ARTICLE IN PRESS

Applied and Computational Mechanics 11 (2017) XXX–YYY

Numerical investigation of heat and mass transfer processes in the combustion chamber of industrial power plant boiler. Part 1. Flow field, temperature distribution, chemical energy distribution

A. Askarova[a,b], V. Maximov[a], S. Bolegenova[a], S. Bolegenova[a],
A. Yergaliyeva[b,*], P. Šafařík[c]

[a] *Research Institute of Experimental and Theoretical Physics, Tole bi 96 a, 050012, Almaty, Kazakhstan*
[b] *Al-Farabi Kazakh National University, Faculty of Physics and Technology, al-Farabi 71, 050040, Almaty, Kazakhstan*
[c] *Czech Technical University in Prague, Faculty of Mechanical Engineering, Technická 4, 166 07, Prague, Czech Republic*

Received 28 August 2017; accepted 11 December 2017

Abstract

In the present paper, the furnace chamber of the BKZ-160 boiler of Almaty TPP-3 (Kazakhstan) has been calculated. The thermal characteristics of the process were studied in the form of the distribution of temperature fields and chemical energy, and the aerodynamics of the combustion chamber was also calculated. The type of fuel, its elementary and fractional composition, exerts the greatest influence on the course of heat-mass exchange processes and aerodynamics. The computational experiment was carried out with two models of particle size distribution: a polydisperse fuel flame (the particle diameter varies from 10 to 120 μm) and monodisperse fuel flame (particle size identical and equal to $d_p = 60\ \mu$m). Based on the results of the computational experiments, the main regularities in the distribution of heat fluxes in the combustion chamber volume and flow aerodynamics were obtained. It is shown that the greatest thermal load falls on the central region of the walls of the combustion chamber and the location of the burner devices, which is typical for both mono- and polydisperse fuel flames. The temperature data obtained as a result of the computational experiment showed better convergence with the empirical data obtained directly at TPP-3. Aerodynamics of the flow for the two selected models of particle size distribution has insignificant differences, but how they affect other characteristics of the process is one of the following tasks in view of the authors. It should be noted that the calculation of the polydisperse fuel flame takes much more calculation time.

Keywords: numerical simulation, combustion, pulverized fuel, monodisperse fuel flame, polydisperse fuel flame, aerodynamic characteristics, thermal characteristics

---

1. Introduction

In the study of a wide range of modern problems of science and technology, numerical simulation of heat and mass transfer process is particularly important and has enormous practical application [12]. Interaction of reacting flows is described by a complex system of nonlinear partial differential equations. Indispensable effective method of theoretical study of such flows is a numerical simulation [13]. Numerical modeling is sufficiently accurate and inexpensive way to analyze complex processes that occur during combustion of the fuel in the combustion chambers of real power plants, and it allows considering simultaneously the complex of processes that are almost impossible to do, conducting in situ experiments [7].

However, today there are modern technologies for measuring temperature fields under extreme conditions, which could not be done earlier. This technology (Acoustic gas temperature

---

[*] Corresponding author. Tel.: +7 705 778 00 68, e-mail: ergalyeva@gmail.com.

https://doi.org/10.24132/acm.2017.395

measurement system) became possible with the use of acoustic methods of temperature measurement. So in the papers [10, 17, 19] detailed application of acoustic temperature sensors in combustion chambers of real power plants was described. The operating principle of this system is based on the realization of the functional dependence of the speed of sound on the temperature of the medium through which it propagates. The temperature fields obtained by this method are in good agreement with the results of numerical simulations carried out in the above-mentioned papers.

However, a study of the complex of processes occurring during combustion of solid fuels is still possible only with the help of numerical simulation methods. The results of which allow to optimally solve scientific and project engineering tasks in this area (improvement, design of new boilers; burners upgrade; development of multistage fuel combustion systems, optimization of combustion processes and other) [5–7, 18]. At the present stage of development of the energy industry, immediate consideration and resolution of environmental issues are required.

Due to the fact that for most countries the main sources of pollutant emissions into the atmosphere are companies operating in the burning of low-quality raw materials as well as with poorly equipped with flue gas cleaning systems, the problem of pollution of the Earth's atmosphere is an urgent, [3,9]. Environmentally hazardous emissions, which are products of coal combustion reactions cause enormous damage to the earth's ecosystem. It is therefore necessary to carry out a detailed study of physical and chemical processes that occur during combustion of energy fuels and to solve the problem of environmentally "pure" making use of coal.

For the better description combustion processes in the real three-dimensional physical-chemistry system it is necessary to consider many factors such as particle size distribution, the speed and temperature of the fuel mixture, a method of supplying fuel mixture, the effect of turbulent fluctuations, multistage chemical reactions, heat exchange by radiation, multiphase flows and other. In this regard the purpose of this research is to carry out numerical experiments for the study of turbulent heat and mass transfer in high-reacting flows, which are formed when burning a high-ash coal-dust flame of different dispersion of fuel in the combustion chamber of a boiler and determination of thermal and aerodynamic characteristics of the combustion chamber operating Thermal Power Plant of Kazakhstan.

2. Basic equations describing the coal-dust flame combustion process

The fundamental laws of conservation of quantities such as mass, momentum, energy [20] are used for the numerical simulation of heat and mass transfer. As the heat and mass transfer in the presence of physical and chemical transformations is the interaction of turbulent motion and combustion processes it is necessary to take into account the law of conservation of components of the reaction mixture, turbulence, multiphase flows, and heat generation due to the radiation of heated fluid and chemical reactions.

To describe the heat and mass transfer processes in high-temperature and chemically reacting flows in the presence of the burning it is necessary to use a mathematical model which constitutes a system of three-dimensional non-autonomous nonlinear partial differential equations. In this complex system includes the continuity equation and the state of a viscous medium, the equation of motion, and heat transfer components of the reacting mixture and products of chemical reactions which are described in paper [21].

Mathematical models of complex heat and mass transfer processes in reacting media are written in the general form of the law of conservation of some quantity Φ (mass, momentum, the energy, component of the mixture). Then the generalized transfer equation in turbulent flow takes the following form:

$$\frac{\partial}{\partial t}(\rho\Phi) = -\frac{\partial}{\partial x_j}(\rho u_j \Phi) + \frac{\partial}{\partial x_j}\left[\Gamma_{\varphi,eff}\frac{\partial\Phi}{\partial x_j}\right] + S_\varphi, \tag{1}$$

here $j = 1, 2, 3$ characterizes the spatial direction component of the coordinate x_j and the velocity u_j [m/s]. Φ – the generalized transport variable $(u_j, T, C, k, \varepsilon)$, S_φ – the source term, $\Gamma_{\varphi,eff}$ – coefficient of molecular and turbulent exchange, ρ is the density [kg/m^3].

