Acta Polytechnica **59**(6):543–553, 2019
DOI:10.14311/AP.2019.59.0543

available online at https://ojs.cvut.cz/ojs/index.php/ap

3-D MODELING OF HEAT AND MASS TRANSFER PROCESS DURING THE COMBUSTION OF SOLID FUEL IN A SWIRL FURNACE

Aliya Askarova[a,b], Saltanat Bolegenova[a,b], Valeriy Maximov[b], Symbat Bolegenova[b], Aizhan Nugymanova[a,*], Pavel Šafařík[c]

[a] *al-Farabi Kazakh National University, Physics and Technology Faculty, al-Farabi av. 71, 050040, Almaty, Kazakhstan*

[b] *al-Farabi Kazakh National University, Scientific Research Institute of Experimental and Theoretical Physics, Tole bi, 94a, 480012, Almaty, Kazakhstan*

[c] *Czech Technical University in Prague, Faculty of Mechanical Engineering, 166 07 Praha 6, Prague, Czech Republic*

[*] corresponding author: nugymanova.aizhana@gmail.com

Abstract. In this work, a comprehensive study of thermal processes and aerodynamic and concentration characteristics of the combustion chamber of the boiler BKZ-75 of the Shakhtinskaya thermal power plant (Kazakhstan) are presented. A comparison of the characteristics of the combustion processes for two cases is given for the direct-flow method of supplying the mixture - the burners are located on opposite-side walls and the swirl-air mixture supplying method - burners with a swirl angle of the air mixture flow and their inclination to the centre of symmetry of the boiler by 30 degrees. The research results allow us to determine the optimal technological parameters of the studied object, to improve the methodology for the numerical study of heat and mass transfer processes in high-temperature and chemically reacting flows in the presence of turbulence, and also develop appropriate technological solutions for installing burner devices (direct-flow or swirl) in the studied combustion chamber.

Keywords: Modeling, thermal power plants, direct-flow and swirl burners, carbon monoxide, nitrogen dioxide.

1. Introduction

The fuel and energy complex in the economy of any state is the most important component of ensuring the functioning and development of productive forces and, improving the living standards of the population [1]. In this regard, the creation of new, highly efficient energy- and resource-saving technologies of energy processes becomes an urgent issue of the choice of operation. Therefore, it is necessary to implement a whole range of measures, the most important of which is the application of the most accurate methods for calculating heat and power processes.

It is possible to increase the efficiency and environmental safety of boiler units of thermal coal-fired power plants with the swirl method of burning fuel, which uses the aerodynamic features of a swirling flow having a complex structure, separation ability and a high degree of turbulence. The Iinternal aerodynamics of the combustion device ensures the achievement of specified technical and environmental indicators when burning fuel in a swirl flow. The optimal organization of the flow aerodynamics can affect the uniform distribution of temperature and heat fluxes, increase the residence time of the fuel particle in the combustion chamber, and consequently, the completeness of fuel burn out, increase slag collection, reduce the emission of toxic ingredients and increase the energy efficiency of the steam generator [2].

At the moment, in the implementation of a comprehensive study of the processes of burning pulverized coal in the combustion chambers of boilers of industrial facilities (thermal power plants, etc.), the most optimal way is to conduct computational experiments using 3D modelling methods and with the use of a modern computer equipment, computer technology and application software packages [3–9].

When conducting a computational experiment to build physicotechnical models, model ideas about the mechanism of really occurring processes in the combustion chambers of energy objects are used. The methodological principles for creating such models are based on an understanding of the flow of technological processes (the stage of combustion pulverized coal, the formation of harmful dust and gas emissions, ash, etc.). Such processes are based on the knowledge of the laws, the so-called “elementary” processes of aerodynamics, mass and heat transfer, chemical kinetics, phase transition processes, nonlinear effects of convective and radiation heat transfer, diffusion processes, etc.

In this paper, using modern technologies of numerical methods [10–18], a comprehensive study of thermal processes and aerodynamic characteristics of the com-

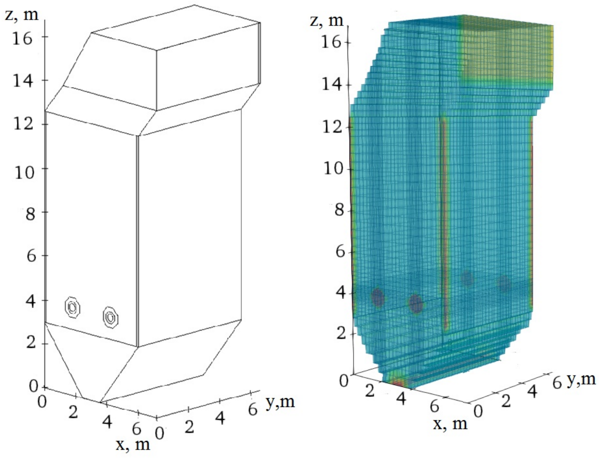

FIGURE 1. Geometry and finite-difference grid of the combustion chamber of the boiler BKZ-75 of the Shakhtinskaya TPP.

bustion chamber of an existing Kazakhstan energy facility (Shakhtinskaya thermal power plant (TPP), Kazakhstan) is carried out. Based on the numerical solution of the system of convective heat and mass transfer equations [19], taking into account the kinetics of chemical reactions, two-phase flow, nonlinear effects of convective and radiation heat transfer and 3D modelling methods, aerodynamic, thermal, and concentration characteristics are obtained over the entire volume of the combustion chamber, in its main sections and on an output from itits output [20–26].

