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Study of combustion processes in the combustion chambers of power facilities

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Simulation of the aerodynamic structure of the flow with a reasonable choice of the turbulence model makes it possible to obtain adequate results with sufficient accuracy for practice. In the proposed article, when studying the processes of heat and mass transfer, we focused our attention on the chosen turbulence model and used the results of the aerodynamic structure to explain the flow of mass flows of nitrogen oxides throughout the space of the combustion chamber. As a result of 3D computational calculations, the distributions of turbulence parameters (k and ε), velocity field (total velocity vector and its components) and nitrogen oxides in the volume of the combustion chamber and at its outlet were obtained. These results will make it possible to effectively control the processes of fuel combustion in real power plants and solve urgent problems of thermal power engineering and ecology.

Keywords: combustion chambers, solid fuel, 3D modeling, flow aerodynamics, nitrogen oxides, turbulence model

INTRODUCTION

All scenarios for the development of energy in the world must meet environmental goals, which in turn provides for a rapid reduction in the use of coal. This approach significantly complicates the development of coal energy in the world in the coming decades. However, the 2021 International Energy Agency (IEA) Coal Report notes that coal consumption could show even higher rates in subsequent years. Global demand for coal will rise to a record 8 billion tons and remain at that level until 2024. This is due to the recovery from the COVID pandemic, which turned out to be very energy-intensive. Gas, wind and sun are not enough to meet the frenzied demand for electricity and there are few technologies that could help replace fossil fuels in the coming years. The main growth in coal consumption came from China, India and the United States. In Europe, the problem was exacerbated by the weather (in recent months it was calm and cool there), the shortage of natural gas and the protracted repairs at nuclear power plants in France. Thus, the world again began to burn coal, despite the protests of environmentalists [1].

According to the WEO, there are two aspects to phasing out coal in the energy sector: 1) stopping the construction of new power plants and 2) managing the reduction of emissions from existing assets. Advanced economies are seeing a faster phase-out of coal in the energy and industrial sectors. Demand will collectively decline by about 40% by 2030. This is due to climate policy and the rapid growth of renewable energy. Ensuring reductions in emissions from the existing fleet of coal-fired power plants is a major challenge for public policy. Given the dependence of a number of countries and regions on coal, the closure or conversion of coal mines and power plants can have serious economic and social consequences. Therefore, the use of coal, on the contrary, is expanding in many emerging market and developing countries [2]. In Kazakhstan, 95% of the mined coal is produced by enterprises of the Karaganda and Ekibastuz coal basins. Thus, the main energy fuel is coal from the Ekibastuz and Karaganda deposits. If we compare the quality of Kazakh coals with the requirements of the world market, then our coals turn out to be far from competitive. The main disadvantages of thermal coals include high costs for the transportation of coal, a large amount of combustion waste, high ash content and rapid wear of boiler units. The problem of depreciation of stations exists in all post-Soviet countries, in the Republic of Kazakhstan it is especially in the cities of Karaganda, Pavlodar, Kokshetau and in a number of cities in the southern regions. According to official statistics, the average wear and tear of the main equipment at thermal power plants in Kazakhstan is estimated at more than 55%. This, in turn, is one of the main reasons for the deterioration of the environmental situation in the regions of the Republic of Kazakhstan. Kazakhstan has developed a Green Energy Doctrine. According

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to the concept of the energy industry, the structure of new energy capacities in 2035 will be as follows: 6.5 GW of renewable energy facilities, over 5 GW of gas generation, over 2 GW of hydroelectric power plants, 1.5 GW of coal generation, as well as 2.4 GW of nuclear generation. It is an important tool for reducing and replacing greenhouse gas emissions, as well as the gradual replacement of generation depending on fossil fuels [3, 4].

Currently, the methods used to reduce emissions of harmful substances (oxides of nitrogen, carbon and sulfur) from industrial facilities at the moment still do not meet environmental requirements and do not give the desired result. In this regard, it is important to comprehensively study the emerging problems and conduct detailed scientific research. This problem is solved with the help of modern information technologies using 3D modeling methods [2, 5-11].

