Numerical experimenting of combustion in the real boiler of CHP

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***Abstract*—**Physical and chemical processes occurring in the combustion chamber are fast and complete oxidation of the fuel (in this case coal) by atmospheric oxygen. These processes occur at high temperatures, accompanied by a large energy release due to chemical reactions and the concentration of all of reacting substances. Mathematical description of the processes taking place in the steam generators, furnaces and reactors with modern computer algorithms, using computer programs allow to solve problems for specific installations.

***Keywords*—**boiler, coal, combustion, fuel, furnace, modeling, numerical research.

I. INTRODUCTION

MODERN development of heat power engineering is characterized by reduction in the use of scarce of liquid fuels, which is a valuable raw material for the petroleum refining industry and the expansion of application of solid fuels. In the last decade there has been widespread deterioration in the quality of solid fuels, due to the depletion of high-quality coal deposits. Combustion of such low-grade fuels with high ash and moisture content leads to considerable difficulties: worsening inflammation and fuel burn, slagging problems, increases mechanical underburning, increases the emission of harmful dust and gas components (ash, oxides of carbon, nitrogen and sulfur, etc.). In this regard, have developed new methods for reducing emissions by using physical models. The numerical experiment is one of the most economical and convenient way for detailed analysis and deeper understanding of complex physical and chemical processes that occur in the furnaces. Combustion of pulverized coal flame in the real world is very complicated for the mathematical analysis of physical and chemical process. The particular complexity of it differs in boiler furnaces, where the axis of the torch is curvilinear, and cold combustion chamber walls shielded cause significant gradient from the periphery to the axis of the flame temperature and all dependent on it physical parameters, which greatly complicates the average temperatures. In this case, even after all possible simplifications have to deal with two or three-dimensional mathematical problem [1]. In modeling the combustion of solid fuel in the furnace uses a variety of different models. In [2] presents the results of the study modes of chemical reactors. Describe the process of making mathematical models of reactors. This contains information on the chemical kinetics and the theory of chemical reactors, which are necessary in the preparation of the mathematical models of industrial power units. In [3] summarized the approximate physical and mathematical model of furnace process, which uses the minimum number of empirical coefficients and dependencies. In [4] justified requirements to develop mathematical models of local combustion of fuel in a diesel engine. In [5] presents the mathematical model of heat exchange and combustion of pulverized coal in the combustion chamber of power boiler, which is based on the model adopted by the non-isothermal incompressible multicomponent gas.

II. PROBLEM FORMULATION

When considering the heat transfer processes in technical reacting flows in combustion chamber of the heat exchange by radiation makes the largest contribution to the total heat transfer. In the flame zone contribution of radiative heat transfer of up to 90% or more [6].Therefore, modeling of heat transfer by radiation in the reacting flow in the combustion chambers is one of the most important steps in the calculation of heat exchange processes in real combustion chamber.

III. MATHEMATICAL MODEL

In general, at a temperature above absolute zero radiates, absorbs and reflects the electromagnetic waves of different frequencies. These frequencies, which are radiative heat transfer material to be driven by the

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characteristics of the substance and its temperature. When modeling technical trends in the temperature range 500-2000 K is only meaningful exchange of radiation in the infrared and in the visible region [7]. The mathematical description of radiative heat transfer is generally allocated a region of space in which the fluid moves. The walls of this space and the material contained in it, absorb and emit radiation in the infrared and visible regions.

Quantities' characterizing the radiation heat transfer is the spectral intensity, which is defined by the following equation:

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

$\Delta E_{\nu,\Theta}$ - here the radiant energy at a frequency ν, emitted from the element of area ΔA, at the solid angle $\Delta\Omega$, in a direction determined by the cosine of the angle Θ (Fig.1).

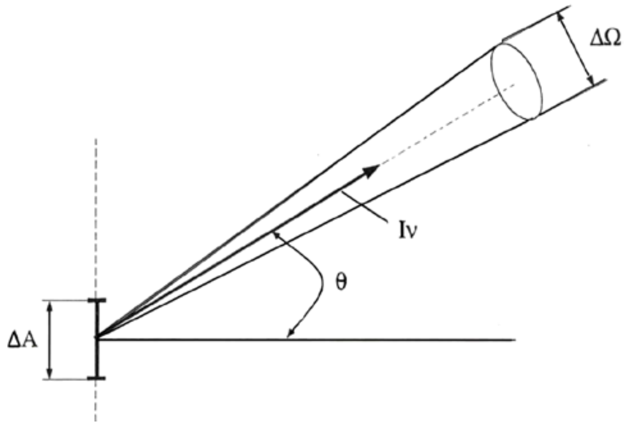


Fig. 1 Determination of the spectral intensity

In emitting, absorbing and scattering environment, the intensity of radiation decreases due to absorption and scattering, and is enhanced by the receipt of the radiant energy from the environment. Scattering is due to both a reflection and a result of diffraction of electromagnetic waves.

Changing in the intensity of the beam of rays is due to the fact that some of the rays changes direction.

