Computational research of burning coal in the real boiler of Almaty CHP

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***Abstract*—**the tendency of development of fuel-energy sector of Kazakhstan at the present stage imposes strict requirements for the use of energy sources. In this case the important thing is the development of the "clean" coal combustion with the smallest possible emission of harmful substances, and therefore it is need to optimize all the constructive and operational parameters of the process.

***Keywords*—**boiler; combustion; emission; flow; fuel; heat- and mass transfer; 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.).

II. Ease of Use

A. Modeling of radiative heat transfer

When considering the heat transfer processes in technical reacting flows in combustion chambers 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 [1].Therefore, modelling 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.

In general, at a temperature above absolute zero radiates, absorbs and reflects the electromagnetic waves of different frequencies. This frequency, which is radiative heat transfer material to be driven by the 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 [2]. 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).

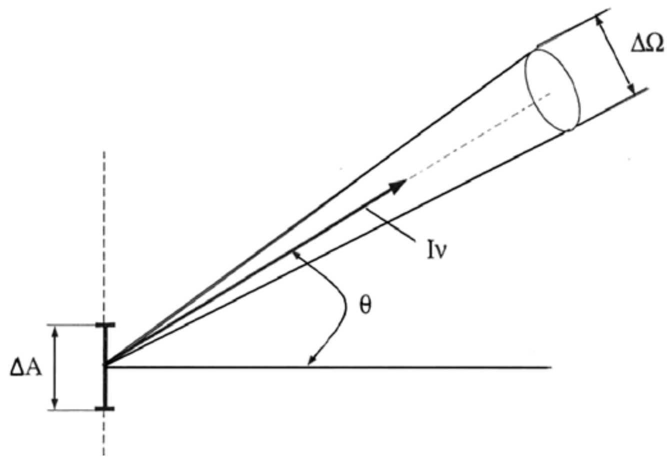


Fig. 1. Determination of the spectral intensity

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:

$$\underbrace{\frac{1}{c}\cdot\frac{\partial I_\nu}{\partial t}}_{I}+\underbrace{\frac{\partial I_\nu}{\partial s}}_{II}=\underbrace{-\left(K_{abs,\nu}+K_{sca,\nu}\right)\cdot I_\nu}_{III}$$

$$+\underbrace{K_{abs,\nu}\cdot I_\nu}_{IV}+\underbrace{\frac{K_{sca,\nu}}{4\pi}\cdot\int_{4\pi}\left(P\left(\Omega_i\to\Omega\right)\cdot I_\nu\left(\Omega_i\right)\right)d\Omega_i}_{V} \quad (1)$$

Here, c - speed of light, I - the 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 *ΔΩ* in other directions;

IV - increased of intensity along the element *ds*, due to its own emission of radiation protection in the direction of *ΔΩ*;

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

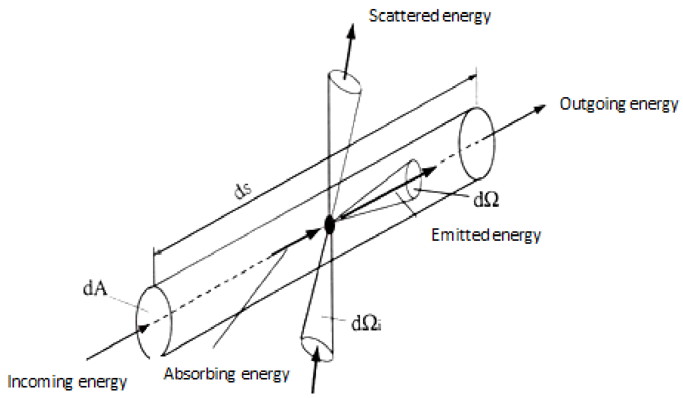


Fig. 2. Change of intensity along the element *ds*

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. 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 integro-differential equation (1):

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

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

$$K_{sca}=\int_0^\infty K_{sca,\nu}d\nu \quad (3)$$

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

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

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

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:

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

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 a 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 [3] 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 [4].

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:

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

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

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

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:

$$K_{abs} = K_{abs,G} + \sum K_{abs,P,k} \quad (8)$$

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

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

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 1.

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	$7.2 \cdot T_G^{-0.4}$	$1100 \cdot T_G^{-0.82}$

B. *Construction of a physical and geometrical model of combustion chamber*

The boiler has a Π-shaped profile with a rectangular prism combustion chamber (Figure 3) the size of which: 6.565x7.168x21.0 (m^3).

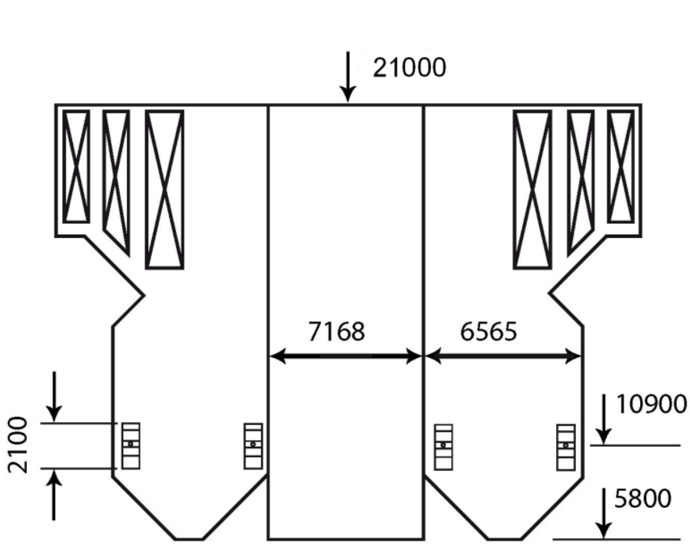


Fig. 3. Layout of the combustion chamber of the boiler BKZ-160

The boiler BKZ-160 Almaty CHP has the Π-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.

