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3D MODELING OF HEAT TRANSFER PROCESSES IN THE COMBUSTION CHAMBER BOILER OF THERMAL POWER PLANTS

Abstract. In the present work, a computer-aided 3D modeling method was used to conduct a comprehensive study of heat and mass transfer processes in turbulent flows of high-temperature reactive media in real geometry. Numerical computations of the thermal processes and aerodynamic characteristics of the flow were made for the combustion chamber of the BKZ-75 boiler at Shakhtinskaya thermal power plant for combustion of high-ash fuel. Using the methods of computer 3D-modeling, we took into account a great number of phenomena and factors affecting the real technological processes in the combustion chambers of industrial facilities. The aerodynamic picture of the studied combustion chamber was obtained, the temperature fields and energy distributions released due to chemical reactions were constructed, and the values of radiation heat fluxes to the main heat-receiving surfaces of the combustion chamber were determined. The results of numerical calculations can be used to design new and modernize existing combustion chambers of industrial boilers working on solid fuel, as they are based on the most advanced physical and mathematical models in this area. The use of modern technologies for 3D numerical computations of solid fuel combustion in the combustion chambers of thermal power plants, will allow us to describe in detail the fields of velocity, temperature, pressure and concentrations of all combustion products and, above all, harmful substances and other characteristics of the coal combustion process throughout the combustion space and at the outlet of the combustion chamber.

Key words. Combustion, modelling, thermal power plant, high ash coal.

Introduction

The study of combustion at the level of mathematical modeling is an intermediate link between research conducted at the level of engineering practice and fundamental science [1-3]. It becomes necessary to create new models that will allow us to make more accurate calculations of the fields of velocity, temperature and concentration of the main components of fuel and combustion products in systems such as combustion chambers, various combustion devices, etc. Limitations of theoretical methods and complexity of experimental investigations predetermined a significant role of numerical methods and numerical computations in the study of complex flows of reacting liquids [4-8]. Though, in most cases, mathematical studies are carried out in one- and two-dimensional approximations, and only in rare cases three-dimensional models are used [9-12], moreover, numerical computations are made with constraints in the computational domain. The first results of three-dimensional modeling of heat and mass transfer processes in the combustion chambers of real power facilities of the Republic of Kazakhstan are presented in [13-16]. So the study of the heat transfer processes in furnaces becomes particularly important.

Lately, whole complexes of programs are created, allowing to carry out numerical studies of the most complex phenomena, which include processes of convective heat and mass transfer in high-temperature and chemically reactive flows in the presence of fast-flowing physical and chemical transformations of substances. For this purpose, commercial packages of universal programs that use the latest achievements of computer technology, mathematics, combustion, heat and mass transfer have been developed and applied [17-19].

Modeling of coal combustion

In the present work, physical-mathematical and chemical models were used to study heat and mass transfer in high-temperature environments [20-22]. These models include a system of three-dimensional Navies - Stokes equations and heat and mass transfer equations, considering the source terms determined by the chemical kinetics of the process, nonlinear effects of thermal radiation, interfacial interaction, and multi-stage chemical reactions. The basic equations used to solve the problem are:

The equation for turbulent kinetic energy dissipation ε:

$$\frac{\partial(p\varepsilon)}{\partial t} = -\frac{\partial(pu_j\varepsilon)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right] + C_{\varepsilon,1} * \frac{\varepsilon}{k} * P - C_{\varepsilon,2} * \frac{\varepsilon^2}{k} * p \qquad (1)$$

where $p\varepsilon$ is transformation of kinetic energy pulsations into internal energy (dissipation); $\sigma_k, \sigma_\varepsilon$ are turbulent Prandtl numbers.

The basic equations used in this work can be written in generalized form as follows:

$$\frac{\partial(p\phi)}{\partial t} = -\frac{\partial(pu_1\phi)}{\partial x_1} - \frac{\partial(pu_2\phi)}{\partial x_2} - \frac{\partial(pu_3\phi)}{\partial x_3} + \frac{\partial}{\partial x_1}\left[\Gamma_\phi\frac{\partial\phi}{\partial x_1}\right] +$$

$$\frac{\partial}{\partial x_2}\left[\Gamma_\phi\frac{\partial\phi}{\partial x_2}\right] + \frac{\partial}{\partial x_3}\left[\Gamma_\phi\frac{\partial\phi}{\partial x_3}\right] + S_\phi \qquad (2)$$

where ϕ is a transport variable; S_ϕ is the source term determined by the chemical kinetics of the process, nonlinear effects of thermal radiation, interphase interaction and multi-stage chemical reactions. The above system of equations is solved numerically using the control volume method described in detail in [21-24] and used in numerical computations of high-ash coal combustion in Kazakhstan's thermal power plants.