Distinguish in the space of an infinitesimal element of length ds. Write the equation of energy balance of radiation. As we take the transport variable intensity of I_ν. In general, this equation is:

$$\underbrace{\frac{1}{c} \cdot \frac{\partial I_\nu}{\partial t}}_{I} + \underbrace{\frac{\partial I_\nu}{\partial s}}_{II} = \\ - \underbrace{\left(K_{abs,\nu} + K_{sca,\nu} \right) \cdot I_\nu}_{III} + \underbrace{K_{abs,\nu} \cdot I_\nu}_{IV} \\ + \underbrace{\frac{K_{sca,\nu}}{4\pi} \cdot \int_{4\pi} \left(P\left(\Omega_i \to \Omega\right) \cdot I_\nu\left(\Omega_i\right)\right) d\Omega_i}_{V} \quad (1)$$

We describe the value of each of the members of the equation above: c - speed of light,

I - change of intensity over time;

The process of heat transfer by radiation is considered to be quasi-stationary. In addition, as the speed of light is large, the change of intensity over time:

$$\frac{1}{c} \cdot \frac{\partial I_\nu}{\partial t} \to 0 \quad (2)$$

II - intensity distribution along the infinitesimal element ds;

III - reduction of intensity along the element ds, due to the absorption and dispersion of the direction $\Delta\Omega$ in other directions;

IV - increased of intensity along the element ds, due to its own emission of radiation protection in the direction of $\Delta\Omega$;

V - Increase of intensity along the element ds, due to the inflow of radiation energy from all directions.

In the balance of radiant energy (1) assumes that came thermodynamic equilibrium. This means that, according to Kirchhoff's Law, absorption and emission coefficients are equal. We also assume that all the surfaces and volumes involved in the radiant heat transfer are considered gray emitters.

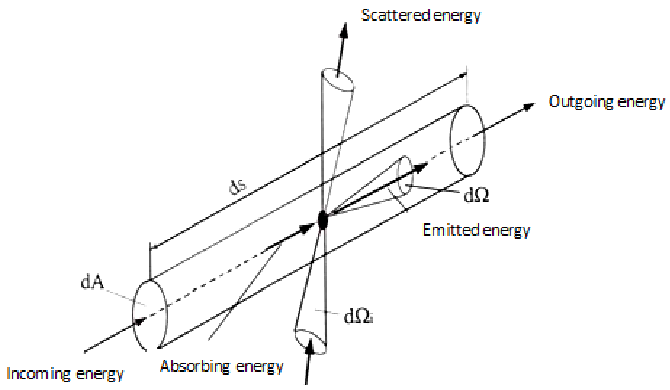


Fig. 2 Change of intensity along the element *ds*

We use the following expression for the calculation of the integrated intensity of the radiation and integrated optical coefficients, which will help to simplify the integral-differential equation (1):

$$I = \int_0^\infty I_\nu d\nu,$$

$$K_{abs} = \int_0^\infty K_{abs,\nu} d\nu$$

$$K_{sca} = \int_0^\infty K_{sca,\nu} d\nu \tag{3}$$

K_{abs} and K_{sca} - optical coefficients of absorption and scattering.

According to Planck's law of black body radiation intensity, we have:

$$I_b = \int_0^\infty I_{b,\nu} d\nu = \frac{\sigma}{\pi}\cdot T^4 \tag{4}$$

Where $\sigma = 5.67 \cdot 10^{-8}$ W/m$^2 \cdot$ K^4 – Stefan-Boltzmann's constant.

Thus, we obtain the energy transfer radiation equation:

$$\frac{\partial I_\nu}{\partial s} = -\left(K_{abs} + K_{sca}\right)\cdot I_\nu + K_{abs}\cdot\frac{\sigma}{\pi}T^4 + \underbrace{+\frac{K_{sca}}{4\pi}\cdot\int_{4\pi}\left(P\left(\Omega_i \to \Omega\right)\cdot I_\nu\left(\Omega_i\right)\right)d\Omega_i}_{V} \tag{5}$$

Change of the intensity of the radiation energy along the element *ds* is the sum of its attenuation due to absorption and scattering, gain from its own emissions and increasing the influx of energy from other directions.

Rigorous mathematical description of the processes taking place in the steam generators, furnaces and reactors together with modern computational algorithms using computer programs allow us to solve these problems for specific power plants. Such computing field experiments allow flexibility to intervene in the process of combustion at any stage, and change the design features of the device, practicing individual technical solutions without the high cost.

For the application of mathematical modelling is necessary to have a reasonably accurate and substantial information about the the physical and kinetic parameters, patterns of physical and chemical phenomena in conditions close to real as well.

Solid equipment can have a significant impact on the convective and diffusive transport in streams with high solids content. The presence of solids in the unburned gases from the combustion chamber slightly (except near the burner), and the effect of the second phase of the calculations can be neglected [8] and the combustion of pulverized coal in the combustion chamber can be described as a two-phase flame gas-dispersed system, and the effect of solid phase on aerodynamics for significant [9].

