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Numerical investigation of heat transfer characteristics of pulverized coal in the combustion chambers of the heat energy centers of Kazakhstan

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This article is devoted to the investigation of thermal characteristics of pulverized coal combustion process in the combustion chamber of the boiler BKZ-420. The greatest changes in the temperature distribution observed in the central part of the combustion chamber in the field of the fuel supply and the air fuel mixture are by burner holes. Carrying out the study of thermal characteristics is an important step during the modeling process of heat and mass transfer from the pulverized coal combustion, which allows to determine the temperature field throughout the volume of the combustion chamber and outlet. It has been determined the optimal combustion technology of high-energy fuel and the best structural parameters of the combustion chamber of the boiler BKZ-420 Almaty thermal power station that improve the wear resistance of power and reduce harmful emissions into the atmosphere (temperature decrease of the furnace wall, opposite the burners on the 300^{0}C, ie 17.24% and secondary reduction of carbon monoxide concentration of CO at the outlet from the furnace at 15% carbon dioxide CO_2 – 4.65%, and nitrogen dioxide NO_2 – 14%).

Key words: BKZ-420, combustion, Ekibastuz coal, heat and mass transfer, modeling, pulverized coal, turbulence, two–phase flow.
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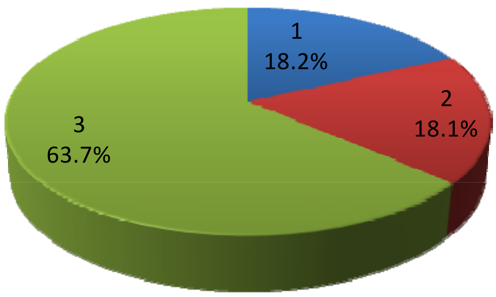
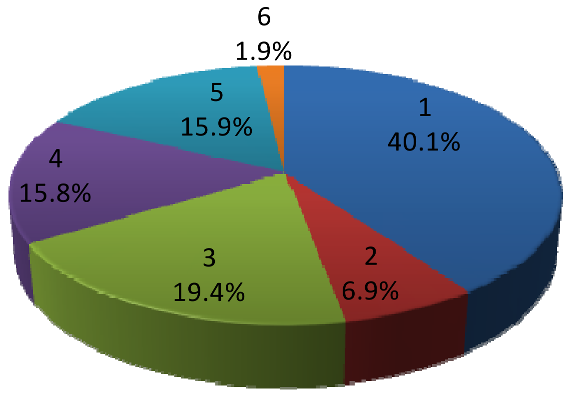
1 Introduction

As coal is a major source of energy of the XXI century, all around the world it is paid more attention to the problem of its efficient and cleaner burning. The coal share in the reserves of fossil fuels shown in the fig.1. Compared with other fossil fuels, coal resources are of approximately four times more than the oil reserves (estimated at 41) or gas reserves (67 years) [1].



1 – oil, 2 – gas, 3 – coal
Figure 1 – The world's proven reserves of fossil fuels

Global Energy Sector at present and in the foreseeable future based on the use of fossil fuels, mainly low-grade coal.Be noted that the deterioration of the quality of steam coal is widespread, and not only in the CIS countries, but also in the developed capitalist countries. To date, the world's thermal power plants (TPP) produce more than 40% of electricity and heat. Although the history had ups and downs in the activity of coal, now it remains one of the most important fuels for energy, especially electricity (Fig.2). According to statistics from 2003 [2], coal provides about 24% of the thermal energy and produces about 40% of the world's electricity. In the near future it is expected to increase its use. According to the forecasts by 2020, the share of coal in the world fuel balance will be more than 50%. Figure 3 shows the share of primary energy in the past and the future.These studies based on availability and forecast growth in demand for energy [6, 7]. Follows from the figure we can observe that the share of oil and gas in power generation by 2100 will decline, while the proportion of coal will grow.



1 – coal, 2 – liquid fuel (fuel oil, diesel fuel), 3 – gas 4 – nuclear energy, 5 – hydropower, 6 –other (solar, wind, geothermal energy, waste, including vegetable origin).

