*Bulgarian Chemical Communications, Volume 51, Special Issue F (pp. 19 - 25) 2019*

# Numerical simulation of turbulent combustion of pulverized coal flame

A. S. Askarova[1], S. A. Bolegenova[1],V. Yu. Maximov[2], S. A. Bolegenova[2], N. R. Mazhrenova[1], Zh. K. Shortanbayeva[1], R. K. Manatbayev[1*], M. R. Mamedova[1]

[1]*Al-Farabi Kazakh National University, Faculty Physics and Technical, Almaty, ave. Al-Farabi 71, Kazakhstan*
[2]*Scientific Research Institute of Experimental and Theoretical Physics, ave. Al-Farabi 71a, 050040 Almaty, Kazakhstan*

The increased demand for solid fuels is accompanied by the need to reduce emissions of pollutants into the atmosphere and to increase the efficiency of fuel combustion process. Thus, research in the field of advanced technologies to improve pulverized coal combustion plants and the use of alternative methods of organizing the combustion process of various types of fuel are currently the most relevant for the entire energy sector of the Republic of Kazakhstan. The main direction in improving pulverized coal combustion and the use of alternative fuels is to meet stringent environmental requirements for specific emissions of harmful substances with exhaust gases, for which there are standards defined.

**Keywords***:* combustion, coal, combustion chamber, boiler, burners, fuel

## INTRODUCTION

The fundamental and applied prospects of the tasks that are proposed for solution in this paper are determined by the prevalence of turbulent flows in nature and technology, as well as the difficulty of their experimental and theoretical research. The prospectivity of the proposed research lies in updating the tasks associated with the development of numerical methods as applied to the study of complex practical problems. The practical value of the study is determined by the universality of the proposed research method, which can be widely used at various energy facilities of the Republic of Kazakhstan.

## JUSTIFICAITON OF RESEARCH TASK

Along with the energy consumption growth, the environmental danger is progressively increasing due to the emissions of harmful substances and industrial waste, which resulted in the development of the Kyoto Protocol that established quotas for these emissions and penalties for their violation.

To solve the problems of modern power engineering and ecology it is especially important to study the processes of heat-and-mass transfer in the high-temperature reacting media and to simulate physical and chemical processes that occur during the combustion of pulverized coal. These problems are related, on the one hand, to the concept of "energy safety" of the country and, on the other hand, to the development of processes of "clean" fuel combustion under strict standards of emission of harmful substances into the environment.

In the conditions of depletion of natural power resources and environmental pollution, implementation of technological processes with the rational use of fossil fuels, increase in the efficiency of energy generation and solution of environmental problems are actual and important tasks [1-5].

Expensive experimental studies on reduced fire models do not strictly comply with all the conditions that correspond to the actual combustion process, as it is necessary to achieve the geometrical and physical resemblance of the objects and to observe basic parameters and operation conditions corresponding to the technological combustion scheme used at the real power facility.

Theoretical investigations of heat-and-mass transfer in the presence of physical and chemical transformations in moving high-temperature responsive environment also cannot answer all the questions. This is because such flows are described by a complex system of non-autonomous nonlinear multidimensional partial differential equations. That corresponds to the transfer of momentum, distribution of heat, components of the reaction mixture and the reaction products, which must take into account a considerable turbulence, multi-phase medium and source terms related to chemical kinetics of the processes.

Analytical solutions of this complex system of equations have not yet been found, and they can be

---

* To whom all correspondence should be sent:
rustem1977@mail.ru

solved only numerically. Recently, the main methods used to study such processes, particularly in the areas of real geometry, are the methods of numerical modeling and on their basis numerical experiments that adequately reflect the actual physical processes occurring in the combustion chambers. Progress in the development of computational models, in the creation of efficient computational algorithms and problem-oriented software packages allows us to solve many problems that are of great practical application in various industries [6-10].

Therefore, it is important to carry out a comprehensive study of physical and chemical processes of heat transfer in the high-temperature environment. This study will be based on the achievements of modern thermal physics, the use of new numerical methods of 3D modeling, construction of efficient computational algorithms and new computational models that enable scientists to describe with high degree of accuracy real physical processes that occur during combustion of power-plant fuels in the combustion chambers of operating power stations.

