an approach was used, which is described in detail in monograph [21], which consists of the following: the entire spectrum of particles of the coal-dust fuel fed into the furnace chamber is subdivided into the groups, and the behavior of each group of particles is characterized by the behavior of its representative — the "marker particle". To compute the parameters characterizing the thermophysical state of the "marker particle" a system of ordinary differential equations is used, which was described in detail in the work [22].

At the solution of the posed problem, the mathematical model must include the initial and boundary conditions for sought functions (velocity, temperature, the concentration of mixture components, etc.), which correspond to the geometry of the chosen furnace chamber and to the real technological process of fuel combustion at the TPS. These conditions were defined as follows.

Initial conditions: $u = 0$, $v = 0$, $w = 0$, $P = 0$ at $t = 0$.

Boundary conditions are set at the free surfaces, to which the burners, the outlet of the boiler furnace chamber as well as the symmetry plane belong, and they are described below.

At the outlet: u_i are the velocity values, c_β is the initial concentration of each component, and the enthalpy h is determined by using the flow temperature at the inlet from the following relation: $C_P = \left.\dfrac{\partial h}{\partial T}\right|_{P=\mathrm{const}}$, where T is the inlet temperature (experiment or computation).

At the outlet: $\left.\dfrac{\partial u_i}{\partial x_i}\right|_{\mathrm{normalA}} = 0$, $\left.\dfrac{\partial h}{\partial x_i}\right|_{\mathrm{normalA}} = 0$, $\left.\dfrac{\partial c_\beta}{\partial x_i}\right|_{\mathrm{normalA}} = 0$; these are the derivatives of the velocity, enthalpy, and concentrations of components, which are normal to the outlet plane. In the symmetry plane: $u_i|_{\mathrm{normalS}} = 0$ is the velocity normal to the symmetry plane, $\left.\dfrac{\partial u_i}{\partial x_i}\right|_{\mathrm{normalS}} = 0$, $\left.\dfrac{\partial h}{\partial x_i}\right|_{\mathrm{normalS}} = 0$ are the derivatives of the velocity and enthalpy, which are normal to the symmetry plane, $\left.\frac{\partial c_\beta}{\partial x_i}\right|_{\text{normalS}} = 0$ are the derivatives of the concentration of components, which are normal to the symmetry plane.

On the solid surface: $u_i|_{\text{normalB}} = 0,\ \left.\frac{\partial u_i}{\partial x_i}\right|_{\text{normalB}} = 0,\ u_i|_{\text{taB}} = 0,\ \partial p|_{\text{boundary}} = 0$ is a pressure correction at the solid surface boundary, $\left.\frac{\partial c_\beta}{\partial x_i}\right|_{\text{normalB}} = 0.$

The boundary conditions for wall temperature are set in the present work by the heat flux $q_{\text{w}} = \alpha(T_{\text{steam}} - T_{\text{surf}})$. At a variable temperature of the furnace chamber wall, one can calculate the heat flux $\dot{q}$ by the formula

$$\dot{q} = \underbrace{\alpha(T_{\text{fg}} - T_{\text{surf}})}_{\text{convection}} + \underbrace{C_{12}(T_{\text{fg}}^4 - T_{\text{surf}}^4)}_{\text{radiation}}, \tag{9}$$

where $C_{12} = \varepsilon_{12}\sigma$, T_{fg} is the temperature of smoke gases, T_{surf} is the temperature of the surface of chamber walls, α is the coefficient of the heat transfer by convection, W/m^2·K, ε_{12} is the wall emissivity, σ is the Boltzmann constant, W/m^2·K^4. The temperature of the chamber wall surface T_{surf} is determined as

$$\dot{q} = K\left(T_{\text{surf}} - T_{\text{steam}}\right),\ T_{\text{surf}} = \frac{\dot{q}}{K} + T_{\text{steam}}, \tag{10}$$

where K is the heat transfer coefficient from the wall surface to the steam mixture in the pipeline.

The boundary conditions for the employed turbulence model are written as $k = 1.5 \times \times\left(u_i\, Tu\right)^2$, where k is the value of the turbulence kinetic energy at the inlet, Tu is the flow turbulence degree, which is determined for technological applications as follows: $Tu = = \left(\frac{\overline{u'^2}}{u^2}\right)^{1/2} = 0.05 \div 0.2;\ \ \varepsilon = C_\mu^{0.75}\frac{k^{3/2}}{L_{\text{m}}}$, where ε is the value of the dissipation rate of the turbulence kinetic energy at the inlet, L_{m} is the mixing length.

At the outlet: $\left.\frac{\partial k}{\partial x_i}\right|_{\text{normalA}} = 0,\ \left.\frac{\partial \varepsilon}{\partial x_i}\right|_{\text{normalA}} = 0$ is the derivative normal to the outlet plane.