Figure 2 – Distribution of energy for the production of electricity in the world [2]

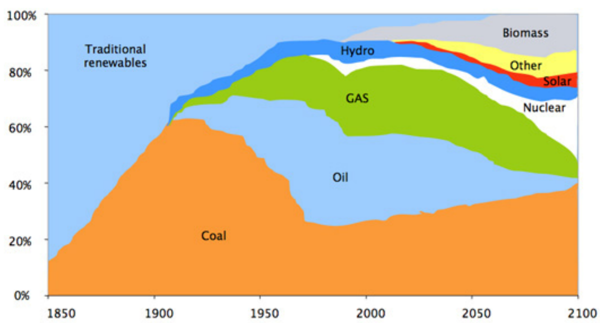


Figure 3 – Primary energy shares from 1850 to 2100 (reprinted from WCI, 2000b)

A direct burning of low-grade coal with high ash content (40-50%), humidity (30-40%), sulfur (1-3%) and low-volatile (5-15%) in the existing furnace devices involves considerable difficulties of -this deterioration of ignition and fuel burn, increasing the fur underburning and harmful dust and gas emissions (greenhouse gases, ash, nitrogen oxides and sulfur). Suffice it to say that the problem of greenhouse gases (carbon dioxide, methane and others.) and the consequent general warming has grown now to universal problem of global climate change on the ground, flooding large areas of land, desertification and others.

Combustion of pulverized coal has the greatest environmental impact on the environment: toxic and greenhouse gases, particulate matter, waste and water filtration, slag disposal fly ash, thermal vents and much more. In addition, the development of the energy sector due to the large-scale transformation of the components of the environment, the negative effects of which may occur for a long time [3]. Coal mines are changing terrain and form specific soil and ground conditions dumps, hydroelectric reservoirs cause changes in seismicity, flood the valley the most productive ecosystems are changing the landscape structure of regions.

The irreplaceable effective method of theoretical investigation of flows of chemically reacting media is numerical simulation. This approach is currently being intensively developed in many countries: build a more advanced model, constructed new numerical algorithms held a variety of computational experiments. Numerical simulation can be used to predict and study the behavior of complex physical systems. In order to give quantitatively correct predictions, the simulation should be described as separate processes operating system and their interaction. The mathematical theory of turbulence is absent so far.In recent decades, some development has been direct simulation of turbulence on large computer systems, accurate implementation of which, however, is fraught with difficult to overcome computational costs now and in the near future.

To date, there are developed variety of mathematical models for calculation of turbulent flows, turbulent combustion and heat radiation transport. Moreover, there are a lot of created powerful computational software packages (FLOREAN, Ansys Fluent and others) that implement these mathematical models. Finally, the possibility of parallel computing and fast development of high-performance computing systems can effectively perform detailed calculations on large grids.The most important issue was reliability of the results of calculations and the experimental data. Thus, the focus of this paper is focused on the ability of modern packages perform the calculation of turbulent Flames with the required accuracy [4].

To achieve this objective is invited to consider a model problem –well documented jet diffusion flame, for which there is credible and detailed measurements of fundamental physical quantities. Comparison with the results of measurements reveals turbulence and combustion models, as recommended, and completely unacceptable for this class of problems as the computing tool that is usedin this work is FLOREAN [4-6]. One of the most interesting and useful from the point of practical application view are questions of modeling heat and mass transfer in the presence of physical and chemical processes in the areas of real geometry. These areas are the combustion chamber of various thermal power plants, internal combustion engines, etc.

For simulation of heat and mass transfer in the presence of physical and chemical processes we used the fundamental laws of conservation of quantities such as mass, momentum, energy. Since heat and mass transfer in the presence of physical and chemical transformations is the interaction of turbulent motions and chemical processes, we must take into account the conservation of the components of the reaction mixture, turbulence, multiphase medium heat due to radiation of heated fluid and chemical reactions.

To write all equations with the above-mentioned physical and chemical phenomena that make up the mathematical model, we consider the complex processes of heat and mass transfer in reacting media, written in the beginning of all these equations in the general form of conservation law of some substance ∅ (mass, momentum, energy, component of the mixture).

In differential form the continuity equation or the conservation law of mass can be written as:

$$\underbrace{\frac{\partial \rho}{\partial t}}_{I} + \underbrace{\frac{\partial \rho u_i}{\partial x_i}}_{II} = 0 \qquad (1)$$

The law of conservation of momentum and the momentum equation is written as follows:

$$\underbrace{\frac{\partial \rho u_i}{\partial x_i}}_{I} + \underbrace{\frac{\partial \rho u_i u_j}{\partial x_j}}_{II} = -\underbrace{\frac{\partial p}{\partial x_i}}_{III} + \underbrace{\frac{\partial \tau_{ij}}{\partial x_j}}_{IV} + \underbrace{\rho g_i}_{V}, \qquad (2)$$

The change of energy in reacting turbulent flows can be caused by the following processes: the total energy flow by convection; the total energy flow through molecular heat transfer; change of energy due to the pressure forces working on the surface of the control region; energy change due to the work of friction forces on the surface of the control volume; energy change due to the work of body forces; absorption or release of energy as a result of chemical changes, or due to the energy of the thermal radiation [7].