It should be noted that more than 80% of all energy produced in the world is produced by burning fossil fuels. Other sources of energy: nuclear power, hydropower, solar and wind power plants in the coming decades will not be able to compete with traditional methods of its production.

The limited fossil fuels resources necessitate the search for more cost-efficient methods of its combustion, while the scale of industrial production is such that the problem of generation of harmful substances during combustion comes to the fore.

Combustion of pulverized coal has the greatest environmental impact: toxic and greenhouse gases, particulate matter, waste and seepage water, slag waste ash, heat waste and much more. Moreover, the development of the energy complex is associated with a large-scale transformation of environmental components, the negative effects of which can manifest for a long time. Coal pits change the topography and form specific soil conditions in dumps, hydroelectric reservoirs cause changes in seismicity, flood the most productive valley ecosystems, and change the landscape structure of the regions [11-15].

Coal industry of Kazakhstan is one of the largest sectors of the country's economy. Today, coal industry of the republic provides 80% of electricity in Kazakhstan. In terms of proven coal reserves, Kazakhstan ranks 8th in the world and contains 4% of the global reserves in its depths. The most valuable for industry power and coking coals are concentrated in 16 deposits [16-21]. Coal reserves of are estimated at 75 billion tons. The Republic of Kazakhstan is among the ten largest coal producers in the world market, ranks third in terms of reserves and production among the CIS countries, and is first in terms of coal mining per capita.

The main power plant coals of Kazakhstan are mined by open-pit method, resulting in their low cost. Coal of Kazakhstan is a cheap energy fuel, and its reserves will be sufficient for many hundreds of years. However, it should be noted their low sulfur and low nitrogen content (less than one percent). Nevertheless, Kazakhstan's coal, being a good energy fuel for its reactivity, have one big disadvantage - high ash content. The ash content of coal supplied from separate Kazakhstan’s fields to CHP plants sometimes exceeds 70%. While in the UK it is 22% in accordance with the law, 9% in the USA, and 8% in Germany [22].

Many of Kazakhstan’s CHP plants primarily use cheap high-ash Ekibastuz coal, which is mined by open-pit method. The adopted coal mining technology and its use without prior enrichment leads to a considerable anthropogenic pressure on the ecosystem. The ash component of coal is a mixture of minerals that are in a free state or are associated with fuel.

## BASIC EQUATIONS OF THE MATHEMATICAL MODEL

The problem of modeling is very complex, as it involves the interaction of turbulent combustion of many chemical components with multiphase processes (particles of gaseous or solid fuel and carbon in the flow field) and with radiant heat transfer.

During particles combustion, it is necessary to take into account the rates of heterogeneous reactions and it is required to know particles distribution by sizes and in space. Emission of pollutants, such as hydrocarbons, soot and nitrogen oxides, can be reduced by appropriately controlling temperature and concentration changes patterns in the combustion area.

For three-dimensional fluid motion with variable physical properties, the field of velocity, temperature and concentration is described by a differential equations system (1 - 4)

a) The continuity equation:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x_i}\left(\rho u_i\right), \qquad (1)$$

b) The equation of motion:

$$\frac{\partial}{\partial t}(\rho u_i) = -\frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial}{\partial x_j}(\tau_{i,j}) - \frac{\partial \rho}{\partial x_j} + \rho f_i, \quad (2)$$

Here: $f_i$ – volume forces; $u_i$ - components of velocity, m/s; $\tau_{i,j}$ – viscous stress tensor.

d) The energy equation:

$$\frac{\partial}{\partial t}(\rho h_i) = -\frac{\partial}{\partial x_i}(\rho u_i h) - \frac{\partial q_i}{\partial x_i} + u_i \frac{\partial \rho}{\partial x_i} + \tau_{ij}\frac{\partial u_j}{\partial x_i} + S_q \quad (3)$$

Here: $h$ – enthalpy; $q_i$– energy flux density due to molecular heat transfer, $S_q$ – energy source.

c) Conservation law for a component of a substance:

$$\frac{\partial}{\partial t}(\rho c_\beta) = -\frac{\partial}{\partial x_i}(\rho c_\beta u_j) + \frac{\partial}{\partial x_i} + R_\beta, \quad (4)$$

where $I$ = 1,2,3; $j$ = 1,2,3; $\beta$=1,2,3,…N; $R_\beta$ - source of substance.