In the symmetry plane: $\left.\frac{\partial k}{\partial x_i}\right|_{\text{normalS}} = 0,\ \left.\frac{\partial \varepsilon}{\partial x_i}\right|_{\text{normalS}} = 0$ is the derivative normal to the symmetry plane.

On the solid surface: $\varepsilon_i|_{\text{boundary}} = 0$ is the value at the solid surface boundary; $k_i|_{\text{boundary}} = 0$ is the value at the solid surface boundary.

The above system of equations is solved numerically by using the control volume method, which has been described in the works [1, 23] and was used subsequently in the numerical experiments on the combustion of a high-ash coal at the Kazakhstan TPS's [3, 4, 7, 24].

Description of the model of the coal-dust torch combustion

One can identify the following stages in a combustion model:

— the pyrolysis with the emission of volatiles and char formation,

— the combustion of volatile products and carbon oxide,

— the char combustion.

Modeling of pyrolysis. The combustion model must describe exclusively the local heat release as a result of the combustion and the influence of combustion products on heat transfer. Therefore, at the choice of the pyrolysis and combustion models, the present authors have refused the use of cumbersome systems with a large number of components. In the present work, a one-stage model of pyrolysis is employed, which was described in studies [1, 25] because in this case, one can derive the stoichiometric coefficients of the pyrolysis reaction from the data of express-analysis, which is important and preferable. Besides, this model works fairly accurately in many cases and is a good compromise for reducing computer expenses.

Modeling of the combustion of volatiles. Pyrolysis products for a reaction-capable mixture while mixing with air. At the description of pyrolysis process, the volatiles are considered as fictitious hydrocarbons. Because only the velocity and heat release at oxidation are mainly of interest, at high temperatures and at a sufficient amount of oxygen, the combustion of volatiles may be presented in the form of a two-stage reaction under the assumption that the volatiles oxidize at first to CO and H_2O [26]:

$$C_xH_y + \left(\frac{x}{2} + \frac{y}{4}\right)O_2 \rightarrow x\mathrm{CO} + \frac{y}{2}H_2O, \tag{11}$$

and at the second stage, the oxidation to CO_2 occurs:

$$x\mathrm{CO} + \frac{x}{2}O_2 \rightarrow x\mathrm{CO}_2. \tag{12}$$

To determine the velocity of the pyrolysis products combustion with allowance for reactions (11) and (12) the concept of turbulent dissipation (Eddy–Dissipation Model, EDM) is employed, which was proposed and considered in detail in the work [27].

Modeling of char combustion. The heterogeneous reaction of the solid carbon combustion on the surface of char particles is determined by the oxygen diffusion from the ambient medium into the boundary layer and into the particle porous medium as well as by the reaction between the carbon and oxygen on the particle surface. The process, which is the slowest among these processes, determines the rate of the char burnout. The carbon oxide and dioxide form, respectively, depending on the diameter and temperature of particles [28]:

$$2\mathrm{C} + O_2 \rightarrow 2\mathrm{CO}, \tag{13}$$

$$\mathrm{C} + O_2 \rightarrow CO_2. \tag{14}$$

The diameter of fuel particles is assumed to vary at the char combustion from d_1 to d_2. The particles size remains constant at the emission of volatile components, and only the fuel density changes from the density value of dry coal to the char density.

The variation of the char carbon concentration ξ_C is determined by the equation

$$d\xi_\mathrm{C}/dt = -K_\mathrm{C}A_\mathrm{sp}\xi_\mathrm{C}, \tag{15}$$

where A_sp is the specific area of a particle, which is related to its mass, and K_C is the constant of the oxidation rate of the char carbon, which has the form

$$K_\mathrm{C} = \frac{p_{O_2}}{1/K_\mathrm{d} + 1/K_\mathrm{kin}}, \tag{16}$$

here K_kin is the constant of the velocity of the kinetic component of the char carbon combustion reaction, K_d is the oxidizer diffusion rate constant, p_{O_2} is the oxygen relative partial pressure.