Molecular and turbulent exchange coefficient is equal to:

$$\Gamma_{\varphi,eff} = \Gamma_{\varphi,lam} + \Gamma_{\varphi,turb}. \tag{2}$$

For the equation of momentum balance:

$$\mu_{eff} = \mu_{lam} + \mu_{turb}. \tag{3}$$

For the equation of energy balance:

$$\Gamma_{h,eff} = \frac{\lambda}{c_p} + \Gamma_{h,turb}. \tag{4}$$

For the law of component conservation:

$$\Gamma_{c^*_\beta,eff} = \frac{\mu_{lam}}{\rho \cdot D_{c^*_\beta}} + \Gamma_{c^*_\beta,turb}. \tag{5}$$

There are λ – coefficient of thermal conductivity $[\mathrm{kW}/(\mathrm{m}\cdot\mathrm{K})]$, c_p – specific isobaric heat capacity $[\mathrm{kJ}/(\mathrm{kg}\cdot\mathrm{K})]$, c^*_β – mass concentration [kg/kg], D – diffusion coefficient [m^2/s].

Turbulent viscosity μ_{turb} $[\mathrm{kg}/(\mathrm{m}\cdot\mathrm{s})]$ is determined by the ratio of the Prandtl-Kolmogorov [14]:

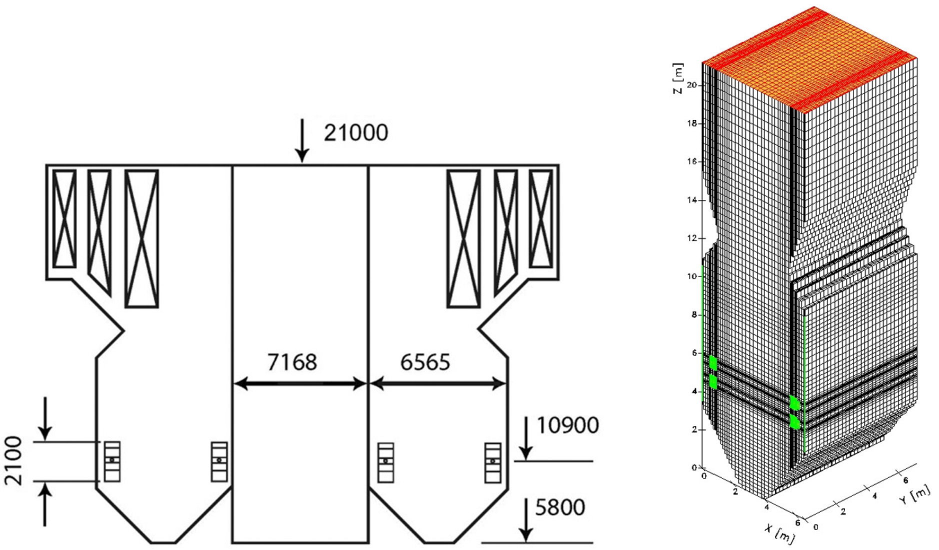
$$\mu_{turb} = c_\mu \cdot \rho \cdot \frac{k^2}{\varepsilon}, \tag{6}$$

where c_μ – the empirical constant, k – turbulent kinetic energy [m^2/s^2], ε – dissipation rate of turbulent kinetic energy [m^2/s^3].

3. Subject of investigation

Computer experiment for the study and modeling of heat and mass transfer processes in the combustion of solid fuels taking into account occurrence at the same time physical and chemical transformations was carried out on a numerical model of the real energy facility. As the researched object is selected the combustion chamber of boiler BKZ-160 Almaty TPP-3 (Kazakhstan) to the block of 173 with a steam generating capacity of 160 t/h. Fig. 1 shows a circuit the combustion chamber of the boiler, the general view and its breakdown into elementary volumes for carrying out computing experiments. The combustion chamber is equipped with 8 straight-through slot burners, arranged on the side walls of the furnace by the tangential scheme. The main characteristics of the studied object are provided in Table 1.

Computational experiments on research heat and mass transfer processes have been carried out by the starting FLOREAN software package [2, 15, 16]. The geometry of the combustion chamber was created by a computer program “PREPROZ”, allowing to obtain the source files “GEOM”, which always re-written when a new object of study (combustion chamber) is selected, taking into account geometry of the burners, their size, shape and location in the space of the



a) b)

Fig. 1. a) Scheme of the furnace, b) general view of the camera, broken down into control volumes

Table 1. The main characteristics of combustion chamber and composition of Ekibastuz coal

Fuel consumption on the burner, t/h	$B^{\Gamma} = B/Z$	3.787	Ekibastuz coal [kg/kg]	
Excess air ratio at the exit from a fire chamber	α_T	1.27		
Excess air ratio in the burners	α_{Γ}	0.68		
Air suction in the furnace	$\Delta\alpha$	40		
Fuel mixture temperature [°C]	T_a	250	W	0.065
The temperature of the secondary air [°C]	T_2	380	A_{dry}	0.369
Height [m]	z (H)	21	C_{daf}	0.448
Width [m]	y	7.168	H_{daf}	0.030
Depth [m]	x	6.565	O_{daf}	0.073
Primary air velocity (fuel mixture) [m/s]	W_1	25	N_{daf}	0.008
The velocity of secondary air [m/s]	W_2	40	S_{daf}	0.007

combustion chamber. During the numerical simulation of heat and mass transfer process the control volume method has been applied. Combustion chamber of a power boiler BKZ-160 has been divided into control volumes using a computational grid: $I = 66$, $J = 32$, $K = 103$. It is possible to obtain 217,536 computational areas. In the following section, there are presented the results of numerical experiments to study the processes of heat transfer and aerodynamics in the combustion chamber of the boiler BKZ-160 Almaty TPP-3 (Kazakhstan) by burning in it high-ash Ekibastuz coal (Table 1).

