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A.S. Askarova[1], S.A. Bolegenova[2], P. Safarik[3], S.A. Bolegenova[2], V.Yu. Maximov[1], M.T. Beketayeva[1], A.O. Nugymanova[2]

[1] Scientific Research Institute of Experimental and Theoretical Physics of al-Farabi Kazakh National University, SRI ETP of KazNU, Almaty, Kazakhstan;
[2] Physical and Technical Physics Faculty of al-Farabi Kazakh National University, Al-Farabi KazNU, Almaty, Kazakhstan
[3] Fluid Dynamics and Thermodynamics Department of Czech Technical University in Prague, CTU in Prague, Prague, Czech Republic
E-mail: Aliya.Askarova@kaznu.kz, Saltanat.Bolegenova@kaznu.kz, pavel.safarik@fs.cvut.cz, bolegenova.symbat@kaznu.kz, valeriy.maximov@kaznu.kz, Beketayeva.m@gmail.com, aijoka01@gmail.com

MODERN COMPUTING EXPERIMENTS ON PULVERIZED COAL COMBUSTION PROCESSES IN BOILER FURNACES

Abstract. The aim of the work is to create new computer technologies for 3D modeling of heat and mass transfer processes in high-temperature physico-chemical-reactive environments that will allow to determine the aerodynamics of the flow, heat and mass transfer characteristics of technological processes occurring in the combustion chambers in the operating coal TPP RK. The novelty of the research lies in the use of the latest information technologies of 3D modeling, which will allow project participants to obtain new data on the complex processes of heat and mass transfer during the burning of pulverized coal in real combustion chambers operating in the CHP of RK. Numerical simulation, including thermodynamic, kinetic and three-dimensional computer simulation of heat and mass transfer processes when burning low-grade fuel, will allow finding optimal conditions for setting adequate physical, mathematical and chemical models of the technological process of combustion, as well as conduct a comprehensive study and thereby develop ways to optimize the process of ignition, gasification and burning high ash coals. The proposed methods of computer simulation are new and technically feasible when burning all types of coal used in pulverized coal-fired power plants around the world. The developed technologies will allow replacing or eliminating the conduct of expensive and labor-consuming natural experiments on coal-fired power plants.

Key words. Combustion, boundary conditions, computer simulation, low-grade coal, pulverized coal, reacting mixture, combustion chamber, numerical experiment.

Introduction

Kazakhstan is currently a developed country rich in natural resources. The fuel and energy complex is the basis for life support and economic development. Kazakhstan coal has high ash content (~ 40%) so they rated as low-grade, despite of it this organic fuel covers more than 40% of the demand for primary energy resources. The use of such quality coal leads to economic and ecological problems, related with ineffective incomplete combustion of fuel, which causes a high level of carbon and nitrogen compounds in the atmosphere.

In this regard, the President of the Republic Nazarbayev N.A. identified the global energy-environmental strategy for sustainable development of Kazakhstan, where he expressed ideas about sustainable energy. According to the adopted “Sustainable Energy Strategy for the Future of Kazakhstan until 2050” [1], the factors of energy independence and development principles include the requirements of ensuring the interests of the new generation and preserving the environment, which are determined by the following parameters: ensuring the world level of economic and technical efficiency throughout the country's energy sector; control the level of environmental impact of energy; the existence of an internal policy aimed at ensuring the availability of all types of energy; possession of the optimal institutional structure of the energy-complex; ensuring participation in international energy markets.

In the main, the country is currently dependent upon fossil fuels for power generation. As shown in Fig. 1 13% of Kazakhstan's power is generated by hydroelectric power plants, and whilst 90% is from thermal-powered plants (75% coal-fired stations).