The oxygen diffusion contribution is determined via the effective diffusion coefficient according to the expression [28]

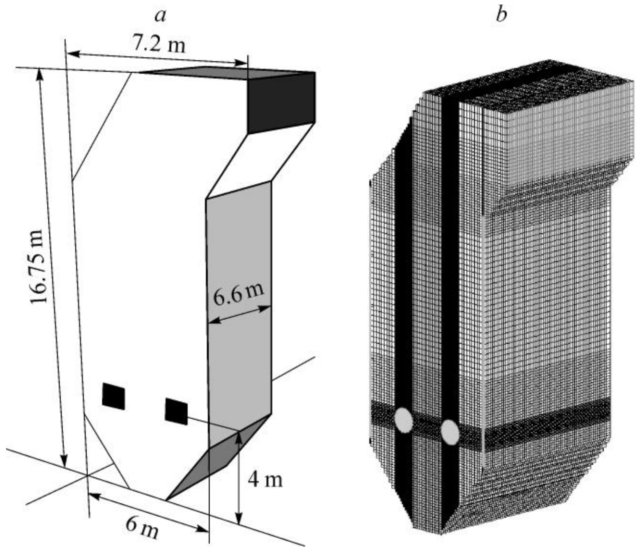

Fig. 2. General view (*a*) of the BKZ-75 boiler of the Shakhtinsk TPS and its discretization by control volumes (*b*).

$$K_{\mathrm{d}} = \frac{\mathrm{Sh}\, M_{\mathrm{C}}\, f_{\mathrm{m}} D_{\mathrm{O_2}}}{R\, d_{\mathrm{p}} T_{\mathrm{gs}}}, \tag{17}$$

where M_C is the carbon molar mass, Sh is the Sherwood number (for spherical particles, we adopt Sh = 2); $T_{\mathrm{gs}} = (T_{\mathrm{g}} + T_{\mathrm{p}})/2$ is the mixture mean temperature, T_g and T_p the temperatures of gas and solid particles, respectively; $D_{\mathrm{O_2}} = D_{0,\mathrm{O_2}} \left(T_{\mathrm{gs}}/T_0\right)^{1.75}$ is the coefficient of the oxygen diffusion to the particle surface, where $D_{0,O2} = 3.49 \cdot 10^{-4}$ m^2/s is the self-diffusion coefficient at T_0 = 1600 K [28], f_m is the mechanism-factor, which is equal to one for a reaction with the formation of CO_2 and is equal to two for a reaction with the formation of CO.

The contribution of chemical reactions is determined via the constant of the chemical reaction velocity, which is expressed by the relation

$$K_{\mathrm{kin}} = k_{0,\mathrm{C}}\, e^{-E_{a,\mathrm{C}}/(RT_{\mathrm{p}})}. \tag{18}$$

The kinetic parameters employed in computations were borrowed from the work [29].

The model of the coal dust combustion, which is used in the present work, accounts for the integral reactions of the oxidation of fuel components to stable finite products of the reaction. The intermediate reactions and the formation and variation of unstable intermediate products are not taken into account.

Description of the investigation object and method

The BKZ-75 boiler of the Shakhtinsk TPS, which is exploited in the Karaganda region of the Kazakhstan Republic, was chosen as the investigation object. The table presents the main data on the regime parameters of the furnace chamber of the BKZ-75 boiler of the Shakhtinsk TPS and also presents the composition of the employed coal.

At present, a progress is observed in the development of three-dimensional computer technologies, which gives the possibility of obtaining the detailed information inaccessible previously about the parameters of turbulent flow, heat and mass exchange, combustion, emission of harmful substances, and other characteristics practically at any point of the furnace

Table

Technical characteristics of the furnace chamber of the BKZ-75 boiler of Shakhtinsk TPS and the input data for executing the numerical experiment

№	Name	Notation	Measurement unit	Value
1	Steam output	D	t/hour	75
2	Boiler efficiency	η	%	80.88
3	Number of burners on the boiler	N_B	pcs	4
4	Mechanical underburning of the fuel	q_4	%	13.37
5	Superheated steam pressure	P_{nn}	kg/cm^2	39
6	Furnace chamber height	H_f	m	16.75
7	Furnace chamber width	b_f	m	6
8	Furnace chamber depth	Γ_f	m	6.6
9	Primary air expense per the boiler*	V_{pa}	m^3/h	31797
10	Secondary air expense per the boiler*	$V_{sec.a}$	m^3/h	46459
11	Hot air temperature	t_{ha}	°C	290
12	Cold air temperature	t_{ca}	°C	30
13	Air excess coefficient	a	–	1.22
14	Coal type	KR200	–	–
15	Design fuel consumption per a boiler	B_{fr}	t/h	12.49
16	Single burner fuel capacity	B_B	t/h	3.2
17	Grinding fineness	R_{90}	%	20
18	Combustion heat	Q^P_H	kkal/kg	4433
19	Emission of volatiles per combustible mass	V^C	%	22
20	Coal density	ρ	kg/m^3	1300

Composition of the employed coal. %

C	H	O	S	N	W^p	A^p
43.21	3.6	5.24	1.04	1.21	10.6	35.1

* m^3/h under normal conditions (273 K and 101.3 kPa).

chamber space [30]. The results of 3D modeling are the basis for choosing the design and regime parameters at the development of new boilers and reconstruction of existing boilers, which are functioning with the most optimal technology of the coal-dust fuel.

