Editor
Aida Bulucea

Recent Advances in Energy, Environment and Financial Science

- **Proceedings of the 12th International Conference on Energy, Environment, Ecosystems and Sustainable Development (EEESD '16)**

- **Proceedings of the 4th International Conference on Management, Marketing, Tourism, Retail, Finance and Computer Applications (MATREFC '16)**

Venice, Italy, January 29-31, 2016

Energy, Environmental and Structural Engineering Series | 45

RECENT ADVANCES in ENERGY, ENVIRONMENT and FINANCIAL SCIENCE

Proceedings of the 12th International Conference on Energy, Environment, Ecosystems and Sustainable Development (EEESD '16)

Proceedings of the 4th International Conference on Management, Marketing, Tourism, Retail, Finance and Computer Applications (MATREFC '16)

Venice, Italy
January 29-31, 2016

Energy, Environmental and Structural Engineering Series | 45

ISSN: 2227-4359
ISBN: 978-1-61804-361-0

Computational experiment on the effect of the boundary conditions for the temperature on the walls of the combustion chamber on the processes of heat and mass transfer

ASKAROVA ALIYA, BOLEGENOVA SALTANAT, BOLEGENOVA SYMBAT, MAXIMOV VALERIY, BEKETAYEVA MERUYERT*, GABITOVA ZARINA, ERGALIYEVA AIGUL, ALDIYAROVA ALIYA, SHORTANBAYEVA ZHANAR, TUYAKBAYEV ALTAI
Physics and Technical Physics
Al-Farabi Kazakh national University
Almaty, 050038, al-Farabi av., 71
KAZAKHSTAN
Beketayeva.m@gmail.com http://www.kaznu.kz

Abstract: - Insufficient knowledge about behavior definition of the heat flow and mass transfer processes during combustion of pulverized coal for various boundary conditions of temperature on the walls of the chamber focuses on realistic model of choice is almost arbitrary. Therefore, in this paper, heat and mass transfer processes have been investigated during combustion high-ash coal in the combustion chamber of the boiler BKZ-75 under different boundary conditions for the temperature of the chamber walls. This will allow more detailed study of the influence of the boundary conditions for the temperature of the walls of the combustion chamber on the processes of heat and mass transfer. In the paper two- and three-dimensional interpretation of the temperature of the fields and carbon dioxide characteristics were obtained in a volume of the combustion chamber. It is shown more adequate results that are close to full-scale, possibly to get when used a mathematical model with inconsistency of the combustion chamber walls.

Key-Words: - Numerical modeling, burning, the boundary conditions for the temperature of the walls, combustion chamber, concentration, heat and mass transfer

1 Introduction

Due to the scenario of development of the Republic of Kazakhstan to improve the efficiency of the energy sector while maintaining its economic benefits and environmental safety set goals [1], which can be solved only by deep and thorough in joint research engineers in the field of technical physics, thermal energy, and information technologies. An important importance has carrying out computational experiments, which can give full information about the nature of heat and mass transfer of complex processes occurring in boilers of heat power objects [2-6].

Computational experiments are based on a correct set of mathematical models of physical processes, which consist of a system of differential equations, algebraic relations and the closing boundary (initial and boundary) conditions [7-13].
Inadequate study of determining the behavior of the heat flow and mass transfer processes in the combustion chamber during the burning of pulverized coal at different boundary conditions of temperature on the walls of the chamber focuses on realistic model of choice is almost arbitrary.

Therefore, in this paper, heat and mass transfer processes have been investigated by burning high-ash coal in the combustion chamber of the boiler BKZ-75 of Shakhtinsk CHP under different boundary conditions for the temperature of the chamber walls. This will allow more detailed study of the influence of the boundary conditions for the temperature of the walls of the combustion chamber on the processes of heat and mass transfer.

2 Problem Formulation

Convective heat transfer between the hot fuel-air stream and the wall at a predetermined temperature determined by the flow in the wall region [21-22]. For adiabatic walls (wall temperature of the combustion chamber is constant), the heat flux is zero ($q_w = 0$) in this case is used as a boundary conditions in the plane of symmetry.

In the case of heat exchange between the wall and the reactive flux can specify the wall temperature or heat flux (for the problem when the furnace wall temperature variable). Assuming known convective heat transfer coefficient α, the heat flux can be expressed as follows:

$$q_W = \alpha(T_{WP} - T_W).$$

When the wall temperature of combustion chamber is variable heat flux $\dot{q}$ can be calculated by the formula:

$$\dot{q} = \underbrace{\alpha(T_{FG} - T_{Surf})}_{convection} + \underbrace{C_{12}(T^4_{FG} - T^4_{Surf})}_{radiation},$$

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

The computational application [23] can investigate two ways of accounting of changes in the boundary conditions of the surface temperature of the wall (Figure 1):
1) fixed constant surface temperature $T_{surf} = const$;
2) the estimated surface temperature of a constant heat transfer and evaporation fixed constant temperature inside the tubes $T_{steam} = const$.

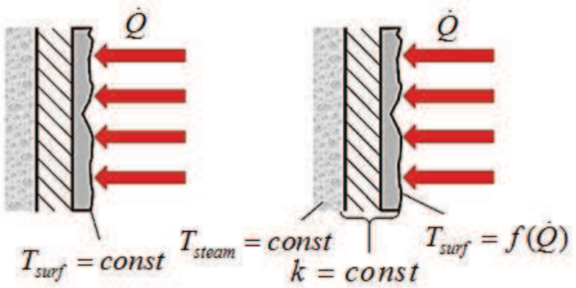


Fig.1 Model of the boundary condition for the temperature of the wall of the combustion chamber

The surface temperature T_{surf} of the chamber wall can be calculated as follows:

$$\dot{q} = k(T_{surf} - T_{steam}),$$

$$T_{surf} = \frac{\dot{q}}{k} + T_{steam},$$

here k - the thermal conductivity between the walls and pipes, W/m^2·K. The temperature of the wall surfaces of the combustion chamber T_{surf} affect the flow of heat, so its calculation procedure is performed iteration:
a) calculation of the heat flow;
b) The calculation of the surface temperature T_{surf};
c) recalculate heat flux to the new value of surface temperature;
d) recalculate a new surface temperature T_{surf}.