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 [5].

On the sides of the combustion chamber there are eight slit dust and gas burners, combined into four blocks (2 burners in each unit), double decker burner (Figure 3).

Arrangement of the burners on the boiler - angular, by tangentially scheme where direct flow burner set at a tangent to the circle of diameter 0.1-0.3 on the depth of the furnace (there are about 60 mm).

Temperature of an aeromixture at the outlet of the burner is equal to 2500 C, and its speed of 25 m/s, i.e. speed ratio of the primary and secondary air in the burners is 1.64, the excess air ratio in the burners is 0.68 and at the exit from the furnace is 1.27. This is the description of the physical model of investigated combustion chamber of the boiler BKZ-160, a common form of which, and its breakdown to control volumes for computational experiments [6-8] are shown in Figure 4.

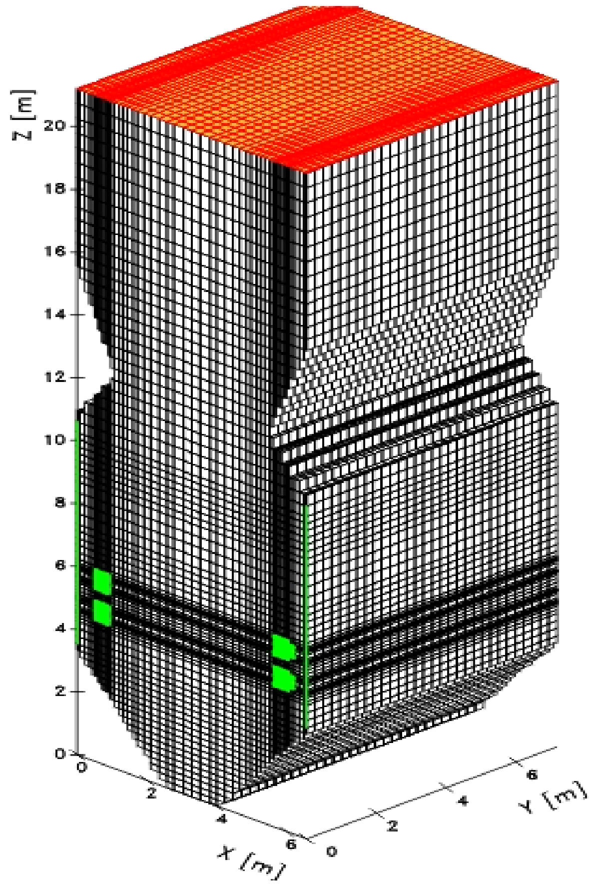


Fig. 4. Common form of boiler and its broken down control volumes for the computational experiments

In Table 2 shows the main characteristics of combustion chamber of the boiler BKZ-160 Almaty CHP

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^{p}_{H}	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	αz	0.68
9	Air suction into the furnace	$\Delta\alpha$	40
10.	Temperature of air mixture, K	T_a	250
11.	Temperature of the secondary air, K	T_2	380
12	Tertiary air temperature, K	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

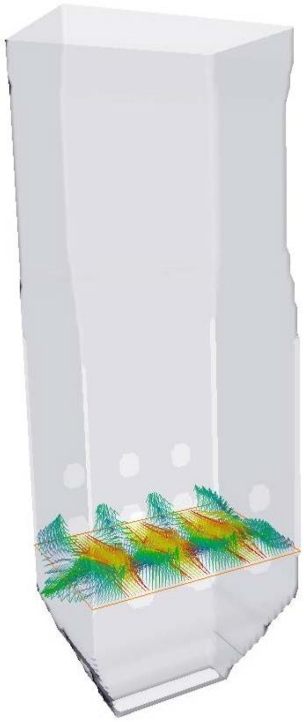
Composition of coal							
BKZ-160, Ekibastuz coal, %	W	A	C	H	O	N	S
	5.8	39.7	55.7	5.52	11.96	1.44	1.32

The physical model of the combustion chamber is constructed in full accordance with Table 2, which reflects the actual process of burning coal, which is carried out directly in the combustion chamber of BKZ-160 Almaty CHP.

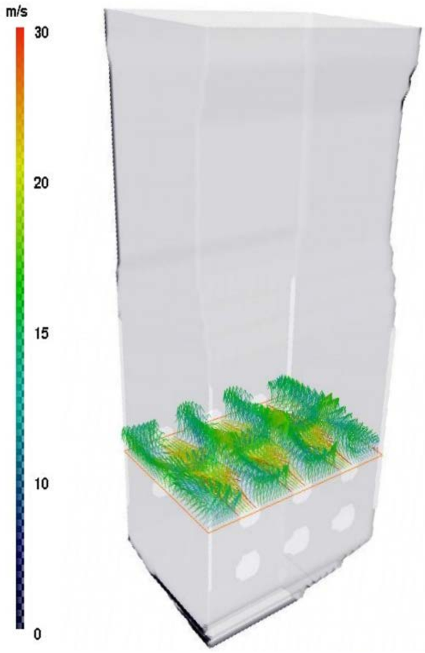
C. Determination of the main characteristics of burning process by computational method

During performance of the work were calculated field of the full speed vector over the entire volume of the combustion chamber. Figures 8-11 presented full speed vector field in three-dimensional image for various sections of the combustion chamber.