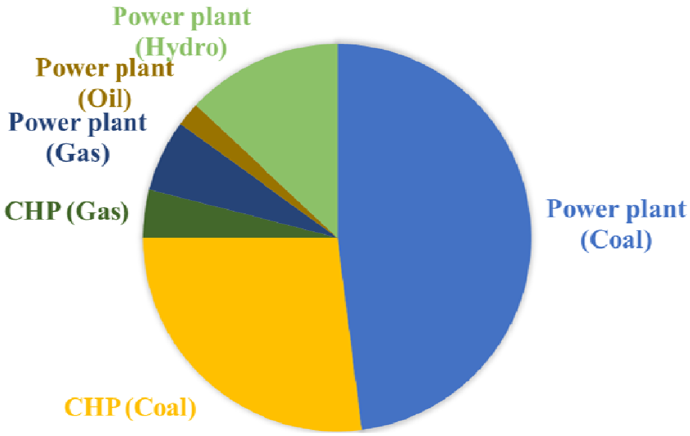

Fig 1 - Kazakhstan's electricity generating capacity (%)

To optimize the combustion of solid fuels, to develop and implement "clean" technologies and to protect the environment and ensure the efficiency of power plants, a deeper study of the issues of burning solid fuels in the combustion chambers of boilers and conducting research of technological processes taking place at TPPs is needed. It is possible with a combination of physical, scientific and applied, technological and engineering research in the field of optimization of solid fuel combustion processes [2-7]. In this regard, it becomes relevant to conduct computational experiments on the study of ignition, heat transfer, and mechanisms for burning out a coal-dust torch in the combustion chambers of boilers of energy facilities.

Methods of pulverized coal combustion research

At present, the intensive development of computer technologies and numerical simulation methods ensures a sufficiently high accuracy, the convergence of numerical results and their agreement with the results of field experiments. The use of computational fluid dynamics CFD allows one to obtain data without field experiments, which can then be used to substantiate the parameters and modes of thermal and hydrodynamic processes in the preparation of subsequent experimental studies on real energy facilities.

To study the complex physicochemical processes occurring while the pulverized coal combustion in furnace of boilers, it is necessary to have certain conditions required for carrying out computational experiments, including a multiprocessor computing system, an adequate physical, mathematical and chemical model and an exact method for solving a system of differential equations that describe the real technological process of burning pulverized coal in the existing power plant.

Numerical simulation uses numerical methods for solving the fundamental equations of heat and mass transfer processes using powerful computers. The theoretical analysis of vortex flows is based on the Navier-Stokes and Reynolds equations [8]. However, due to the nonlinearity and interconnectedness of these equations, their solution in the general case can be found only numerically [9]. The predominant method in the numerical simulation of subsonic currents and heat and mass transfer is the well-proven algorithm of SIMPLE Patankar-Spalding [10].

The description of the numerical model is based on a number of physical laws of conservation of mass, momentum, energy [11]. The mathematical model consists of a system of differential equations, algebraic closing relations and boundary (initial and boundary) conditions.

Since most practical flows are turbulent, the conservation equations must be considered in averaged and filtered by time or spatial forms, which must be closed using additional turbulent models [12]. For the formulation of a mathematical model, we consider the basic equations.

Since there are no sources of mass, only the transformation of the constituent components takes place. In this case, the equation of conservation of mass or the continuity equation takes the form (where the first term of the equation describes the flow nonstationarity, the second term is convective transport):

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \qquad (1)$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i+F_i \qquad (2)$$

The first term of the equation describes the nonstationarity of the flow, the second - convective transport, the third and fourth terms - surface forces (pressure gradient and molecular diffusion), the fifth - mass forces (gravity), the sixth - external mass forces.

The energy conservation equation takes into account energy transfer due to conductivity, diffusion, and viscous dissipation:

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial}{\partial x_i}(\rho h u_i)=\frac{\partial p}{\partial t}+u_i\frac{\partial p}{\partial x_i}-\frac{\partial}{\partial x_i}\left(k_{eff}\frac{\partial T}{\partial x_i}\right)-\frac{\partial}{\partial x_{ij'}}h_{j'}J_{j'}+(\tau_{ij'})_{eff}\frac{\partial u_j}{\partial x_j}+S_h\,, \qquad (3)$$

where $h=\sum_{j'} m_{j'}h_{j'}$ – enthalpy for ideal gases, $h=\sum_{j'} m_{j'}h_{j'}+{p}/{\rho}$ – enthalpy for incompressible flow of gas, $h_{j'}=\int_{T_{ref}}^{T} c_{p,j'}dT$ – enthalpy for flow $J_{j'}$ diffusion substance, $k_{eff}=k_l+k_t$ – effective thermal conductivity (the sum of laminar and turbulent thermal conductivity), $(\tau_{ij'})_{eff}$ – effective stress tensor, S_h – source term that takes heat into account due to chemical reactions and other volumetric energy sources (heat due to radiation, convective exchange between particles and the gas phase, and heat of combustion).