To solve the problem, the mathematical model should include specific initial and boundary conditions for desired functions (velocity, temperature, concentration of the mixture components, etc.) corresponding to the geometry of the selected combustion chamber and the real technological process of fuel combustion at TPPs.

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

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

Input: u_i are speed values, c_β is the initial concentration of each component, the enthalpy h is determined by the input flow temperature from the following relation:

$$C_P = \frac{\partial h}{\partial T} \qquad (3)$$

where T is the temperature at the inlet (experiment or calculation).

Output: $\left.\frac{\partial u_i}{\partial x_i}\right|_{normalA} = 0$, $\left.\frac{\partial h}{\partial x_i}\right|_{normalA} = 0$, $\left.\frac{\partial c_\beta}{\partial x_i}\right|_{normalA} = 0$ are derivatives of velocity, enthalpy and concentration of components normal to the output plane.

In the plane of symmetry: $u_i|_{normalS} = 0$ is the velocity normal to the plane of symmetry, $\left.\frac{\partial u_i}{\partial x_i}\right|_{normalS} = 0$, $\left.\frac{\partial h}{\partial x_i}\right|_{normalS} = 0$, are the derivatives of velocity and enthalpy normal to the plane of symmetry, $\left.\frac{\partial h}{\partial x_i}\right|_{taS} = 0$ is the derivative of the enthalpy tangential to the plane of symmetry, $\left.\frac{\partial c_\beta}{\partial x_i}\right|_{normalS} = 0$ is the derivative of component concentrations normal to the plane of symmetry.

On the solid surface: $u_i|_{normalB} = 0$, $\left.\frac{\partial u_i}{\partial x_i}\right|_{normalB} = 0$, $u_i|_{taB} = 0$, $\partial p|_{boundary} = 0$ is the correction for pressure on the border of the solid surface, $\left.\frac{\partial c_\beta}{\partial x_i}\right|_{normalB} = 0$.

The boundary conditions for the temperature on the wall are determined by the convective heat flux $q_w = \alpha(T_{Steam} - T_{Surf})$. In case of variable temperature of the wall of the combustion chamber, the heat flux can be calculated by the formula:

$$\dot{q} = \underbrace{\sigma(T_{FG} - T_{sufr})}_{convection} + \underbrace{C_{12}(T_{FG}^4 - T_{Surf}^4)}_{radiation} \qquad (4)$$

where $C_{12} = \varepsilon_{12}\sigma$, T_{FG} is the temperature of the flue gases, T_{Surf} is the surface temperature of the chamber wall, α is the coefficient of heat transfer by convection, W/(m^{2}K), ε_{12} is the emissivity wall, σ is the Boltzmann constant, W/(m^{2}K^4).

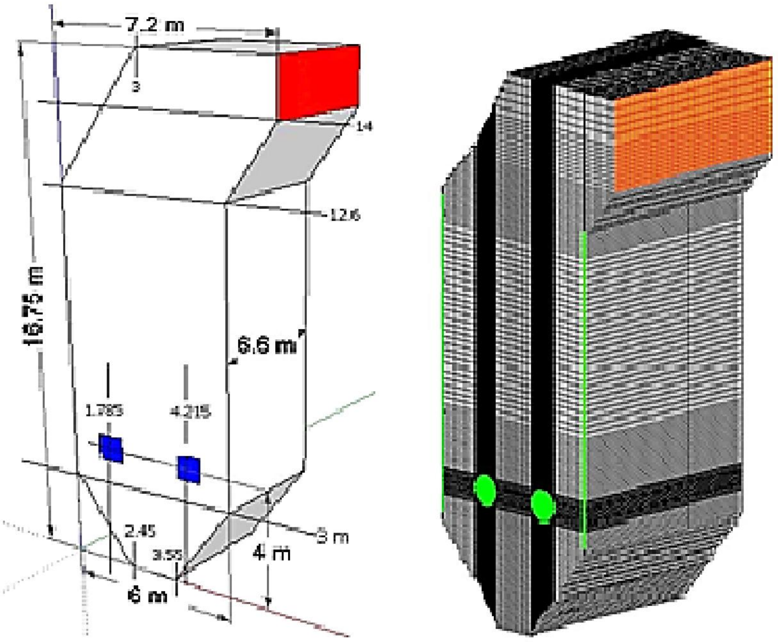
In this work the radiant heat exchange was calculated using the flux model described in [25-26]. The modeling method was developed by Lockwood, Shah [25] and De Marco, Lockwood [26].

