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COMPUTATIONAL EXPERIMENTS FOR RESEARCH OF FLOW AERODYNAMICS AND TURBULENT CHARACTERISTICS OF SOLID FUEL COMBUSTION PROCESS

Abstract. Some of the most interesting and useful from the point of view of practical application are the issues of heat and mass transfer modeling in the presence of physicochemical processes in real geometry areas. Such areas are the combustion chambers of various heat and power plants, and internal combustion engines.

Key Words: combustion chamber, boiler, burners, solid fuel, high-ash coal, numerical simulation, computational experiment.

Introduction

Currently, there is an increased interest in the study of heat and mass transfer processes in high-temperature environments in the presence of combustion therein. These processes run under conditions of strong non-isothermality and flow turbulence, multiphase environment, significant influence of nonlinear effects of thermal radiation, interphase interaction, and multiple stages of chemical reactions occurring at that time. Such phenomena are widespread, and they play an important part in thermophysical processes and their study is an urgent task of macrokinetics, combustion and explosion physics and present-day thermophysics.

Turbulent high-temperature and chemically-reactive media are exceptional in terms of their physicochemical properties, hands-on capabilities and engineering applications. Research on heat and mass transfer in such media is relevant in the creation of new physicochemical technologies, in the design of aviation and rocket technology, in the development of new furnace units, gas turbines and internal combustion engines.

Of particular relevance is the study of heat and mass transfer in high-temperature reactive media and simulation of physicochemical processes occurring during combustion of pulverized coal fuel to solve the problems of modern power engineering and ecology. Consideration of these issues is relevant in connection with the concept of "energy security" of the country, on the one hand, and the development of "clean" fuel combustion processes in compliance with strict standards for the environmental emissions of harmful substances, on the other hand.

There is an increased interest in the study of heat and mass transfer processes in the presence of physicochemical transformations, currently observed. Examination of the patterns of such flows is of fundamental importance in constructing a theory of physics of combustion and explosion and an enormous practical orientation in the creation of new physicochemical technologies and in the development of technological processes and systems with the rational utilization of energy resources.

To study heat and mass transfer processes, the most commonly used methods are well-known methods of the turbulent jets theory [1-9], when researchers use pre-selected velocity or temperature profiles, integral laws of conservation of momentum, heat content, etc. And, the selected profiles with sufficient approximation approximate the experimental profiles.

Mathematical Model and Basic Equations

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 radiation transport. Modeling in varying degrees includes particle size distribution (calculated in finite size ranges at all points in the region), flow or zone characteristics of radiation transfer, and soot distribution data (soot is formed as a result of thermal decomposition of hydrocarbons and is eliminated by oxidation; both processes represent a complex chemical kinetics problem).

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

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

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

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

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

where $I = 1,2,3$; $j = 1,2,3$; β=1,2,3,…N.

To simulate turbulent viscosity, the well-known *k-ε* turbulence model was used, comprised of the equation for the conservation of 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 a flow with forced and natural convection.

In flows with high solids content, solid media has a significant effect on convective and diffusive transport. However, the presence of solids in carbon monoxide from coal dust combustion units is so insignificant (with the exception of near-burners area) that the second phase effect is neglected in the calculations [10-13]. Then the process of burning solid fuel in the combustion chambers can be represented as follows: the flame is a two-phase gas-dispersed system, and the effect of the solid phase on the flow aerodynamics is insignificant [14].

In determining the integral absorption coefficients K_{abs}, it is necessary to take into account the mechanisms of emission of gas and solid particles. If there is a thermodynamic equilibrium between gas and solid particles, the radiation of suspension is described by adding dust and gas emissions. Thus, the share contributed by gas and solid particles is described by the following sum [15-16]:

$$K_{abs} = K_{abs,G} + \sum K_{abs,P,k} \tag{5}$$

The values of the mass coefficient and the absorption coefficient of the radiation effect of water vapor and carbon dioxide used in this work are presented in Table 1.

$$K_{abs,G} = a_{CO_2} \cdot k^*_{CO_2} \cdot p_{CO_2} + a_{H_2O} \cdot k^*_{H_2O} \cdot p_{H_2O} \tag{6}$$

Building a physical and geometric model of the problem of pulverized coal torch burning in the combustion chamber of the BKZ-160 boiler

The computational experiment in the work was performed for the combustion chamber of the BKZ-160 boiler at Almaty Thermal Power Plant (Kazakhstan), steam generating capacity is 160 t/h, at a pressure of 9,8 MPa and a steam superheat temperature of 540°C. Thermal performance for steam 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.