To study the turbulent burning flow of an industrial flame, the averaged conservation equations are used, supplemented by a two-parametric k-ε model of turbulence [13].

Simulation of the combustion process in the gas phase is a complex process involving numerous chemical reactions of fuel and oxidizer through the formation of intermediates and final products of combustion. The task is further complicated because of the interaction between turbulence and the kinetics of the combustion process, in view of the fact that turbulent reactive flows are characterized by sharp fluctuations in temperature and density, under the strong influence of exothermic reactions of the combustion process. To simulate the combustion of the gas phase, a simple chemical reaction system developed by Spalding is used. The model describes the global nature of the combustion process, where the complex mechanism of chemical kinetics is replaced by infinitely fast chemical reactions between fuel and oxidant [14].

So for mathematical modeling of processes occurring in combustion devices during coal combustion, the FLOREAN computer program [15-16] based on numerical solution of three-dimensional equations of energy and substance transfer taking into account chemical reactions is used. All mathematical models represent a complex system of nonlinear three-dimensional partial differential equations. They consist of the equations of continuity of the medium, the state of an ideal gas and the motion of a two-phase medium, heat transfer equations, chemical kinetics, and diffusion for the components of the reacting mixture, taking into account the radiative and turbulent transport described by the k-ε model of turbulence. For numerical calculation were used the primary and boundary conditions, also control volume method for solving the differential equations [17].

Setting of the computing experiments in boiler of RK

In the present work, for carrying out computational experiments on pulverized coal combustion used software package FLOREAN. Creating a database for modeling is carried out using the PREPROZ software package [18], where the generated files contain the geometric data of the process under study, the initial and boundary conditions for modeling the process of heat and mass transfer in the reacting flows. General view of the boiler BKZ is shown in Fig. 2.

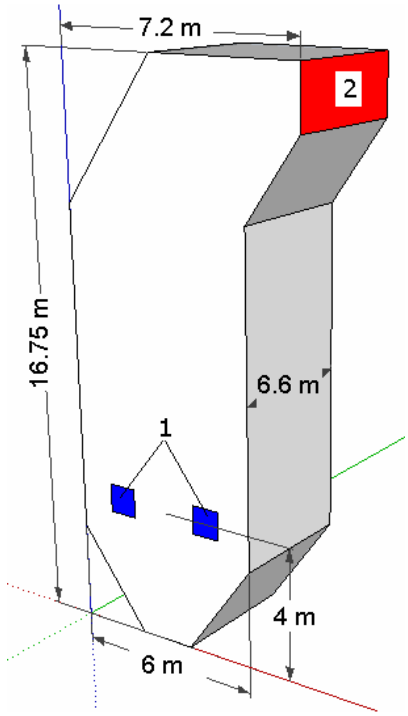

Fig. 2 - General view of the boiler BKZ-75 of Shakhtinskaya CHPP (RK)

Pipes front, rear screens and the lower part form in the furnace space the area of the cold funnel. In tables 1 and 2 there showed basic geometric parameters also technical parameters of the combustion chamber of the BKZ-75 boiler. The characteristics of the coal are presented in Table 3.