To model turbulent viscosity, the well-known *k-ε* turbulence model was used. Consisting of the equation of conservation of the kinetic energy of turbulence *k*, its dissipation rate *ε* and the model relation for turbulent viscosity. The k-*ε* turbulence model is the standard model for forced and natural convection flows.

a) The standard k-ε turbulence model:

$$\frac{\partial\left(\bar{\rho} k\right)}{\partial t} = -\frac{\partial\left(\bar{\rho}\,\bar{u}_j k\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + \quad (5)$$
$$+P - \bar{\rho}\varepsilon,$$

Where P is the production of kinetic energy of turbulence, which is determined by the following relation:

$$P = \left[\mu_{turb}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right]\frac{\partial \bar{u}_i}{\partial x_j} - \left[\frac{2}{3}\rho k \delta_{ij}\right]\frac{\partial \bar{u}_i}{\partial x_j} \quad (6)$$

and the equation for the dissipation of turbulent kinetic energy ε:

$$\frac{\partial\left(\bar{\rho}\varepsilon\right)}{\partial t} = -\frac{\partial\left(\bar{\rho}\,\bar{u}_j \varepsilon\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + \quad (7)$$
$$+C_{\varepsilon,1}\frac{\varepsilon}{k}P - C_{\varepsilon,2}\frac{\varepsilon^2}{k}\bar{\rho},$$

Here, is the conversion of the kinetic energy of the pulsating motion into internal energy (dissipation).

Initial conditions: $u = 0$, $v = 0$, $w = 0$, $P = 0$, at t = 0.

The boundary conditions must be set on the free surfaces, which are the burners, the exit from the combustion chamber of the boiler and the plane of symmetry.

For velocity, we set the values of its normal and tangential component and their gradient:

At the input: $u_i$ - velocity values at the inlet.

At the output: $\left.\frac{\partial u_i}{\partial x_i}\right|_{no} = 0$, in the plane of symmetry: $\left.u_i\right|_{no} = 0$, $\left.\frac{\partial u_i}{\partial x_i}\right|_{no} = 0$.

## PHYSICAL STATEMENT OF PROBLEM

The computing experiment in the work was carried out for the combustion chamber of the BKZ-160 boiler at Almaty Thermal Power Plant (Kazakhstan), with a steam capacity of 160 t/h, a pressure of 9,8 MPa and a superheating temperature of 540°C.

Steam heating capacity Q = 119,5 MW (97,8 Gcal/h), thermal power of the furnace N = 124,4 MW (107 Gcal/h). The boiler is designed to burn coal.

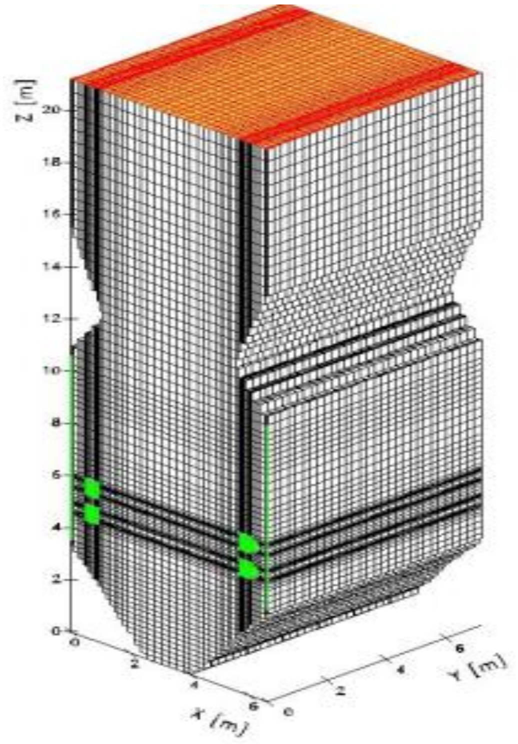

**Fig.1.** General view of the combustion chamber of the boiler BKZ-160 and its breakdown into control volumes

There are 4 blocks of direct-flow slot burners (2 burners per block), directed tangentially to a circle with a diameter of 60x4 with a step of 64 mm on the sides of the furnace chamber. The screens are divided into 12 separate circulation circuits. Front and rear screen pipes form a cold funnel in the bottom part, while in the upper part the rear screen pipes are bent into combustion chamber, forming an "aerodynamic" nose. After the "aerodynamic" nose the rear screen pipe run into chambers, from where steam-water mixture is sent to the boiler drum through the slag screen.