In the general case, at the implementation of the numerical modeling, the entire computational region is subdivided by a difference grid into discrete points or volumes (Fig. 2), the continuous field of variables is replaced with the discrete values in grid nodes, and the derivatives entering the differential equations are replaced with their approximate expressions via the differences of function values in grid nodes.

The authors used the program complex FLOREAN [1, 2, 31–35] to implement the numerical experiments. This program package makes it possible to conduct complex computational experiments on the modeling of reacting multiphase flows in regions of real geometry (furnace chambers of the TPS and cogeneration plants). The employed finite difference grid has the resolution of 110×61×150 or 1006500 control volumes.

Investigation of aerodynamic characteristics of the combustion chamber of an industrial boiler

The aerodynamics of two-phase turbulent flows at the coal-dust fuel combustion conditions the character of the entire combustion process. For example, there are known some very economical techniques of reducing the emission of harmful nitrogen-containing substances into the atmosphere using various aerodynamic techniques [1, 2, 35, 36].

The vortex transfer is the aerodynamic basis of the entire combustion process in furnace devices. The main property of the aerodynamic structure of the vortex flow is a perfect formation

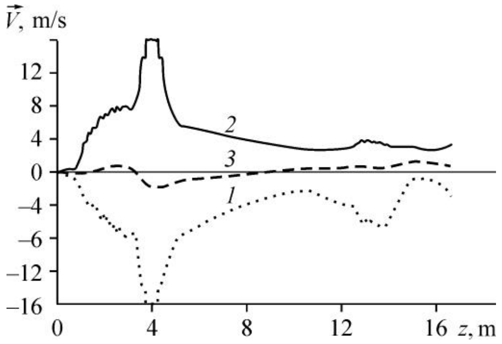

Fig. 3. Variation of the full velocity vector modulus over the height of the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS.
The $|\vec{V}|$ values: minimum (*1*), maximum (*2*), mean (*3*).

of a mixture of the coal dust fuel and oxidizer (air oxygen), without which it is impossible to reach neither the required intensity of the processes nor admissible figures on harmful emissions, nor a high level of the combustion economy [1, 2].

Figures 3–6 show the results of numerical experiments on the investigation of aerodynamic characteristics of the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS.

Figure 3 shows the minimum, maximum, and mean values of the full velocity vector modulus $|\vec{V}| = \sqrt{U^2 + V^2 + W^2}$ in a cross section depending on the furnace chamber height in accordance with the sign of the velocity *Y*-component. An analysis of the figure shows that at the height of four meters, the flow velocity reaches its maximum value. Right at this height, the burner devices are mounted, through which the air mixture injection occurs with the maximum velocity equal to 16 m/s. One can also notice in the figure that in the region of the location of burner devices, the values of the full velocity vector averaged over the cross section take the negative values in accordance with the sign of the velocity *Y*-component. This is probably due to the presence of a reverse flow arising near this region.

Figure 4 shows the 3D distribution of the air mixture flow trajectory inside the combustor volume of the boiler under study. One can see in Fig. 4*a* the air mixture supply from opposite burners both in the positive and negative directions with respect to the symmetry plane, and an analysis of Fig. 4*b* shows that the air mixture flow with combustion products has a whirling

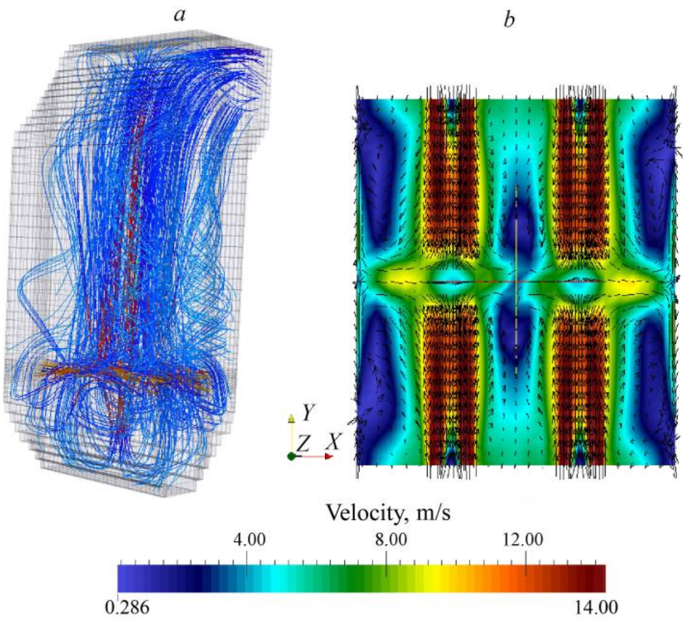

Fig. 4. Three-dimensional distribution of the trajectory of the air mixture flow within the combustor volume (*a*) and the full velocity vector in the cross section of burners (*b*).