The results of the studies allow us to determine the optimal technological parameters of the investigated object, to improve the methodology for the numerical study of heat and mass transfer processes in high-temperature and chemically reacting flows in the presence of turbulence, and also develop appropriate technological solutions for installing burner devices (direct-flow or swirl) in the combustion chamber under study.

2. Description of the combustion chamber for conducting computational experiments

For carrying out computational experiments, the combustion chamber of the BKZ-75 boiler installed at the Shakhtinskaya TPP (Shakhtinsk, Kazakhstan) was selected. The steam boiler of the factory mark BKZ-75–vertically water-tube, with a productivity of 75 t/h (51.45 Gcal/h) [27]. The boiler is equipped with four pulverized coal burners which are installed in two on the front and back walls in one tier. During the operation of this combustion chamber, direct blowing of dust from individual dust preparation systems is used, which is provided by two hammer mills. Fig. 1 shows the geometry and the finite-difference grid of the combustion chamber of the BKZ-75 boiler for conducting computational experiments.

In the computational experiment for the steam boiler BKZ-75, the dust of Karaganda ordinary coal grade KR-200 was burned, the characteristics of which are indicated in the Table 1.

The designs of various burner devices of the combustion chamber of the BKZ-75 boiler are shown in Fig. 2. To conduct computational experiments in the combustion chamber of the BKZ-75 boiler, two cases were investigated: 1) the direct-flow method of supplying an air mixture - burners are located on opposite-side walls; 2) swirl air mixture supplying method - burners with a swirl angle of the air mixture flow and their inclination to the centre of symmetry of the boiler by 30 degrees.

3. Results of Numerical Modeling

Figures 3-13 show the results of computational experiments, the aerodynamic flow pattern (distribution of the overall velocity), temperature and concentration fields of carbon monoxide CO and nitrogen dioxide NO_2 for two cases of fuel supply to the combustion chamber of the BKZ-75 boiler, direct-flow and swirl.

The distribution of the overall velocity vector field in various cross-sections of the combustion chamber of the BKZ-75 boiler is shown in Figures 3 - 4. We can see that with the direct-flow method of supplying the air mixture, the flows, colliding in the center centre at a right angle (Fig. 3a), are dissected, and combined into two main streams are and sent to the exit from the combustion chamber (Fig. 4a).

With the swirl method of supplying the air mixture, four swirling flows directed from the swirl burners collide with each other in the central part at an angle of 30 degrees (Fig. 3b), and then, combined, are sent to the exit from the combustion chamber, with the formation of a swirl flow of higher intensity (Fig. 4b).

Figures 5 - 6 illustrate the temperature fields in various cross-sections of the combustion chamber of the BKZ-75 boiler for the two studied modes of the supply of air mixture (direct-flow and swirl). We see that the temperature has maximum values in the region close to the location of the burner.

With a direct-flow method of supplying the air mixture, the temperature value area of the burner section ($z = 4.0$ m) of the combustion chamber of the BKZ-75 boiler is 620.56 °C, and the region of maximum temperature values for the direct-flow burner is located near the walls of the combustion chamber, which causes their additional heat load (Fig. 5a, Fig. 6a).

The average temperature in the case of swirl burners with a swirl angle of 30 degrees is distributed differently. Here, the temperature in the burner area increases and amounts to 834.74 °C, and the core of a torch is observed in the centre of the combustion chamber (Fig. 5b, Fig. 6b), thereby reducing the thermal load on its walls. This is due to the swirl character of the flow, providing a maximum convective transport and an increase in the residence time of coal particles in the combustion chamber of the boiler.

Name	Symbol	Unit	Value
Type of coal	KR-200	-	-
Grinding fineness	R_{90}	%	20
Coal density	ρ	kg/m^3	1350
Calorific value of coal	Q_c	kJ/kg	$3.4162 \cdot 10^4$
Dry ash content	A^d	%	35.10
Volatile release to combustible mass	V	%	22.00
Humidity (coal as received)	W^{ar}	%	10.60
Carbon (coal as received)	C	%	79.57
Hydrogen (coal as received)	H_2	%	6.63
Oxygen (coal as received)	O_2	%	9.65
Sulfur (coal as received)	S_2	%	1.92
Nitrogen (coal as received)	N_2	%	2.23
The chemical composition of the ash (macro components)			
	SiO_2	%	60.2
	Al_2O_3	%	25.5
	Fe_2O_3	%	5.85
	CaO	%	3.65
	MgO	%	1.05
	TiO_2	%	0.95
	SO_3	%	0.8
	K_2O	%	1.65
	Na_2O	%	1.06

Table 1. Characteristics of the combustion chamber of the boiler BKZ-75 and fuel.

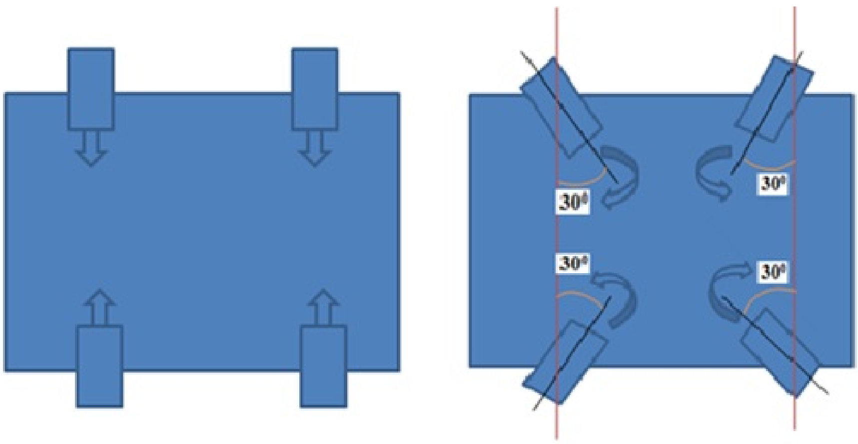

Figure 2. Designs of burner devices of the combustion chamber of the boiler BKZ-75: left) direct-flow burners; right) swirl burners.