A radiation-convective steam superheater is installed on the boiler. The radiation part of the super-heater is made in the form of screen heating surfaces located behind the aerodynamic nose, and ceiling superheater pipes.

Convective surfaces of the superheater are in the upper exhauset duct. In the convective part, behind the convective superheater, a water economizer and a tubular air preheater of 2 and 1 stages are arranged in series.

The pulverized-coal system with a dust bunker has got 2 ball-pulverized mills ShBM-250 and 2 mill exhausters BM-50/1000. Dust is dried by hot air. Dust is supplied from dust bins through eight ULPP-1 dust feeders and then transported through pulverized fuel pipes to the burners.

Air is supplied to air heater through two blower fans VD 15.5. 2 exhaust fans are used to remove flue gas. Ash extraction from the furnace is dry. Fly ash is trapped in wet fly ash collectors.

8 straight-through slot burners of the BKZ-160 boiler furnace are located on the side walls of the furnace in a tangential pattern. Every two burners are combined into a burner assembly.

Each burner has one air-and-fuel mixture channel and two secondary air channels above and below air-and-fuel mixture channel and separated by lined walls. The upper and lower burners are also separated by a partition in the center of which a fuel oil nozzle is mounted for flame kindling and lighting.

Fuel capacity of one burner is 4 t/h. Secondary air flow rate through the burner is $V = 6000\ nm^3/h$ with an excess air coefficient $\alpha=0.38$. The secondary air heating temperature is t=380°C. The cross-sectional area of secondary air channels at the burner outlet is $F=0.2m^2$, which ensures secondary air velocities level at the burner outlet of W = 40 m/s.

Coal dust is supplied to the burners with hot air. Air consumption for transporting dust per burner is $V=4850\ nm^3/h$. The primary excess air coefficient is $\alpha=0.3$. The balance temperature of the air mixture at the burner outlet is t = 250°C. The cross-sectional area of the air-and-fuel mixture channel is $F=0.105\ m^2$, which ensures the speed of the air mixture at the burner outlet $W_1=25$ m/s. The ratio of the velocities of secondary and primary air is $W_2/W_1 = 1.64$. The excess air coefficient in the burners is $\alpha_g = \alpha_1+\alpha_2 = 0.68$.

Hot air consumption per mill is 12,000 $nm^3/h$. After the mill, exhaust air is fed into the furnace through 4 waste burners located from the rear and from the front of the boiler.

Based on the air balance with the excess air coefficient at the furnace outlet being $\alpha_t = 1.27$, false air inflow into the furnace and dust systems make up about 40%, which deteriorates the efficiency of the boiler.

In the burners' area, where the ignition takes place, the flame is essentially non-uniform. However, at a distance from the burners, the concentrations of dust, oxygen and combustion products are equalized, as well as the temperature over the cross section of the flame.

Almaty TPP-3 is equipped with six BKZ-160 boilers with steam capacity of 160t/h each.

## COMPUTING EXPERIMENT RESULTS

This section presents the results of computer simulation of the turbulent combustion of a pulverized coal flame in the BKZ-160 boiler chamber.

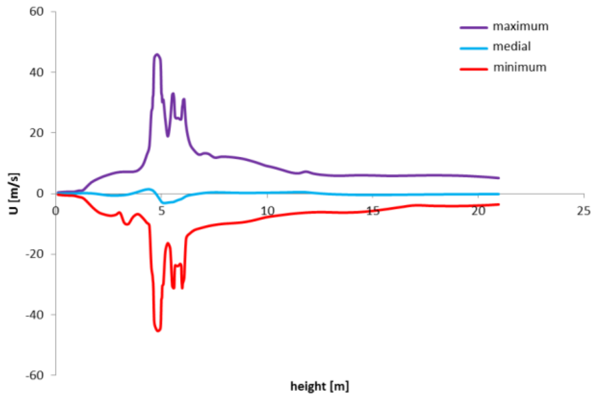

**Fig.2.** Distribution of velocity component U along the height of the combustion chamber

Graphs analysis (Fig.2 and Fig.3) of the maximum, minimum and medial values of full velocity components: U, V, indicates the symmetry of flows distribution in each section of combustion chamber.