Table 1 - Basic geometric parameters of the combustion chamber of the BKZ-75 boiler

Name	Symbol	Unit	Value
Height of the combustion chamber	(Z) $H_т$	m	16.75
Width of the combustion chamber	(X) $b_т$	m	6
Depth of the combustion chamber	(Y) $Г_т$	m	6.6
Frontal and posterior wall area	F_{fr}, F_p	m^2	90.675
Area of the right side wall	F_{s1}	m^2	92.4
Area of the left side wall	F_{s2}	m^2	110.55
Ceiling wall Area	F_s	m^2	27.72
Area of hearth wall	F_h	m^2	7.26
Cross-sectional area of the air-blast channel in the burner	F_a	m^2	0.12
The cross-sectional area of the secondary air duct in the burner	F_{sa}	m^2	0.25

The furnace chamber of the BKZ-75 boiler is equipped with four axial-blade vortex pulverized-coal burners, which are located in one stage of two burners on the side walls of the chamber and direct dust injection from individual dust preparation systems is used.

Table 2 - Technical parameters of the combustion chamber of the boiler BKZ 75-39FB Shakhtinskaya CHP

Name	Value
Number of burners on the boiler, $N_{b,}$ pc.	4
The performance of a single burner for fuel, $B_{b,}$ t/h	3.2
The primary air flow to the boiler, $V_{pa.}$, Nm^3/h	31797
Secondary air consumption per boiler, V_{sa}, Nm^3/h	46459
The temperature of hot air, t_{ha}, °C	290
The excess air factor in the furnace, α	1.2
Value of the suction cup, $\Delta\alpha$ Firebox and festoon Superheater Economizer Air Heater	 0.1 0.03 0.02 0.03
Estimated fuel consumption per boiler, B_c, t/h	12.49
Cold air temperature, t_{ca}, °C	30
Pressure at the inlet, P, mbar	$1.013 \cdot 10^3$
Hydrodynamic resistance of the burner air mixture channel, *ΔP,* mm of water column	67.1
The temperature of the air mixture, t_{am}, °C	140
The wall temperature, t_w, °C	430.15

Table 3 - Characteristics of Karaganda coal grade KR-200

Name	**Symbol**	**Unit**	**Value**
Type of coal	KR-200	-	-
Milling dispersity	R_{90}	%	20
Coal density	ρ	kg/m^3	1350
Heat of combustion	Q_y	kJ/kg	$3.4162 \cdot 10^4$
Ash	A^c	%	35.10
Volatiles	$V^Г$	%	22.00
Humidity	W^P	%	10.60
Carbon	C	%	43.21
Hydrogen	H_2	%	3.6
Oxygen	O_2	%	5.24
Sulfur	S_2	%	1.04
Nitrogen	N_2	%	1.21
Chemical composition of ash (macrocomponents)			
	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

Considered coals are difficult to enrich. Their inner component is almost indestructible (the organic part consists of plant matter, brought from mineral impurities deposited with plant residues, and the infiltration part of the mineral salts contained in the water circulating through the cracks). Thus, their enrichment does not justify the economic costs associated with the enrichment process.

Results of computing experiments on pulverized coal combustion processes in boiler furnace of RK

The aerodynamics of two-phase turbulent flows during the combustion of pulverized coal which is vortex transfer [19] causes the nature of the leaking of the entire combustion process. The main role of the aerodynamic structure of the vortex flow is the perfect mixture of fuel mixture with oxidant. Fig. 3a shows that the flow of the air mixture with the combustion products has a vortical character in the burners' zone (Z ~ 4 m). It can be seen that the total velocity vector has its maximum values V ~ 16 m/s there. This is because the counter flow currents, blown from the burner devices, are directed at maximum speed to the center of the furnace space, collide. And here, dissecting into several vortices, form a return flow up and down over the furnace space. This vorticity character arises from turbulence (Fig. 3b) due to the interaction of the air mixture with the oxidant [20].