In view of the above reasons, the energy equation in a general form can be written as:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}\left(u_i(\rho E + p)\right) = \frac{\partial}{\partial x_i}\left(k_{eff}\frac{\partial T}{\partial x_i} - \sum_{j'} h_{j'} J_{j'} + u_j\left(\tau_{ij}\right)_{eff}\right) + S_h, \qquad (3)$$

Where k_{eff}– effective thermal conductivity, which is determined by the sum of $k_l + k_t$ (laminar and turbulent thermal conductivity, respectively), J_j– diffusive flux component j`.

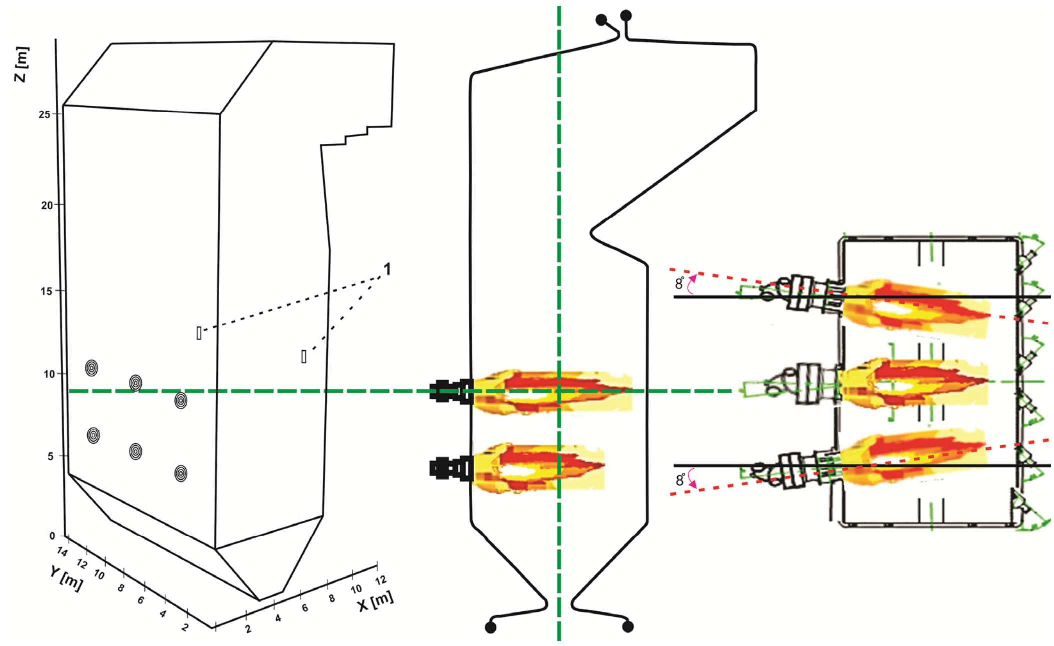
The law of conservation for the components of the reaction mixture.

$$\frac{\partial}{\partial t}\left(\rho C_\beta\right) = -\frac{\partial}{\partial x_i}\left(\rho C_\beta u_i\right) + \frac{\partial}{\partial x_i}\left(\frac{\mu_{eff}}{\sigma_{\beta eff}}\frac{\partial C_\beta}{\partial x_i}\right) + S_\beta \quad (4)$$

The combustion chamber of the boiler BKZ-420, steam capacity of 420 T/h, located on the Almaty CHP-2was selected as the object of research. The boiler E-420-13,8-560 BT (BKZ-420-140-7) designed for operation with Ekibastuz coal to produce superheated steam at thermal power plants with cogeneration turbine for high steam parameters.

In the combustion chamber provides dry ash removal [8-9]. Ash removal mechanized, using a continuous screw conveyors and crushers. Combustion chamber – prismatic, open type, with plan dimensions axes of pipes 14,46 × 12,052 × 29,102 (m^3). The furnace is shielded all-welded gas-tight evaporator walls made of pipe Ø60 × 6 mm welded strip 20 × 6 mm (steel 20). Step pipes panels is 80 mm.

The combustion chamber of the boiler is equipped with six double-flow vortex pulverized coal burners arranged in two levels with three burners on the front wall of the boiler. Extremes burner turned to the center of the furnace by 8 degrees. Performance of one burner of Ekibastuz coal is 12 T/h. In the furnace of combustible dust of low-grade high ash Ekibastuz coal with an ash content 40%, volatile 24%, humidity 5% and the highest calorific value equal 16,750 kJ/kg. Coal fineness is equal to R_{90} = 15%. All numerical calculations were performed on the above methodology [10-12].