Results of numerical computations

As the object of research has been chosen the boiler BKZ-75 (Fig. 2) located at Shakhtinskaya TPP (Kazakhstan) [27-30]. For numerical simulation, the entire computational domain is divided by a difference grid into discrete points or volumes (Fig. 2b). The resulting finite-difference grid has the resolution of 110×61×150 or 1 006 500 control volumes [31-36].

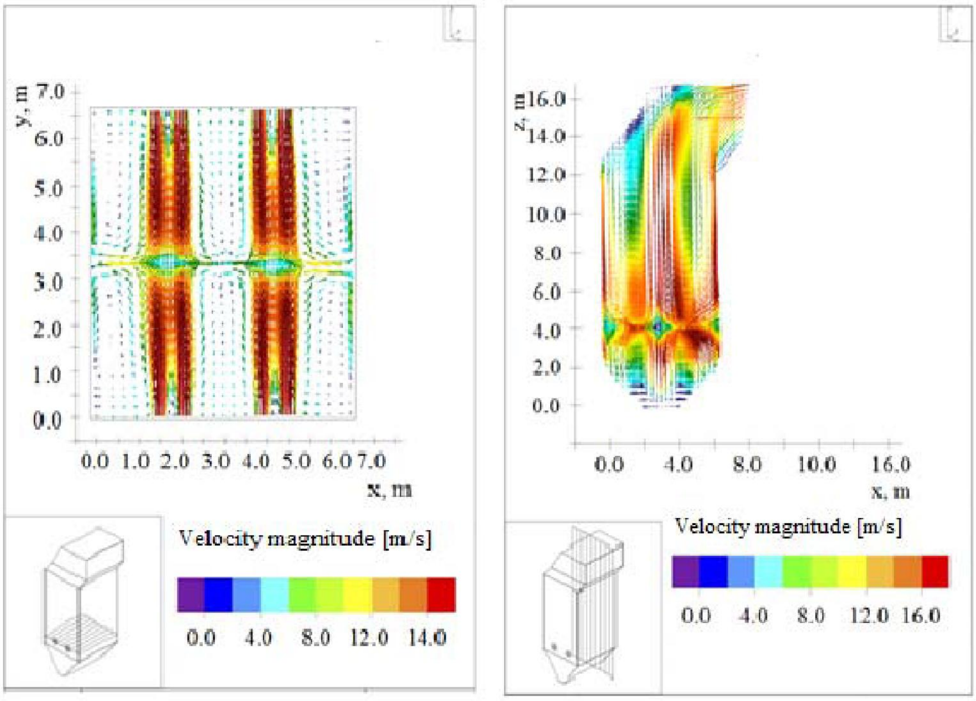
This paper presents the results of calculations give changes in the velocity and radiant vectors in the sections of the combustion chamber and the temperature profile shown in Figs. 3-5.

Fig. 3 illustrations the three-dimensional distribution of the full velocity vector in the volume of the combustion chamber. An analysis of Fig. 3a shows that the flow of the air mixture with combustion products has a vortex character in the region of the burners and in the lower part of the combustion chamber. In the center of the combustion chamber, the flux forms several vortices with the presence of a return flow up and down the space of the combustion chamber (Fig. 3b).