3D *modeling technique*

In the context of tightening environmental requirements and economic feasibility, detailed studies using computer technologies are required for modeling (development) of new and modernization of existing thermal power plants in order to introduce environmentally friendly coal technologies [12-14]. With the help of three-dimensional modeling of the processes occurring inside the combustion chambers of power facilities, it is possible to study in detail the influence of design and operating parameters, as a result of which it is possible to find specific ways to improve the economic and environmental component of the operation of facilities, while significantly reducing the amount of experimental research.

Works using CFD methods are widely used in studies of the combustion of various fuels in many foreign countries. In particular, German scientists in their studies [15-18] use European coals as fuel, the ash content A of which does not exceed 8% compared to Kazakhstani (A ~ 40%). Therefore, the CFD methods in this work have been developed and adapted for researching precisely the combustion processes of high-ash Kazakh coals.

To conduct computational experiments on 3D modeling of heat and mass transfer processes in the combustion chamber, the FLOREAN software package [19–21] was used as a basis, which is based on solving conservative equations for the gas-fuel mixture using the control volume method.

The computer software package consists of a sub-model of the balance of momentum, energy, matter components, k-ε turbulence model, SIMPLE pressure correction method, six-stream thermal radiation model. This software package has been used to calculate flows in the combustion chambers of many thermal power plants both abroad [22–27] and in Kazakhstan. This software package was adapted to the task of burning high-ash Kazakh coal in the combustion chamber of the CHPP of the Republic of Kazakhstan.

As is known, the system of conservation and transport equations does not have an analytical solution and can only be solved numerically. For a numerical solution, the entire computational domain is divided by a difference grid into discrete volumes; the continuous field of variables is replaced by discrete values at the grid nodes. The derivatives included in the differential equations are replaced by their approximate expressions in terms of the differences in the values of the functions at the grid nodes. For each cell of the computational domain, physical conservation laws and differential transfer equations are used, which are integrated over the volume of each cell. The starting point for each balance value lies in the center of each control volume, since the value of the values for the control volume is stored at the center point. The stationary control volume corresponds to the justified Euler approach for flows, and the change in the transport quantity is described in a unit volume, and the values of the transport quantity are determined at each point of the considered area separately. As it is known the control volume method is flow-oriented.

In fact, there are no universal measures to judge the convergence of computational experiments. However, for most practical computational problems, convergence criteria can be established. In the FLOREAN program, the task of convergence and accuracy of calculations and simulation of combustion processes is carried out in the A1-Flamme subprogram, which is based on the following stages of calculation: beginning of iterations; model inclusion; control of calculations using relaxation factors; convergence issues.

3D modeling of aerodynamics and turbulence

The mixing of air and fuel during combustion, along with the efficient transfer and distribution of heat, can affect the overall performance of the combustion system. The tasks of stable combustion of fuel and transfer of generated heat to the system are determined by the aerodynamics of the burner system and the aerodynamics of the technological system as a whole. Therefore, understanding and optimizing the aerodynamics of the system is very important for the efficient operation of the entire boiler unit.

Aerodynamic issues can be assessed using analytical, physical and computational (CFD) simulation capabilities to evaluate and optimize the combustion process in an industrial plant. The aerodynamics of the flow is usually adjusted in such a way that conditions favor combustion at a given location in the flow. This may take the form of a recirculation zone formed by swirl, contour expansion, or a combination of both. In practice, the recirculation zone holds the flame root, creating a significant reverse flow, drawing hot flame products to the nozzle without introducing foreign objects into the flame. However, this flow requires careful design of the flow conditions, flow rate, burner position and geometry.