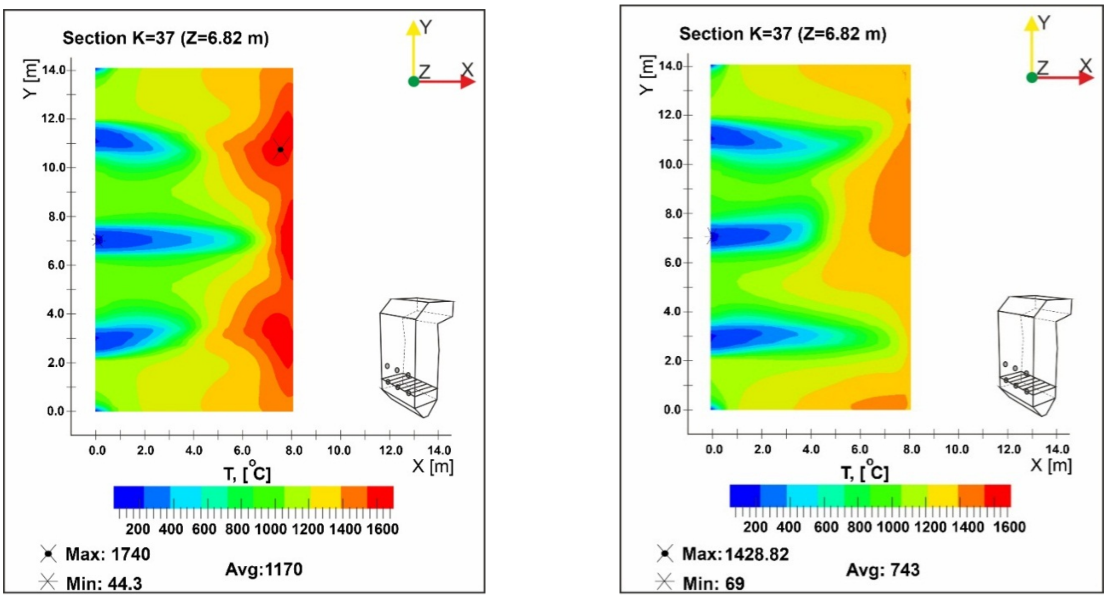
a) б) c)

(a) – 3D view of BK-420 boiler and its breakdown into control volumes
(b) – Burners establish arranged on two levels
(c) – Top view on the cross section (h = 10.75m) 1 – hole pattern (16x60 cm)
Figure 4 - General view of the industrial boiler BKZ-420 of the Almaty TPP-2

On the front wall of the combustion chamber are six vortex dual-flow pulverized coal burner (Fig.4) two layers (three on stage). Extremes burner turned to the center of the furnace by 8 degrees. In Fig.4 and in the opposite side of the wall is the area of the second tier of burners which is opening for supply of additional air turned to the center at 45 degrees, and the size of which is 14x60sm. In carrying out computational experiments, the initial step is to build the geometry of the object that is under study, as well as get it finite difference grid [13-16]. In addition, the used software package need to create a source files that contain physical and geometrical data of the investigated process, as well as initial and boundary conditions for modeling the heat and mass transfer in turbulent flows high.

The work is devoted to the study of the thermal characteristics of pulverized state fuels combustion process in the combustion chamber of the boiler BKZ-420. Figures 5-12 show the calculated temperature data fields. We see that the greatest changes in the distribution of temperatures observed in the central part of the combustion chamber in the supply of fuel and air fuel mixture through holes burners. Carrying out the study of thermal characteristics is an important step during the modeling process of heat and mass transfer from the pulverized coal combustion, which allows to determine the temperature field throughout the volume of the combustion chamber and outlet.

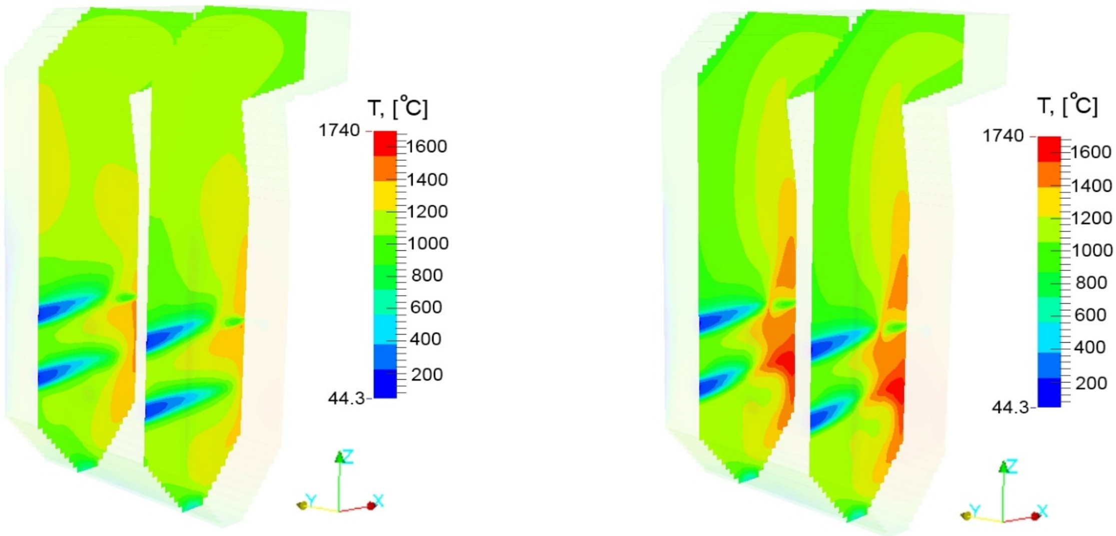
Figure 5 shows the temperature field in region of the lower belt burner at mass flow of air equal to 5kg/s and 10 kg/s. For the case where the air flow through holes is 5 kg/s temperature reaches the opposite wall burners at values 1740 °C and with flow rate 10 kg/s – 1440 °C. This can be attributed to the large amount of additional air of low temperature (T = 340 °C) supplied through the holes in the section z = 10.8 m, which led to decrease in the wall temperature about 300 °C and to protect it from overheating [17].