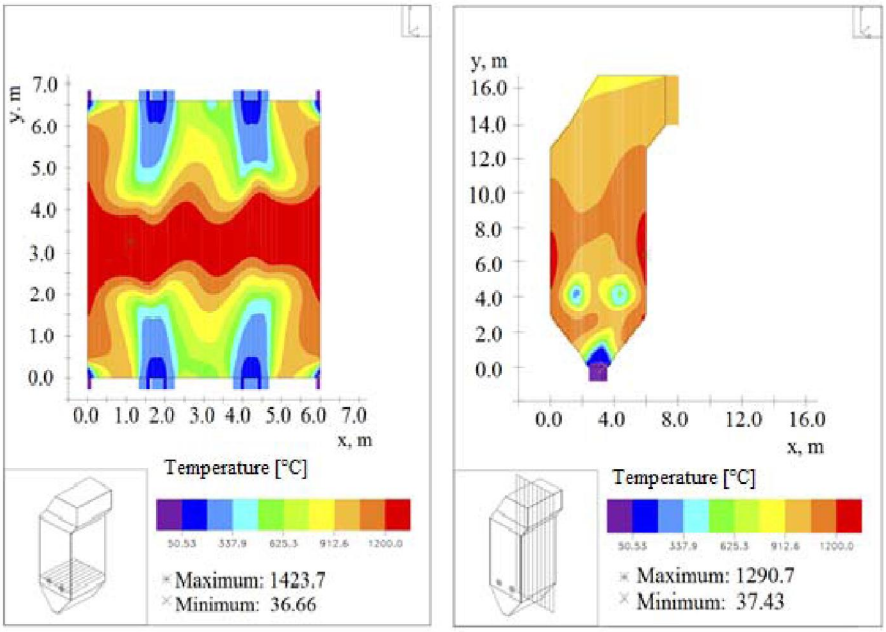
a) b)

Figure 2 - General view of the BKZ-75 boiler at the Shakhtinskaya TPP a) and its discretization for control volumes b)



a) cross section (z= 4.0 m), b) longitudinal section (y=3.3 m)

Figure 3 - Velocity distribution in the combustion chamber



a) cross section (z= 4.0 m) b) longitudinal section (y=3.3 m)

Figure 4 - Temperature distribution in the combustion chamber

Fig. 4 shows the temperature distributions characterizing thermal behavior of a pulverized coal flow in the studied combustion chamber. It can be noted that the temperature reaches its maximum values in the region close to the location of the burners, because here, due to the vortex character of the flow, a maximum convective transfer is observed and, as a result, the residence time of coal particles increases, which leads to an increase in temperature in this zone.

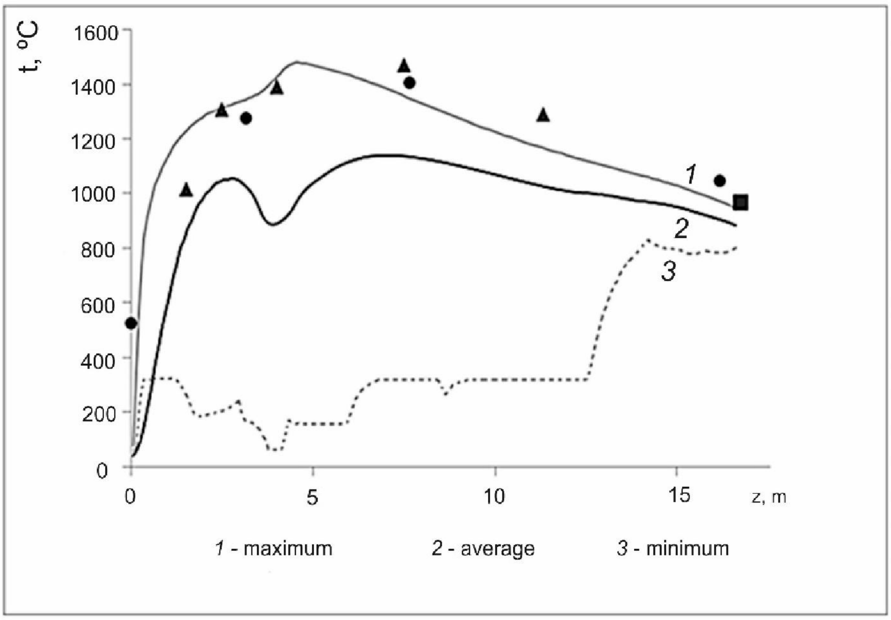
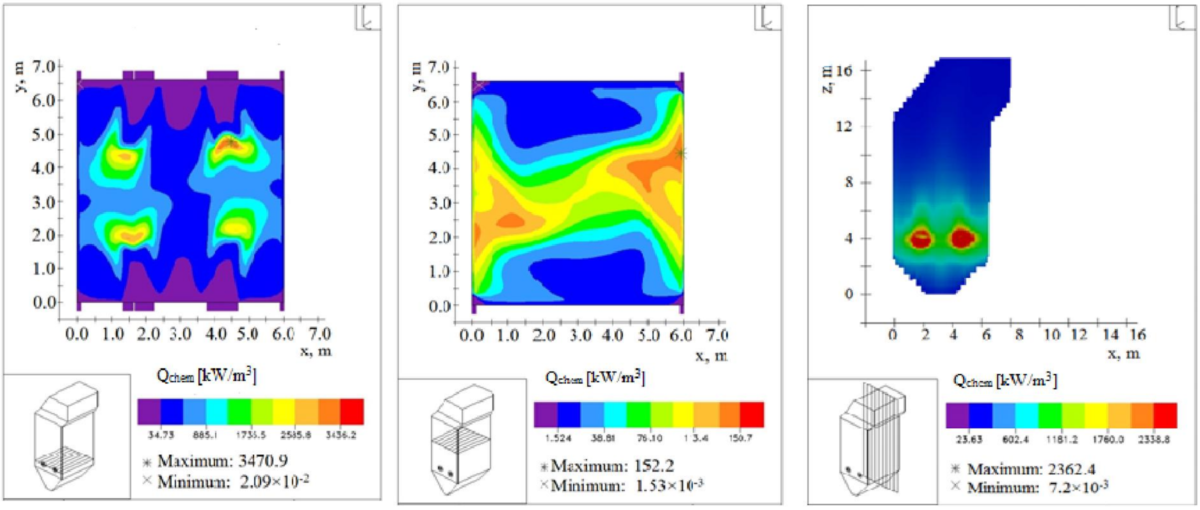