2.1 The mathematical formulation

The theoretical analysis of vortex flows are Navier-Stokes and Reynolds, however, due to non-linearity and interconnectedness of these equations in their decision can generally be found only numerically. The predominant method in numerical simulation of heat and mass transfer, and subsonic flows is well-established algorithm of Patankar-Spalding is SIMPLE. This method is very technologically in the software implementation, meets the requirements of conservatism, and allows using relaxation factor to control the course of the computational process.

Fundamentals of numerical modeling - the development of the mathematical description of the physical system, which takes into account the impact of physical and chemical processes, such as combustion of fuel aerodynamic movement of the gases, air and poly disperse particles of fuel, as well as heat and mass transfer [6-9]. Description of the numerical model is based on a number of physical laws of conservation of mass, momentum, energy and others [8-9]. In addition, were used the fundamental relations for the circuit chosen systems of equations [10-13].

The equation of conservation of mass can be written as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = S_i,$$

where, S_i - the source of supply. It determines the mass added to the continuous phase, and any other sources, certain specific physical problem.

The equation of conservation of momentum can be written Navier-Stokes equations in the form:

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

The first term describes the unsteady flow, the second - convective transfer, the third and fourth terms - surface forces (pressure gradient and molecular diffusion), the fifth - the mass forces (gravity), the sixth - the external mass forces. Energy conservation equation takes into account the transfer of energy by conduction, diffusion and viscous dissipation:

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

Generalized transport equation for variable flow, means the mass, or the kinds of components, the momentum or energy can be written in the form of a generalized transport equation in turbulent flows:

$$\frac{\partial(\rho\varphi)}{\partial t}+\frac{\partial}{\partial x_i}(\rho\varphi u_j)=\frac{\partial}{\partial x_i}(\Gamma_\varphi\frac{\partial\varphi}{\partial x_i})+S_\varphi .$$

2.2 Physical formulation

To carry out computational experiments with the use of 3D modeling was selected combustion chamber of the boiler BKZ-75, operating in Shakhtinsk CHP. As a basis for numerical calculations used a computer software package FLOREAN [14], which is widely used in research on the processes highly reactive currents in the combustion chambers of the many thermal power facilities in the Republic of Kazakhstan [15-20], as well as abroad.

Boiler BKZ-75 (Figure 2) has a block vertical tube design, U-shaped pattern of motion of the working environment based on natural circulation.

Combustion chamber completely shielded pipe diameter of 60×3 mm and consists of 12 separate circulation circuits. The combustion chamber of the boiler BKZ-75 is equipped with four-bladed axial swirl coal dust burners that are arranged in one tier two burners on the side walls of the chamber (Figure 3).

The Karaganda coal burned in this thermal power station has the following characteristics: C – 79.57%, H_2 – 6.63%, O_2 – 9.65%, S_2 – 1.92%, N_2 – 2.23%, W – 10.6%, A – 35.1%. Q – $3.4162\cdot10^4$ kJ/kg. To carry out computational experiments was built by the geometry of the object according to the real circuit, and was composed of its finite-difference grid, which has steps along the axes X, Y, Z: 59×32×67, which is 126 496 control volumes.

Technical parameters of the combustion chamber of the boiler BKZ-75 are shown in Table below.

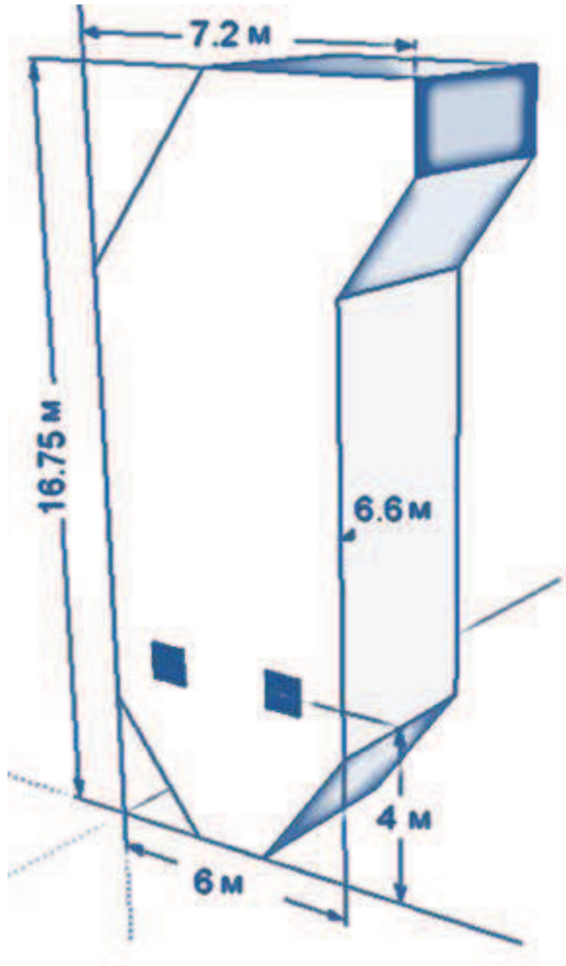
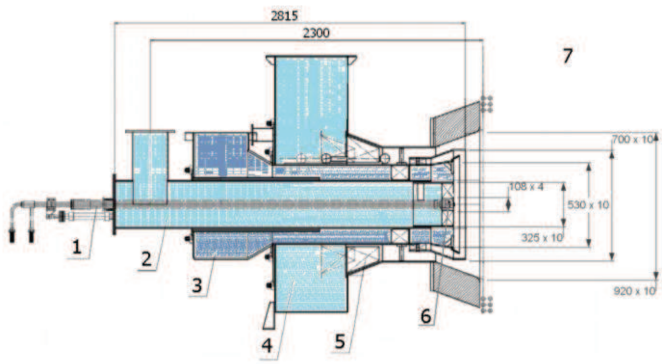