In this model, we take the heat transfer between particles and gas by radiation. The influence of the solid phase to the coefficients of turbulent exchange using the following empirical relationship:

$$\Gamma_{P,\,eff} = \frac{\mu_{P,eff}}{\sigma_{P,turb}} = \frac{\mu_{eff}}{\sigma_{P,turb}}\left(1 + \frac{\rho_P}{\rho_G}\right)^{-1/2} \tag{6}$$

For turbulent viscosity considering solid particles we use the following expression:

$$\mu_{P,\,eff} = \mu_{G,eff}\left(1 + \frac{\rho_P}{\rho_G}\right)^{1/2} \tag{7}$$

For the turbulent Prandtl-Schmidt numbers considering particles selected the following numerical values: $\sigma_{P,turb} = 0.7$.

Share contributed by the gas and solid particles, described by the sum:

$$K_{abs} = K_{abs,G} + \sum K_{abs,P,k} \tag{8}$$

Here, to simplify the model of radiation is assumed that the emission band of the two gases completely overlaps, and mass factors and the specific absorption rate depend on the temperature of the gas. Then the absorption coefficient, we have the following relation

$$K_{abs,G} = a_{CO_2}\cdot k^*_{CO_2}\cdot p_{CO_2} + a_{H_2O}\cdot k^*_{H_2O}\cdot p_{H_2O} \tag{9}$$

The values of the mass coefficient and the coefficient of absorption of radiation by water vapor and carbon dioxide used in this study are presented in Table 2.

Table I

The mass coefficient and the coefficient of absorption of radiation

β component	a_β [1]	k^*_β,

		$[1/(m \cdot bar)]$
CO_2	$0.275\text{-}8.4\ 10^{-5} \cdot T_G$	$85.0 \cdot T_G^{-0,33}$
H_2O	$7.2 \cdot T_G^{-0.4}$	$1100 \cdot T_G^{-0.82}$

When modeling the reacting flows, containing substances in the solid phase, it is necessary to take into account that the effect of solid particles on the radiative heat transfer can be several times greater than that of components in the gas phase (water vapor and carbon dioxide). Considering solid phase absorption and emission coefficients can be written as:

$$K_{abs,P,k} = X_{abs} \cdot \tilde{n}_{P,k} \cdot d_{P,k}^2 \cdot \frac{\pi}{4},$$

$$K_{Sca,P,k} = X_{Str} \cdot \tilde{n}_{P,k} \cdot d_{P,k}^2 \cdot \frac{\pi}{4}. \tag{11}$$

Where $\tilde{n}_{P,k}$ - the number of particles in a volume element. Coefficients X_{abs} and X_{Sca} are defined experimentally and for the pulverized coal flame has the values: X_{abs} = 0,85 and X_{Sca} = 0,15. These values were found for the coefficients of scattering $a_{Sca} > 30$:

$$a_{Sca} = \frac{\pi \cdot d_P}{\lambda_{Sca}} \tag{12}$$

The wavelengths correspond to 21 microns of $dP > 200$ microns, the average length of a wave up to 3 microns corresponds $dP > 29$ microns. Therefore, the ratio is really not for the entire range of particle sizes. According to an error that occurred when receiving the resultant values are neglected. In the radiation model we shall consider only the forward scattering is in good approximation is permissible in pulverized-coal flames. Thus, the scattering does not lead to a weakening of the intensity and subsequently ignored.

IV. SETTING A GEOMETRIC MODEL

The boiler BKZ-160 Almaty CHP has the П-shaped profile with a rectangular prismatic combustion chamber (Figure 3), the size of which: 6.565x7.168x21.0 (m^3). It is equipped with six boilers, each has a steam capacity of 160 t/h.

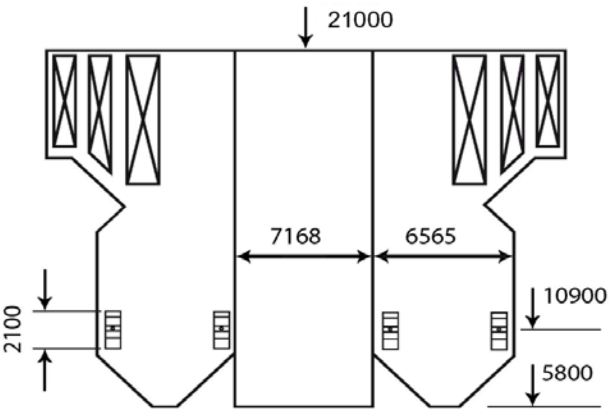


Fig. 3 Scheme of the boiler BKZ -160

Boilers BKZ-160 manufactured at the Barnaul boiler plant, they have at the bottom of a cold funnel to remove slag, and an individual system for the preparation of coal dust holding bins of two ball mill drum. The burner has a single channel for aero mixture and two channels for the secondary air, the top and bottom of the channel and separated aeromixture lined piers. After each burner comes 3.787 t/h coal dust, and the performance of the boiler as a whole at rated load is 30 t/h. Consumption of secondary air flow through the burner is V = 6000 nm^3/h. At the exit of the burner it has a speed of 40 m/s and temperature 380 ^{0}C. Aeromixture temperature at the exit of the burner is 250 ^{0}C, and its rate of 25 m/s, so rate of ratio of secondary and primary air in the burners equal to 1.64, excess air ratio in burners is 0.68, and the output of the furnace is 1.27.