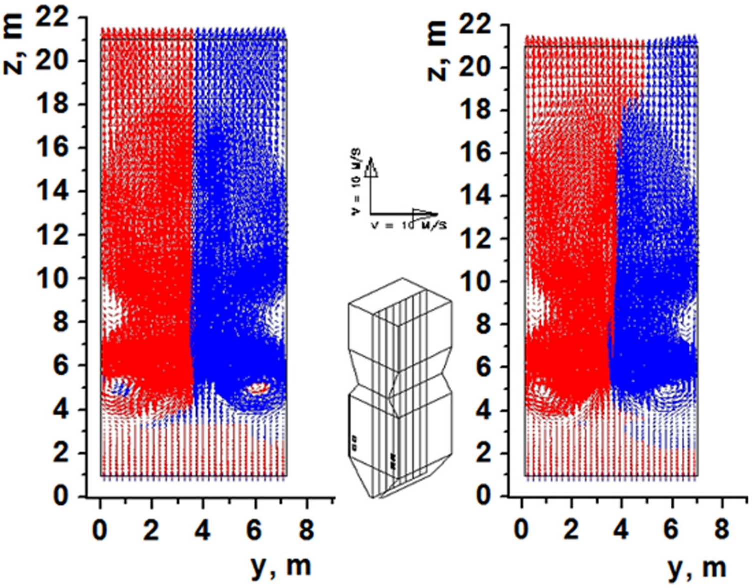
4. The results of numerical experiment

Many analytical researches are conducted in the simplified conditions which differ from real furnace process. Such simplifications somewhat distort a true picture of process of burning. One such simplification is the constant average diameter of the coal particles, but in reality such coal cannot be obtained. The more real process of coal combustion in the thermal power station corresponds to the following percentage distribution of coal particle size: $d_p = 10\ \mu\text{m} - 10\%$; $d_p = 30\ \mu\text{m} - 20\%$; $d_p = 60\ \mu\text{m} - 40\%$; $d_p = 100\ \mu\text{m} - 20\%$; $d_p = 120\ \mu\text{m} - 10\%$. Polydisperse flame, at this choice of distribution of particles of coal, is calculated and for monodisperse flame calculations the average particle diameter of 60 microns was chosen.

This paper presents the results of numerical modeling of aerodynamics and heat transfer in combustion of Ekibastuz coal, which heating value is 17.56 MJ/kg, in the camera of an industrial boiler BKZ-160. Comparison of results of computing experiment on burning of a monodisperse flame with results of modeling of burning of a polydisperse flame is carried out. A comparative analysis of the data from in-situ experiment was also carried out.

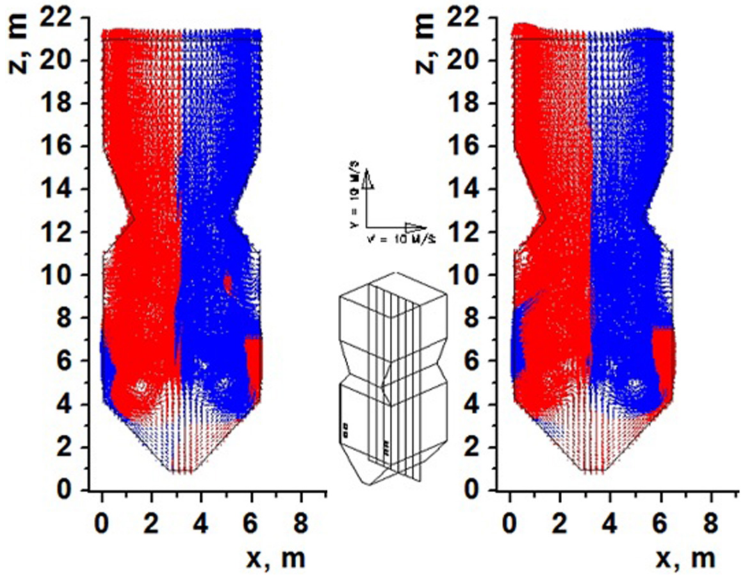
Research of aerodynamic characteristics of pulverized coal flow

Figs. 2–5 show the field of a vector of full speed throughout the volume of the combustion chamber of the boiler BKZ-160 during the combustion of monodisperse and polydisperse flames. The received high-speed fields allow to visually analyzing the aerodynamics of reacting flows in the combustion chamber. Fields of a vector of full speed $V = \sqrt{u^2 + v^2 + w^2}$ shows the magnitude of the flow velocity of the medium and its direction at every point.



a) Monodisperse flame b) Polydisperse flame

Fig. 2. Field of a vector of full velocity in the longitudinal section of the combustion chamber ($x = 3.16$ m)



a) Monodisperse flame b) Polydisperse flame

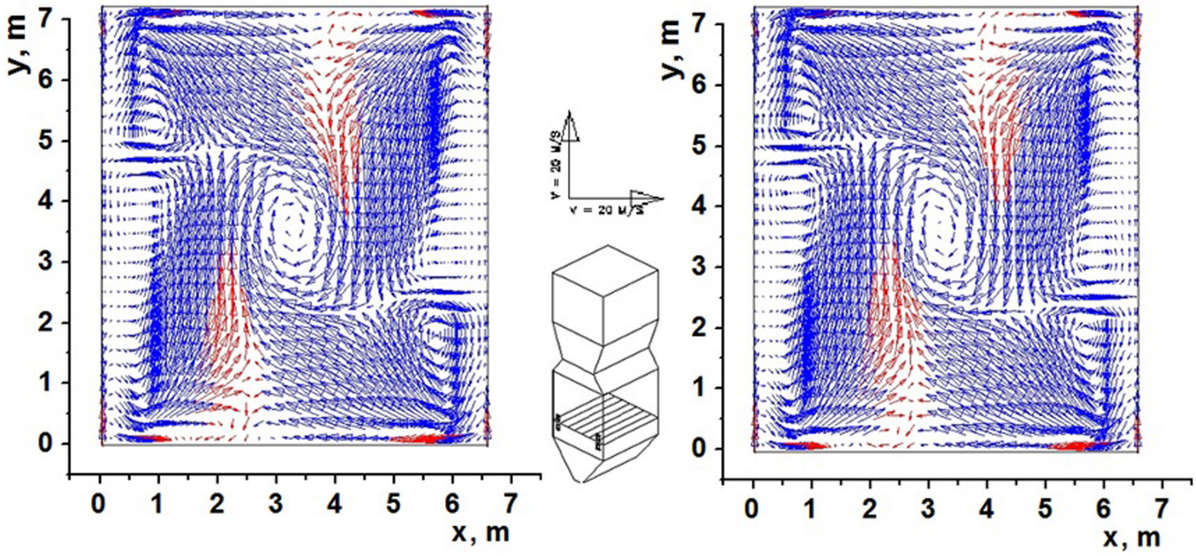
Fig. 3. Field of a vector of full velocity in the longitudinal section of the combustion chamber ($y = 3.7$ m)

In the three-dimensional graphs (Figs. 2–5) picture of the aerodynamics of dust and gas flow is observed. In Figs. 2–4 the area of fuel and oxidizer is clearly visible: counter dust and gas streams from opposing tangential burners create a vortex in the central part on the location of burners and level of active burning zone. Part of the flow is directed down to the funnel, forming two symmetrical vortex in the area below the burner arrangement (Figs. 2 and 3), it is typical both for burning of a monodisperse flame and for burning of a polydisperse flame.