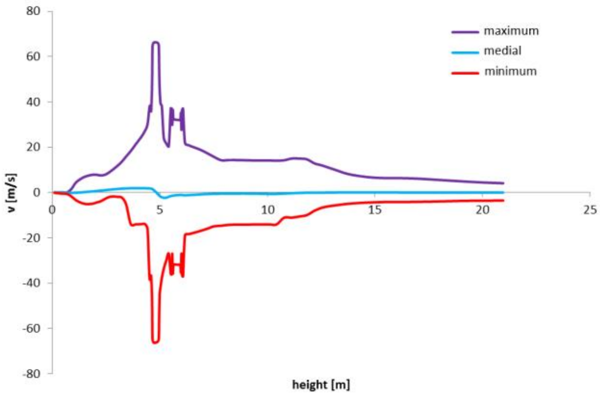

**Fig.3.** Distribution of velocity component V along the height of the combustion chamber

Figs.3-4 shows the minimum, maximum and average values of the full velocity vector along the height of the combustion chamber. At a height of four meters, the vector of full velocity reaches its maximum value. It is at this height that burner devices are installed through which the aerosol is injected at a maximum velocity reaching its value.

From a physical point of view, the velocity value cannot be negative, therefore, in the above figure, the negative values of the total velocity vector should be interpreted as the outflow of the mixture flow from opposite burners, where, according to the initial physical conditions, the flows have the same velocities, which is reflected in Figs.3-4.

As the flow reaches fuel mixture and the combustion products to the output speed falls monotonically, except for the deflection of the boiler chamber, in which we observe a certain peak area distribution vector full speed. In this region, the flow again becomes unsteady and therefore the velocity undergoes minor changes. This reflects the real aerodynamic picture of the physical and chemical processes occurring in the studied configuration of the combustion chamber.

The kinetic energy of turbulence k and the dissipation of turbulent energies ε, determined by relations (5) and (7) through the pulsating velocity components.

When the maximum turbulent kinetic energy k and its dissipation ε reach the central region opposite the burners. This is understandable, since in this region there is a collision of dust and gas flows from opposite tangentially located burner devices, which leads to a maximum perturbation of the flow in this region of the combustion chamber and to a high level of turbulence here. And this, in turn, provides high values of turbulent kinetic energy and its dissipation directly depend on the pulsations of the velocity (disturbances) and the level of turbulence.

Significant turbulization of the flow occurs with good filling of the combustion space, therefore, with an increased residence time of the combustible mixture in the combustion space.

Due to the slightly rarefied filling of the chamber section above the burners, vortices develop at the front and rear walls. Part of the upward flow is directed to the exit from the furnace. Excess flow recycles, forming vortex regions near the walls in the area above the burners.

The presence of rotation of flows in the near-wall zone promotes uniform heating of surfaces and a decrease in slagging of screens, which allows reducing corrosion and thermal overheating. To the exit from the combustion chamber, the upward flow expands intensively and at the exit is evenly distributed over the entire cross section.

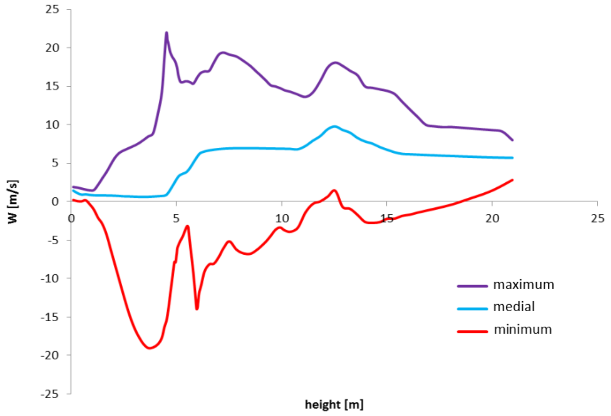

**Fig.4.** Distribution of velocity component W along the height of the combustion chamber

Only in the distribution of velocity component W is there no symmetry (Fig.4). From the analysis of the graphs obtained, we can draw the following conclusion: in the area where the burners are located, the fuel and air supply speed reaches its highest values.