The physical model of the combustion chamber is built in full compliance with the reflecting actual process of burning coal, which is carried out directly in the combustion chamber of the boiler BKZ-160 Almaty CHP. Were set all parameters (fuel, its characteristics, methods and speed of the fuel and oxidant capacity of power plant, the parameters of coal, its composition, temperature of aeromixture, primary, secondary and tertiary air, etc.). This recorded in the built physical and geometrical models of the combustion chamber.

Table II

Characteristics of combustion chamber of boiler BKZ-160

№	Name, characteristics, Dimension	Designation	Value
1.	Fuel consumption for boiler, t/h	B	30
2.	Fuel consumption on the burner, kg/h	$B^{\Gamma}=B/Z$	3.787
4.	Combustion heat, MJ/kg	Q_H^p	12.2
5.	Volatile, %	V^F	32
6.	Diameter of coal particles, m*10^{-6}	d^{par}	60
7.	Excess air coefficient at the outlet of the furnace	αm	1.27
8.	Excess air coefficient in the burners	$\alpha г$	0.68
9	Air suction into the furnace	$\Delta\alpha$	40
10.	Temperature of air mixture, К	T_a	250
11.	Temperature of the secondary air, К	T_2	380
12	Tertiary air temperature, К	T_3	380
13.	Type of used burners	*Slotted*	
14.	Number of burners, pcs	n_B	8
15.	Number of tiers, pcs	N	2
16.	The height of combustion chamber, m	$z(H)$	21.000
17.	The width of combustion chamber, m	Y	6.565
18.	The depth of combustion chamber, m	X	7.168
19.	The rate of the primary air (air mixture), m/s	W_1	25
20.	The rate of the secondary air (air mixture), m/s	W_2	40
21.	Flow rate of secondary air, nm^3/h		6000
22.	Excess coefficient of secondary air		0.38
23.	Flow rate of primary air, nm^3/h		4850
24.	Excess coefficient of primary air		0.3

Composition of coal

BKZ-160, Ekibastuz coal, %	W	A	C	H	O	N	S
	5.8	39.7	55.7	5.52	11.96	1.44	1.32

Computational experiments on the combustion chamber of boiler PK-39 were also carried out in [10]. The use of a modern software for the creation of the computational domain is not allowed to apply the restrictions that were imposed on the computational domain in [10]. Creating the database for simulation is carried out in several stages, with the program complex PREPROZ [11]. In the generated files contain geometric data of researched process, the initial and boundary conditions for the simulation of heat and mass transfer in reacting flows. PREPROZ created using basic files containing background information, which are then used in the software package FLOREAN [12, 13]. This computer software package allows for complex computational experiments to simulate reacting multiphase flows in the areas of real geometry.

When creating a geometric model, each wall of the combustion chamber is described separately in the form of numerical codes. First entered the walls of their corner points. Input and output are set primarily as a type of holes and then are set the coordinates of the spatial position of burners on certain walls. Hole of burner (log) described in the form of concentric circles (for round burners), yield - in a rectangle with the corresponding coordinates in the space. In [10], due to the limitations imposed by creating a geometric model, circular holes were replaced with an equal rectangular area, which also affected the accuracy of the calculations In accordance with a given geometry of the lattice is created for numerical simulation (Figure 1). In the process of creating the final version of the computational domain, the grid has repeatedly edited in order to create the most optimal variant for further calculations of physical processes in the furnace volume. At our option for lattice computing experiments established the size 27x61x60 which contains 98820 control volumes. In [10] the computational experiments were carried out for 21 648 control volumes (estimated grid 16x33x41). The ability to reduce the control volume, especially in the region of the burners allows you to get a more accurate result. In this case, thanks to an improved computer model, by which all numerical experiments were carried out in this thesis, the calculation time increases slightly.

This is the description of the physical model the investigated combustion chamber of the boiler BKZ-160, a common form of and its broken down control volumes for the computational experiments which are presented in Figure 4.