There are many techniques for changing combustion aerodynamics in relation to the requirements for using different types of fuel, obtaining different temperatures in different conditions, and using different heat transfer modes. A change in one variable can have serious consequences for the stability of the flame and the entire combustion process. There are also various criteria that can be used to optimize the industrial combustion process. Small improvements in combustion aerodynamics or heat transfer efficiency can result in direct fuel savings or result in an overall reduction in process air pollutant emissions.

The main scientific challenge is the need for a better understanding of turbulence and its effects on the transfer of momentum, heat and mass in engineering applications, including aerodynamics, industrial flows and combustion systems. While significant advances in direct numerical modeling (DNS) of turbulence and turbulent combustion, as well as the development of large eddy simulations (LES) for engineering flows, have provided valuable insights into the physics of many turbulent flows and have led to rapid improvements in turbulence and combustion modeling in industry, nonetheless, serious turbulence modeling problems remain.

It is relevant to study the nature of turbulent flows inside the combustion chamber. Velocity fluctuations characterize turbulent flows. They contribute to the mixing of transported characteristics such as momentum, energy and concentration of the components, and also cause fluctuations in these characteristics. Since these pulsations can be small scales, but have a high frequency, their calculation directly in practical technical calculations is a very difficult task. Currently, there is not a single universal model that describes the entire spectrum of turbulent flows. In practice, semi-empirical relationships are used that describe the effect of turbulence parameters on the main characteristics. In this case, the instantaneous (exact) constitutive equations can be averaged over time, represented as an ensemble average, which leads to modified systems of equations that require less computational effort to solve. However, the modified equations contain additional unknown variables.

In this article, the standard *k*-*ε* turbulence model was used to describe turbulent flow. This model is a simple two-parameter turbulence model that solves two transport equations that define the turbulent velocity and the length scale. Turbulent energy *k* and dissipation *ε* were obtained from the equations:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i k)=\frac{\partial}{\partial x_i}((\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_i})+G_k+G_b-\rho\varepsilon \quad (1)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i\varepsilon)=\frac{\partial}{\partial x_i}|(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_i}|+G_{1\varepsilon}\frac{\varepsilon}{k}(G_k+ \quad (2)$$
$$+(1-C_\mu)G_b-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Constants *k*-*ε* of the turbulence model are: $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ, σ_K, σ_ε which have the following values: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.

Stability, economy and reasonable accuracy for a wide range of turbulent flows make the k-ε turbulence model the most useful in industrial applications. The constant coefficients for this model are obtained empirically and therefore it is semi-empirical. It should be noted that the simulation of flows in the presence of turbulence, which are based on the solutions of equations for turbulent characteristics (the kinetic energy of turbulence and its dissipation), makes it possible to obtain the desired accuracy of the solution, while eliminating inexpedient machine costs associated with obtaining it.

The basis of the computational experiment

As an object of study for conducting a computer experiment in this paper, we chose the combustion chamber of an actually operating Kazakhstani CHP boiler, the dimensions of which are shown in Table 1. A boiler of this brand can be operated using brown and hard coal, peat, anthracite fine and lean coal. However, due to the fact that the power facility is located closer to the local Karaganda coal deposit, low-grade Karaganda coal with an ash content of more than A ~ 35% is mainly burned here.

On the side walls of the combustion chamber, the boiler has two axial-vane vortex burners located opposite each other. Technical parameters of the combustion chamber of the boiler and data on the coal burned are presented in Tables 2 and 3.

Table 1. Main geometrical parameters

Name	Value
Combustion chamber height (*Z*), *m*	16.75
Combustion chamber width (*X*), *m*	6
Depth of combustion chamber (*Y*), *m*	6.6
Front and back wall area, m^2	90.675
Right side wall area, m^2	92.4
Left side wall area, m^2	110.55
Ceiling wall area, m^2	27.72
Bottom wall area, m^2	7.26
Cross-sectional area of the air mixture channel in the burner, m^2	0.12
Cross-sectional area of the secondary air duct in the burner, m^2	0.25