Areas with a steep increase in pressure can be determined from the distribution of maximum, minimum and medial pressure values over the cross section (XY) (Z=const) (Fig.5). Naturally, these are areas where the burner tiers are located, which is due to the maximum velocity values.

The strongest pressure change occurs in the area of the burners, i.e. in the field of fuel and oxidizer supply. As the burners move away from this area, the pressure monotonously decreases.

The maximum convective transfer is observed in the blended fuel plane supply and in the combustion chamber symmetry plane. Combustion reactions here are the most intense, resulting in significant temperature changes in this area.

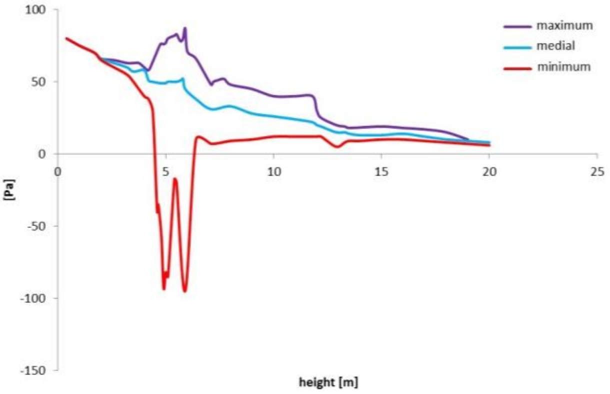

**Fig.5.** *P* pressure distribution along the height of the combustion chamber

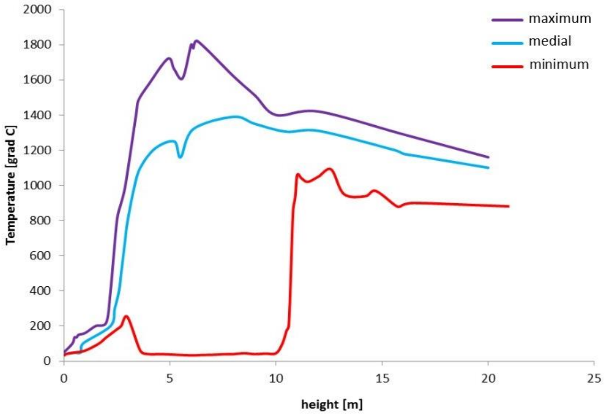

**Fig.6.** Distribution of temperature along the height of the combustion chamber

Fig.6 shows the distribution of the maximum, minimum and medial temperatures in cross-sections (X, Y) along the height of the boiler. The minima on all curves are related to the low temperature of the fuel mixture entering this area of combustion chamber through burners. Temperature maxima are observed directly in sections passing through the burner axis. Near the reaction zone, peaks in the distribution of temperature and its gradient are detected in the flame. As you move toward the outlet of combustion chamber, the temperature drops evenly.

## CONCLUSIONS

The work has developed physical and mathematical model of combustion chamber of the Kazakhstan power boiler BKZ-160 at Almaty thermal power plant with a tangential supply of pulverized coal, which adequately reflects the main elements, the configuration of combustion chamber, the arrangement of its burners and the real high-ash coal combustion process therein.

Computational experiments were carried out to simulate pulverized coal flame combustion process in combustion chamber of the BKZ-160 power boiler, and determine key characteristics of the flow aerodynamics: the full velocity and pressure P field.

The obtained results of numerical simulations of the aerodynamics process correctly reflects the real flow pattern that occurs in the combustion chambers of existing industrial boilers with a tangential supply of dust and gas mixture.

The results of numerical modeling of aerodynamics of the BKZ-160 furnace boiler showed that in the combustion chambers with the tangential supply of fuel and oxidizer, the organization of the vertical directional rotational movement of the flue gases occurs.

## ACKNOWLEDGMENT

This work was supported by the Ministry of Education and Science of the Republic of Kazakhstan (grants AP05132988, AP05133590 and BR05236730).

## REFERENCES

[1] V. Maksimov, V. Messerle. Numerical simulation of the coal combustion process initiated by a plasma source. *Thermophysics and aeromechanics* **21**, 747-754 (2014).