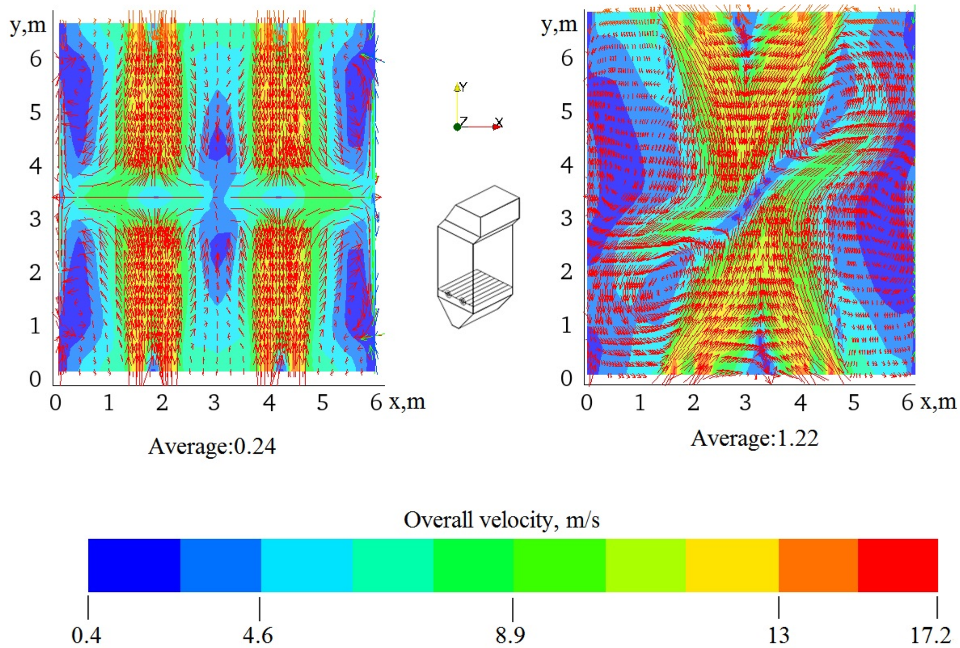

Figure 3. Distribution of the overall velocity in the area of the burner section ($z = 4.0$ m) of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

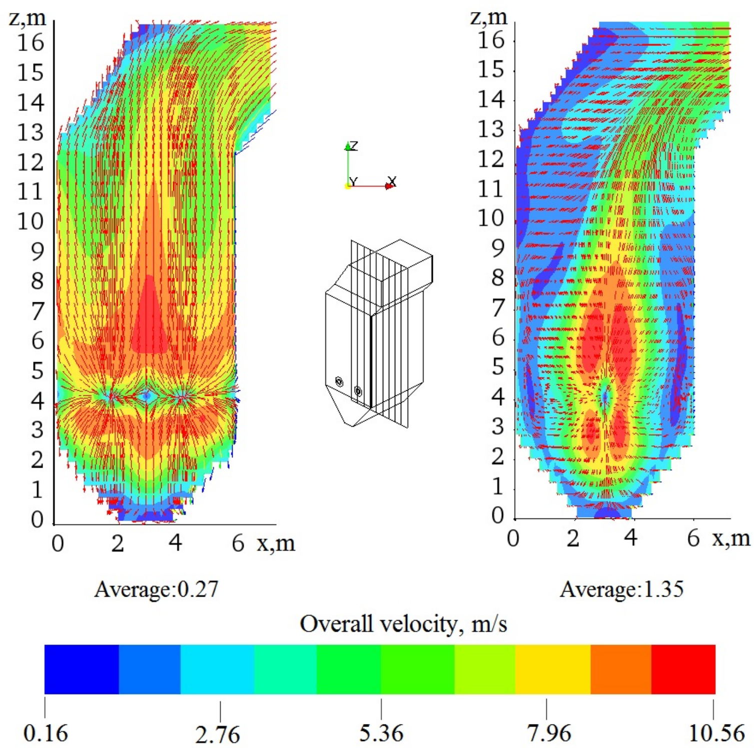

Figure 4. Distribution of the overall velocity in the central section ($y = 3.3$) of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