However, in a longitudinal section of the combustion chamber ($x = 3.16$ m) symmetry is broken relative to the vertical axis of the chamber when burning polydisperse flame (Fig. 2b), and in cross-section ($y = 3.7$ m) there are minor differences in the area of active burning (Fig. 3a, b). It means that burning of dust and gas streams with different particle sizes affects to the character of the flow stream. In cross-section chamber at a level between the lower and upper tiers of burners ($z = 5.3$ m) there is a clear picture of the current. Streams of pulverized fuel entering the combustion chamber, creating three-dimensional turbulence in the center of the chamber, whose velocity reaches 20 m/s, thereby improving process of mixing and increasing the intensity of heat and mass transfer [11], but the apparent differences in the nature of monodisperse and polydisperse burning flames is not observed (Fig. 4a, b).

The central whirled movement of a coal-dust flow leads to uniform heating of walls of the combustion chamber, reduces the slagging thermal shields and thermal losses. It prolongs service life of separate elements of the boiler system, and also increases a heat removal surface. At the exit of the combustion chamber (Fig. 5a, b) the velocity field is aligned, the vortex flow of a current weakens, the uniform current relative to the center of the combustion chamber is observed, due to the thrust generated at the output of the furnace (area of fuel and oxidant). There is a slight difference in the distribution of vectors of full speed at the exit from the combustion chamber for a mono- and polydisperse flames (Fig. 5a, b). But the velocity at the exit from the combustion chamber reaches 5 m/s for both cases.

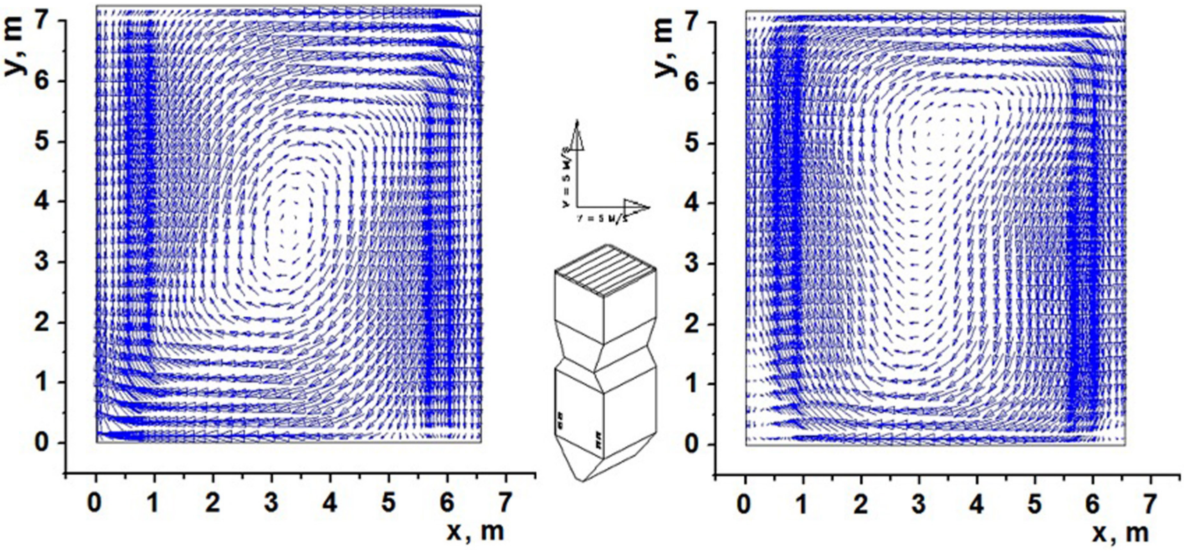
Analyzing the obtained data, it is possible to make the conclusion that the most combustion occurs in the burner zone location, i.e. area of mixing of fuel and an oxidizer. Vortex character of a current weakens in process to an exit of a turbulent flow from the combustion chamber, and



a) Monodisperse flame

b) Polydisperse flame

Fig. 4. Field of a vector of full velocity in the cross-section of the combustion chamber ($z = 5.3$ m)



a) Monodisperse flame b) Polydisperse flame

Fig. 5. Field of a vector of full velocity at the exit from a combustion chamber ($z = 20.96$ m)

at the exit of the combustion chamber (Fig. 5a, b) there is substantially uniform velocity profile. It is shown that aerodynamics of a current when burning monodisperse and polydisperse flames has some differences, however if it is necessary to carry out quickly evaluation calculations, then the numerical simulation of the aerodynamic characteristics of the coal combustion process is possible to be performed by use the model of burning averaged particle size, that in turn reduces expenses of machine time.

Research of thermal characteristics of pulverized coal flow

The area of installation of burners is an area with the greatest changes of speeds, changes velocity fluctuations and the area with the most intense occurring processes of physical and chemical transformations of pulverized coal. In this part of the combustion chamber, fuel component oxidation reactions is going from maximum values, as indicated by the maxima in the distribution of chemical energy (Figs. 6–8).

Fuel mixture enriched with carbon of fuel and oxygen of air supplied through the burners, and in this area the maximum quantity of heat energy is released. In this regard, there is a distinct maximum of chemical energy Q_{chem} (Fig. 6a, b), which is observed near the upper and lower tiers of burners (two peaks in the distribution curve Q_{chem}, $z = 5$ m and $z = 5.94$ m).

In the process of promoting the flow from the area of the burner to up the intensity of the chemical processes is reduced and the values of the chemical energy decrease. Clearly it shows that the minimum value of the energy released by a chemical reaction, is observed in both cases at the exit of the combustion chamber where processes of burning with heat production are almost complete.