Fig.2 General View of the boiler BKZ-75 of Shakhtinsk CHP



1 - Heavy oil wire, 2 - air for combustion of fuel oil 3 - fuel mixture box, 4 - secondary air ducts, 5 - blading, 6 - heavy oil nozzle 7 - combustion chamber

Fig.3 Scheme of pulverized coal burner in longitudinal section, is used in the combustion chamber of the boiler BKZ-75-39FB of Shakhtinskaya CHP

Table Technical parameters of the combustion chamber of the boiler BKZ-75 of Shakhtinsk CHP

Designation	Value
Number of burners on the boiler, N_b, ps.	4
Capacity of one burner in fuel, B_b, t/h	3.2
Primary air flow to the boiler, V_{pa}, Nm^3/h	31797
Secondary air flow to the boiler, V_{sa}, Nm^3/h	46459
Hot air temperature, t_{ha}, °C	290
Air ratio in the furnace, α	1.2
Calculated fuel consumption for the boiler, B_c, t/h	12.49
Cold air temperature, t_{ca}, °C	30
Pressure at inlet, P, mbar	$1.013 \cdot 10^3$
Pressure drop of the fuel mixture burner channel, ΔP, mm.w.c.	67.1
Fuel mixture temperature, t_{fm}, °C	140
Wall temperature, t_w, °C	430.15

In case of simulation of combustion processes in order to determine the formation of harmful substances in the combustion chambers, a model to describe the transfer of heat energy must be as accurate as possible to predict the temperature distribution in the combustion space, since the kinetic processes of chemical reactions in very strong function of temperature.

In combustion chambers of the boiler, with the proviso that all known emitting properties and the temperature distribution in the reaction medium and on the walls, it is possible prediction radiant heat from the flame and products of combustion to the walls and the heating surfaces. However, in most cases the temperature itself - unknown option so the laws of conservation of the total energy and radiation energy equation together in one system.

3 Problem Solution

Figure 4 shows the distribution plots of maximal, minimal and average values of the temperature in height of the furnace volume of the boiler BKZ-75 for two cases of changing of boundary conditions for the temperature of the furnace walls.

Minimal temperatures in the burners are obtained for two cases of boundary conditions due to the low temperature of the injected fuel mixture (140°C). As can be seen from the curves change of boundary conditions for the temperature of the walls greatly affect the nature of the temperature distribution in the combustion chamber.

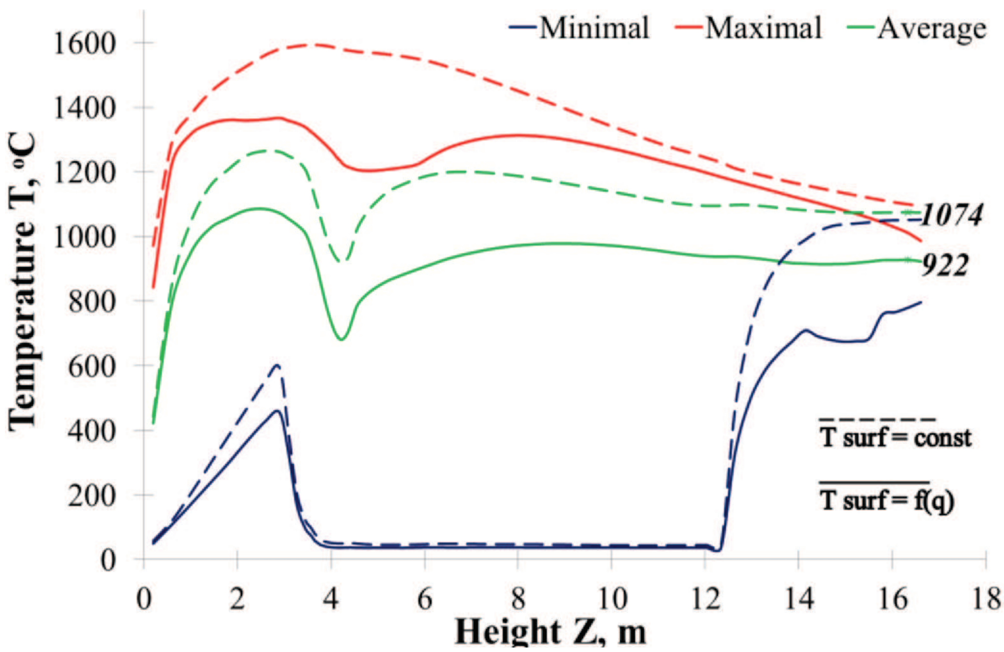


Fig.4 Changing the temperature in height of the combustion chamber of boiler BKZ-75 at two boundary conditions for the temperature of the walls

Figure 4 shows that although the distribution of the maximum, average and minimum temperature values along the Z axis of the combustion chamber for both boundary conditions are qualitatively similar, it can be seen that at constant temperature chamber walls all temperatures higher than in the case where the wall temperature variable and determined by the heat flow. Based on the mean temperature is not possible to notice that the difference for the two cases is about ~152°C, which is about 14%.

Significant differences occur in the temperature distribution at the location of burners and forth along the length of the torch towards the outlet of the combustion chamber. This is because by blowing fuel mixture from the burner, the ignition of the fuel and its combustion heat is given to the emerging part of the combustion chamber walls, the temperature of which changes all the time [24-27].