Table 1 - Mass coefficient and absorption coefficient of gas radiation

B Component	a_β [1]	k^*_β, $[1/(m \cdot bar)]$
CO_2	$0.275\text{-}8.4\ 10^{-5} \cdot T_G$	$85.0 \cdot T_G^{-0,33}$
H_2O	$7.2 \cdot T_G^{-0.4}$	$1100\ T_G^{-0.82}$

On either side of the furnace chamber there are 4 units of direct-flow slot burners (2 burners per unit), directed tangentially to a circle with a diameter of 60x4 with a step of 64 mm. The screens are divided into 12 independent circulation loops. Pipes of the front and rear screens in the lower part form a cold funnel, and in the upper part of the rear screen pipes are bent into the combustion chamber, forming an "aerodynamic" nose. After the "aerodynamic" nose of the rear screen pipes are gathered into chambers, where a steam-water mixture is sent to the boiler drum through the festoon.

Performance of one burner in terms of fuel is 4 tons/h. The secondary air flow rate through the burner is V = 6000 nm^3/h with an excess air coefficient of α=0,38. The secondary air heating temperature is t=380°C. The cross-sectional area of the secondary air channels at the burner outlet is F=0,2m^2, which ensures the level of velocities of the secondary air at the burner outlet being W=40 m/s.

Hot air consumption per mill is 12000 nm^3/h. After the mill the exhaust air is fed into the furnace through 4 dump burners located from the back and the front of the boiler.

Based on the air balance with the excess air coefficient at the furnace outlet being $\alpha_т$ = 1,27, false air inflows into the furnace and dust systems make up about 40%, which impairs the efficiency of the boiler.

In the burners' area, where the ignition takes place, the torch 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 [16-26].

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

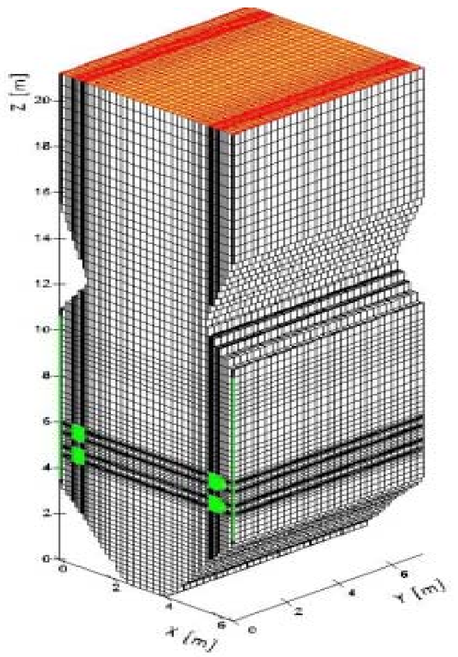

Figure 1 - General view of the boiler BKZ-160 combustion chamber and its breakdown into control volumes

Results of the Computational Experiment

Below are the results of a 3-D simulation of solid fuel (coal) combustion processes in the combustion chamber of the constructed model.

The fields in the figures are shown as arrow-vectors, the length of which represents the full velocity value, their direction is related to the full velocity direction at the selected point of the combustion chamber. The flow aerodynamics in the furnace chamber, shown in Figures 3-5, built on the calculated velocity data, fully coincides with the description of the nature of the flow in tangential furnaces, available in the literature.

The volumetric pattern of vectors' disposition clearly shows the flow pattern: places of tangential fuel supply (coal) and oxidizer (air) at different velocities through burners located on the front and rear walls of the combustion chamber, formation of a conditional circle in the center of the combustion chamber and flow symmetry (Figure 2-5).

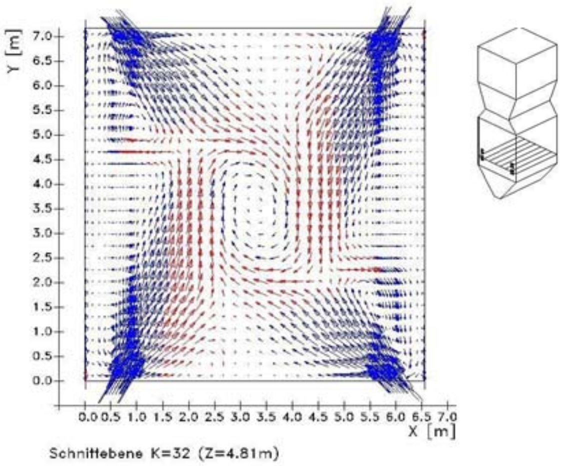

Figure 2 - Vector field of full velocity V in the cross section of combustion chamber in the lower burner tier (h = 4.81m)