a) 5 kg/s b) 10 kg/s

Figure 5 – The distribution of temperature T in the combustion chamber cross-section burners in the zone of the lower layer (h = 6,82 m)

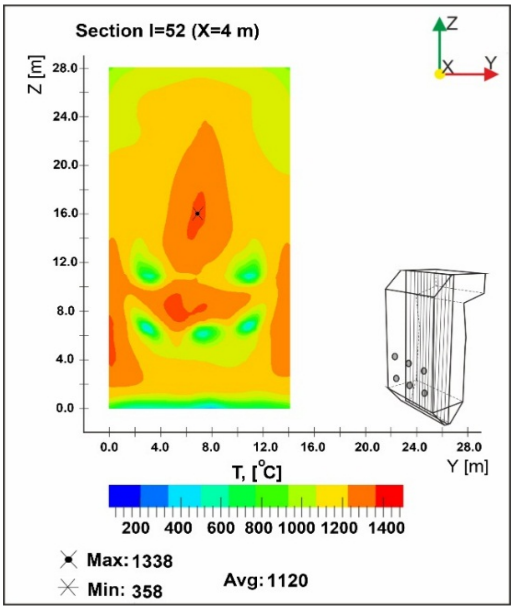
Figure 6 shows three dimensional temperature distribution in the field of two longitudinal sections (Y1=2.95 m and Y3=11.4775 m) of the combustion chamber located in the outer areas of the upper and lower burner stages [18]. We see that with a flow rate of additional air that is equal to 5 kg/s Maximum temperature is observed at the wall, located opposite to the burners and 1740°C is in the lower burners layer (Z = 6.82m). A flow of air at 10 kg/s can be seen that the temperature at the wall is significantly reduced by approximately 350°C.



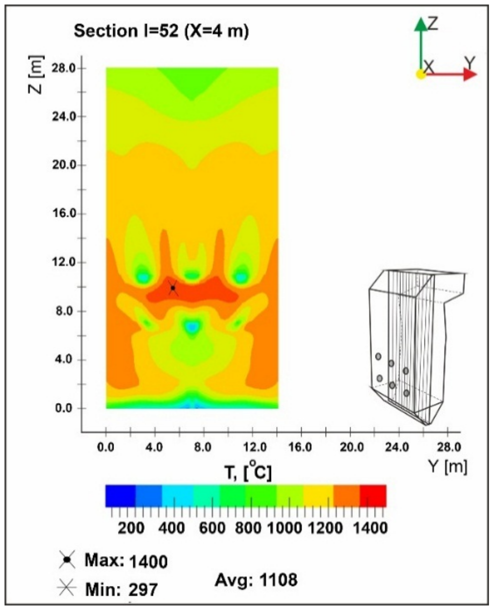
a) 5 kg/s b) 10 kg/s

Figure 6 – Three-dimensional distribution of the temperature field in the longitudinal sections Y1 = 2.95 m and Y3 = 11.4775 m of the combustion chamber

Figure 7 shows the temperature distribution in the longitudinal section along the X-axis (X = 4.01m). It can be seen from the analysis that at low mass flow rate of air (5 kg/s) of counter burner flame is formed in the area between the burners (Fig. 7a), while at high flow rate (10 kg/s) the temperature field (Fig. 7b), as it were extends in height of the combustion chamber.