Obtained velocity fields can visually analyze the motion of the reacting flow in the combustion chamber in the various sections.



a) section Z = 7,32 m

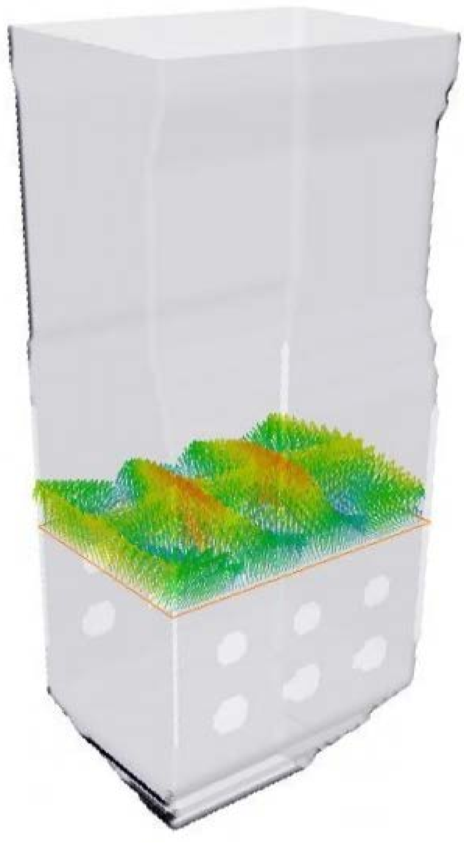


b) section Z = 10.12 m

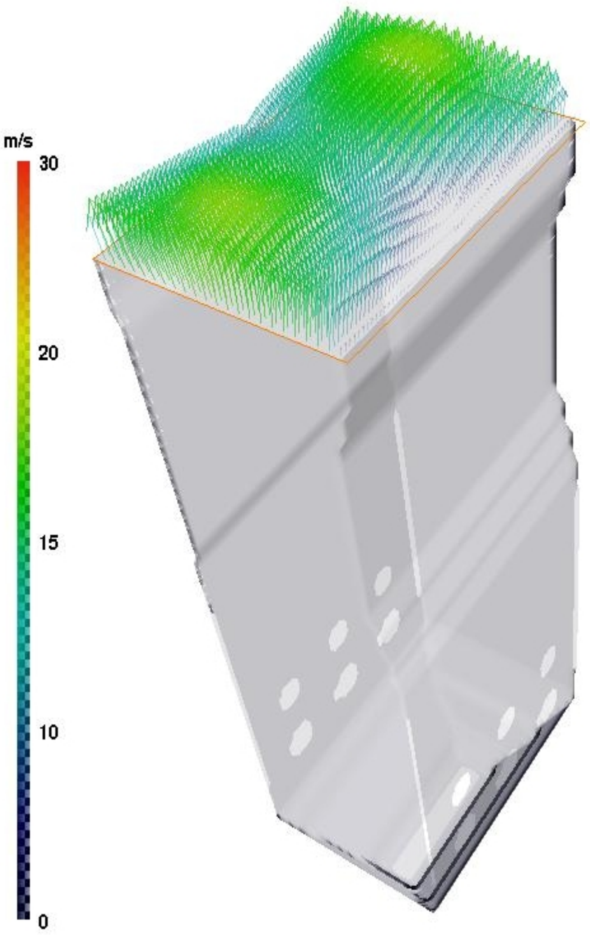
Fig. 5. Three-dimensional vector field of full speed at the sections of burners

At the end of the burner gas jets ejected from the environment, causing them to flow rate increases. At the same initial amounts of motion counter flows collide in the center of the furnace at almost the same speed in them. Swirling stream, supplying fuel through the burner counter located in the plane (XY) when Z = 7,32 m (Figure 5 a) and Z = 10,12 m (Figure 5 b) create the volumetric vorticity of the flow in the central region of combustor. In the field of burners flow is almost horizontal, and as upward movement angle of elevation increases. In the corners of the furnace due to the direct impact on the chamber wall the flow spreads, and its angle of elevation increases.

Part of the flow directed at a small angle downward, developing into two vortices (Figures 5-6). Due to intensive vortex motion dust and gas flows inside the combustion chamber significantly increases the residence time of the fuel particles in the furnace, which allows for more complete combustion, and is technically possible to use coal dust of larger fractions.