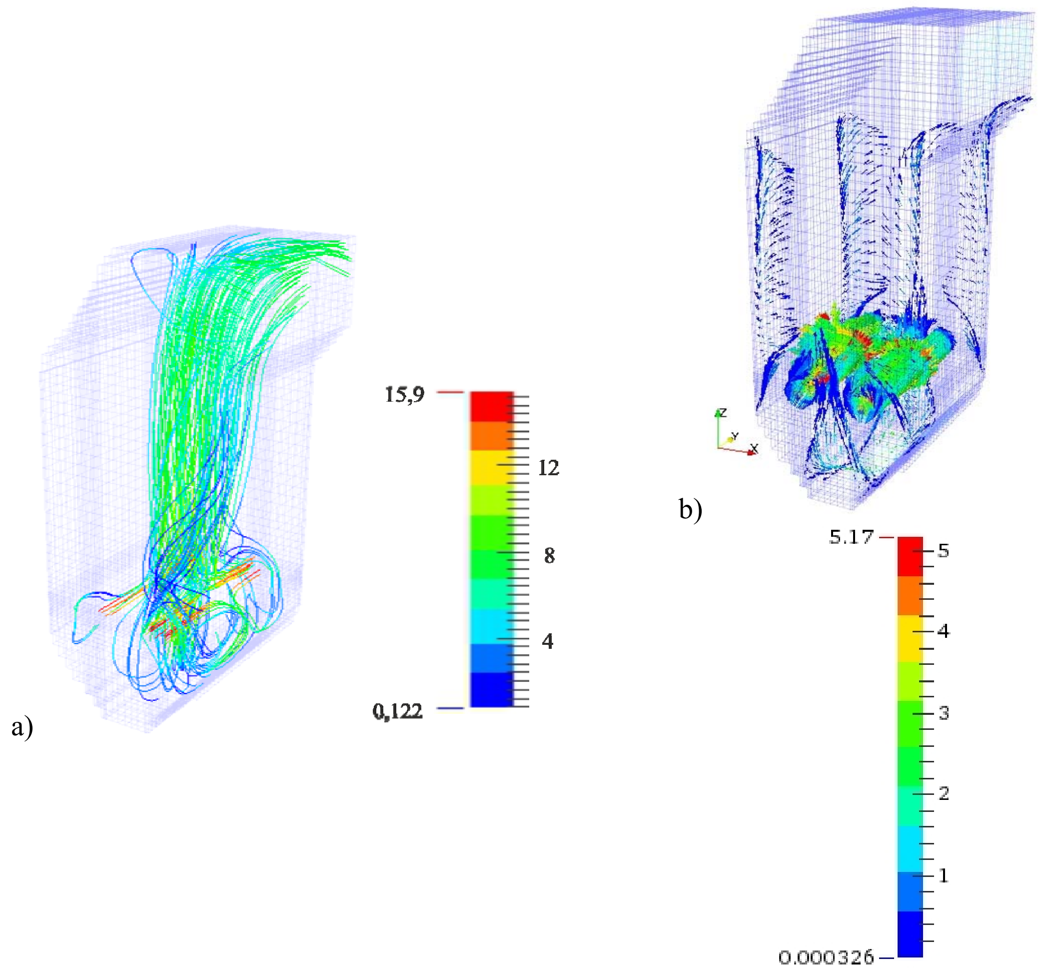

Fig. 3 - Three-dimensional distribution of the full-velocity vector (a) and turbulence (b) in the volume of the combustion chamber of the boiler BKZ-75-39FB Shakhtinskaya CHPP

The fuel mixture and oxidizer (air) coming from the opposite burners, so the temperature values reach their maximum in the core region of the torch at an altitude of about three meters, it is the lower part of burners. Here, due to the vortex nature of the flow maximum convective transfer and an increase in the residence time of coal particles are observed. As a result temperature rises to its value 1100°C (see Fig. 4). On the height of the combustion chamber, it can be seen a gradual decrease in temperature to the exit from the furnace. At the exit the temperature fields are equalized: in the rotary region of the furnace, the average temperature is T = 941°C, and at the outlet from the combustion space T = 879°C.

Analyzing the verification of obtained computational data with the theoretical calculation at the outlet from the boiler [21] and with natural data from TPP [22]. Analyzing the results it is seen a good agreement.