Table 2. Technical parameters

Name	Value
Number of burners on the boiler, *pcs*	4
Fuel capacity of one burner, *t/h*	3.2
Primary air flow per boiler, Nm^3/h	31797
Secondary air flow per boiler, Nm^3/h	46459
Hot air temperature, *°C*	290
The coefficient of excess air in the furnace	1.2
Estimated fuel consumption for the boiler, *t/h*	12.49
Cold air temperature, ^oC	30
Inlet pressure, *mbar*	$1.013 \cdot 10^3$
Hydrodynamic resistance of the air mixture channel of the burner, *mm w.st.*	67.1
Air mixture temperature, *°C*	140
Wall temperature, *°C*	430.15

Table 3. Characteristics of Karaganda coal

Name	Value
Grinding fineness (R_{90}), *%*	20
Density of coal, kg/m^3	1350
Heat of combustion of coal, kJ/kg	$3.4162 \cdot 10^4$
Heat of combustion of coke, kJ/kg	$3.2814 \cdot 10^4$
A^c, %	35.10
$V^Г$, %	22.00
W^P, %	10.60
C, %	79.57
H_2, %	6.63
O_2, %	9.65
S_2, %	1.92
N_2, %	2.23

To carry out computational experiments, the geometry of the investigated boiler was constructed according to its real scheme, and its finite-difference grid was compiled for numerical modeling of the processes of solid fuel combustion in the boiler combustion chamber. The finite difference grid has steps along the X, Y, Z axes: 59×32×67, which is 126 496 control volumes (Fig. 1). On Fig. 1 the location of the burners, the areas of the belt of burners, the outlet zone, and the areas of additional air supply can be seen. The choice of such a fine mesh makes it possible to provide an adequate picture of the combustion process of pulverized coal at any point in the combustion chamber.

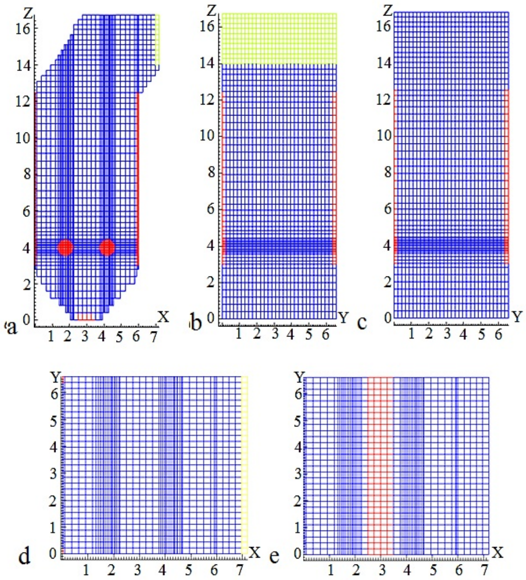

Fig. 1. Grid breakdown of the combustion chamber into control volumes (a - front side, b - right side, c - left side, d - ceiling, e - bottom)

For the mathematical description of pressure and velocity, the effective method of the SIMPLE algorithm was used in this work. Here the problems of discretization of the momentum and continuity equations are solved. SIMPLE uses corrections for the relationship between velocity and pressure to obtain mass-conserved pressure fields. Once the pressure fields are obtained, the momentum equations can then be solved to obtain preliminary velocity fields. Pressure correction and velocity corrections were calculated using the continuity equation.

In this article, when studying the processes of heat and mass transfer, we focused our attention on the chosen model of turbulence and used the results of the aerodynamic structure to explain the flow of mass flows of nitrogen oxides throughout the space of the combustion chamber.

RESULTS AND DISCUSSION

Using the modern 3D modeling method, the flow aerodynamics (full velocity vector *V*) (Fig. 2), turbulent characteristics (turbulence kinetic energy *TE*, dissipation energy *ED*) (Figs. 3, 4) and the concentration of nitrogen oxides *NO* (Fig. 5) were calculated throughout the volume of the combustion chamber and at its outlet.