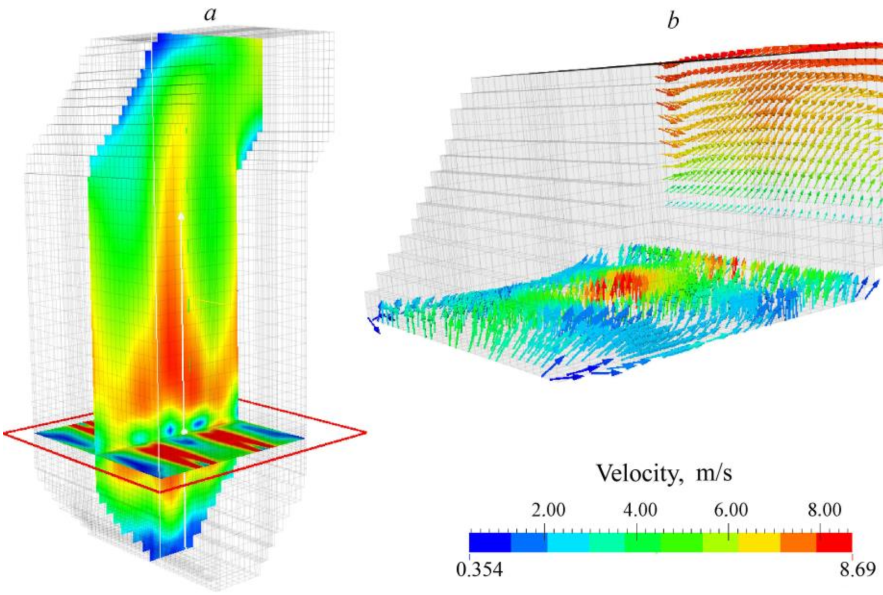

Fig. 5. Distribution of the full velocity vector in the combustor main cross sections: in the region of burners (*a*) and in the chamber revolving portion at its outlet (*b*).

character in the region of burners and in the bottom part of the furnace chamber. The latter is explained by that the counter flows blown from burner devices collide when they move with the maximum velocity towards the combustion chamber center. In this region, the flow forms several vortices with the presence of a reverse flow upwards and downwards over the combustion chamber space (Fig. 5*a*). Such a character of the vorticity arises because of flow turbulence and at the expense of the collision of counter-flows of the air mixture from opposite burners. Towards the outlet from the furnace chamber space, one observes a gradual smoothing of the flow. In the rotary part of the combustion chamber and at its outlet, the flow velocity ranges from 4 to 8 m/s (Fig. 5*b*). In the vortex region with the largest variations of velocity fields, that is where the processes of physical and chemical conversions at the coal-dust fuel (the region of the burners belt) occur intensively, one observes also the maximum disturbances of turbulent flows. This is evidenced by the maxima in the distribution of turbulent characteristics of the process such as the turbulence kinetic energy k and its dissipation ε, the mean values of which are shown in Fig. 6. As one can see in Fig. 6, the turbulence kinetic energy k as well as its dissipation ε reach their maximum values in the region of burner devices

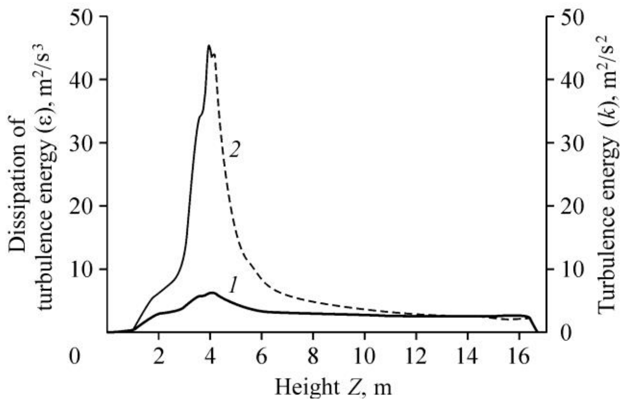

Fig. 6. Distribution of turbulent characteristics over the height of the combustor of the BKZ-75 boiler of the Schakhtinsk TPS.
1 — turbulence kinetic energy (k), *2* — dissipation of the turbulence kinetic energy (ε).

lying at the height of 4 meters because this region is a zone of the collision of coal-dust flows with the largest disturbance of the swirl flow. The aerodynamics of vortex flows affects most significantly the length of the torch, its emissivity as well as the intensity of the processes of heat and mass transfer at the combustion of the coal-dust fuel in the furnace chamber.