The analysis of the two-dimensional distribution graph of average values of chemical energy shows that the energy released during the combustion of polydisperse flame, takes large values in the zone burners, in contrast to combustion of monodisperse (Fig. 6b). This is apparently due to the presence of large-size fractions $d_p = 100\ \mu\text{m} - 20\%$; $d_p = 120\ \mu\text{m} - 10\%$ with a greater surface area of interaction in polydisperse flame.

The above mentioned is confirmed by the three-dimensional distribution of the chemical energy in the volume of the combustion chamber. Distributions of chemical energy Q_{chem} in

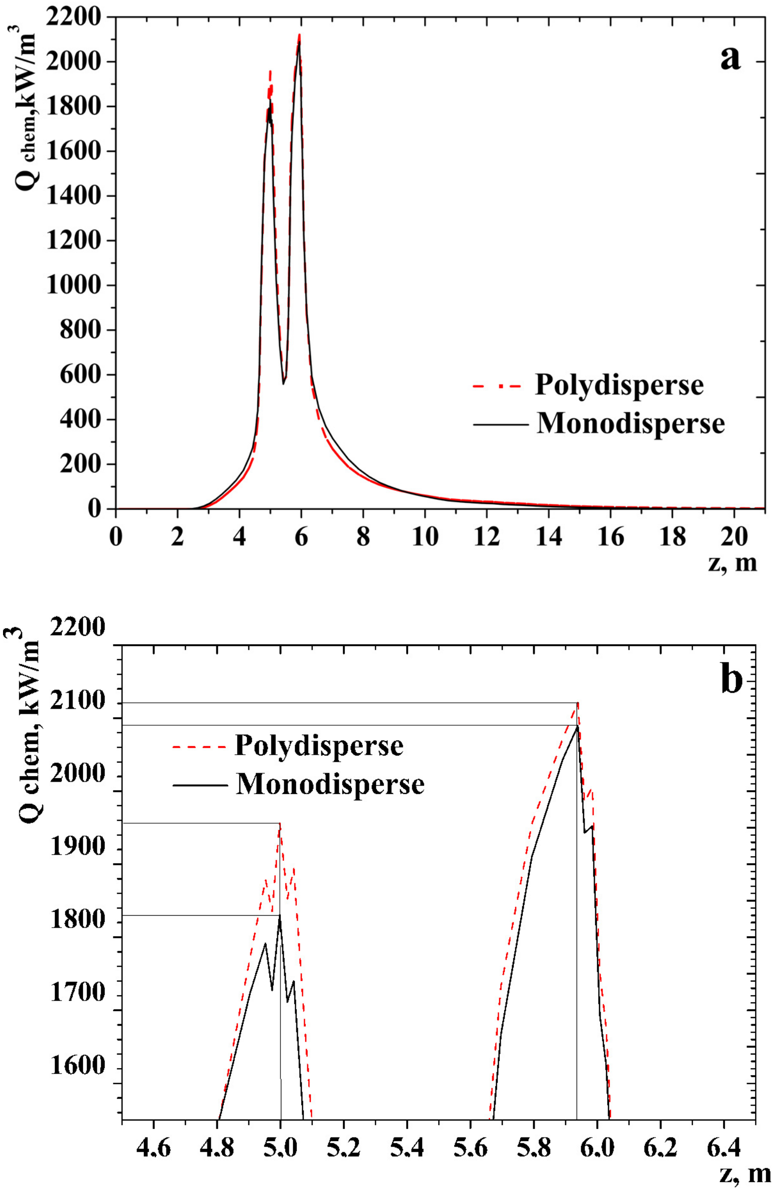
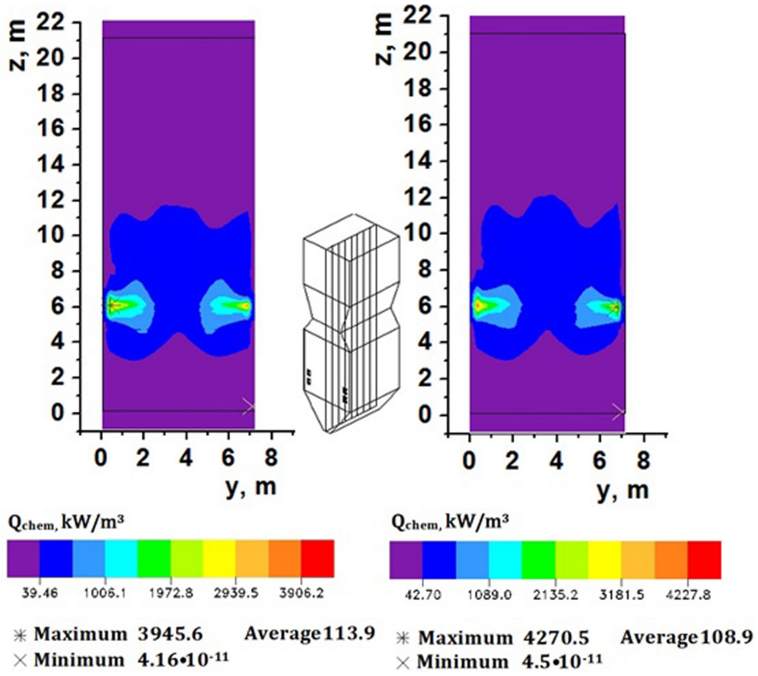


Fig. 6. Comparison of the average values of the chemical energy $Q_{chem.}$: a) along the entire height of the combustion chamber, b) in active burning zone