a) in an arbitrary cross section Z = 12.50 m

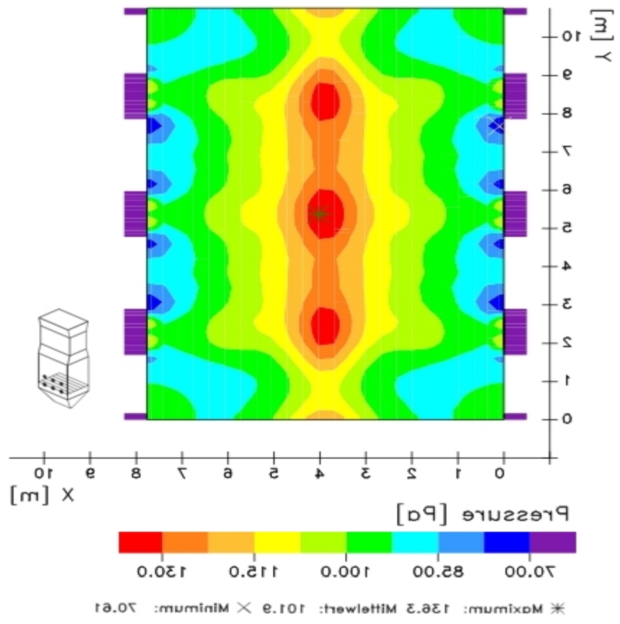


b) at the chamber outlet Z = 29.79 m

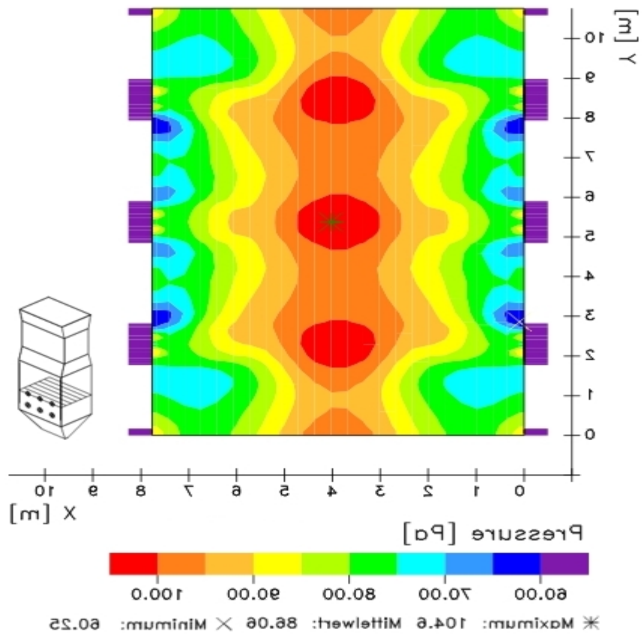
Fig, 6. Three-dimensional vector field of full speed

Thus, the maximum convective transport in consideration physical models observed in a mixture of pulverized coal flow in the plane of symmetry of the furnace depth. The nature of the velocity distribution in the volume of the combustion chamber characterizes the established pattern in the chamber: the most intense burning is observed in the central part of the furnace.

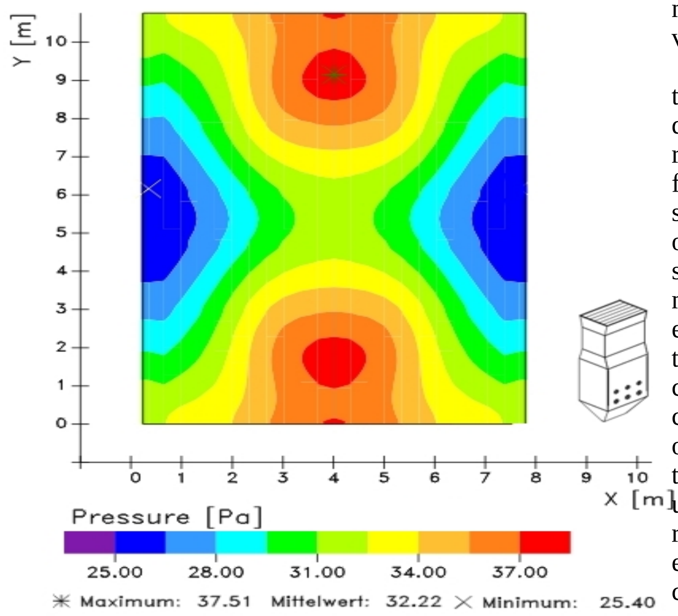
As a result of computational experiments were also obtained distribution of pressure values (Figure 7) calculated for each value of Z = const.



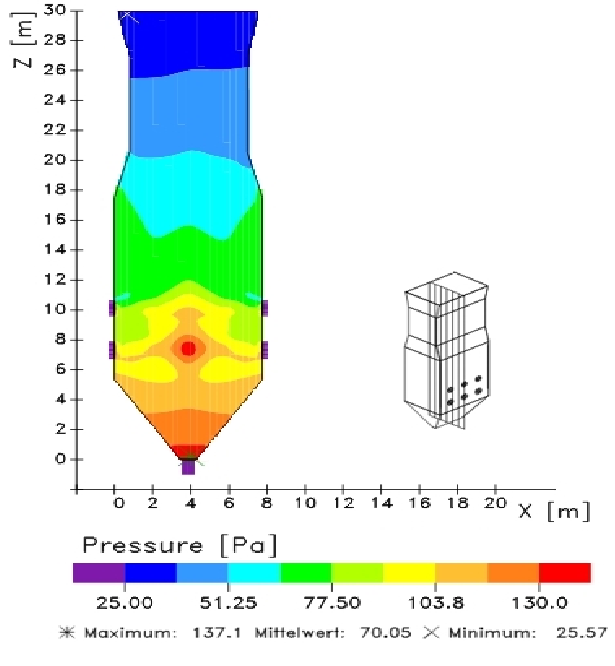
a) section Z = 7.32 m



c) section Z = 10.12 m



d) section Y = 5.38 m



d) section Z = 29.79 m

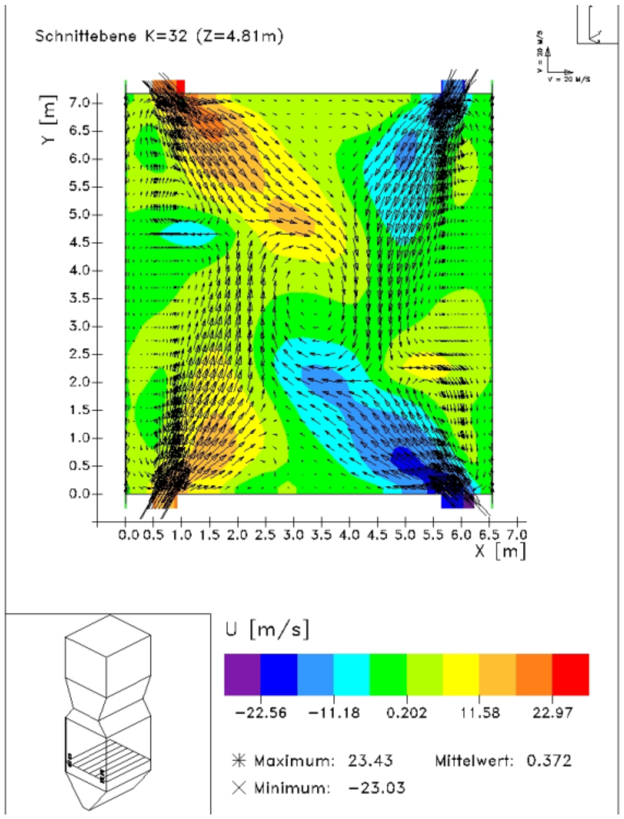
Fig. 7. Distribution of pressure in the combustion chamber at the various sections

As seen in figure 7, the strongest change in pressure occurs in the region of the burner, i.e. of fuel and oxidant. As we move away from this area burner pressure decreases monotonically and the output value is the estimated average value of P ~ 25.4 Pa.