Investigation of heat transfer characteristics in the combustor of an industrial boiler

In the process of heat transfer in combustors, the heat transfer by radiation makes the largest contribution to the integral heat transfer. In the flame zone, the radiation heat transfer contribution amounts up to 90 % and to an even higher amount [37]. In this connection, the modeling of radiation transfer in reacting flows is one of the most important stages at the computations of the heat transfer processes in real furnace chambers. At the coal-dust fuel and mazut combustion, the central region of the flame is the radiation source, which arises near the surface of fuel particles. The particles of char and ash as well as combustion products are the radiation sources in such a case.

At the mathematical description of the radiant heat exchange, one identifies as a rule a region of the space, in which the flows of the coal-dust mixture move. The walls of this space and the substance enclosed therein absorb and emit the radiation in the infrared and visible regions. The spectral intensity, which is determined by the relation [38]

$$I_\nu = \lim_{\Delta A, \Delta\Omega \to 0} \left(\frac{\Delta E_{\nu,\Theta}}{\Delta A \cdot \Delta\Omega \cdot \cos\Theta} \right), \tag{19}$$

is a quantity characterizing the heat transfer by radiation. Here $\Delta E_{\nu,\Theta}$ is the radiant energy with frequency ν, which is emitted from the area element ΔA in the solid angle $\Delta\Omega$, in the direction determined by the cosine of the angle Θ.

The equation for the radiant energy balance is written in the general form as

$$\frac{\partial I_\nu}{\partial s} = -\left(K_{\text{abs}} + K_{\text{sca}}\right) \cdot I_\nu + K_{\text{abs}} \cdot \frac{\sigma}{\pi} T^4 + \frac{K_{\text{sca}}}{4\pi} \int_{4\pi} \left[P\left(\Omega_i \to \Omega\right) \cdot I_\nu\left(\Omega_i\right) \right] d\Omega_i, \tag{20}$$

where K_{abs} and K_{sca} are the optical coefficients of the absorption and scattering, σ is the Boltzmann constant, T is the absolute temperature. It is impossible to obtain the analytic solution of the integro-differential equation (20). However, one can use different models, which are applied by the researchers at the execution of numerical experiments. So the present authors have used a six-flux model of the radiant heat exchange described in the work [39] for computing the heat transfer by radiation in the furnace chamber of the boiler under study.

As a result of executing the numerical experiments on the study of heat-transfer characteristics, temperature profiles (Figs. 7 and 8), and the heat release intensity at combustion (Figs. 9 and 10) were obtained, and the radiation heat fluxes on the main heat-receiving surfaces of the boiler BKZ-75 combustor of the Shakhtinsk TPS (Fig. 11) were determined.

Figures 7 and 8 show the temperature distributions characterizing the thermal behavior of the coal dust flow in the furnace chamber under study. One can note that the temperature reaches its maximum values in a region close to the location of burner devices because one observes here the maximum convective transfer because of the vortex character of the flow and, as a result, the residence time of coal particles increases, which leads to a temperature growth in the given zone. One can see in Fig. 8 that at the height of 4 meters, a minimum in the mean values of temperature distribution is also observed. This is explained by that in this region,

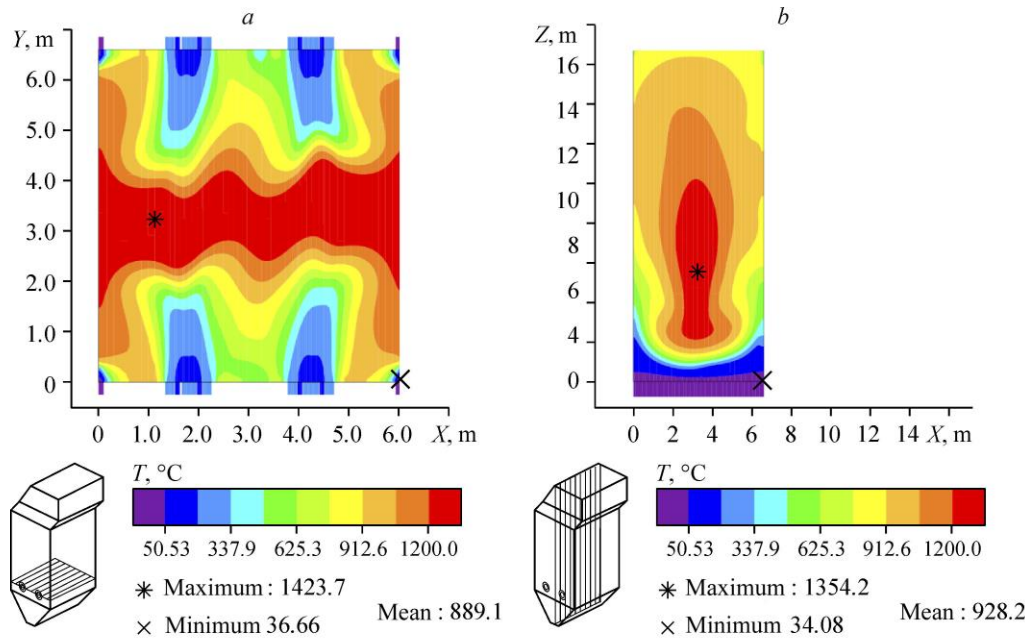

Fig. 7. Distribution of temperature *T* in cross sections of burners (*a*), in the central longitudinal section of the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS (*b*).