Figure 5 -Temperature distribution along the height of the furnace chamber

Lines correspond to numerical computations; ■ are theoretical values obtained by the method of thermal calculation (CBTI – Central Boiler-and-Turbine Institute) [37]; ▲, ● are the experimental data obtained at the thermal power plant [38-39]

Analysis of Fig. 5 shows that the results of numerical simulation of temperature dependence on the height of the combustion chamber agree with enough accuracy with the theoretical values obtained by the method of thermal calculations suggested by CBTI (Central Boiler-Turbine Institute) [37] and the data obtained directly at TPP [38-39]. This enables us to assess the reliability of the obtained results and the applicability of the physical, mathematical and numerical model to further study of thermal characteristics of the BKZ-75.



a) the burner section b) the central section c) the longitudinal section

Figure 6 - Energy distribution in chemical reactions

As a result of numerical simulation, the energy distribution of chemical reactions in the main sections of the furnace space, the radiation vector profiles in the central sections of the furnace and the distribution of the radiant energy flow to the walls of the combustion chamber were obtained.

The Fig. 6 illustrations that chemical reactions with the highest heat release occur in the fuel and oxidizer supply, i.e. near the installation of burners. In this area mixing of combustible substances and oxygen in the air reaches its maximum level due to intensive mixing, turbulent pulsations and a vortex flow character. This in turn contributes to an increase in the rate of the chemical reaction of carbon oxidation with the release of the maximum amount of energy (Q_{chem}= 3470.9 kW/m^3).

Conclusion

Based on the results of us study, the following conclusions can be drawn:

- The temperature reaches its maximum values in the area close to the location of burners as here, due to the vortex character of the flow, the maximum convective transfer is observed and as a result, the residence time of coal particles increases, which leads to an increase in the temperature in this zone.
- The energy released by chemical reactions reaches its maximum value 3470.9 kW/m^3 in the section of burners. In central part of the combustion chamber this value is 152.2 kW/m^3.
- The physical and mathematical model used in the numerical calculations adequately describes burning of high-ash coal in the combustion chamber of the BKZ 75-39 boiler at Shakhtinskaya TPP, Kazakhstan. The obtained results are in good agreement with the experimental data, which were obtained specially at the thermal power station.