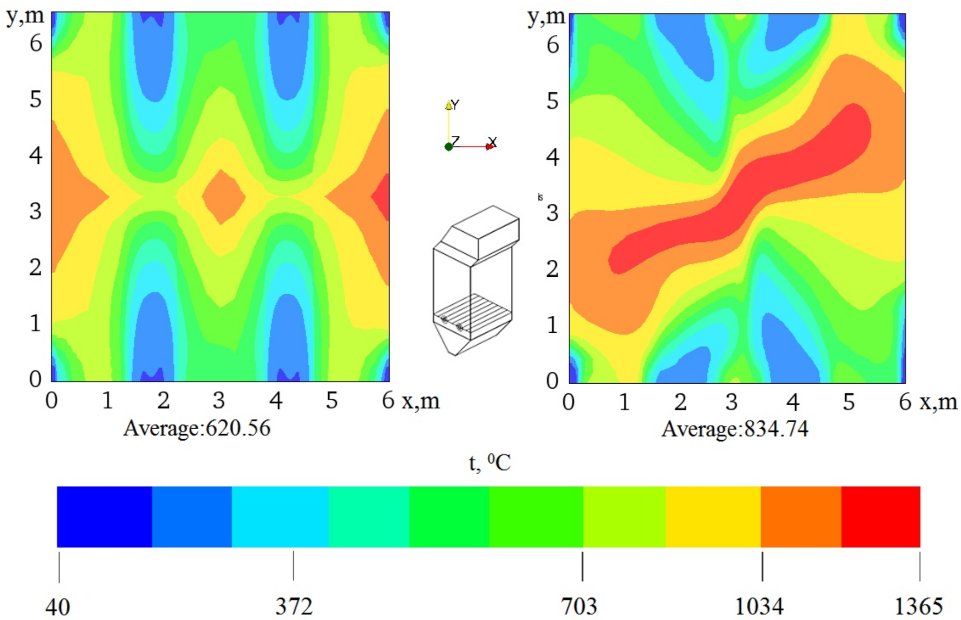

Figure 5. Temperature distribution in the area of the burner section ($z = 4.0\,\mathrm{m}$) of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

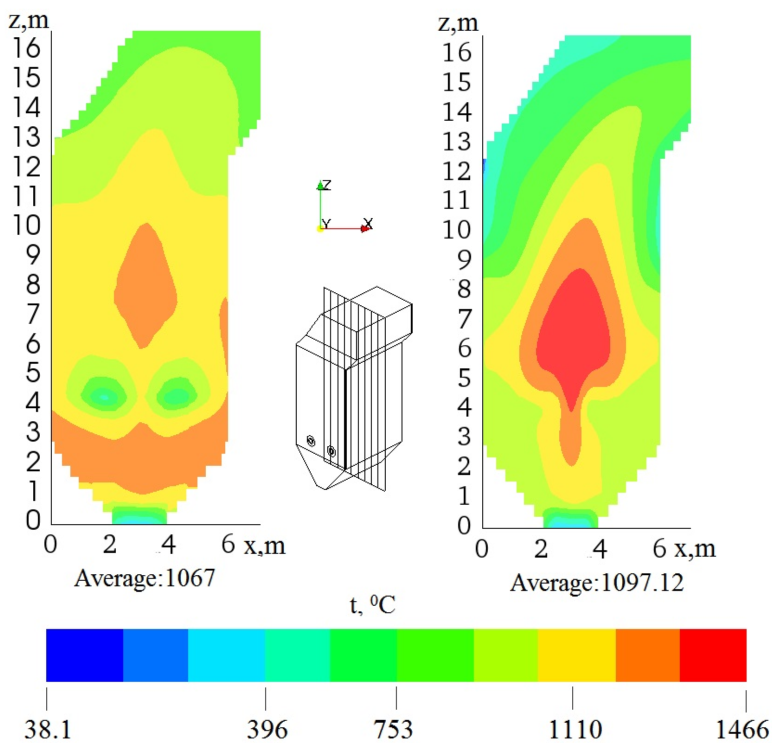

Figure 6. Temperature distribution in the central sections ($y = 3.3$) of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

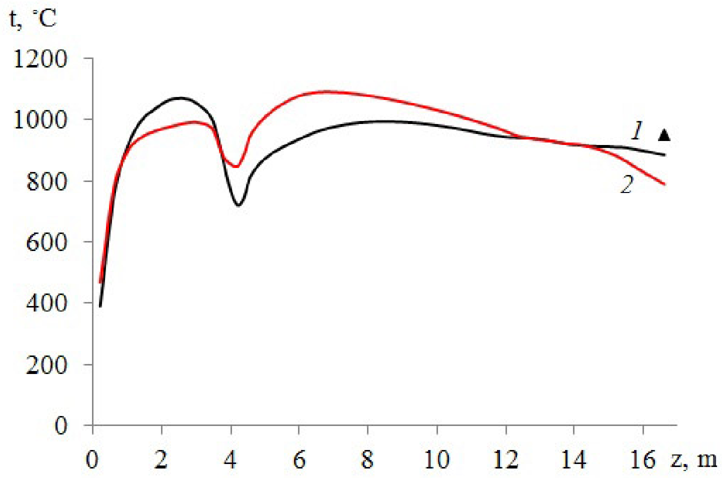

Figure 7. Temperature distribution along the height of the combustion chamber of the BKZ-75 boiler with: 1– direct-flow method of supplying an air mixture; 2 – swirl method of supplying an air mixture; ▲ – are theoretical values obtained by the method of thermal calculation (CBTI - Central Boiler and Turbine Institute) [28].

Figure 7 shows a comparative analysis of the distribution of the average temperature in the cross section over the height of the combustion chamber for the two studied modes of the air mixture supply (direct-flow and swirl). In the case of a swirl method of supplying an air mixture, an increase in the extent of the zone of maximum temperatures is observed. The minimal in the curves are associated with the low temperature of the air mixture entering the combustion chamber through the burners. The temperature at the outlet of the combustion chamber is confirmed by its theoretical value calculated by the method of CBTI (Central Boiler-and-Turbine Institute) for direct-flow supplying of air mixture [28]. An increase in the temperature in the core of the flame and a decrease in its output has a significant effect on the chemical processes of the formation of combustion products.