a — section *k* = 52 (*z* = 4 m), *b* — section *I* = 51 (*x* = 3 m).

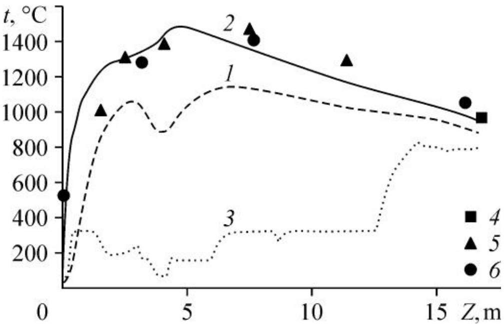

Fig. 8. Temperature distribution along the furnace chamber height.

Lines — numerical experiment (mean (*1*), maximum (*2*), and minimum (*3*) temperature values), *4* — theoretical value obtained by the CKTI method of thermal computation [40], *5*, *6* — experiments on the TPS [41].

the burner devices are located, through which the coal dust fuel and the oxidizer are fed with a low initial temperature equal to 290 °C. Because the burners are mounted on opposite walls and are directed towards one another, these flows diverge at the furnace chamber center in the zone of the collision of the flows of air mixture (Figs. 4 and 5). Part of the flow moves to the zone of a cold funnel and forms two longitudinal vortices at the height of 2.5 meters, and part of the flow moves to the outlet under the arising thrust action. As a result of these processes, one observes at the heights of 2.5 and 6.5 meters the maxima in the mean values of temperature distribution, and one observes the minimum in the cross section itself of the burners at the height of 4 meters.

The distribution of the heat release intensity Q_{chem} at the combustion of a coal-dust fuel in the furnace space is shown in Figs. 9 and 10. An analysis of these Figures shows that the heat release intensity at the combustion Q_{chem} reaches its maximum value in the region of the belt of furnace burners (~ 5567 kW/m^3), as was to be expected. As the coal-dust flow moves to the outlet, the intensity of combustion processes relaxes and Q_{chem} amounts only to ~ 12 kW/m^3 at the furnace chamber outlet. This points to the termination of oxidation processes, which is confirmed by the pattern of the Q_{chem} distribution in different sections of the furnace chamber of the BKZ-75 boiler (Fig. 9*b*).

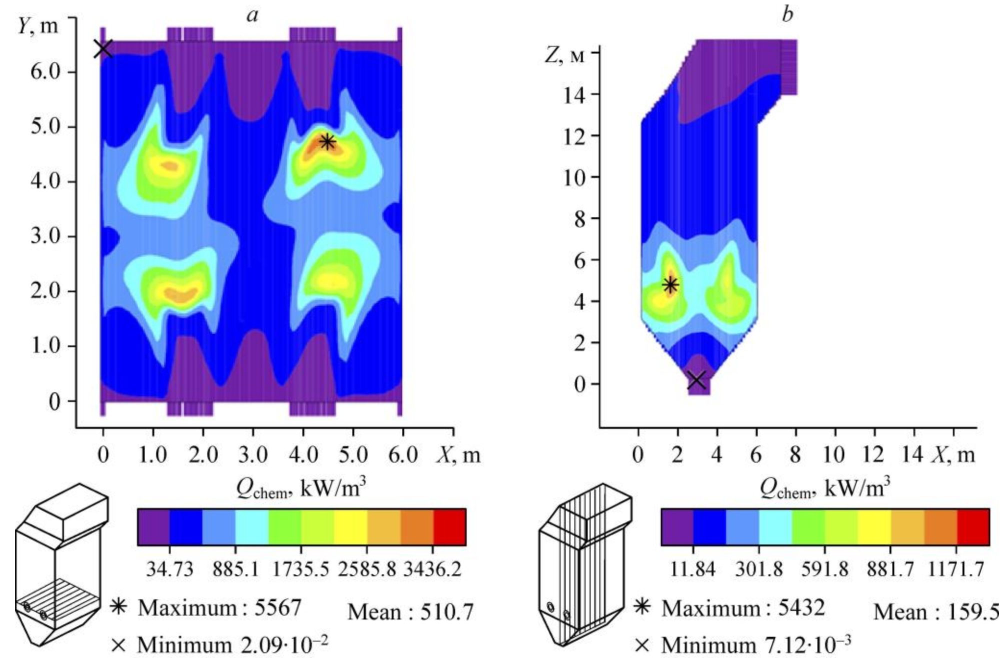

Fig. 9. Distribution of the heat release intensity at the combustion Q_{chem} in cross sections of burner devices (*a*) and in the central longitudinal section of the combustor under study (*b*).
a — cross section $k = 52$ ($Z = 4$ m), *b* — section $J = 32$ ($Y = 3.36$ m).