a) 5kg/s



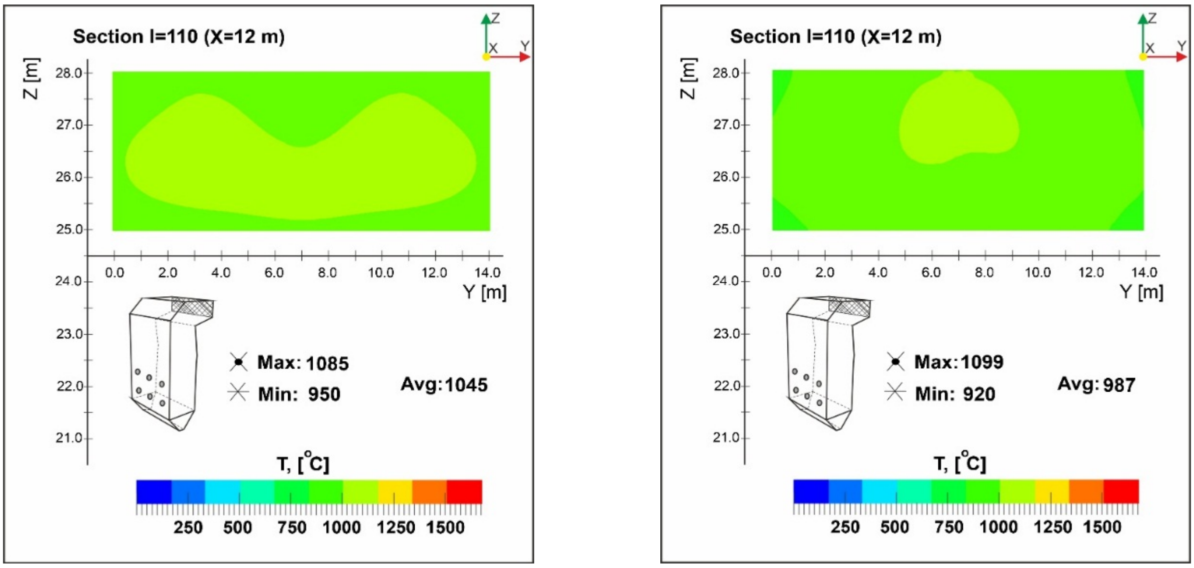
b) 10 kg/s

Figure 7 – The temperature field in the longitudinal section X = 4.01 m for different values of the mass air flow

Figure 8 shows the temperature field at the outlet of the combustion chamber for two values of the additional air flow holes: 5 kg/s and 10 kg/s. As can be seen from the figures, in the second case (Figure 8b), high-temperature region is smaller than in the first case (Figure 8a).

Since the burner and secondary air holes for disposed on opposite walls and directed toward each other at the center of the combustion chamber in the zone of contact currents, as mentioned earlier, dissected. Part of the flow goes to the cold zone of the funnel, forming two longitudinal vortex at an altitude lower than 10.8 meters, and the part formed by the thrust directed towards the exit. Further, as we move out of the combustion chamber and chemical processes are weakened (Figure 8), the temperature drops and at the outlet of its average value is about 1045 °C for flow 5 kg/s (Figure 7a) and 987 °C – for consumption 10 kg/s (Figure 8b).

The foregoing is confirmed by two-dimensional graph of the temperature distribution along the height of the combustion chamber for two different mass flow of additional air through the hole shown in Figure 9. Analysis of the figure shows that at a height z1 =6.82 and z2 = 10.8 meters located burners through which served cold aero mixture, the observed minimum in the temperature distribution. At the outlet chamber when the air mass flow rate 5 kg/s temperature higher compared with 10 kg/s feed [19].



a) 5 kg/s b) 10 kg/s

Figure 8 – Temperature at the outlet from the field of the combustion chamber (X = 12 m)