Due to the lack of heat exchange with the medium in screen tubes provided maintain a constant wall temperature, the level of turbulent pulsations increases in the entire volume of flue unit, thereby raising the temperature.

As we move to the exit of the combustion chamber, the physical processes with chemical transformations between the hot combustion gases and oxidant are weakened, which leads to a lowering of the temperature at the outlet of the furnace. Thus, at the outlet of the combustion chamber when the temperature of the variable temperature chamber walls has an average value 922°C, and in the case of constant wall temperature, the average temperature is equal 1074°C.

By analyzing the three-dimensional temperature distributions in Figures 5-6, it is possible to make a similar conclusion: the temperature in all selected sections of the combustion chamber at a value which can be determined by the temperature scale, everywhere above for boundary conditions, when the temperature of the chamber walls is maintained constant.

In the field of burning devices temperature values reach 1252°C for the case of $T_{surf}=const$, and reaches values 1585°C for the case of $T_{surf}=f(q)$ (Figure 6). At the section of camera rotation zone (Z=12.65m) temperature fields differ only quantitatively.

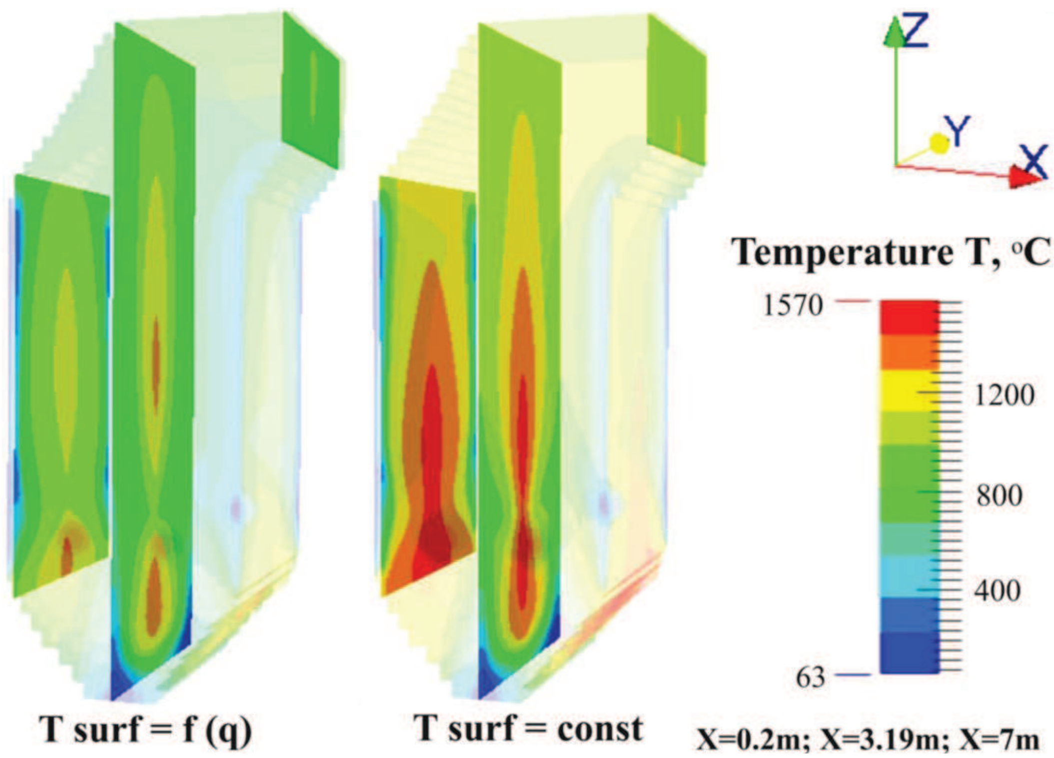


Fig.5 Three-dimensional temperature distribution in the longitudinal sections of the combustion chamber of the boiler BKZ-75