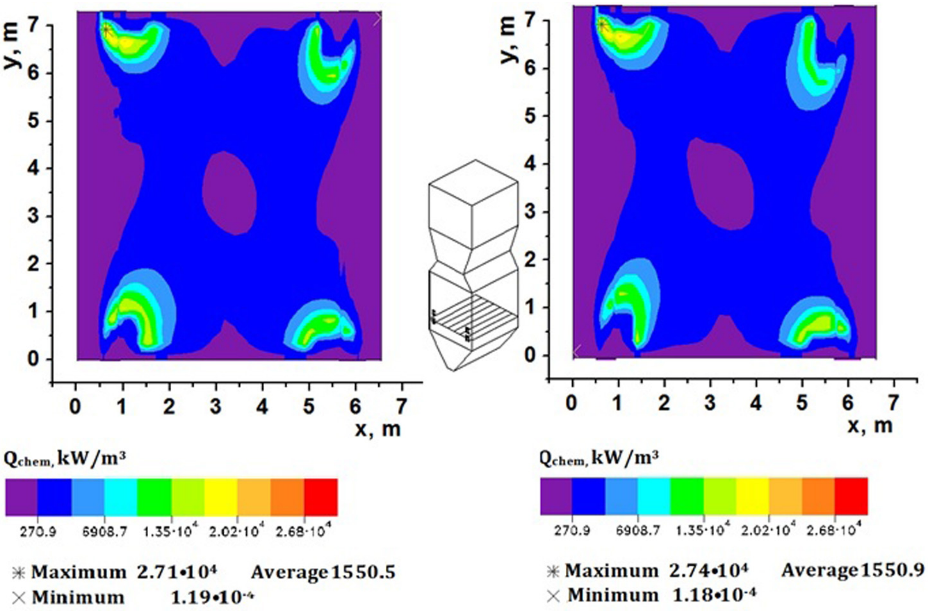
the longitudinal ($x = 3.16$ m) and across ($z = 4.81$ m) sections of the combustion chamber are depicted in Figs. 7 and 8. It can be seen that with increasing diameter of the coal particles, it takes a longer combustion time, and the average values of the chemical energy of the interaction will take large values (Figs. 6–8). So average values of chemical energy in longitudinal section ($x = 3.16$ m) of a combustion chamber when burning a monodisperse flame is 113.9 kW/m^3 (Fig. 7a), and for polydisperse – 108.9 kW/m^3 (Fig. 7b). In cross-section ($z = 4.81$ m) of the combustion chamber average values of chemical energy is 1 550.5 kW/m^3 (Fig. 8a) and 1 550.9 kW/m^3 (Fig. 8b), respectively, for mono- and polydisperse flames.

Carrying out research of thermal characteristics is an important step in modeling heat and mass transfer processes in the combustion of pulverized coal and allows determining the temperature field over the entire volume of the combustion chamber and the outlet of the furnace [4, 8].



a) Monodisperse flame b) Polydisperse flame

Fig. 7. Distribution of the chemical energy in a longitudinal section of the combustion chamber ($x = 3.16$ m)



a) Monodisperse flame b) Polydisperse flame

Fig. 8. Distribution of chemical energy in the zone of burners ($z = 4.81$ m)

Figs. 9–12 show the temperature profiles that characterize the thermal behavior of pulverized coal flow in the combustion chamber of the boiler BKZ-160 Almaty TPP. It can be seen that in both cases (mono- and polydisperse flames) the greatest changes in the temperature distribution are in the region of burner (Fig. 9). This is due to the fact that in this region most intensive mixing of carbon fuel with air oxygen occurs, also intensive chemical reactions of oxidation take place in this area. Maxima of the temperature are due to the fact that there is a process

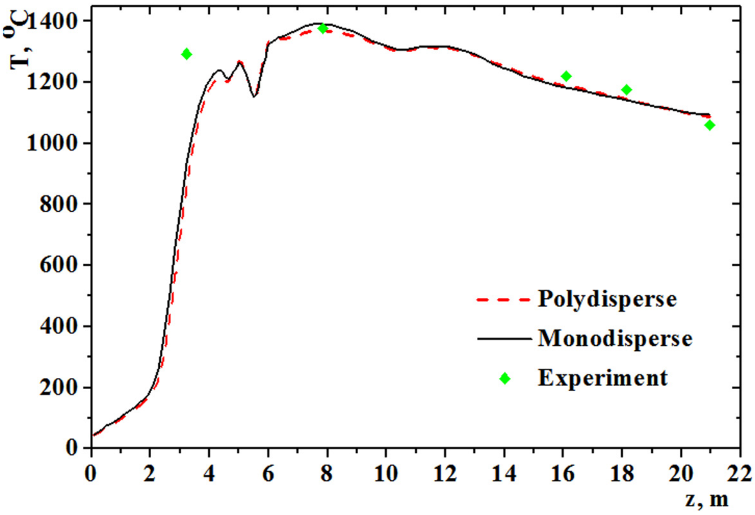
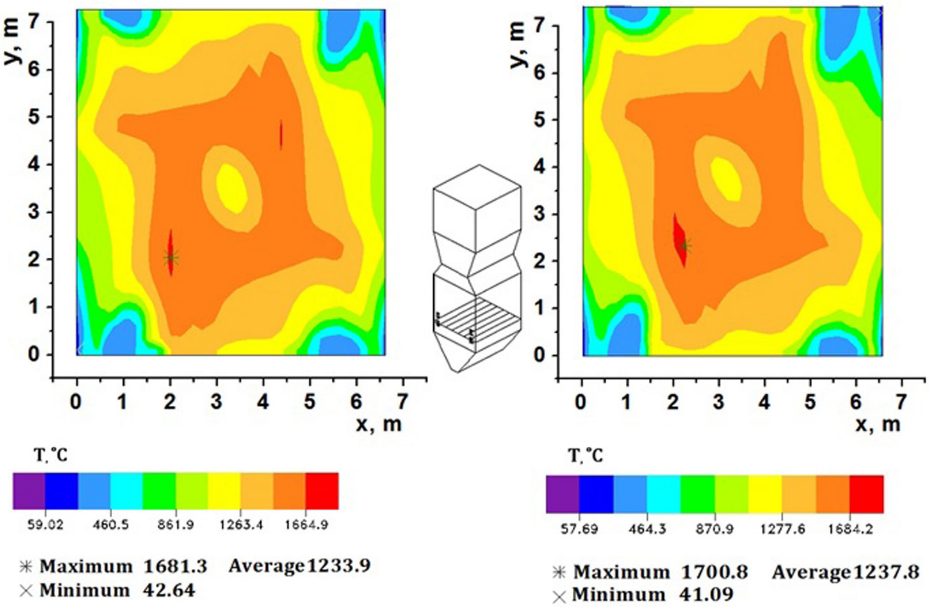


Fig. 9. Comparison of average temperature values for poly- and monodisperse flames and a comparison with the field experiment [1]