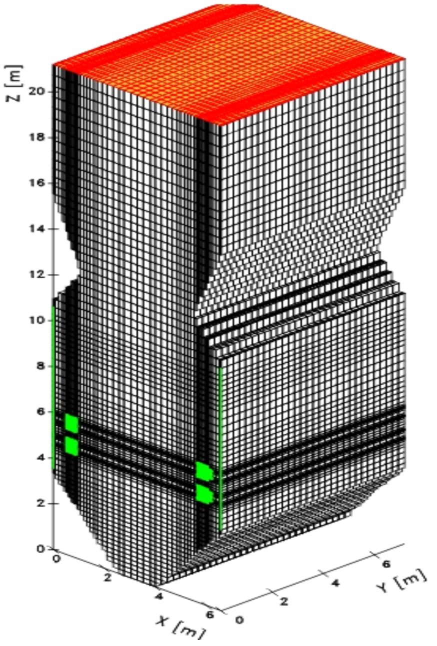
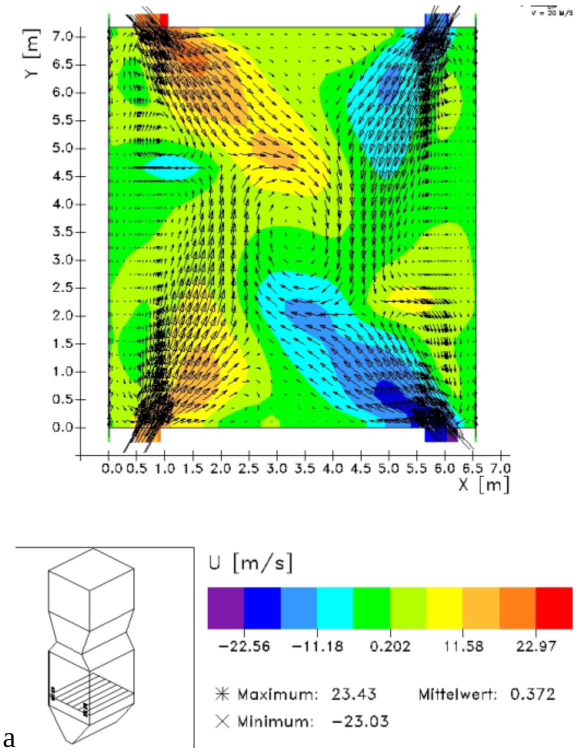


Fig. 4 Common form of boiler and its broken down control volumes for the computational experiments

I. RESULTS OF NUMERICAL RESEARCH

Below shows the results of the 3D modelling of burning of solid fuel (coal) in the combustion chamber.



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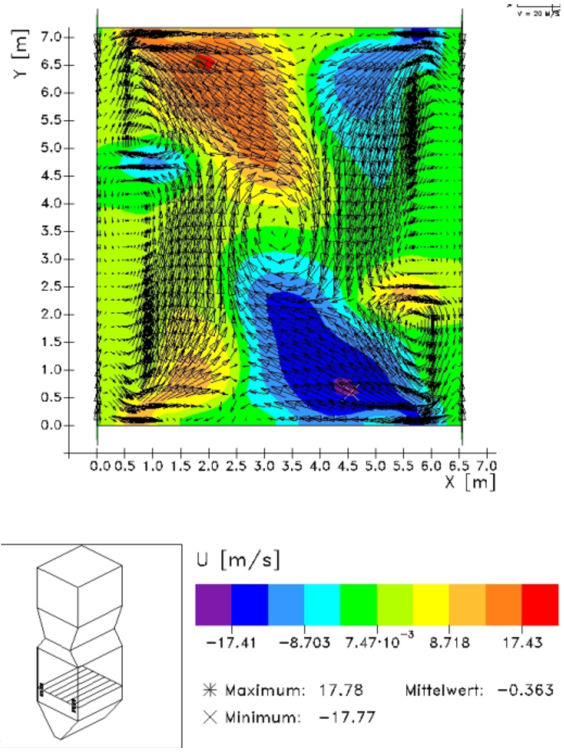

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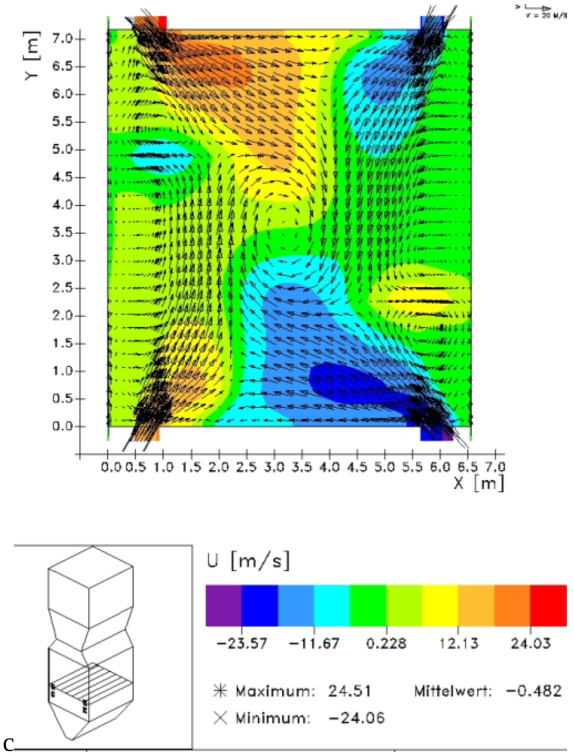