[2] A.S. Askarova, E.I. Karpenko, V.E. Messerle Plasma enhancement of combustion of solid fuels. *Journal of High Energy Chemistry* **40**, 111-118 (2006).

[3] V.E. Messerle, A.B. Ustimenko, Z.Kh. Gabitova Numerical simulation of pulverized coal combustion in a power boiler furnace. *High temperature* **53**, 445-452 (2015).

[4] A.S. Askarova, S.A. Bolegenova Computational method for investigation of solid fuel combustion in combustion chambers of a heat power plant. *High temperature* **53**, 751-757 (2015).

[5] S.A. Bolegenova, Sh.S. Ospanova Numerical research of aerodynamic characteristics of combustion chamber BKZ-75 mining thermal power station. *Procedia Engineering* **42**, 1250-1259 (2012).

[6] A.S. Askarova, S.A. Bolegenova 3D 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* 699-709 (2016).

[7] A. Ergalieva, A.B. Ustimenko, V.E. Messerle 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**, 125-134 (2016).

[8] Z. Kh. Gabitova, M. Beketayeva Control of Harmful Emissions Concentration into the Atmosphere of Megacities of Kazakhstan Republic. International Conference on Future Information Engineering. *IERI Procedia* 252-258 (2014).

[9] R. Leithner, S. Vockrodt, A. Schiller Firing technique measures for increased efficiency and minimization of toxic emissions in Kazakh coal firing. 19th German Conference on Flames. Germany. VDI Gesell Energietechn; Verein Deutsch Ing. Combustion and Incineration. VDI Berichte, **1492,** 93 (1999).

[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, **6-268**, 158 (1992).

[11] R. Leithner Energy Conversion Processes with CO2-Separation Not Reducing Efficiency. Handbook of Combustion. Wiley VCH Verlag GmbH & Co. (2010).

[12] B. Epple, R. Leithner, W. Linzer, H. Walter . Simulation von Kraftwerken und wärmetechnischen Anlagen. Springer-Verlag: Vienna (2009).

[13] S.V. Patankar Numerical Heat Transfer and Fluid Flow. Hemisphere Publishing Corporation. (1980).

[14] M.A. Leschziner Practical Evaluation of three finite difference schemes for the Computation of Steady State Recirculation Flows. Computer *Methods and Applied Mechanics an Engineering* **23,** 293-312 (1980).

[15] V.E. Messerle, A.B. Ustimenko, O.A. Lavrichshev Comparative study of coal plasma gasification. *Fuel* **64,** 172-179 (2016).

[16] V.E. Messerle, A.B. Ustimenko Mathematical modeling of the processes of solid fuel ignition and combustion at combustors of the power boilers. 7th *Int. Fall Seminar on Propellants, Explosives and Pyrotechnics. Xian,* 672-683 (2007).

[17] M.A. Buchmann, A.S. Askarova Structure of the flame of fluidized-bed burners and combustion processes of high-ash coal. Gesell Energietech, Combustion and incineration – eighteenth dutch-german conference on flames. VDI Berichte, 241-244 (1997).

[18] A.S. Askarova, E.I. Karpenko, V.E. Messerle, A.B. Ustimenko Plasma-supported coal combustion in boiler furnace. *IEEE Transactions on Plasma Science* **35(6)**, 1607-1616 (2007).

[19] R. Leithner, A. Ergalieva, A. Nugymanova Computational modeling of heat and mass transfer processes in combustion chamber at power plant of Kazakhstan. *MATEC Web of Conferences* **5**. (2016).

[20] A. Askarova, A. Boranbayeva, S. Bolegenova, K. Berdikhan Application of numerical methods for calculating the burning problems of coal-dust flame in real scale. *Int. J. of Applied Engineering Research* **11-8**, 5511-5515 (2016).

[21] A. Askarova, S. Bolegenova Influence of boundary conditions to heat and mass transfer processes. *Int. J. of Mechanics* **10**. 320-325. (2016).

[22] P. Safarik, V. Maximov 3D modeling of heat and mass transfer processes during the combustion of liquid fuel. *J. of thermal science* **24-3,** 275-282 (2015).