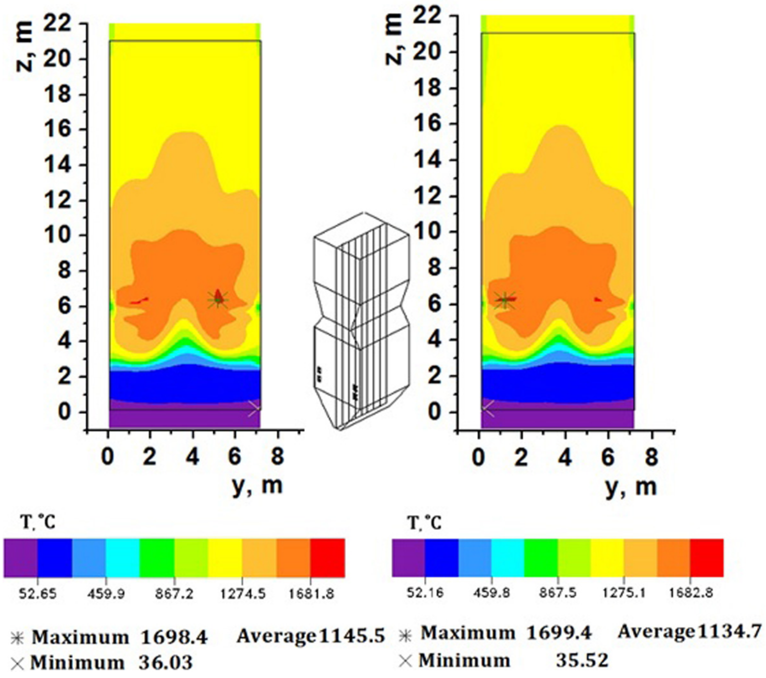
of ignition when fuel and an oxidizer are mixed, a chemical process of interaction leads to the release of a large amount of heat. The minima of the temperature are due to the fact that fuel mixture supplied through the burner is cold ($T_a = 250\,°\mathrm{C}$). This is typical for both polydisperse flame and monodisperse flame.

In a zone of active burning average values of temperature of polydisperse flame have smaller values in comparison with monodisperse (Fig. 9). This can be explained by the presence of large fractions of carbon particles in the polydisperse flame, that ignite and burn slower than smaller particles. Fig. 9 shows the experimental points received as a result of measurements directly on thermal power plant [1]. Thus, it can be seen that the numerical simulation results are in good agreement with the results of field experiment. It is leading to the conclusion of the applicability of the proposed physical-mathematical model of combustion processes, used in this paper.



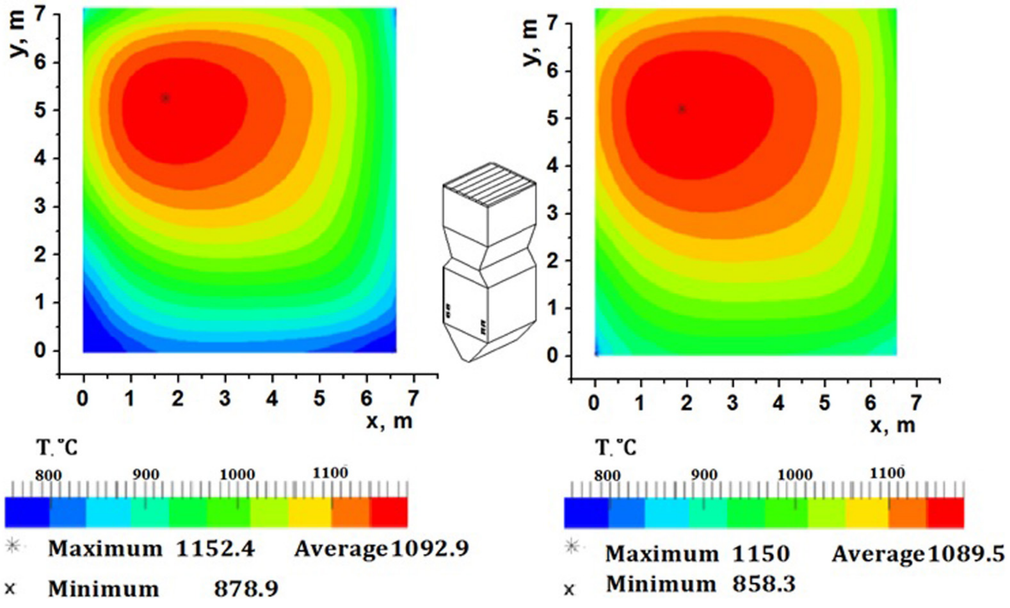
a) Monodisperse flame b) Polydisperse flame

Fig. 10. Temperature distribution in the cross section of the combustion chamber ($z = 4.81$ m)



a) Monodisperse flame b) Polydisperse flame

Fig. 11. Temperature distribution in a longitudinal section of the combustion chamber ($x = 3.16$ m)



a) Monodisperse flame b) Polydisperse flame

Fig. 12. Temperature distribution at the outlet of the combustion chamber ($z = 20.96$ m)

Figs. 10–12 present graphs of temperature distribution in different sections of the combustion chamber. The graphs obtained by means of the 3-D modeling make it possible to describe fully the temperature field at any point of the combustion chamber with very high accuracy. As expected the temperature distribution at the outlet of the combustion chamber are similar (Fig. 12a, b) and equal to 1 092.9 °C for monodisperse, and 1 089.5 °C for polydisperse flame. Analysis of the data leads to the conclusion that the results of polydisperse flame modeling are in better agreement with the data of experiments performed at the thermal power plant. For example, the output value of the temperature measured directly at thermal power plant [1] is closer to the temperature value for polydisperse flame (Fig. 9) and equal $T = 1\,060\,^{\circ}\mathrm{C}$. This follows from the fact that in real practice the coal is a polydispersed coal dust, and, in practice, it is not possible to obtain particles of the same size.

5. Conclusion

In this paper, study of aerodynamic and thermal characteristics of the combustion process of monodisperse and polydisperse flames was conducted. Heat transfer processes represented by the distribution of temperature and thermal field were investigated.

According to the results of the study, the following conclusions can be made:

1. By analyzing the flow aerodynamic it can be said that it correctly describes the mass transfer processes occurring in the volume of the furnace. In the center of the combustion chamber is formed vertical swirling motion associated with tangential fuel supply. This leads to increases the residence time of coal particles in the furnace, and consequently reduces underburning associated with carryover of unburned particles from the flue gases.
2. It is shown that the thermal characteristics of the process take maximum values in an area where the ignition and combustion of fuel. In the area of the burner there are maximum and minimum temperature values that are respectively related to the ignition of dust-gas mixture and the cold temperature fuel mixture. All chemical processes are attenuated from the belt of burners to out of the combustion chamber that leads to lower temperatures.
3. According to a study of the combustion process of mono- and polydisperse coal it is possible to approve, that the model of polydisperse dust burning more accurately reflects the actual combustion process occurring in the combustion chamber.

It is impossible to achieve the perfect value of coal fineness in actual conditions.