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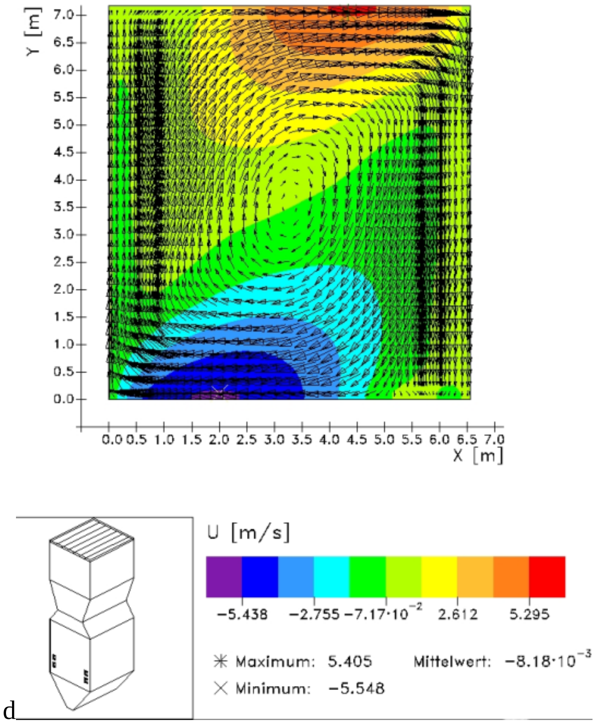
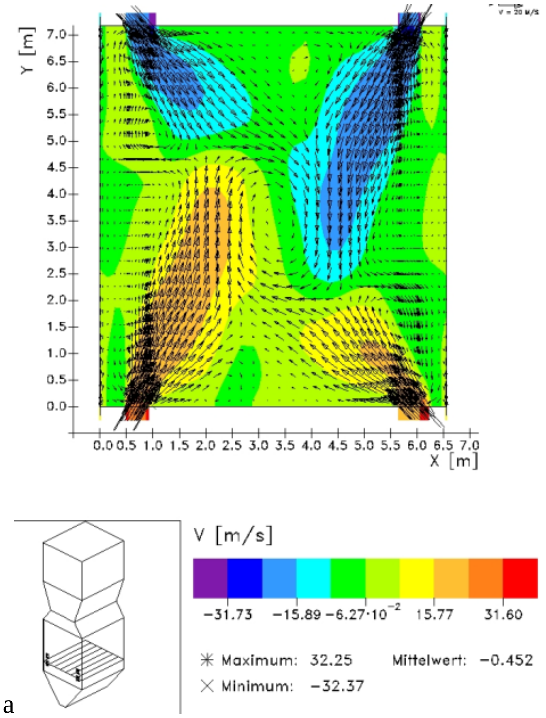


d

Fig. 5 (a, b, c, d) – Distribution of U-component of the vector of full speed in different sections of the investigated sections of combustion chamber

Figure 5 clearly shows the aerodynamic flow pattern of a mixture of pulverized coal flow through the tangential burner. Analysis of Figures 5 - 7 shows that using tangential flow of pulverized coal mixture in the center section formed vortex flow, causing the fuel burns completely due to a long stay in the maximum temperatures. This in turn reduces the mechanical nedozheg and solves the problem of slagging.



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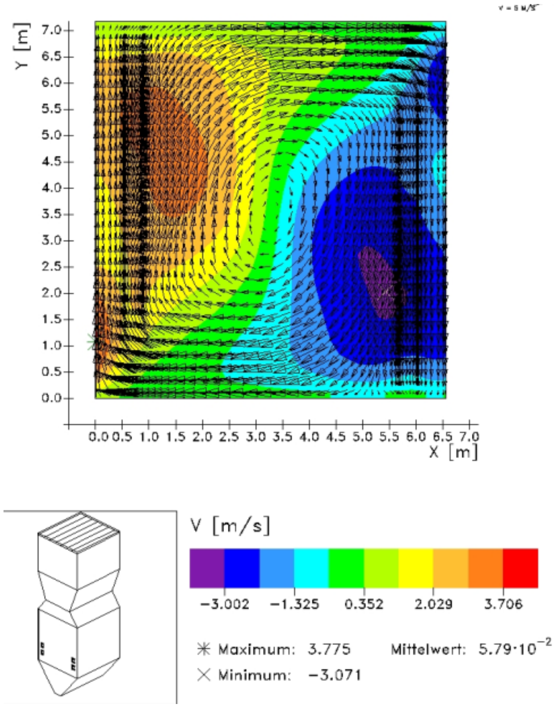
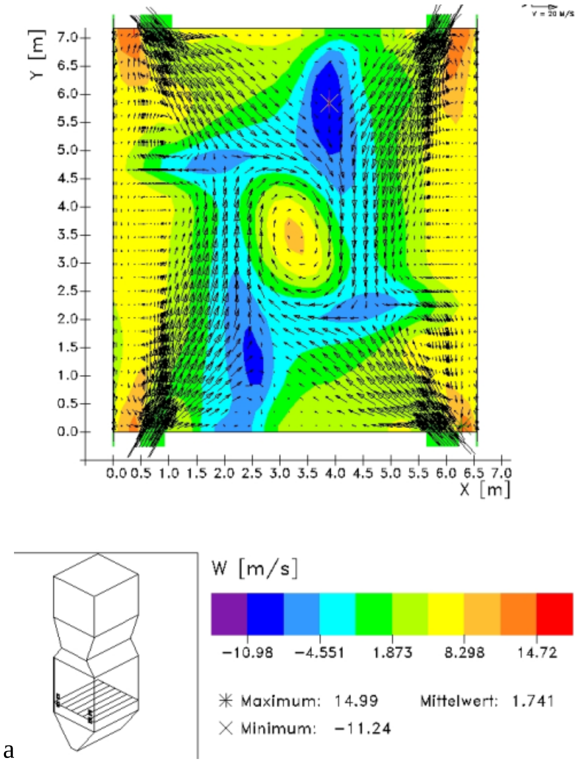