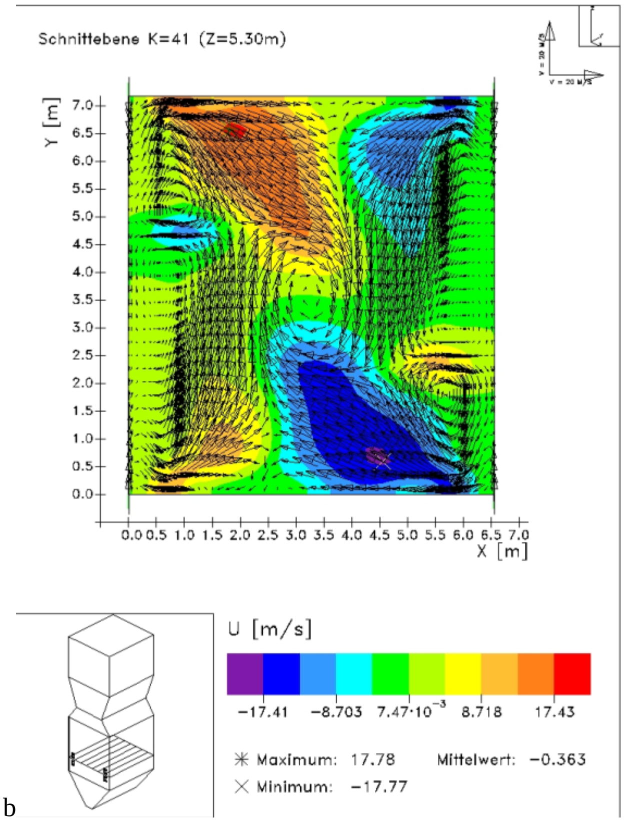
Realized numerical study of aerodynamic characteristics of the combustion process in the combustion chamber demonstrated the complexity of the ongoing process. The results suggest that in the area of the burners were a vortex flow due to the location of burners and the vortex method of supplying coal dust flows into the combustion space. Presence of vortex motion provides a rapid ignition and flame stabilization. Hot gases are swept into the torch, heat the fuel mixture and intensified ignition. Active updrafts are also engaged areas near the furnace wall, which in its turn affects the convective component of the heat in the combustion chamber. Nature of the motion of the vortex flow inside the combustion chamber leads to increase ignition of flame at the output of the burner; and enhanced heat and mass transfer in the vortex intensifies burning. In this case manages to achieve uniform heating of the combustion chamber surfaces and reduce their slagging that prolongates validity period of equipment. Due to the circulation of particles in a vortex flame combustion occurs with sufficient completeness, even with rough grinding, which can significantly extend the range used by coal dust.

D. *Results of 3D modeling*

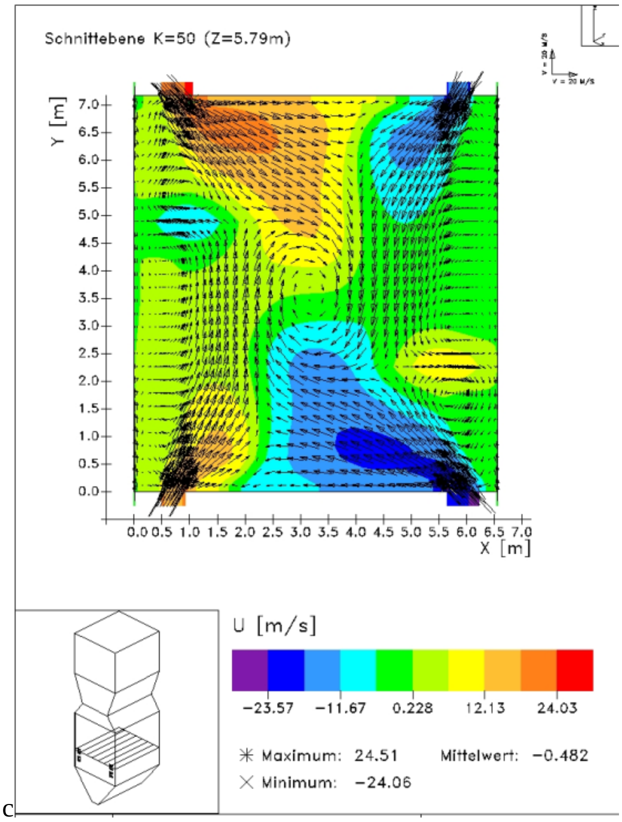
Below presented results of 3-D modeling [10] of solid fuel (coal) combustion processes in the combustion chamber of the constructed model.