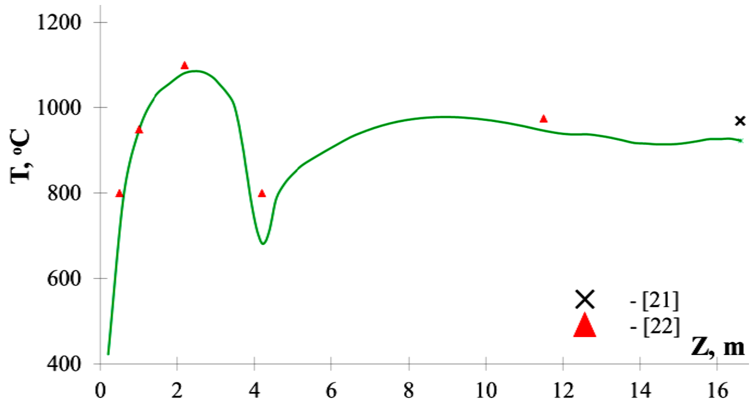

Fig. 4 - Distribution of the temperature by the height
of the combustion chamber and its verification with the known data [21-22]

The distribution of CO_2 concentration in the central part (Fig. 5) is less than at the outlet. The final stages of complete combustion of energy fuel, with the greatest amount of formation of combustion products of CO_2 take place to the output area. The verification of obtained results with known data [22] from real TPP shows the good compliance.

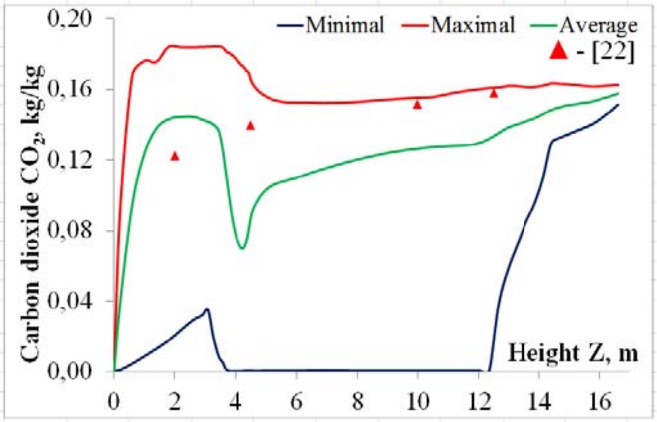

Fig. 5. Two-dimensional distribution of the CO_2 concentrations by height
of the boiler and its verification with the known data

Concentration of nitrious oxides NOx as shown in figure 6 has a maximal value at the burners zone (Z=4 m) in a region where the injected flows are met (central part). At the outlet from the chamber the average value of the NOx is about ~ 700 mg/Nm^3. From the comparing with experimental data [22-24] and MPC norms [25], as it shown in Fig. 8 it can be said that obtained results correspond quite well to the picture of real formation of NOx emissions with acceptable values for ecologically clean operation of energy fuel in this boiler.

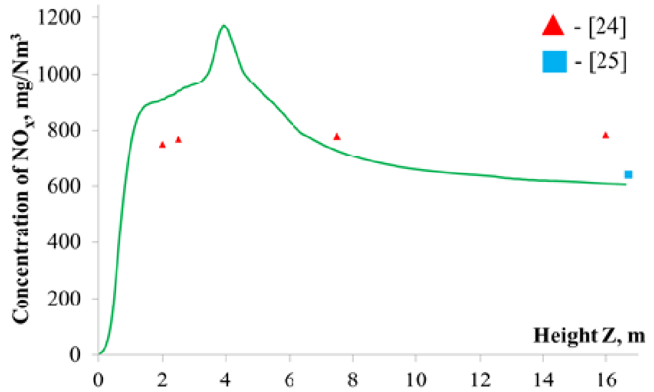

Fig.6 - Distribution of the NOx concentrations by height and its verification with the known data

3D computer simulation of the combustion of pulverized coal fuel allows for better understanding of the problems of computational fluid dynamics (CFD), mathematical and numerical modeling of solid fuel combustion processes, and the mechanism of chemical interaction between combustion products. The results of the conducted research contribute to the solution of the actual problems of thermal physics, technical physics, thermal power engineering and environmental safety, since they make it possible to give recommendations on optimization of burning processes of low-grade energy fuels in order to increase energy efficiency and improve the ecological situation and create "clean" energy production.