Fig. 6 (a, b) – Distribution of V-component of the vector of full speed in the burner section and in upper section of investigated combustion chamber



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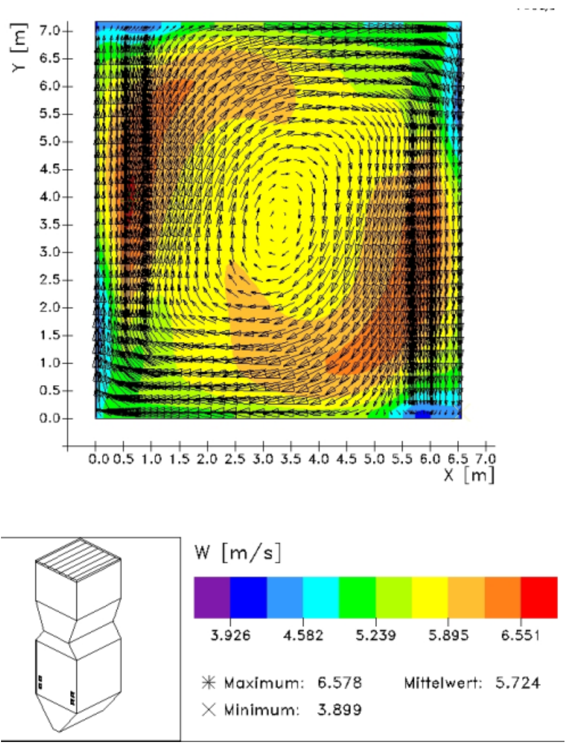
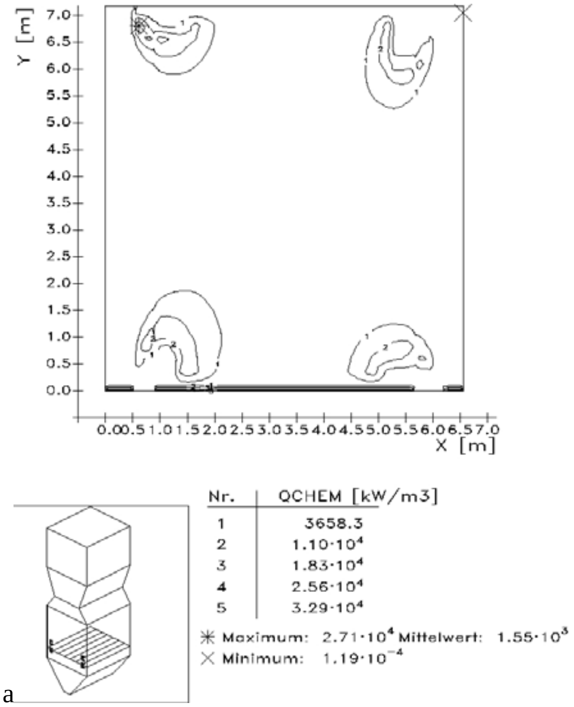


Fig. 7 (a, b) – Distribution of W-component of the vector of full speed in the burner section and in the upper section of investigated combustion chamber

In addition, as a result of the computational experiments obtained isosurface distribution of chemical energy, shown in Figure 8.



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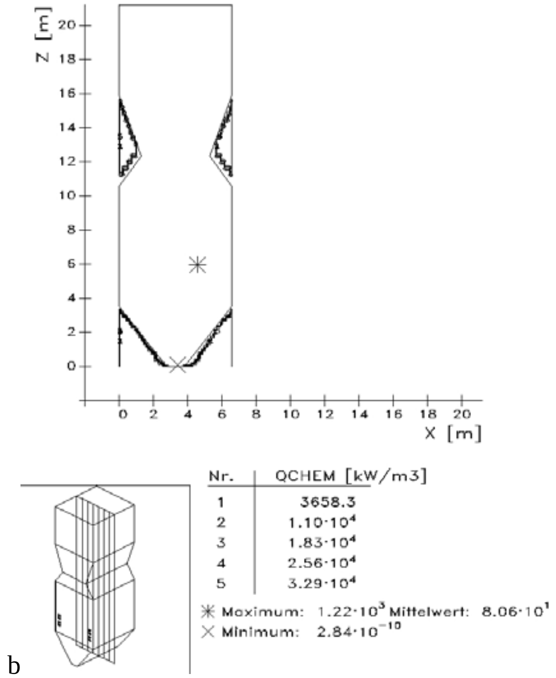