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ЖЫЛУ ЭЛЕКТР СТАНЦИЯЛАРЫНЫҢ ЖАНУ ҚАЗАНЫНДА ЖЫЛУ АЛМАСУ ПРОЦЕСТЕРІН 3D МОДЕЛЬДЕУ

Аннотация. Бұл жұмыста нақты геометрия аймақтарында (ЖЭС, ЖЭО) жоғары температурадағы әсер ететін ортадағы турбулентті ағындарында жылу және масса тасымалының процестерін жан-жақты зерттеу үшін компьютерлік 3D модельдеу әдісі пайдаланылды. Шахтинск ЖЭО зауытындағы БКЗ-75 қазандықтың жану камерасында жылу процестерін және ағынның аэродинамикалық сипаттамаларын зерттеуге арналған есептік эксперименттер жоғары күлді жанармайдың жануы кезінде жүргізілді. Компьютерлік 3D модельдеу әдістерін пайдаланған кезде өндірістік объектілердің жану камераларында нақты технологиялық үрдістер ағынынна әсер ететін құбылыстар мен факторлардың ең көп саны ескерілді. Зерттелетін жану камерасының аэродинамикалық сұлбесі ұсынылған, химиялық реакциялар арқылы пайда болатын температура өрістері мен энергия бөлу, сондай-ақ жану камерасының негізгі жылу алатын беттеріне радиациялық жылу ағындарының мәндері алынады. Орындалған есептеу эксперименттерінің нәтижелері қатты отынмен жұмыс істейтін өнеркәсіптік қазандықтардың жану камераларын жаңа және жобалау кезінде, физикалық және математикалық модельдер осы саладағы ғылымның даму деңгейіне арналған ең толық, заманауи және оңтайлы болып табылады мүмкін. Жану камерасында жылу электр станцияларының жану камераларында қатты отынды жағу бойынша 3D есептеу эксперименттеріне арналған заманауи технологияларды қолдану барлық жану өнімдерінің, сонымен бірге жану аймағындағы жанғыш көмір процесінің зиянды заттар мен басқа да сипаттамаларының жылдамдығын, температурасын, қысымын және концентрациясын егжей-тегжейлі сипаттауға мүмкіндік береді.

Түйін сөздер. Жылу масса алмасу, жану, қатты отын, плазмалық активация, ародинамикалық ағыс, концентрация және темпераура өрісі, зиянды заттардың қалдықтары.

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3D-МОДЕЛИРОВАНИЕ ПРОЦЕССОВ ТЕПЛООБМЕНА В КАМЕРЕ СГОРАНИЯ КОТЛА ТЕПЛОВЫХ ЭЛЕКТРИЧЕСКИХ СТАНЦИЙ

Аннотация. В настоящей работе методами компьютерного 3D-моделирования проведено комплексное исследование процессов тепломассопереноса в турбулентных течениях высокотемпературных реагирующих сред в областях реальной геометрии (ТЭС, ТЭЦ). Вычислительные эксперименты по исследованию тепловых процессов и аэродинамических характеристик течения проведены в топочной камере котла БКЗ-75 Шахтинской ТЭЦ при сгорании в ней высокозольного энергетического топлива. При использовании методов компьютерного 3D-моделирования учтено наибольшее количество явлений и факторов, влияющих на протекание реальных технологических процессов в камерах сгорания промышленных объектов. Представлена аэродинамическая картина исследуемой топочной камеры, построены температурные поля и распределения энергии, выделяющейся за счет химических реакций, а также получены значения радиационных тепловых потоков на основные тепловоспринимающие поверхности камеры сгорания. Результаты проведенных вычислительных экспериментов, могут быть использованы при проектировании новых и доработке существующих топочных камер промышленных котлов, использующих твердое топливо, поскольку используемые физико-математические модели являются наиболее полными, современными и оптимальными для данного уровня развития науки в этой области. Применение современных технологий для проведения 3D-вычислительных экспериментов по сжиганию твердого топлива в топочных камерах ТЭС, позволит подробно описать поля скорости, температуры, давления и концентраций всех продуктов сжигания и прежде всего вредных веществ и других характеристик процесса сжигания угля по всему топочному пространству и на выходе из топочной камеры.

Ключевые слова. Тепломассоперенос, горение, твердое топливо, плазменная активация, аэродинамика течения, концентрационные и температурные поля, выбросы вредных веществ.

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