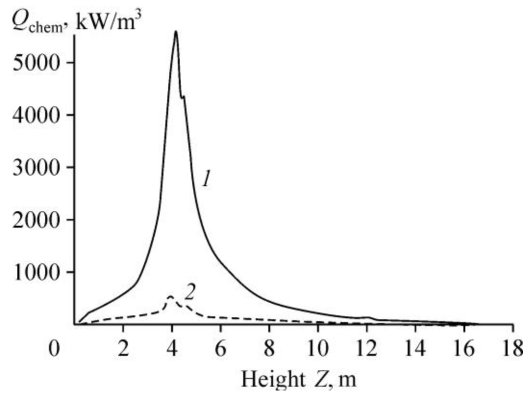

Fig. 10. Distribution of the heat release intensity at combustion Q_{chem} along the height of the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS.
1 — maximum values, *2* — mean values.

Figure 11 shows the results of modeling the radiation heat fluxes Q_{rad} on the main heat-receiving surfaces of the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS. An analysis of the figure shows that on all heat-receiving surfaces, the incident radiant heat flux is distributed uniformly and amounts to 90–100 kW/m^2. This is due to the fact that all walls of the boiler furnace chamber are located symmetrically with respect to one another, and the boundary conditions on them are the same. The obtained pattern of the distribution of heat fluxes on the combustion chamber walls contributes to an analysis of the optimal location of furnace shields at the optimization of operation regimes of the burner under study to eliminate the overheating of these shields. This will make it possible to ensure a uniform heating of chamber walls, which in turn will favorably affect the effective heat removal from the boiler shields and, consequently, will affect the total efficiency of the boiler unit.

Thus, a complex investigation of the heat and mass transfer processes in turbulent flows of high-temperature reacting media in the regions of real structures (TPS's, cogeneration plants) has been conducted in the present work by the method of three-dimensional modeling. The numerical experiments on the investigation of thermal processes and aerodynamic characteristics of the flow have been conducted in the furnace chamber of the BKZ-75 boiler of the Shakhtinsk

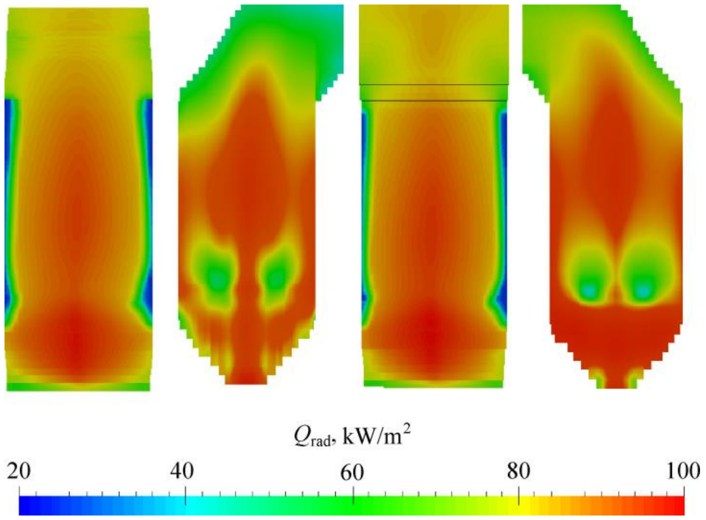

Fig. 11. Distribution of radiation heat fluxes Q_{rad} on the main heat-receiving surfaces of the combustion chamber of the BKZ-75 boiler of the Shakhtinsk TPS.

TPS at the combustion therein of a high-ash power-plant fuel. At the use of the methods of three-dimensional modeling, the largest number of the phenomena and factors have been taken into account, which affect the real technological processes in combustion chambers of industrial objects. The aerodynamic pattern of the furnace chamber under study has been presented, the temperature fields and distributions of the energy released at the expense of chemical reactions have been plotted. The values of radiation heat fluxes on the main heat-receiving surfaces of the combustion chamber have also been obtained.

The results of executed numerical experiments will help to optimize the techniques of the combustion of the low-grade Kazakhstan coal and, at the same time, to develop a concept of the power production with the minimum amount of harmful substances.

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