Analysis of Fig. 2 shows that in the volume of the combustion chamber, as the flow of the air mixture and combustion products moves towards the exit, the speed monotonically decreases, with the exception of the exit area of the boiler combustion chamber, where its surge is observed. This is due to the fact that here the geometry of the combustion chamber changes, and the flow, due to a change in its direction, becomes unsteady, forming an additional vortex, while increasing the turbulence of the flow, which leads to a change in velocity in this region of the combustion space. The full velocity vector is obtained by: $\vec{V} = \sqrt{U^2 + V^2 + W^2}$.

Fig. 2a shows the three-dimensional distribution of the full velocity vector over the depth of the combustion chamber (Y=3.19m) in its central region. In the figure, you can see how the flows collide in the center of the furnace, here the speed is highest (~ 11 m/s). Countercurrent flows blown from the burners, heading at maximum speed to the center of the furnace space, collide. And here, splitting into several vortices, they descend into the region of the cold funnel, forming vortex currents. The other part goes up to the exit from the combustion chamber. This nature of vorticity arises as a result of turbulence due to the interaction of the air mixture with the oxidizer. Above Z=8m in height, towards the exit from the furnace space, there is a gradual smoothing of the currents, the speed of which lies in the range of 4-8 m/s.

The following Fig. 2b shows the field of the full velocity vector in the area of the reversing chamber (Z=12.65m) and in the section at the exit (X=7m) from the boiler combustion chamber. As the turbulent flow moves towards the exit from the combustion chamber, the vortex nature of the flow weakens, then it intensifies in the region of the rotary section of the boiler, and an almost uniform velocity profile is observed at the exit from the chamber.

It is noticeable that in the section of the turning area of the chamber, the maximum values of velocity (~ 9 m/s) are concentrated in the central part and in the near-wall area, which can be explained to some extent by the asymmetry of the furnace geometry in this area. At the exit from the furnace space, the velocity is almost equalized, no mixing of flows is observed and its average value is ~ 4 m/s.

The presence of a swirling flow in the combustion chamber causes characteristic distributions of the main aerodynamic parameters (velocity components, turbulent and dissipative kinetic energy of turbulence) throughout the volume of the chamber. The results are shown in Figs. 3 and 4.

In the vortex region with the greatest changes in the velocity fields, that is, where the processes of physical and chemical transformations occur intensively during the combustion of pulverized coal, there are also maximum disturbances of turbulent flows and their turbulent characteristics. This is evidenced by the maxima in the distribution of the turbulent characteristics of the process, such as the kinetic energy of turbulence *TE* and its dissipation *ED*.

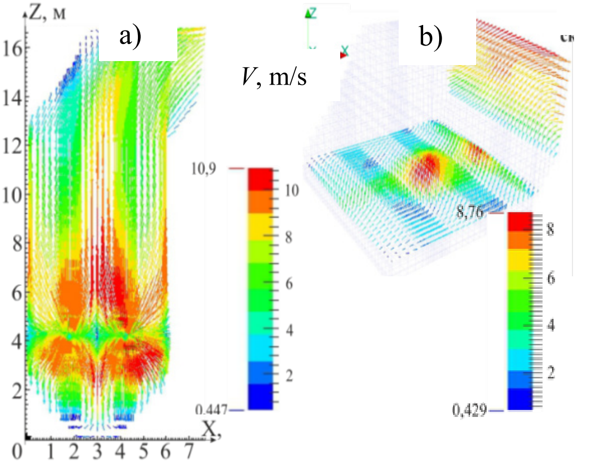

Fig. 2. Distribution of the total velocity vector V in a) longitudinal central section along the depth of the furnace (Y=3.19m); b) turning area (Z=12.65m) and at the outlet of the furnace (X=7m)

From the analysis of three-dimensional distributions of turbulent characteristics presented in Figs. 3 and 4, it can be seen that the active mixing of the fuel and oxidizer flows coming from counter burners leads to the fact that the flow in this area is highly turbulent, and the kinetic energy of turbulence and its dissipation reach maximum values here.