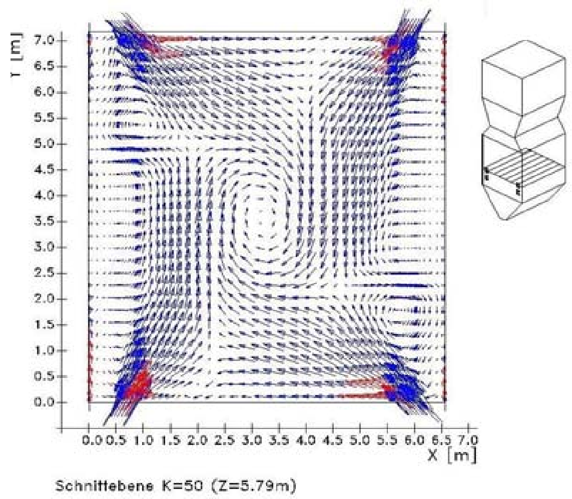

Figure 3 – Vector field of full velocity in the cross section of combustion chamber in the upper burner tier (h=5.79м)

The flows of pulverized coal, secondary and tertiary air entering the furnace space create a volume vortex-type flow in the center of combustion chamber, which undoubtedly improves the mixing process and increases the intensity of heat and mass transfer.

This, in turn, results in an increase in the residence time of coal particles in the combustion chamber and to a decrease in chemical and unburned carbon loss due to their more complete burnout.

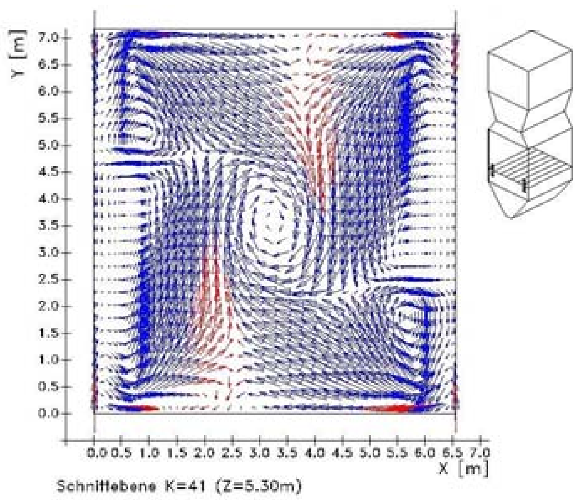

Figure 4 – Full velocity vector field V in the cross section of combustion chamber in the area between the burner tiers (h=5.30m)

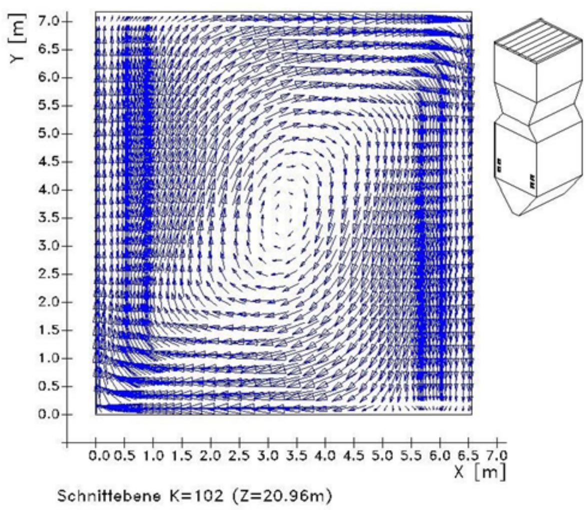

Figure 5 – Full velocity vector field V at combustion chamber outlet (h=20.96m)

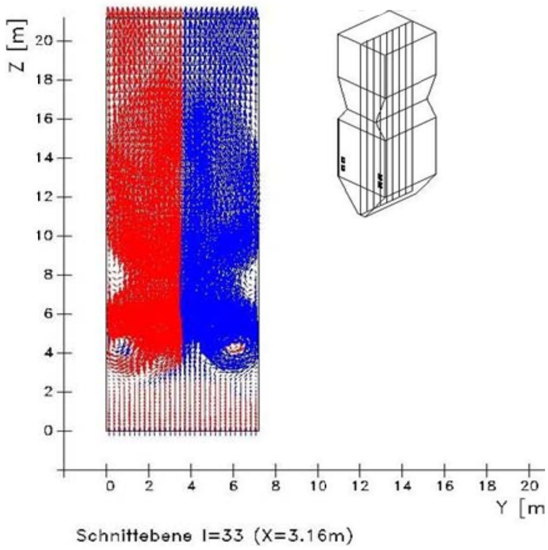

Figure 6 – Full velocity vector field in the longitudinal cross-section of combustion chamber at (x=3.16m)