Conclusion

In order to reduce emissions and meet the growing demand for electricity, it is urgently necessary to develop and implement new cost-effective and environmentally friendly (safe) technologies, as well as to modernize existing energy supply facilities.

Concluding results of conducting research we can propose the new physical-mathematical and chemical models of simulation low-grade Kazakhstan coal combustion in the real chambers of the energy objects. Used method give an adequate character of the processes of heat and mass transfer and formation of emissions of harmful substances during burning of low-quality Karaganda coal of grade KR-200 with high ash content (more than 35%) in the combustion chamber of the existing power boiler BKZ-75 of Shakhtynskaya CHPP.

By comparisons of numerical experiment results held in this work with natural data from TPP we can propose the observed method of research of combustion processes is reliable. The results carried out in this work and used method of computational study can be useful in the design and development of new, as well as in the improvement of existing combustion chambers of power boilers of TPP.

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А.С. Асқарова[1], С.Ә.Бөлегенова[2], П. Шафаржик[3], С.Ә. Бөлегенова[2], В.Ю. Максимов[1], М.Т. Бекетаева[1], А.О. Нұғманова[2]

[1] Әл-Фараби атындағы Қазақ ұлттық университетіне қарасты эксперименталдық және теориялық физиканың ғылыми-зерттеу институты, әл-Фараби атындағы ҚазҰУ ЭТФ ҒЗИ, Алматы, Қазақстан;
[2] Әл-Фараби атындағы Қазақ ұлттық университетін физика-техникалық факультеті, әл-Фараби атындағы ҚазҰУ, Алматы, Қазақстан;
[3] Прага қ. Чех Техникалық университетінің сұйық динамикасы мен термодинамика факультеті, Прага қ. Чех Техникалық университеті, Прага, Чех Республикасы

ҚАЗАНДЫҚТАРДЫҢ ЖАНУ КАМЕРАЛАРЫНДА ШАҢТЕКТЕС КӨМІРДІҢ ЖАНУ ПРОЦЕСТЕРІНІҢ ЗАМАНАУИ КОМПЬЮТЕРЛІК ТӘЖІРИБЕЛЕРІ

Аннотация. Жобаның мақсаты жоғарытемпературалы физика-химиялық әрекеттесуші орталардағы жылу масса тасымалдану процестерін 3D моделдеудің жаңа компьютерлік технологияларын құру болып табылады. Олар ҚР қызмет ететін көмірлі ЖЭС-ң жану камераларында болатын технологиялық процестердің ағыстар аэродинамикасын, жылу масса алмасу сипаттамаларын анықтауға мүмкіндік туғызады. Зерттеулердің жаңашылдығы ең жаңа 3D моделдеудің ақпараттық технологияларын қолдану болып табылады. Ол жоба қатысушыларына ҚР іске қосылған ЖЭС-ң реалды жану камераларындағы шаң-көмірлі отынның жануы кезінде жылу масса тасымалданудың күрделі процестерінің жаңа мәліметтерін алуға жәрдемдеседі. Төменгісұрыпты отынды жағу кезінде термодинамикалық, кинетикалық және жылу және масса тасымалдау процестерін үш өлшемді компьютерлік модельдеуді ескергендегі сандық моделдеу жану процесінің технологиялық процесінің адекватты физикалық, математикалық және химиялық үлгілерін орналастыру үшін оңтайлы жағдайларды табуға мүмкіндік береді, сондай-ақ жан-жақты зерттеулер жүргізуге көмек береді, осылайша жану процесінің тұтану, газдану және жоғары күлді көмірлерді жағуда жаңа жолдарды ұсынуға мүмкіндік береді. Жобаның дамуына ұсынылған компьютерлік модельдеу әдістері - бүкіл әлем бойынша көмірмен жұмыс істейтін жылу электр станцияларында қолданылатын көмірдің барлық түрлерін жағуда жаңа және техникалық мүмкіншілігі зор болып табылады. Ұсынылып отырған технологиялар көмірмен жұмыс істейтін электр станцияларында орындалатын қымбат және еңбек шығындары қажет етілетін табиғи эксперименттерді ауыстыруға немесе жоюға мүмкіндік береді.