Figures 8 - 10 below show the distribution of carbon monoxide concentrations CO in various sections of the combustion chamber for the studied modes of the supply of air mixture (direct-flow and swirl).

An analysis of the figures shows that with a direct-flow method of supplying an air mixture, the average values of the concentration of carbon monoxide CO in the central sections (for $y = 3.3$) are $6 \cdot 10^{-3}$ kg/kg (Fig. 8a), while with a swirl method of supplying an air mixture, the minimum average values of the concentration of carbon monoxide are observed CO – $4 \cdot 10^{-3}$ kg/kg (Fig. 8b). As the combustion chamber moves upwards, the concentrations of carbon monoxide CO decrease and, at the outlet ($x = 7.1$), make up $7 \cdot 10^{-4}$ kg/kg for the direct-flow method of supplying the air mixture (Fig. 9a), and $6 \cdot 10^{-4}$ kg/kg for the swirl method of supplying the air mixture (Fig. 9b). This is confirmed by Fig. 10, which shows the curves of the distribution of carbon monoxide concentrations over the height of the combustion chamber of the BKZ-75 boiler for the two studied cases.

The concentration distributions of nitrogen dioxide NO_2 in various cross-sections of the combustion chamber are shown in Figures 11 - 13. As can be seen from the figures, the zone of the maximum formation of nitrogen dioxide NO_2 is the region of high temperatures and intense swirl flow. Intensive mixing of fuel and oxidizing agent created by turbulent flows of injected aerosol mixtures near the burners, as well as the high temperature in the torch core, create favourable conditions for the formation of nitrogen dioxides. In this area, the concentration of nitrogen dioxide NO_2 reaches its maximum values equal to $1067.63\,\mathrm{mg/m}^3_n$ (Fig. 11a) with a direct-flow method of supplying an air mixture, and $1045.91\,\mathrm{mg/m}^3_n$ (Fig. 11b) with a swirl method of supplying an air mixture.

However, towards the exit from the combustion chamber (Figures 12 - 13), a uniform decrease in the NO_2 concentration is observed, since this region contains less oxygen and a fuel component. In addition, in the case of the use of swirl burner devices, the temperature along the height of the combustion chamber monotonously decreases, as a result of which the rate of formation of nitrogen dioxide NO_2 decreases. At the outlet of the combustion chamber, the average value of the concentration of nitrogen dioxide NO_2, when using a direct-flow method of supplying an air mixture, is $564.34\,\mathrm{mg/m}^3_n$ (Fig. 12a and Fig. 13 curve 1), and with swirl burner devices – $439.35\,\mathrm{mg/m}^3_n$ (Fig. 12b and Fig. 13 curve 2), which is $125\,\mathrm{mg/m}^3_n$ less.

The obtained results point to the advantages of the selecting swirl burners to optimize the combustion of high-ash coal in the furnaces of power plants and reduce harmful dust and gas emissions into the environment.

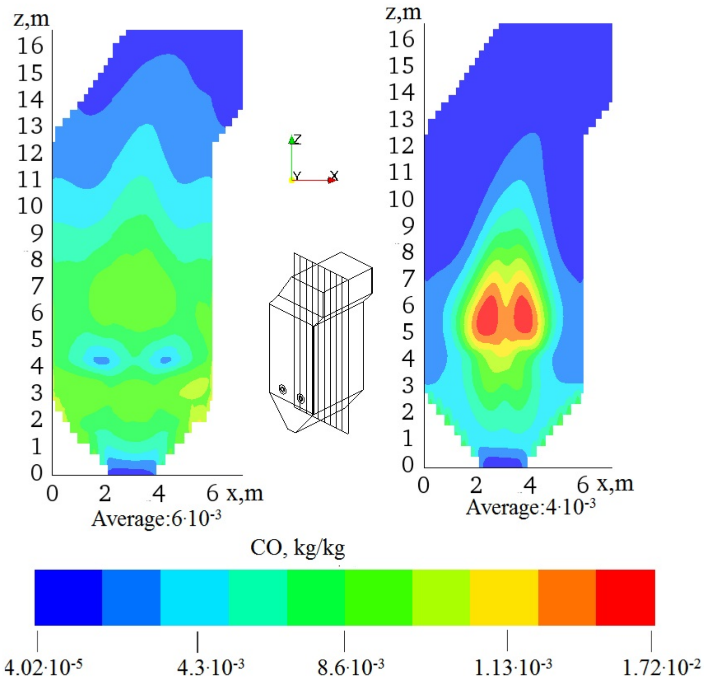

Figure 8. Distribution of carbon monoxide CO in the central sections ($y = 3.3$) of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

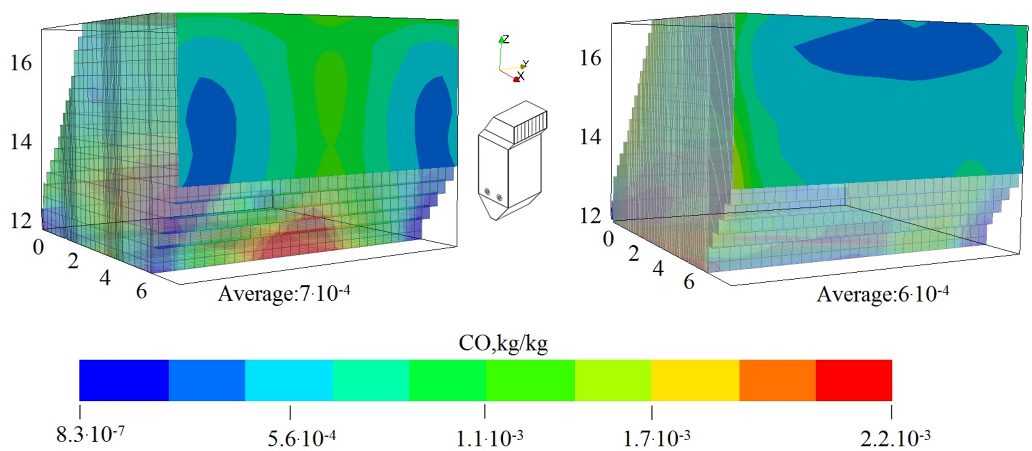

Figure 9. Distribution of carbon monoxide CO at the outlet of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