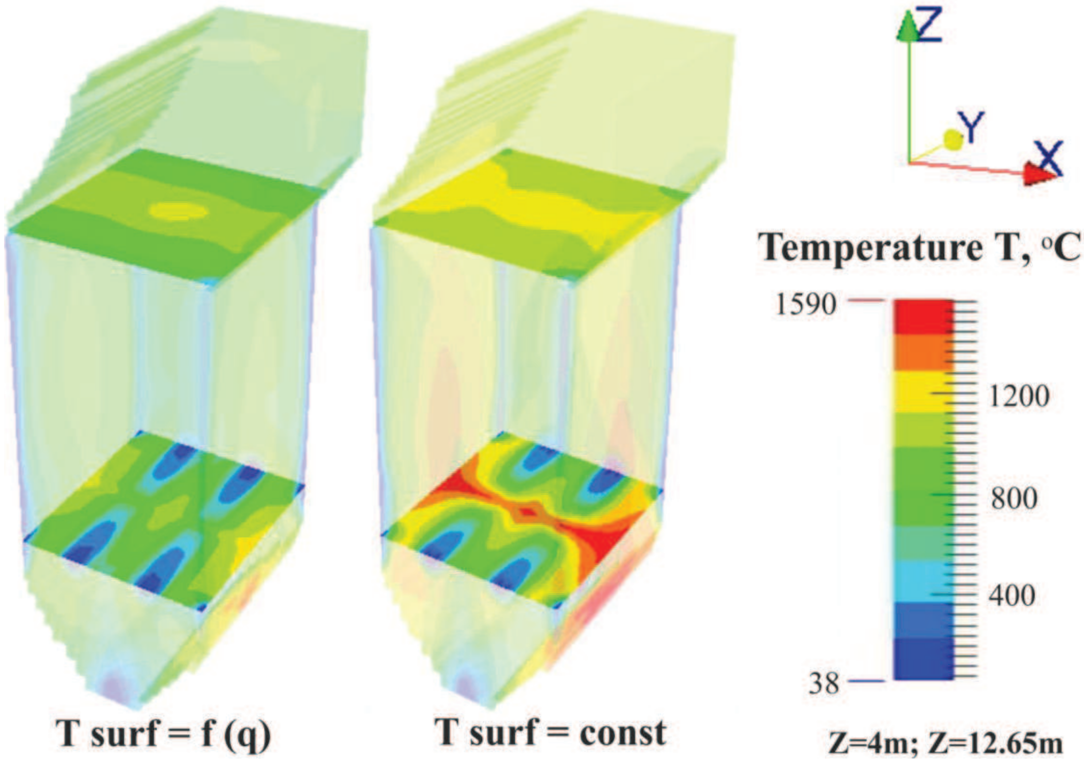


Fig.6 Three-dimensional temperature distribution in the cross-sections of the combustion chamber of the boiler BKZ-75

Air oxygen O_2 in the furnace reacts with the fuel and hot combustion products actively and reduces its concentration throughout the furnace (Figures 7,9). As it is seen from the figures its concentration at the outlet of the furnace is about 6%, when its maximal values are at the burners installed section (~23%). It's known that the main product of the combustion of the solid fuel at high temperatures with the oxygen of air are carbon oxides CO and carbon dioxides CO_2 (see Figures 8,10).

Comparing the results of numerical experiments to determine the concentrations of CO_2 for two boundary conditions the temperature of the combustion chamber wall can be said that they are also quite different.

The largest differences in ~7% for the average concentration of carbon dioxide observed in the ignition, and the formation of the flame in the burner zone. This is due to the instability of ignition, combustion stabilization processes within the plume, an intensive process of oxidation and the formation of the combustion products, etc [28-33]. At the exit of the furnace, where the combustion process substantially completed, the differences in the profiles the concentration of CO_2 for different boundary conditions on the walls of the furnace are smoothed and are only ~1.2%.

ISBN: 978-1-61804-361-0

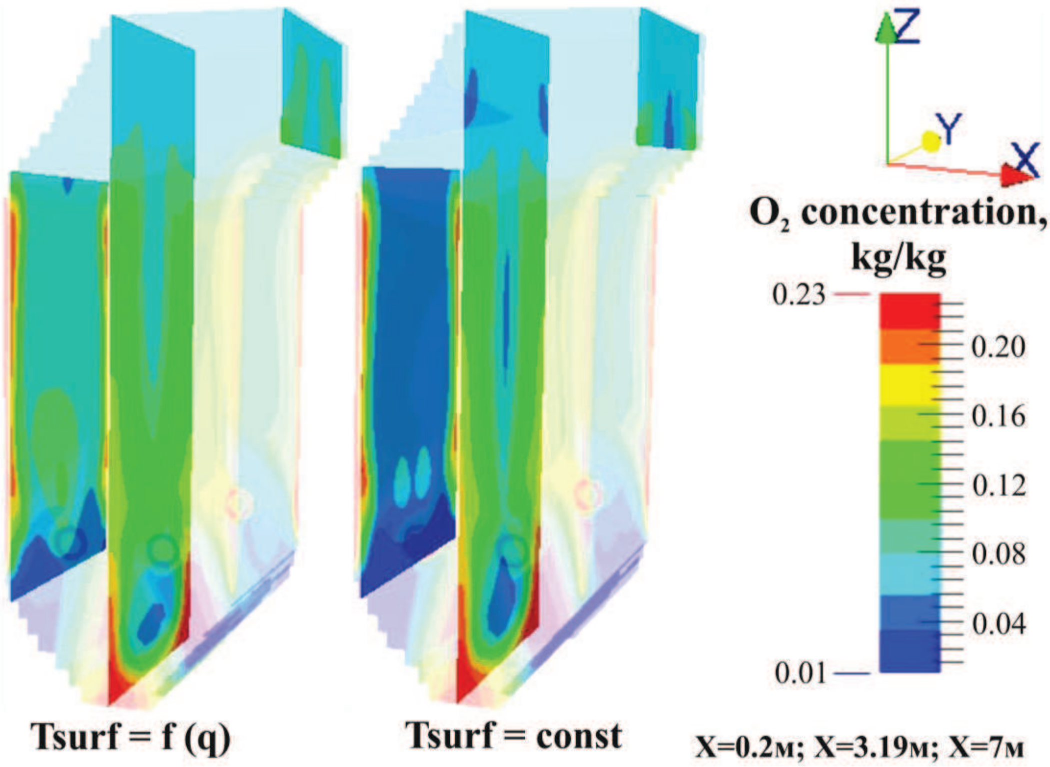


Fig.7 Three-dimensional distribution of the concentrations of O_2 in the longitudinal section of the combustion chamber of the boiler BKZ-75