Түйін сөздер. Жану, шекаралық шарттар, компьютерлік моделдеу, төменгі сұрыпты көмір, шаңкөмірлі отын, әсерлесетін қоспа, жану камерасы, сандық тәжірибелер

А.С.Аскарова[1], С.А.Болегенова[2], П.Шафаржик[3], С.А.Болегенова[2], В.Ю.Максимов[1], М.Т.Бекетаева[1], А.О.Нугманова[2]

[1] Научно-исследовательский институт экспериментальной и теоретической физики при Казахском национальном университете имени аль-Фараби, НИИ ЭТФ при КазНУ имени аль-Фараби, Алматы, Казахстан;

[2] Физико-технический факультет Казахского национального университета имени аль-Фараби, КазНУ имени аль-Фараби, Алматы, Казахстан;

[3] Департамент динамики жидкости и термодинамики Чешского Технического Университета г.Прага, ЧТУ г. Прага, Прага, Чешская Республика

СОВРЕМЕННЫЕ КОМПЬЮТЕРНЫЕ ЭКСПЕРИМЕНТЫ ПРОЦЕССОВ СЖИГАНИЯ УГОЛЬНОЙ ПЫЛИ В ТОПОЧНЫХ КАМЕРАХ КОТЛОВ

Аннотация. Целью работы является создание новых компьютерных технологий 3D моделирования процессов тепломассопереноса в высокотемпературных физико-химически реагирующих средах, которые позволят определять аэродинамику течения, тепломассообменные характеристики технологических процессов, происходящих в топочных камерах в действующих угольных тепловых электрических станций Республики Казахстан. Новизна исследований заключается в использовании новейших информационных технологий 3D моделирования, которые позволят участникам проекта получить новые данные о сложных процессах тепломассопереноса при горении пылеугольного топлива в реальных топочных камерах, действующих ТЭЦ РК. Численное моделирование, включающее термодинамическое, кинетическое и трехмерное компьютерное моделирование процессов тепломассопереноса при сжигании низкосортного топлива позволит найти оптимальные условия для постановки адекватной физико-математической и химической модели технологического процесса горения, а также провести комплексное исследование и тем самым разрабатывать пути оптимизирования процесса воспламенения, газификации и сжигания высокозольных углей. Предлагаемые к разработке методы компьютерного моделирования являются новыми и технически реализуемы при сжигании всех типов углей, используемых на пылеугольных ТЭС по всему миру. Разрабатываемые технологии позволят заменить или исключить проведение дорогостоящих и трудоемких натурных экспериментов на угольных ТЭС.

Ключевые слова. Горение, граничные условия, компьютерное моделирование, низкосортный уголь, пылеугольное топливо, реагирующая смесь, топочная камера, численный эксперимент.

Information about authors:

Askarova A.S. - SRI ETP of Al-Farabi Kazakh national university, professor, Dr.of Phys.-math.Sci., Aliya.Askarova@kaznu.kz;

Bolegenova S.A. - Al-Farabi Kazakh national university, professor, Dr.of Phys.-math.Sci., Saltanat.Bolegenova@kaznu.kz

Safarik P. - Czech Technical University in Prague, professor, Cd. of Tech.Sci., pavel.safarik@fs.cvut.cz

Bolegenova S.A. - Al-Farabi Kazakh national university, Sen. Lecturer, PhD, bolegenova.symbat@kaznu.kz

Maximov V.Yu. - SRI ETP of Al-Farabi Kazakh national university, scientific engineer, PhD, postdoctoral student, valeriy.maximov@kaznu.kz

Бекетаева М.Т. - SRI ETP of Al-Farabi Kazakh national university, scientific engineer, PhD, Beketayeva.m@gmail.com

Nugymanova A.O. - Al-Farabi Kazakh national university, Lecturer, PhD Student, aijoka01@gmail.com