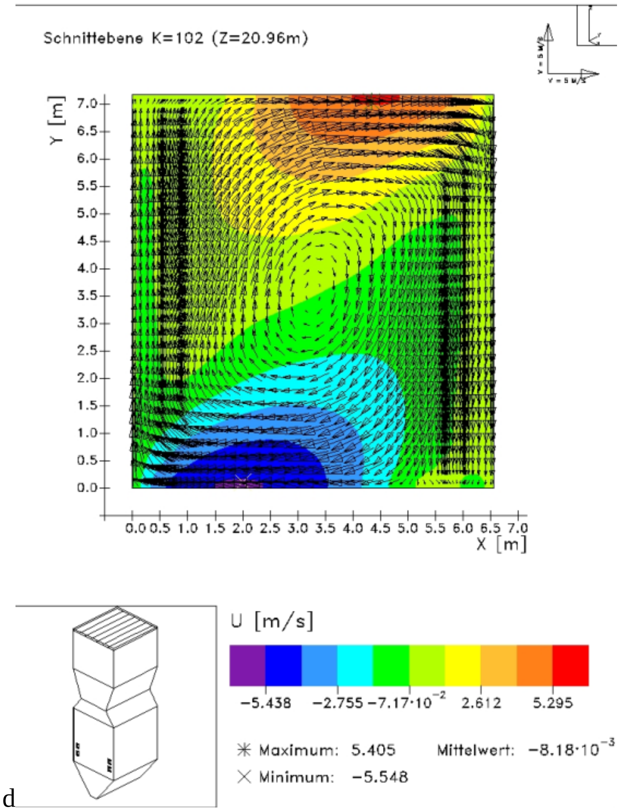
a



b



c



d

Fig. 8. (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 8 clearly shows the aerodynamic flow pattern of a mixture of pulverized coal flow through the tangential burner.

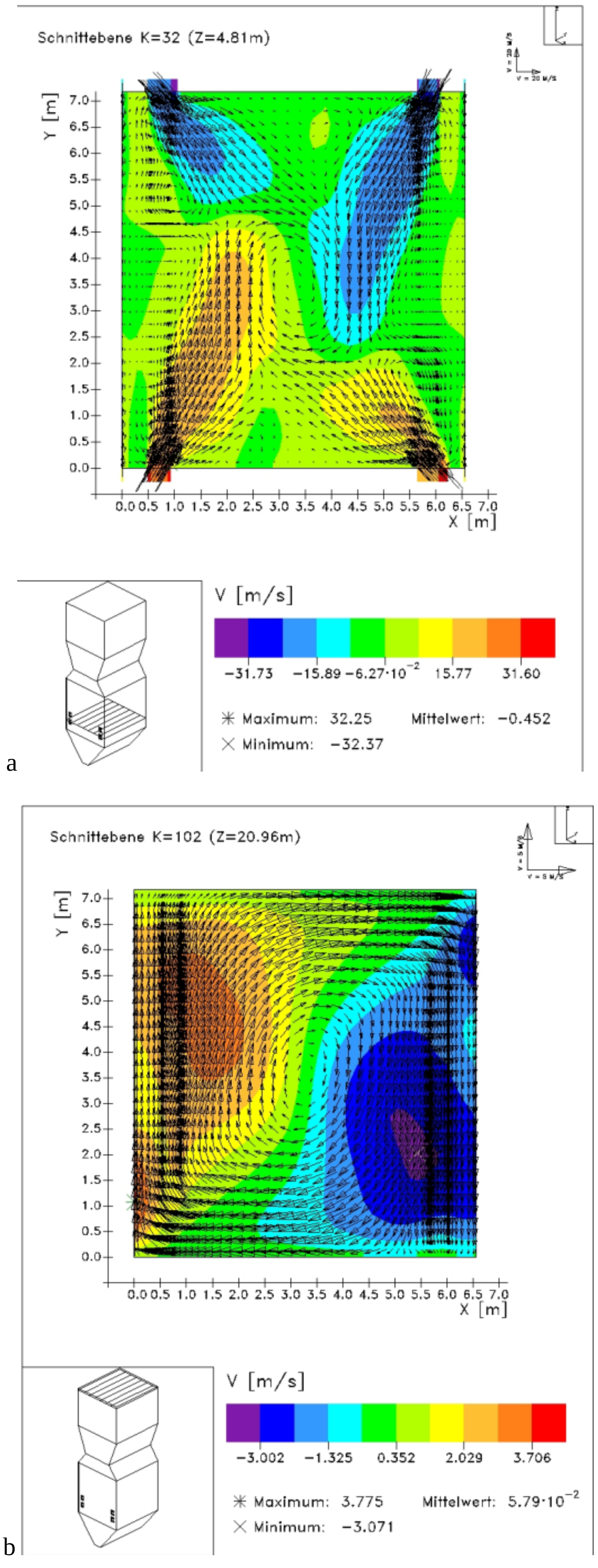


Fig. 9. (a, b) – Distribution of V-component of the vector of full speed in the burner section and in upper section of investigated combustion chamber