Therefore there is a need to use the model of polydisperse flame in the simulation of turbulent heat and mass transfer and not to resort to a simplified model of monodisperse flame. The model of monodisperse is convenient for applying when it is necessary to show quickly show the overall picture of burning or aerodynamic flow. The results obtained in this study will give recommendations for optimizing the burning process of pulverized coal in order to reduce pollutant emissions and creations of power stations on ‘pure’ and an effective utilization of coal.

Acknowledgements

Work is performed under the financing of the Ministry of Education and Science of the Republic of Kazakhstan Grant No. 0115PK0059. The last author, P. Šafařík, expresses thanks for support from the Technology Agency of the Czech Republic in the frame of the Competence Centre Advanced Technology of Heat and Electricity Output, No. TE01020036.

References

[1] Alijarov, B. K., Alijarova, M. B., Combustion of Kazakh coals in thermal power stations and large-power boiler houses, Almaty, 2011. (in Russian)

[2] Askarova, A. S., Bekmukhamet, A., Bolegenova, S. A., Beketayeva, M. T., Maximov, V. Y., Ospanova, Sh. S., Gabitova, Z. K., Numerical modeling of turbulence characteristics of burning process of the solid fuel in BKZ-420-140-7C combustion chamber, International Journal of Mechanics 8 (2014) 112–122.

[3] Askarova, A. S., Bekmukhamet, A., Bolegenova, S. A., Ospanova, Sh. S., Symbat, B., Maximov, V. Y., Beketayeva, M. T., Yergaliyeva, A. B., 3-D modeling of heat and mass transfer during combustion of solid fuel in BKZ-420-140-7C combustion chamber of Kazakhstan, Journal of Applied Fluid Mechanics 9 (2) (2016) 699–709.

[4] Askarova, A. S., Bolegenova, S. A., Bekmukhamet, A., Maximov, Y. V., Beketayeva, M. T., Ospanova, Sh. S., Gabitova, Z. K., Investigation of turbulence characteristics of burning process of the solid fuel in BKZ 420 combustion chamber, WSEAS Transactions on Heat and Mass Transfer 9 (2014) 39–50.

[5] Askarova, A. S., Bolegenova, S. A., Bolegenova, S., Bekmukhamet, A., Maximov, V. Y., Beketayeva, M. T., Numerical experimenting of combustion in the real boiler of CHP, International Journal of Mechanics 7 (3) (2013) 343–352.

[6] Askarova, A. S., Messerle, V. E., Ustimenko, A. B., Bolegenova, S. A., Maksimov, V. Y., Numerical simulation of the coal combustion process initiated by a plasma source, Thermophysics and Aeromechanics 21 (6) (2014) 747–754.

[7] Askarova, A. S., Messerle, V. E., Ustimenko, A. B., Bolegenova, S. A, Maximov, V. Y., Gabitova, Z. K., Numerical simulation of pulverized coal combustion in a power boiler furnace, High Temperature 53 (3) (2015) 445–452.

[8] Bolegenova, S. A., Bekmuhamet, A., Maximov, V. Y., Mathematical simulation of pulverized coal in combustion chamber, Procedia Engineering 42 (2012) 1259–1265.

[9] Buchmann, M. A., Askarova, A. S., Structure of the flame of fluidized-bed burners and combustion processes of high-ash coal, Gesellschaft Energietechnik, Combustion and Incineration – Eighteenth Dutch-German Conference on Flames, VDI ?erichte 1313 (1997) 241–244.

[10] Deuster, M., Acoustic gas temperature measurement, Proceedings of VDI Forum 05F0012003 Wissenforum Temperature Measurement Technique, Aldenhoven, Germany, 2009.

[11] Gorokhovski, M., Chtab-Desportes, A., Voloshina, I., Askarova, A. S., Stochastic simulation of the spray formation assisted by a high pressure, AIP Conference Proceedings 1207 (2010) 66–73. https://doi.org/10.1063/1.3366446

[12] Karpenko, E. I., Karpenko, Y. E., Messerle, V. E., Ustimenko, A. B., Mathematical modelling of the processes of solid fuel ignition and combustion at combustors of the power boilers, Proceeding of the 7th International Fall Seminar on Propellants, Explosives and Pyrotechnics, Xian, 2007, pp. 672–683.

[13] Karpenko, E. I., Messerle, V. E., Ustimenko, A. B., Plasma enhancement of combustion of solid fuels, Journal of High Energy Chemistry 40 (2) (2006) 111–118.

[14] Kolmogorov, A. N., The equations of turbulent motion of an incompressible fluid, Izvestiya AN SSSR 6 (1) (1942) 56–66. (in Russian)

[15] Leithner, R., Numerical simulation, Computational fluid dynamics CFD: Course of lecture, Braunschweig, 2006.

[16] Leithner, R., Lavrichsheva, Y. I., Müller, H., Magda, A., Combustion of low-rank coals in furnaces of Kazakhstan coal-firing power plants, VDI Berichte 1988 (2007) 497–502.

[17] Madejski, P., Janda, T., Modliński, N., Nabaglo, D., A combustion process optimization and numerical analysis for the low emission operation of pulverized coal-fired boiler, In: Developments in combustion technology, (eds.) K. G. Kyprianidis and J. Skvaril, InTechOpen, 2016.

[18] Messerle, V. E., Ustimenko, A. B., Askarova, A. S., Bolegenova, S. A., Bolegenova, S. A., Maximov, V. Y., Yergaliyeva, A. B., Reduction of noxious substance emissions at the pulverized fuel combustion in the combustor of the BKZ-160 boiler of the Almaty heat electropower station using the “Overfire Air”’ technology, Thermophysics and Aeromechanics 23 (1) (2016) 125–134.

[19] Modliński, N., Madejski, P., Janda, T., Szczepanek, K., Kordylewski, W., A validation of computational fluid dynamics temperature distribution prediction in a pulverized coal boiler with acoustic temperature measurement, Energy 92 (2015) 77–86. https://doi.org/10.1016/j.energy.2015.05.124

[20] Müller, H., Numerical calculation of three-dimensional turbulent flows in steam generators with heat transfer and chemical reactions using the SNCR method and coal combustion, Fortschritt-Berichte VDI-Verlag 6 (1992) No. 268. (in German)

[21] Vockrodt, S., Leithner, R., Schiller, A., Askarova, A. S., Buchman, M., Firing technique measures for increased efficiency and minimization of toxic emissions in Kazakh coal firing, Proceedings of the 19th German Conference on Flames, VDI Berichte 1492 (1999) 93–97.