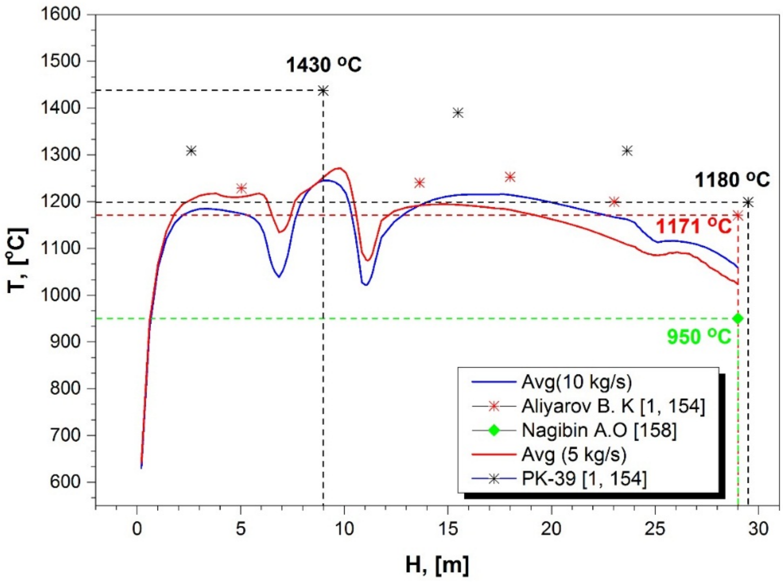


Figure 9 – The average temperature by the height of the boiler furnace

The outlet temperature of the combustion chamber confirmed it experimental value (T = 1171 °C) obtained directly on the CHP, presented in the paper and numerically. Comparing these values, we can conclude: computational experiment conducted to determine the values of the temperature in the volume of the combustion chamber, with sufficient accuracy is consistent with the measured values of temperature (Figure 9). This gives an indication of the reliability of the results and applicability of physical, mathematical and numerical model for further study of the thermal and concentration characteristics of the combustion chamber 420 BKZ Almaty CHP-2.

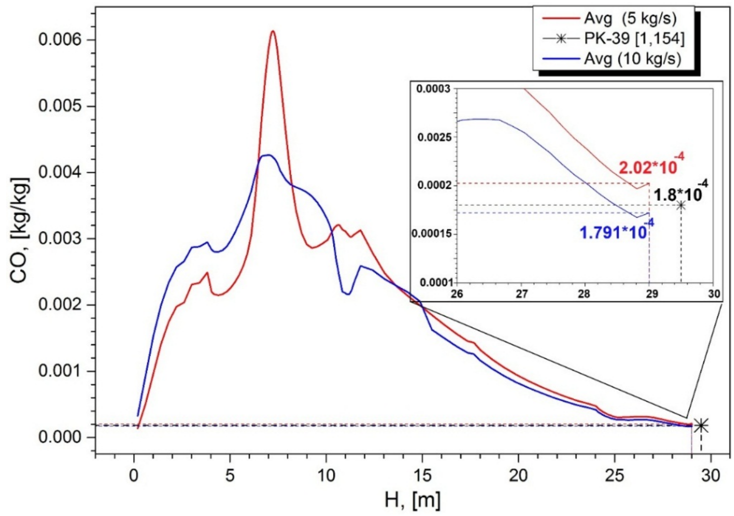
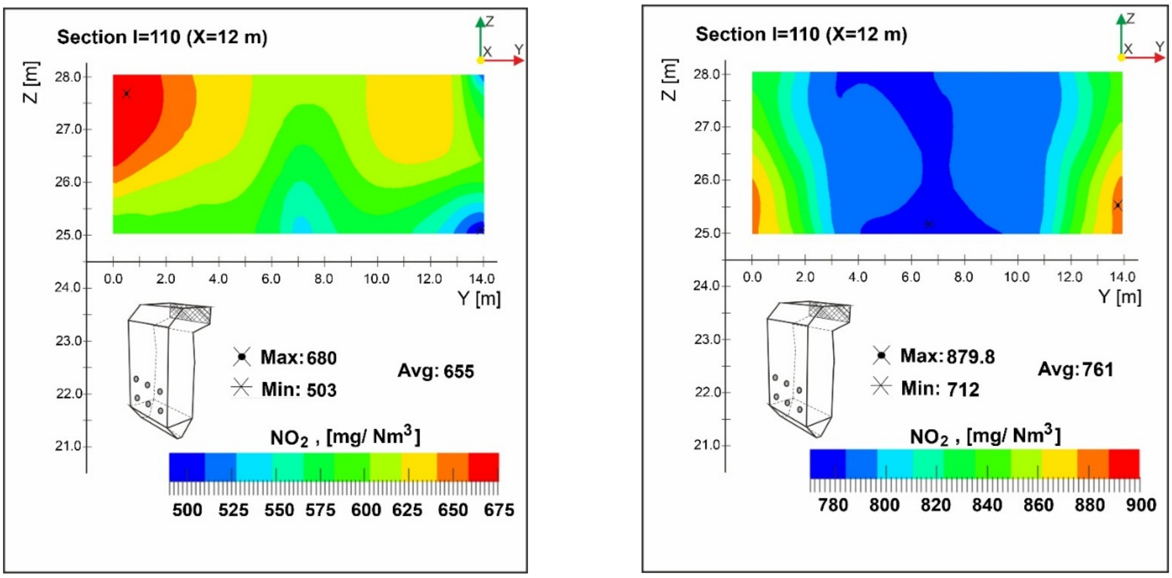


Figure 10 – Distribution of the concentration of carbon monoxide CO in height of the combustion chamber



a) 5 kg/s б) 10 kg/s

Figure 11 – Distribution of the concentration of nitrogen dioxide NO_2 at the outlet of the combustion chamber (X = 12 m)

Figure 10 shows the distribution of average values of the concentrations of carbon monoxide CO by height of the combustion chamber for two different values of the additional mass flow of air through the holes located on the opposite side of the burners. We see that at both the color and three-dimensional graphs of the temperature field at the exit of the combustion chamber the air mass flow equal to 5 kg/s, the concentration of carbon monoxide CO as compared with the above case, when the flow rate is 10 kg/s [20].