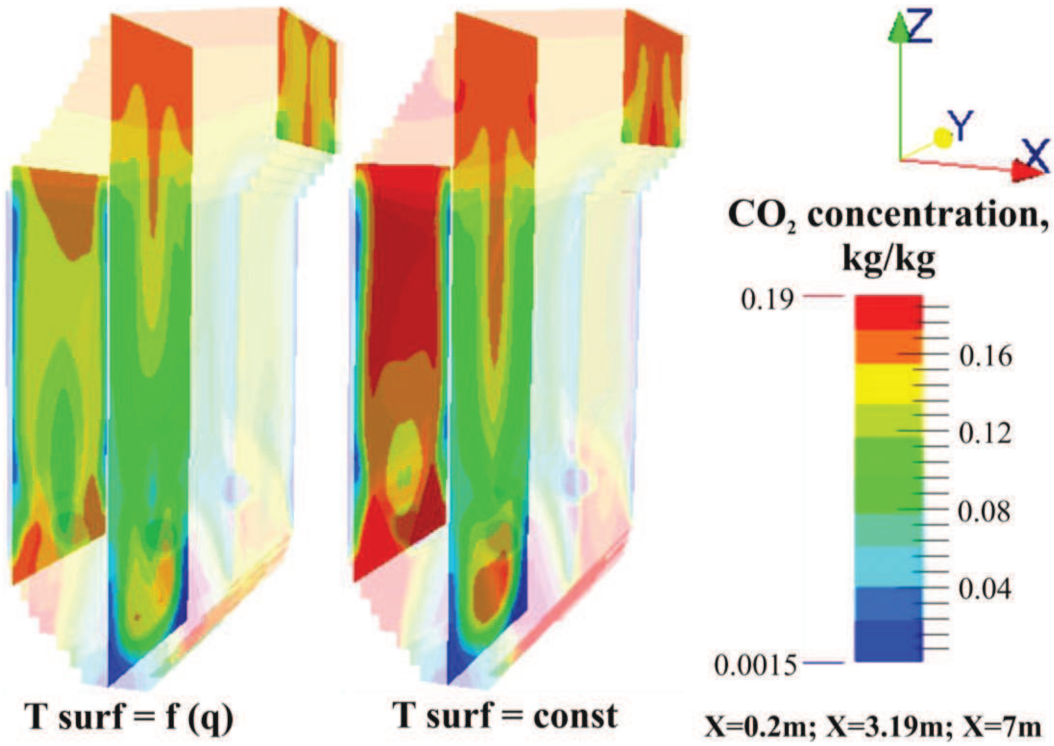


Fig.8 Three-dimensional distribution of the concentrations of CO_2 in the longitudinal section of the combustion chamber of the boiler BKZ-75

ISBN: 978-1-61804-361-0

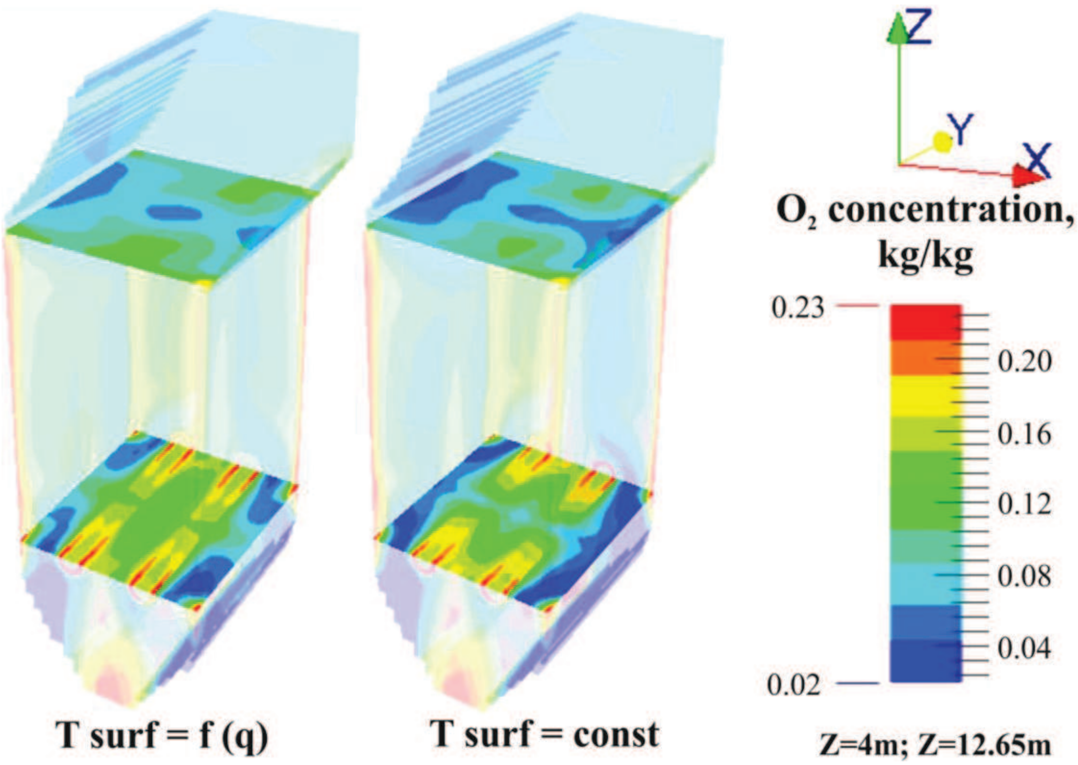


Fig.9 The three-dimensional distribution of the concentrations of O_2 in the cross-sections of the combustion chamber of the boiler BKZ-75