Fig. 8 (a, b) – Isosurfaces of energy distribution of chemical reaction

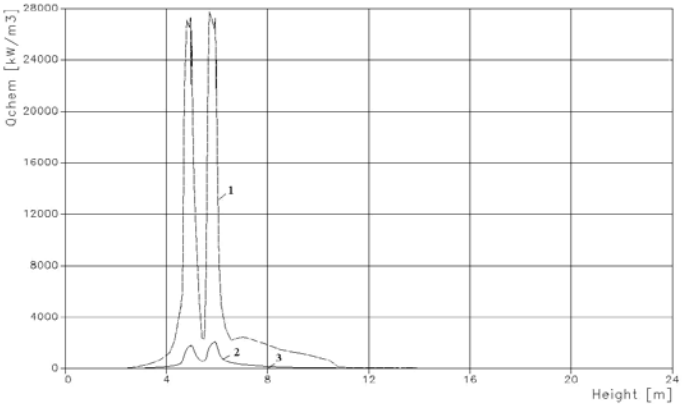

Fig. 9 – The distribution of chemical energy Q_{chem} by the height of the combustion chamber
1 -maximal; 2 - medium; 3 – minimal values Q_{chem} at the cross section of combustion chamber

Figure 9 shows the distribution of energy released or absorbed due to leakage in the combustion chamber of chemical reactions between the components of coal and air. As expected, the maximum intensity of chemical reactions occurs in the central part of the combustion chamber, precisely in the area of the burners. The thermal energy which is released due to chemical reactions of oxidation of hydrogen to carbon oxides leads to the fact that in the area where there is the highest concentration of carbon, hydrogen and oxygen, we observe the maximum of chemical energy Q_{chem}.
According to the pictures can be seen that there are two maximum values of Q_{chem}. which corresponds to two tiers of burning holes through which fuel and oxidant are supplied and where the concentration of substances entering into chemical interaction is maximized.

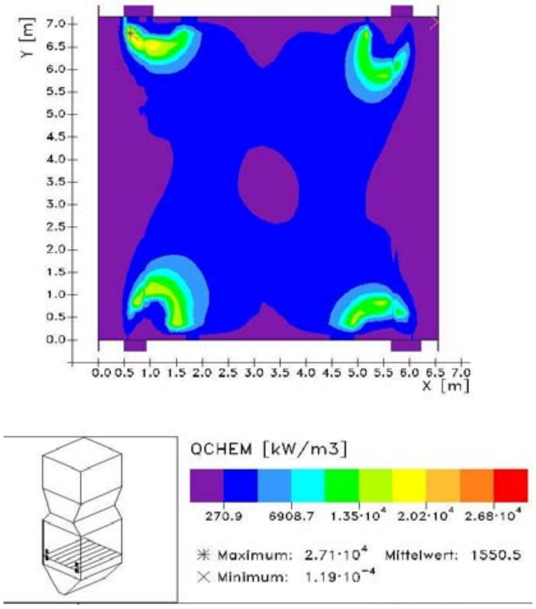

Fig. 10 – The distribution of the chemical energy Q_{chem} in cross section of combustion chamber at the lower tier of burners

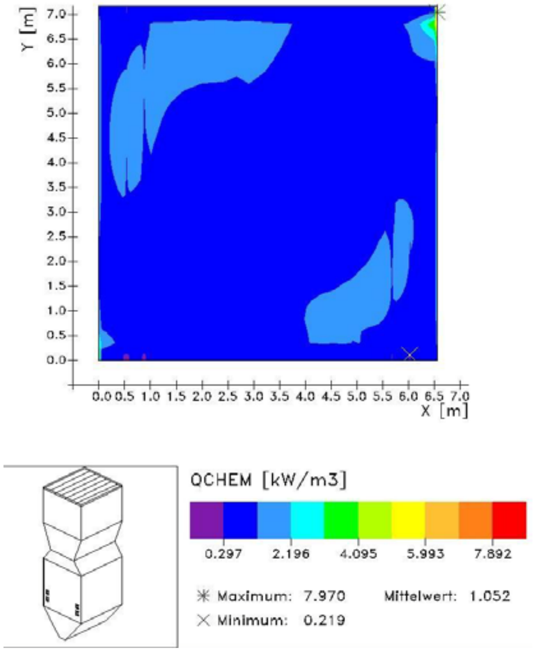

Fig. 11 – The distribution of chemical energy Q_{chem} at the outlet of the combustion chamber

Figures 10-11 shows that the motion to the exit from the combustion chamber the energy released due to the processes of chemical interaction is reduced.

In Figure 8-11 clearly seen areas where take place the most intense chemical reaction of combustion. The resulting curves of distribution of the energy released during the flow of the chemical reaction between the fuel (coal) and an oxidant (air), allow us to determine its numerical value at any point in the combustion chamber boiler BKZ-160 Almaty CHP.

V. CONCLUSION

The results obtained in this work allows to do conclusion that in location area burners has a vortex flow caused by the location of burners and pulverized way of giving vortex flow in the combustion chamber. The presence of the vortex motion provides a more rapid ignition and flame stabilization. Hot gases are swept into the torch, heat the fuel mixture and intensify inflammation. Active ascending currents are also busy area near the walls of the furnace, which in its turn has an impact on the convective component of the heat in the combustion chamber. Amplified heat and mass transfer in a vortex intensifies burnup of coal particles. At the same time can achieve uniform heating of the combustion chamber surfaces and reduce their slagging that extends the hardware [14]. By circulating particles in the vortex torch burning occurs with sufficient fullness, even coarse grind, which can significantly extend the range of use of pulverized coal.

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