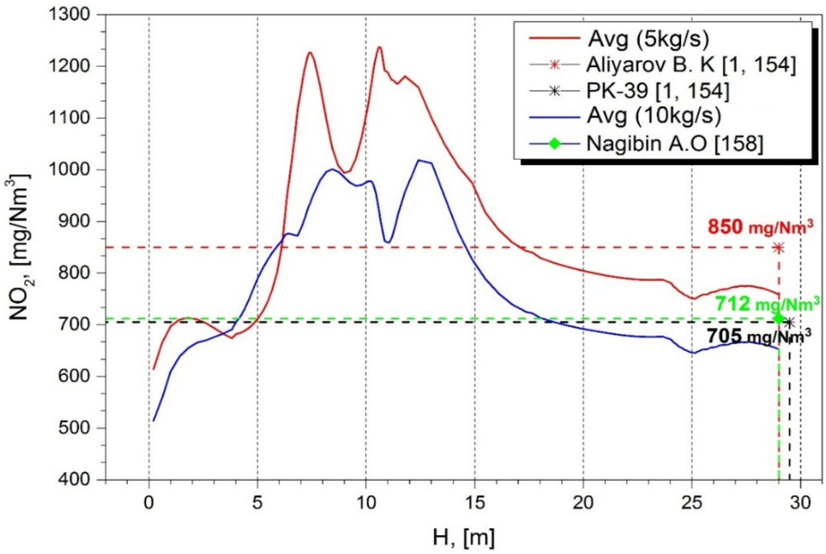


Figure 12 – Graph of the average values of nitrogen dioxide NO_2 in height the combustion chamber for different values of the mass flow of additional air

At the output (Figure 11) we have mean concentration NO_2 = 761 mg/Nm^3 for additional air flow equal to 5 kg/s (Figure 11a), the mean value for the NO_2 concentration at the outlet section of equal 655 mg/Nm^3 to flow-10 kg/s with (Figure 11b), which is quite acceptable emission standards for NO_2, adopted by the CHP. In the proposed version the coal combustion (secondary air flow rate is 10 kg/s) decreased by 14% in comparison with the first case.Thus, it can be seen that increasing the supply air flow further reduces the average concentration of nitrogen dioxide NO_2.

Figure 12 shows the comparative distribution of average values of NO_2 concentrations by the height of combustion chamber. Analyzing the picture, you can notice that as you move out of the combustion chamber concentration of nitrogen dioxide is reduced. This is primarily due to the destruction of nitrogen dioxide NO_2 in its interaction with hydrocarbons, carbon, oxygen, etc., with a decrease in temperature in the upper layers of the gas mixture and of course decrease in these areas, the nitrogen concentration of fuel and oxidizer, which is already chemically reacted in the field below burners.

The main characteristics of heat transfer in the combustion chamber, such as the temperature T, concentration of carbon oxides (CO), nitrogen dioxide (NO_2) experiencing the greatest changes in the locations of the burners, which are supplied through the fuel (coal) and oxidant (air) [21-22]. This can be explained by the fact that of the core of torch location in the burner zone which have higher temperatures, with the most intensive chemical reactions between the constituent parts of coal and the air with maximum formation of the products of these reactions (carbon and nitrogen oxides) and maximum heat release Q_{chem}.

Conclusion

Such a pattern of behavior characteristics of heat and mass transfer process in the combustion chamber during combustion in coal-dust flame it adequately reflects the actual process of combustion occurring in the combustion chamber coal-fired thermal power plant. The comparison of calculated values of the unknown quantities and the the experimental data obtained empirically CHP showed good qualitative agreement.

The optimal combustion technology of high-energy fuel and the best structural parameters of the combustion chamber of the boiler BKZ-420 Almaty thermal power station that improve the wear resistance of power and reduce harmful emissions into the atmosphere (temperature decrease of the furnace wall, opposite the burners on the 300^{0}C, ie 17.24% and secondary reduction of carbon monoxide concentration of CO at the outlet from the furnace at 15% and nitrogen dioxide NO_2 – 14%) are obtained in present work.

In this connection it can be argued that started in the thesis of physical and mathematical, chemical and geometrical models of combustion coal-dust flame in the combustion chamber correctly reflect the aerodynamic flow and processes occurring in it heat and mass transfer. The results obtained by 3-D modeling of the processes that occur during combustion of solid fuel in the combustion chamber of real CHP (the boiler BKZ-420 Almaty CHP-2) allow the development of new technical solutions for the most efficient and clean energy production, both in existing power plants and the creation of new flue boilers.

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