The kinetic energy of turbulence and the energy of dissipation reach their maximum values in the region of the belt of burners and in the lower region of the combustion chamber. These areas are a zone of collision of dusty coal flows, which is caused by unsteady perturbations of the swirling flow with sharp jumps of turbulent fluctuations. The kinetic energy of turbulence in the longitudinal central section along the depth of the furnace (Y=3.19m) has its maximum value equal to 10 m^2/s^2 (Fig. 3a), and the dissipation energy is ~ 84 m^2/s^3 (Fig. 4a). Towards the exit, the average value of both parameters decreases to ~ 0.8 (Figs. 3b, 4b).

Next, let's consider the influence of the aerodynamic structure on the formation and distribution of harmful emissions such as nitrogen oxides in the combustion chamber (Fig. 5). When coal is burned, the fuel *NO* formation model takes into account coal pyrolysis, homogeneous combustion of hydrocarbons, and heterogeneous combustion of coke, considering the influence of the mineral content (in particular, ash content) of the fuel, as well as correlations at high temperatures.

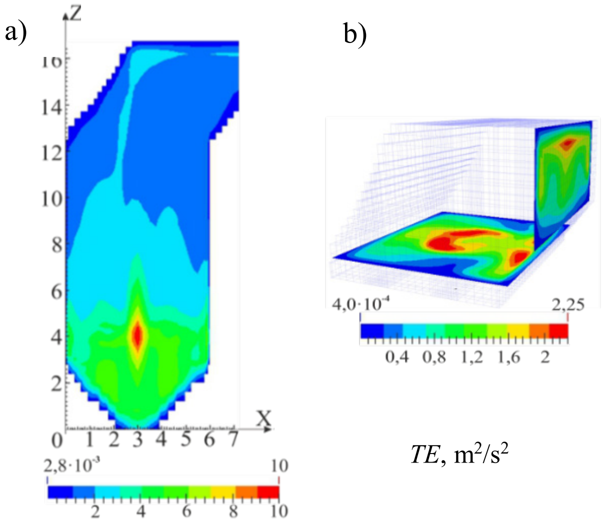

Fig. 3. Distribution of the kinetic energy of turbulence *TE* in a) longitudinal central section along the depth of the furnace (Y=3.19m); b) turning area (Z=12.65m) and at the outlet of the furnace (X=7m)

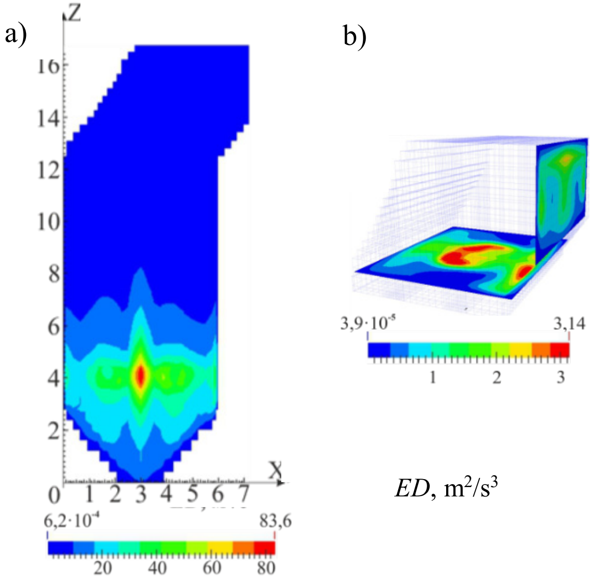

Fig. 4. Distribution of the dissipation energy *ED* in a) longitudinal central section along the depth of the furnace (Y=3.19m); b) turning area (Z=12.65m) and at the outlet of the furnace (X=7m)

Analysis of Fig. 5 of the distribution of concentrations of nitrogen oxides *NO* in the area of the location of the burner devices and at the outlet of the combustion chamber indicates the influence of flow aerodynamics on the processes of formation of concentration fields of nitrogen oxides *NO*. Intensive mixing of fuel and oxidizer, created by turbulent flows of air mixture injected from the burners, provides favorable conditions in this zone for the formation of nitrogen oxides *NO*. Thus, the concentrations of nitric oxide *NO* reach their maximum values of 5206.2 mg/Nm^3 (Fig. 5a).