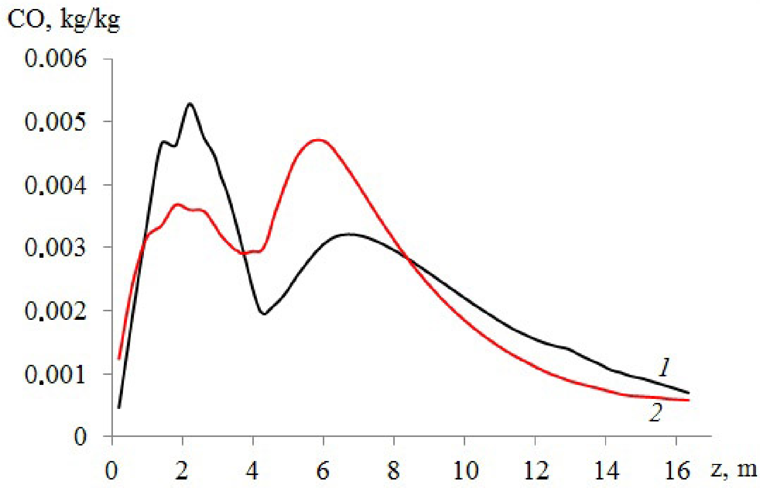

Figure 10. Distribution of the concentration of carbon monoxide CO over the height of the combustion chamber of the boiler BKZ-75 with: 1 - direct-flow method of supplying an air mixture; 2 - swirl method of supplying an air mixture.

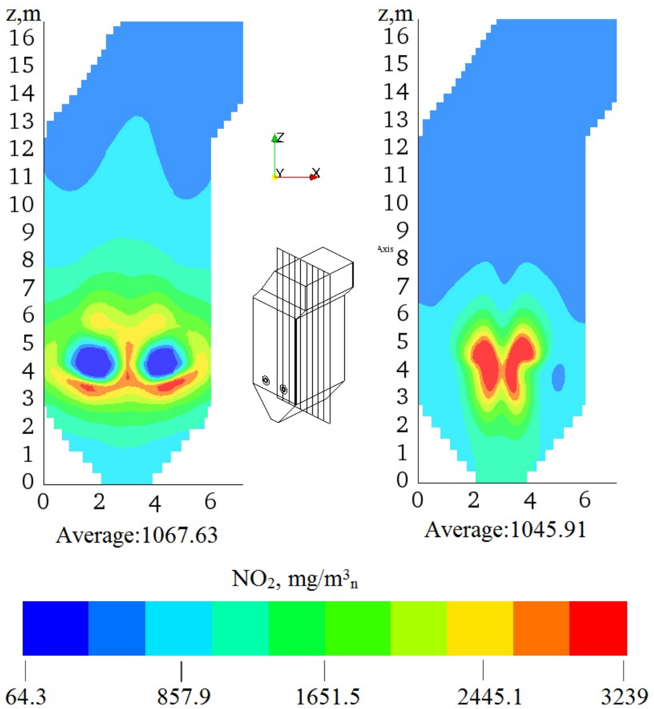

Figure 11. Distribution of nitrogen dioxide NO_2 in the central sections ($y = 3.3$) of the combustion chamber of the BKZ-75 boiler with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

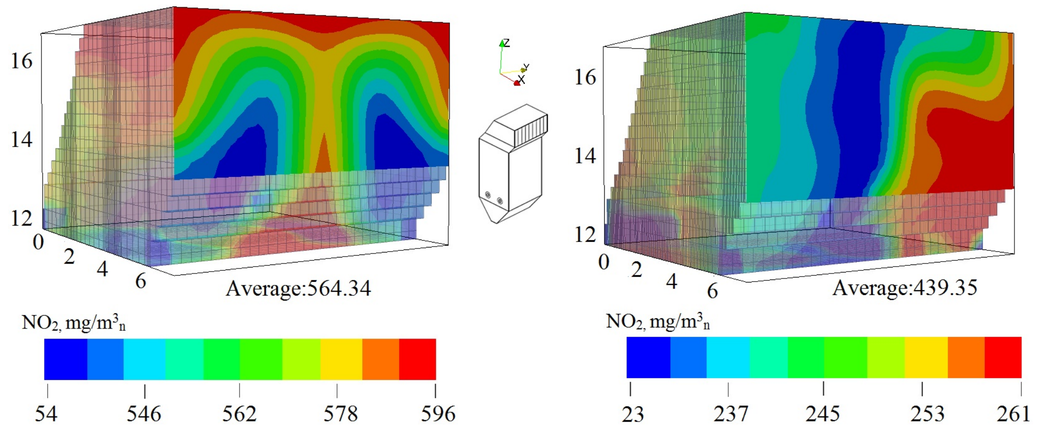

Figure 12. Distribution of nitrogen dioxide NO_2 at the outlet of the combustion chamber of the boiler BKZ-75 with: a) direct-flow method of supplying an air mixture; b) swirl method of supplying an air mixture.