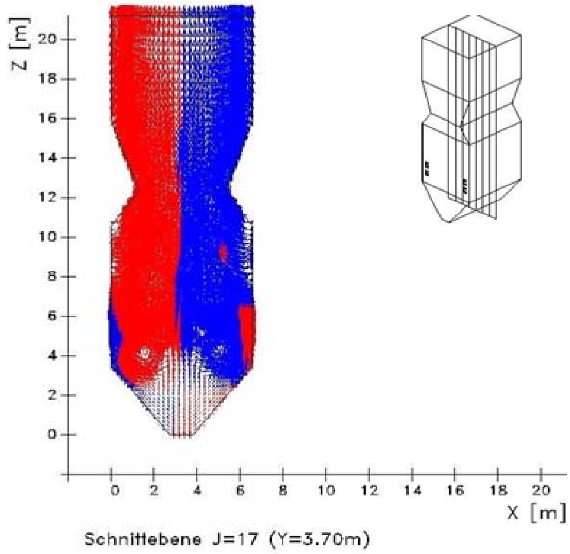

Figure 7 – Full velocity vector field V in the longitudinal cross-section of combustion chamber (y=3.70m)

Counter dust and gas flows from opposing burners hitting the walls of the combustion chamber create a reverse flow (Figure 4), and part of the flow goes down to the funnel, forming two symmetrical vortices below the burners (Figures 6 and 7). In the area below the burner belt (k<32, h<4.61m), the formation of a reverse flow (Figure 6 and 7) can be observed, which is typical for all types of combustion chambers and is associated with air inflows from the bottom of the chamber, made in a funnel form.

The central vortex motion of a pulverized coal flow results in a uniform heating of combustion chamber walls, in a reduction in the slagging of thermal screens and heat losses. Event at the combustion chamber outlet (k=102, h=20.96m), the velocity field levels off, no large velocity gradients are observed, the vortex nature of the flow goes down, and a uniform symmetrical flow is observed relative to the center of the chamber (Figure 5).

This character of the flow results in the fact that the most intense combustion occurs in the central zone of the combustion chamber, in the region of the burner belt. It is here that all the thermophysical and concentration characteristics of the process occurring in the combustion chamber reach their extreme values, as indicated by the analysis of the temperature and concentration fields presented below.

Conclusion

Computational experiments were carried out on the 3-D modeling of the combustion process of a pulverized coal torch in the combustion chamber of the utility boiler BKZ-160, and main characteristics of the flow aerodynamics were determined: full-velocity field $V = \sqrt{u^2 + v^2 + w^2}$.

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ҚАТТЫ ОТЫННЫҢ ЖАНУ ПРОЦЕСІНІҢ ТУРБУЛЕНТТІК СИПАТТАМАЛАРЫ ЖӘНЕ АҒЫС АЭРОДИНАМИКАСЫН ЗЕРТТЕУ БОЙЫНША ЕСЕПТЕУ ТӘЖІРИБЕЛЕРІ

Аннотация. Тәжірибеге қолдану тұрғысынан ең қызықты және пайдалы болып, нақты геометрия саласында физика-химиялық процестер болған кезде жылумассаалмасуды модельдеу мәселелері бар. Мұндай салалар әр түрлі жылу энергетикалық қондырғылардың жану камералары, іштен жану қозғалтқыштары болып табылады

Түйін сөздер: Жану камерасы, қазандық, жанарғы, күлділігі жоғары көмір, қатты отын, сандық моделдеу, сандық тәжірибе.

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ВЫЧИСЛИТЕЛЬНЫЕ ЭКСПЕРИМЕНТЫ ПО ИССЛЕДОВАНИЮ АЭРОДИНАМИКИ ТЕЧЕНИЯ И ТУРБУЛЕНТНЫХ ХАРАКТЕРИСТИК ПРОЦЕССА ГОРЕНИЯ ТВЕРДОГО ТОПЛИВА

Аннотация. Одними из интереснейших и полезных с точки зрения практического применения являются вопросы моделирования тепломассопереноса при наличии физико-химических процессов в областях реальной геометрии. Такими областями являются камеры сгорания различных теплоэнергетических установок, двигатели внутреннего сгорания.

Ключевые слова: Топочная камера, котел, горелки, твердое топливо, высокозольный уголь, численное моделирование, вычислительный эксперимент.

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