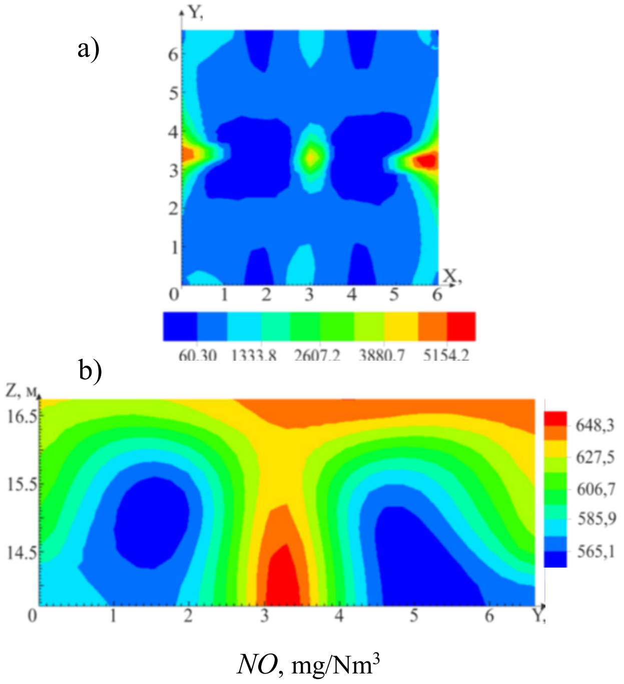

Fig. 5. Distribution of the concentration of nitrogen oxides *NO* in a) zone of the furnace burner belt (Z=3.98m); b) at the exit from the furnace (X=7.14m)

As we move towards the exit from the furnace, the chemical reactions of nitrogen oxidation decay, which is explained by afterburning and the described behavior of the aerodynamics of turbulent flows. This leads to a decrease in *NO* concentrations in the upper regions of the furnace space. The maximum concentration of nitric oxide *NO* at the outlet of the furnace (X=7.14 m) is 649.2 mg/Nm^3 (Fig. 5b). The average value of the concentration of nitric oxide *NO* at the outlet of the furnace is 613.1 mg/Nm^3, which corresponds to the MPC (640 mg/Nm^3) for coal-fired CHPPs of the Republic of Kazakhstan.

The aerodynamic characteristics obtained during the computational experiment reflect the real technological process observed in the combustion chambers. These results indicate that in the central region of the combustion chamber there is a sharp change in aerodynamic characteristics (velocity, kinetic energy of turbulent pulsations and dissipation energy) associated with the formation of a vortex flow, which weakens as the pulverized coal flow and combustion products move to the exit.

The conducted studies testify to the complexity of heat and mass transfer processes occurring during the combustion of pulverized coal fuel in the combustion chambers of industrial boiler plants. An analysis of the results obtained shows that such a detailed study of the aerodynamic pattern that takes place in the combustion chamber of the boilers of operating TPPs is possible only by numerical simulation methods and by conducting computational experiments.

CONCLUSIONS

The presence of a volumetric vortex flow in the central region of the combustion chamber has a positive effect on the combustion process of pulverized coal fuel (heat exchange and mass transfer), since, due to the turbulent nature of the flow, intensive mixing of the fuel components with the oxidizer occurs here, which means that more complete burnout of coal dust is ensured.

The justified choice of the turbulence model made it possible to obtain with sufficient accuracy the aerodynamics of the flow and the distribution of nitrogen oxides over the entire space of the combustion chamber. The results obtained will make it possible to effectively control the processes of fuel combustion in real power plants and solve urgent problems of thermal power engineering and ecology.

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