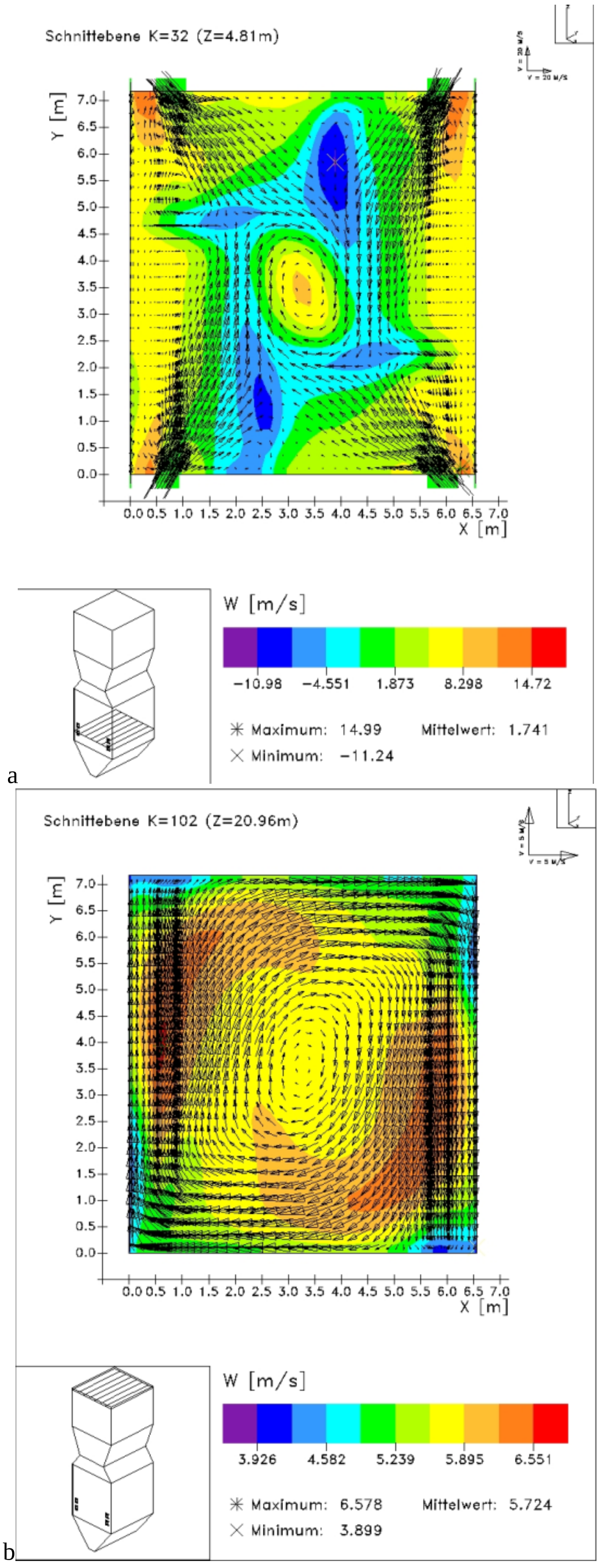
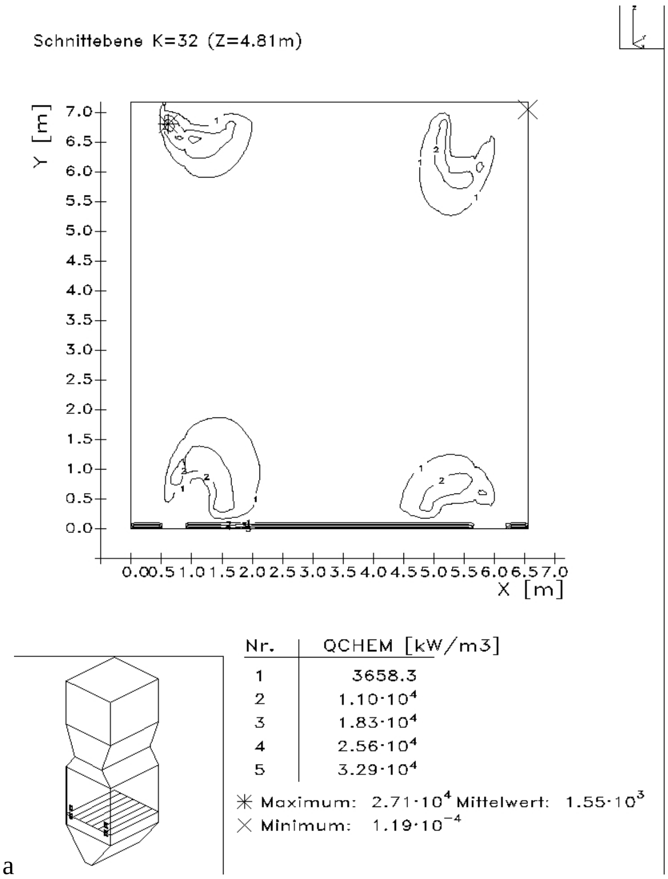


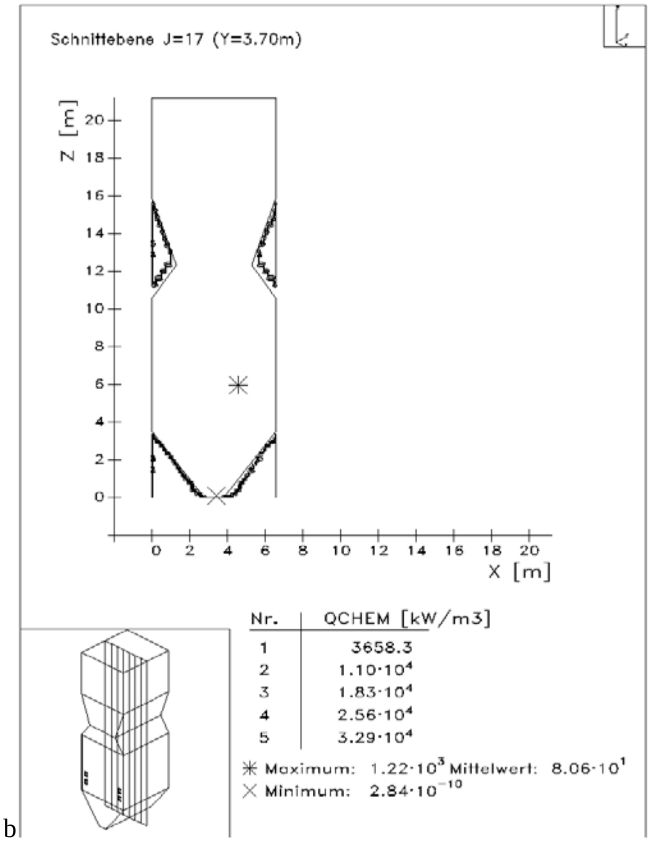
Fig. 10. (a, b) – Distribution of W-component of the vector of full speed in the burner section and in the upper section of investigated combustion chamber

Analysis of Figures 8 - 10 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.