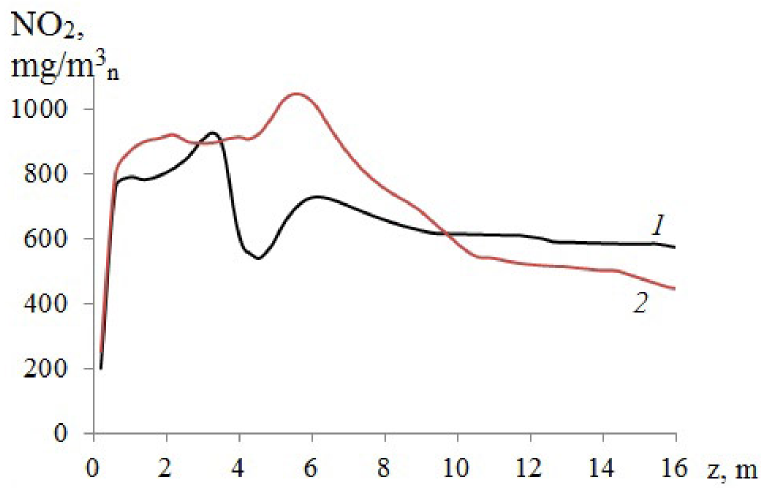

Figure 13. Distribution of the concentration of nitrogen dioxide NO_2 along the height of the combustion chamber the boiler BKZ-75 with: 1 – direct-flow method of supplying an air mixture; 2 – swirl method of supplying an air mixture.

4. Conclusion

Based on the research results, the following conclusions can be formulated:

- A comparison of the characteristics of combustion processes for two cases is given for a direct-flow method of supplying the air mixture – burners are located on opposite-side walls and a swirl method of supplying the air mixture – burners with a swirl angle of the air mixture and their inclination to the boiler symmetry centre by 30 degrees.
- The results of computational experiments on the distribution of the overall velocity, temperature fields, concentration fields of carbon oxides CO and nitrogen dioxides NO_2 over the entire volume of the combustion chamber and their comparative analysis for the two studied modes of the supply of air mixture (direct-flow and swirl) are presented.
- Two cases of the method of supplying the air mixture with the direct-flow and swirl methods of supplying the mixture were investigated, and it was found that the aerodynamics of the flow in both cases is different. In the direct-flow method of supplying air mixtures, the flows, colliding in the centre at a right angle, are cut in the region of the cold funnel and towards the exit from the combustion chamber, with the formation of a swirl flow of lower intensity. In the swirl method of supplying the air mixture, four swirling flows area of the burner section guided from the swirl burners collide with each other in the central part of the combustion chamber at an angle of 30 degrees. Then, having united in two main streams, they interact, forming swirl flows in the horizontal region of the combustion chamber. High stability of the swirl flow position increases the residence time of the coal dust in the combustion zone and will significantly reduce high concentrations of harmful substances.
- During a swirl feed of an air mixture, an increase in the extent of the zone of maximum temperatures is observed. The temperature values greatly differ depending on the area of the burner section. An

increase in the temperature in the flame core and a decrease in its outlet have a significant effect on the chemical processes of the formation of combustion products, since the temperature is the main factor in determining the rate of combustion of the components of the fuel mixture.

- The swirl method of supplying the mixture is preferable for the studied combustion chamber, since, at the outlet from the combustion chamber, the average concentration of carbon monoxide CO and nitrogen dioxide NO_2 decreases when using swirl burners. The value of the concentration of harmful substances (NO_2, CO) at the exit from the combustion chamber corresponds to the maximum permissible concentrations standards adopted in the power system of the Republic of Kazakhstan.

Acknowledgements

This work was supported by the Ministry of Education and Science of the Republic of Kazakhstan No. BR05236730, No.AP05132988 and No.AP05133590.

The last author, P. Safarik, expresses thanks for the support by the Project No. CZ.2.16/3.1.00/21569 Centre 3D Volumetric Anemometry.

References

[1] National energy statistics action plan for the Republic of Kazakhstan. Produced with the support of the INOGATE Programme, 20013, p. 38.

[2] Y. A. Anikin, et al. Swirl steam generator of a new type modeling of furnace processes. In *VIII All-Russian Conference with the International Part "Combustion of Solid Fuel"*, pp. 51–66. Institute of Thermophysics named after S.S. Kutateladze SORAN, 2012.

[3] R. Leithner, H. Müller, A. Magda, et al. Combustion of low-rank coals in furnaces of kazakhstan coal-firing power plants. *VDI Berichte* pp. 497–502, 2007.

[4] A. Askarova, S. Bolegenova, V. Maximov, A. Bekmuhamet. Mathematical simulation of pulverized coal in combustion chamber. *Procedia Engineering* **42**:1150 – 1156, 2012. doi:10.1016/j.proeng.2012.07.507.

[5] S. S. Ospanova, et al. The computational study of heat and mass transfer processes at combustion of pulverized Kazakh coal in real conditions of energy objects. *Bulgarian Chemical Communications* **50**:61–67, 2018.

[6] V. Messerle, A. Askarova, S. Bolegenova, et al. 3D-modelling of Kazakhstan low-grade coal burning in power boilers of thermal power plant with application of plasma gasification and stabilization technologies. *Journal of Physics: Conference Series* **1261**:12–22, 2019. doi:10.1088/1742-6596/1261/1/012022.