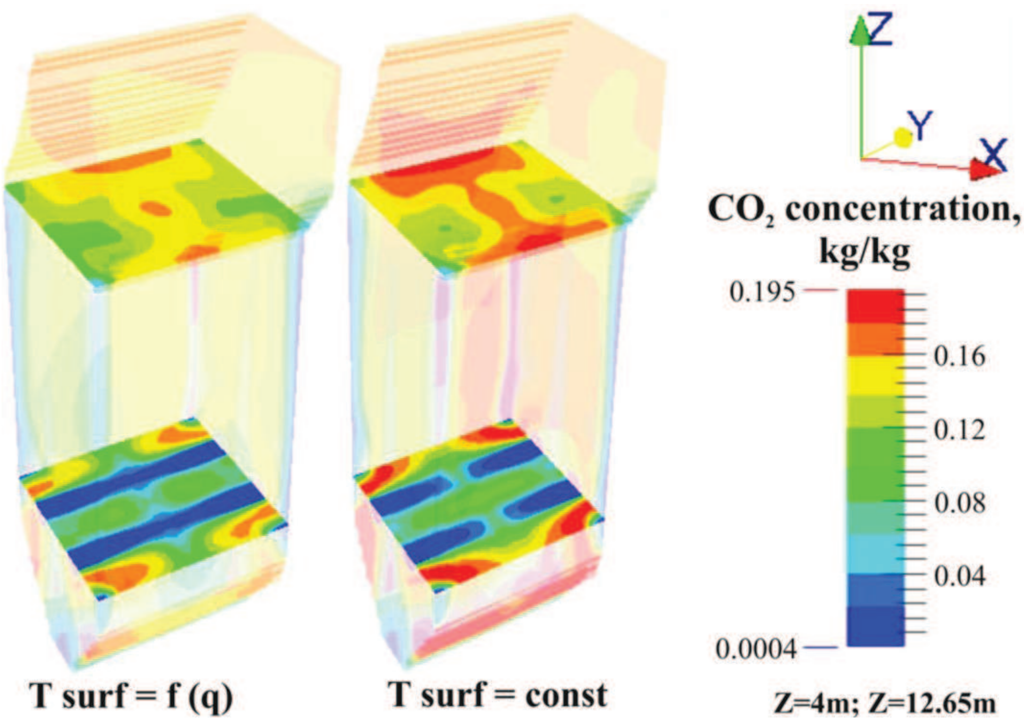


Fig.10 The three-dimensional distribution of the concentrations of CO_2 in the cross-sections of the combustion chamber of the boiler BKZ-75

To select a boundary condition for the temperature of the walls of the combustion chamber, best describes the actual process conditions are close to the CHP, we compared the results of numerical simulations with the theoretically calculated value of the temperature at the outlet of the combustion chamber of the boiler BKZ-75 (Figure 11) obtained by CKTI normative method [34].

It may be noted a good agreement with the theoretical point of numerical results output from the furnace using the boundary condition of impermanence of wall temperature. The temperature at the outlet of the combustion chamber when the computational experiment is equal to T = 922°C, and theoretically calculated value for the boiler BKZ-75 is equal to T = 968°C.

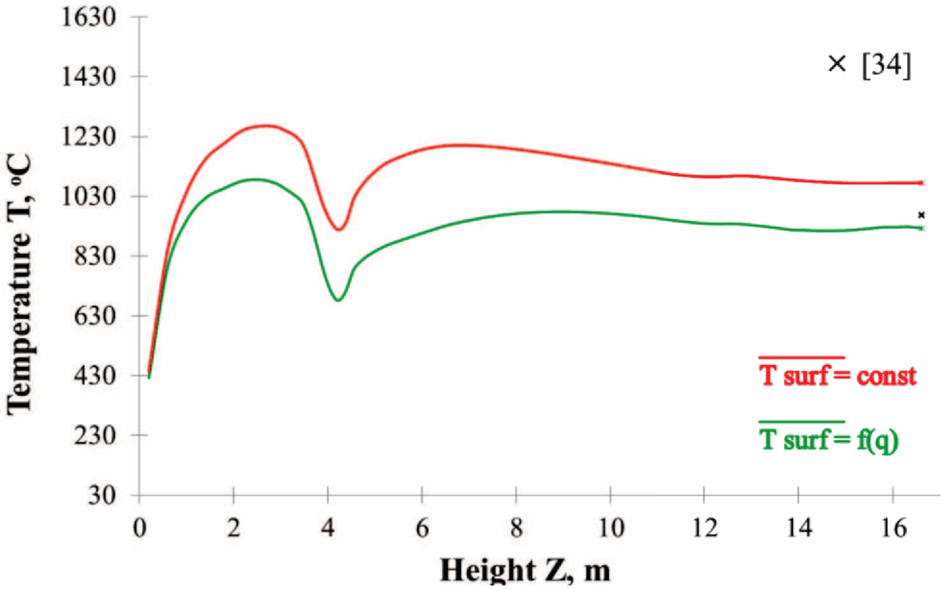


Fig.11 Comparison of the results of computer simulations in the combustion chamber of the boiler BKZ-75 from the field data and theoretically calculated value

4 Conclusion

The difference between the theoretically calculated values at the outlet of the furnace with the result of a computational experiment is only ~4.6% for the boundary conditions, when the temperature of the chamber walls of the variable. However, at a fixed temperature of the surface of the walls of the combustion chamber for computational experiment requires less computer time. This means that the increased power requirements and computing (processor frequency and RAM of the computer). Accordingly, when performing such complex computational experiments on burning low-grade coal in the boiler furnaces actual operating purposes must take into account these two conditions to select the optimum ratio: the time and resources expended and the accuracy of the experiment and produce results that are in agreement with the real data.

References:

[1] N. Nazarbayev, Strategii ustoychivoy energetiki budushchego Kazakhstana do 2050 goda, Ekonomika, 2011.

[2] A.S. Askarova, V.E. Messerle, A B. Ustimenko etc., Numerical Simulation of Pulverized Coal Combustion in a Power Boiler Furnace, *High Temperature*, Vol.53, No.3, 2015, pp. 445-452.

[3] V.E. Messerle, A.B. Ustimenko, Yu.V. Maximov, etc., Numerical Simulation of the Coal Combustion Process Initiated by a Plasma Source, Journal of Thermophysics and Aeromechanics, Vol.21, Iss.6, 2014, pp. 747-754.

[4] M.A. Gorokhovski, A. Chtab-Desportes, I. Voloshina, etc., Stochastic simulation of the spray formation assisted by a high pressure, 6-th International Symposium on Multiphase Flow, Heat Mass Transfer and Energy Conversion, Vol.1207, 2010, pp. 66-73.

[5] S.A. Bolegenova, M.T. Beketayeva, Z. Gabitova, etc., Computational Method for Investigation of Solid Fuel Combustion in Combustion Chambers of a Heat Power Plant, High Temperature, Vol.53, No5, 2015, pp. 751-757.