In addition, as a result of the computational experiments obtained isosurface distribution of chemical energy, shown in Figure 6.



a



b

Fig. 11. (a, b) – Isosurfaces of energy distribution of chemical reaction

In Figure 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.

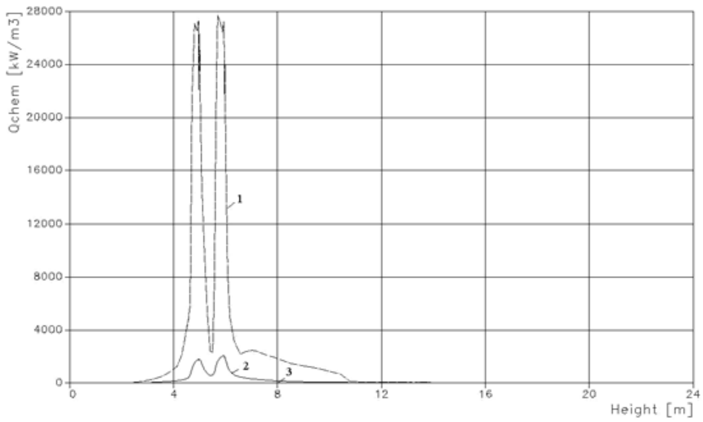


Fig. 12. The distribution of chemical energy Q_{chem} by the height of the combustion chamber
1 -maximal; 2 - medium; 3 – minimal values Q_{chem} at the cross section of combustion chamber

Figure 12 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.

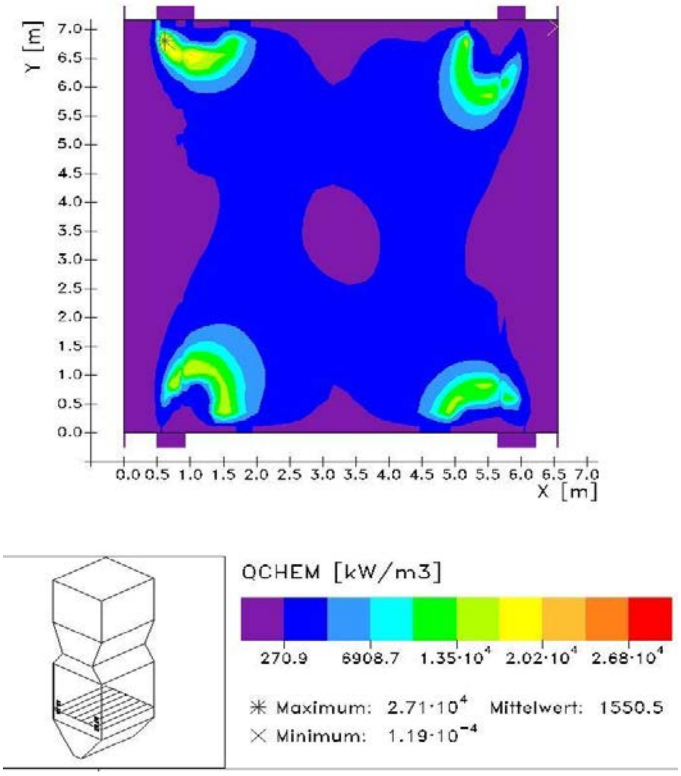


Fig. 13. The distribution of the chemical energy Q_{chem} in cross section of combustion chamber at the lower tier of burners

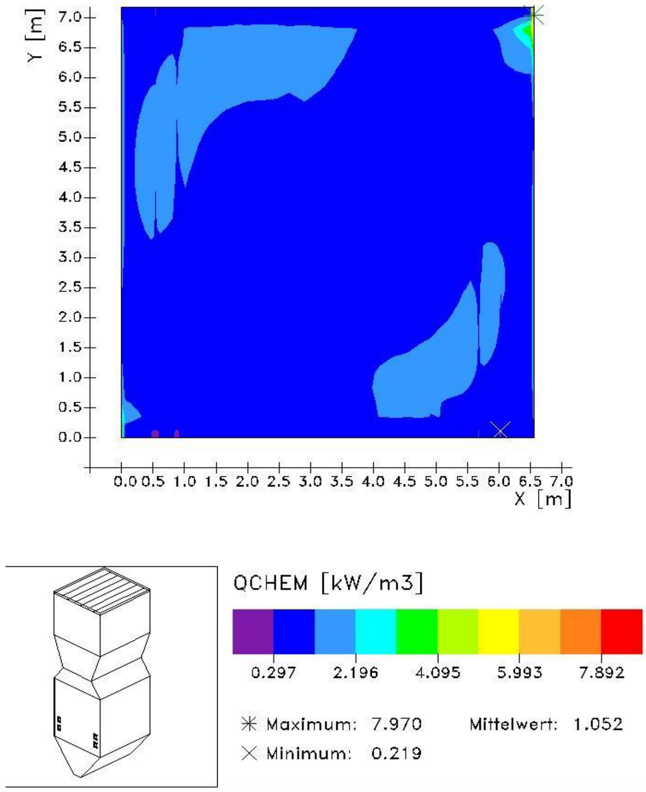


Fig. 14. The distribution of chemical energy Q_{chem} at the outlet of the combustion chamber

Figures 13-14 shows that the motion to the exit from the combustion chamber the energy released due to the processes of chemical interaction is reduced.

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.

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