[7] A. Askarova, S. Bolegenova, V. Maximov, et al. Control of harmful emissions concentration into the atmosphere of megacities of Kazakhstan Republic. *IERI Procedia* **10**:252 – 258, 2014. International Conference on Future Information Engineering (FIE 2014), doi:10.1016/j.ieri.2014.09.085.

[8] R. Leithner, E. I. Heierle, et al. Cfd code florean for industrial boilers simulations. *WSEAS Transactions on heat and mass transfer* **4**:98–107, 2009.

[9] A. S. Askarova, E. I. Heierle, S. A. Bolegenova, et al. CFD study of harmful substances production in coal-fired power plant of Kazakhstan. *Bulgarian Chemical Communications* **48**:260–265, 2016.

[10] H. Müller. Numerische Berechnung Dreidimensionaler Turbulenter Strömungen in Dampferzeugern mit Wärmeübergang und Chemischen Reaktionen am Beispiel des SNCR-verfahrens und der Kohleverbrennung. *Fortschritt-Berichte VDI-Verlag* p. 46, 1992.

[11] R. Backreedy, L. Fletcher, L. Ma, et al. Modelling pulverised coal combustion using a detailed coal combustion model. *Combustion Science and Technology* **178**:763–787, 2006. doi:10.1080/00102200500248532.

[12] A. Askarova, V. Maximov, S. Bolegenova, et al. Investigation of heat and mass transfer processes in the combustion chamber of industrial power plant boiler. Part 2. Distribution of concentrations of O2, CO, CO2, NO. *Applied and Computational Mechanics* **12**:127–138, 2018. doi:10.24132/acm.2018.396.

[13] A. Georgiev, et al. The use of a new "clean" technology for burning low-grade coal in on boilers of Kazakhstan TPPs. *Bulgarian Chemical Communications* **50**:53–60, 2018.

[14] A. S. Askarova, V. E. Messerle, A. B. Ustimenko, et al. 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):125–134, 2016. doi:10.1134/S0869864316010133.

[15] V. Messerle, A. Askarova, A. Ustimenko, et al. Optimization of the combustion of power station coals using plasma technologies. *Journal Thermal Engineering* **51**:488–493, 2004.

[16] A. S. Askarova, S. A. Bolegenova, V. Y. Maximov, M. T. Beketayeva. Modeling of heat mass transfer in high-temperature reacting flows with combustion. *High Temperature* **56**(5):738–743, 2018. doi:10.1134/S0018151X1805005X.

[17] Leithner, Reinhard, Askarova, Aliya, Bolegenova, Saltanat, et al. Computational modeling of heat and mass transfer processes in combustion chamber at power plant of kazakhstan. *MATEC Web Conf* **76**:06001, 2016. doi:10.1051/matecconf/20167606001.

[18] A. Askarova, S. Bolegenova, V. Maximov, A. Bekmuhamet. Mathematical simulation of pulverized coal in combustion chamber. *Procedia Engineering* **42**:1150 – 1156, 2012. doi:10.1016/j.proeng.2012.07.507.

[19] A. Askarova, S. Bolegenova, S. Bolegenova, et al. Simulation of low-grade coal combustion in real chambers of energy objects. *Acta Polytechnica* **59**(2):98 – 108, 2019. doi:10.14311/AP.2019.59.0098.

[20] A. S. Askarova, S. A. Bolegenova, V. Y. Maximov, et al. Mathematical modeling of heat and mass transfer in the presence of physical-chemical processes. *Bulgarian Chemical Communications* **48**:272–277, 2016.

[21] A. Askarova, A. Bekmukhamet, S. Bolegenova, et al. 3-D modeling of heat and mass transfer during combustion of solid fuel in BKZ-420-140-7C combustion chamber of Kazkhstan. *Journal of Applied Fluid Mechanics* **9**(2):699–709, 2016. doi:10.18869/acadpub.jafm.68.225.22881.

[22] A. Askarova, V. Messerle, I. Loktionova, A. Ustimenko. 3D Modeling of the Two-Stage Combustion of Ekibastuz Coal in the Furnace Chamber of a PK-39 Boiler at the Ermakovo District Power Station **50**(08):633–638, 2003.

[23] N. Mazhrenova, et al. 3D modelling of heat and mass transfer processes during the combustion of liquid fuel. *Bulgarian Chemical Communications* **48**:229–235, 2016.

[24] A. Askarova, S. Bolegenova, A. Bekmukhamet, et al. Using 3D Modeling technology for investigation of conventional combustion mode of BKZ-420-140-7C combustion chamber. *Journal of Engineering and Applied Sciences* **9**(01):24–28, 2014. DOI:10.3923/jeasci.2014.24.28.

[25] M. Buchmann, A. Askarova. Structure of the flame of fluidized-bed burners and combustion processes of high-ash coal. In *Proceedings of the18th Dutch-German Conference on Flames*, Gesell Energietech, Combustion and Incineration, pp. 241–244. VDI Berichte, 1997.

[26] S. Bolegenova, et al. Investigation of the different reynolds numbers influence on the atomization and combustion processes of liquid fuel. *Bulgarian Chemical Communications* **50**:68–77, 2018.

[27] M. Gorokhovski, A. Chtab-Desportes, I. Voloshina, A. Askarova. Stochastic simulation of the spray formation assisted by a high pressure. *AIP Conference Proceedings* **1207**(1):66–73, 2010. DOI:10.1063/1.3366446.

[28] Thermal calculation of boilers. Normative method, Publishing House AOOT "NCPO CKTI", 1998.