[6] A.S. Askarova, S.A. Bolegenova, A. Bekmukhamet, etc., Numerical experimenting of combustion in the real boiler of CHP, International Journal of Mechanics. Vol.7, Iss.3, 2013, pp. 343-352.

[7] A.B. Ustimenko, A.S. Askarova, V.E. Messerle, A. Nagibin, Pulverized coal torch

combustion in a furnace with plasma-coal system, Journal of Thermophysics and Aeromechanics, Vol.7, Iss.3, 2010, pp. 435-444.
[8] H. Müller, Numerische Simulation von Feuerungen. CFD–Vorlesung, TU, IWBT, 1997.
[9] D. Spolding, The calculation of combustion processes: Future application of combustion theory report RF/TN/A/8, 1971.
[10] W. Pauker, Creating data sets for Florean using the tool PREPROZ, IWBT, 1997.
[11] R. Leithner Numerical Simulation. Computational Fluid Dynamics CFD: Course of Lecture, IWBT, 2006.
[12] A.S. Askarova, E.I. Karpenko, V.E. Messerle, et al., Plasma enhancement of combustion of solid fuels, Journal of High Energy Chemistry, Vol.40, Iss.2, 2006, pp. 111-118.
[13] S.A. Bolegenova, V.Yu. Maksimov, A. Bekmuhamet, etc., Mathematical simulation of pulverized coal in combustion chamber, Journal of Procedia Engineering, Vol.42, 2012, pp. 1150-1156.
[14] H. Müller, Numerische simulation von Feuerungen. CFD-Vorlesung, IWBT, 1997.
[15] Yu.V. Maximov, M. Beketayeva, Sh. Ospanova, et al., Investigation of turbulence characteristics of burning process of the solid fuel in BKZ 420 combustion chamber, WSEAS Transactions on Heat and Mass Transfer, Vol.9, 2014, pp. 39-50.
[16] Y. Heierle, R. Leithner, H. Müller, etc., CFD Code FLOREAN for Industrial Boilers Simulations, WSEAS Transactions on heat and mass transfer, Vol.4, Iss.4, 2009, pp. 98-107.
[17] Yu.E. Karpenko, E.I. Karpenko, A.S. Askarova, et al., Mathematical modeling of the processes of solid fuel ignition and combustion at combustors of the power boilers, 7-th International Fall Seminar on Propellants, Explosives and Pyrotechnics. Theory and Practice of Energetic Materials. China, 2007, Vol.7, pp. 672-683.
[18] Ye.I. Lavrishcheva, E.I. Karpenko, A.B. Ustimenko, etc., Plasma-supported coal combustion in boiler furnace, IEEE Transactions on Plasma Science, Vol.35, Iss.6, 2007, pp. 1607-1616.
[19] I.V. Loktionova, E.I. Karpenko, A.S. Askarova, V.E. Messerle, A.B. Ustimenko, Optimization of the combustion of power station coals using plasma technologies, Thermal Engineering, Vol.51, Iss.6, 2004, pp. 488-493.
[20] A.S. Askarova, Ye.I. Lavrichsheva, M.Zh. Ryspayeva, Numerical investigation of influence of coal particles sizes on the process of turbulent combustion in the furnace chambers, 17th International Congress of Chemical and Process Engineering, 2006, F5.6.
[21] Г. Шлихтинг, Теория пограничного слоя, ИЛ, 1969.
[22] 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, Reiche 6, No.268, 1992, 158 p.
[23] R. Leithner, H. Müller, CFD studies for boilers, Second M.I.T. Conference on Computational Fluid and Solid Mechanics, Cambridge, 2003, P. 172.
[24] D.B. Spolding, Osnovi teorii goreniya, Gosenergoizdat, 1959.
[25] G.F. Knorre, i dr., Teoriya topochnikh processov, Energiya, 1966.
[26] P. Safarik, V. Maximov, M.T. Beketayeva, et al., Numerical Modeling of Pulverized Coal Combustion at Thermal Power Plant Boilers, Journal of Thermal Science, Vol.24, Iss.3, 2015, pp. 275-282.
[27] A. Askarowa, M.A. Buchmann, Structure of the flame of fluidized-bed burners and combustion processes of high-ash coal, Combustion and Incineration, Vol.1313, 1997, pp. 241-244.
[28] A.S. Askarova, I.V. Loktionova, V.E. Messerle, A.B. 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, Journal of Thermal engineering, Vol.50, Iss. 8, 2003, pp. 633-638.
[29] B.D. Kancnelson, I.Ya. Marone, O vosplamenenii i gorenii ugolnoi pili, Teploenergetika, No.1, s. 30-35.
[30] R. Leithner, H. Müller, A. Askarova, Ye. Lavrichsheva, A. Magda, Combustion of low-rank coals in furnaces of Kazakhstan coal-firing power plants, *VDI Berichte*, Iss. 1988, 2007, pp. 497-502.
[31] V.E. Messerle, E.I. Karpenko, A.B. Ustimenko, etc., Plasma enhancement of coal dust combustion, 35-th EPS Conference on Plasma Physics, Hersonissos, 2008, Vol.32, pp. 148-152.
[32] S. Vockrodt, R. Leithner, etc., Firing technique measures for increased efficiency and minimization of toxic emissions in Kasakh coal firing, Combustion and incineration, Vol.1492, No.1999, P. 93.
[33] A.S. Askarova, A. Bekmukhamet, S.A. Bolegenova, et al., Numerical modeling of turbulence characteristics of burning process of the solid fuel in BKZ-420-140-7c combustion chamber, International Journal of Mechanics, Vol.8, 2014, pp. 112-122.
[34] Teplovoi raschet kotlov: Normativnyi metod, NPO CKTI, 1998.