Mathematical Modeling of Processes in Combustion Chambers of Coal-Fired Boilers

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Abstract: Research in the field of advanced technological processes to improve the combustion of pulverized coal and the use of alternative methods of combustion of various fuels are currently the most relevant to the entire energy complex of the Republic of Kazakhstan.
The main direction of improvement of pulverized coal combustion and utilization of alternative fuels types are the implementation of stringent ecological requirements in terms of specific emissions of harmful substances with exhaust gases of boilers. And at this stage, the creation of technologies that describe the main processes of formation of harmful dust-gas emissions, and development of recommendations for their reduction is a first task for researchers.
At the modern stage development of industry of the Republic of Kazakhstan there is a question about improving the efficiency of processes related to energy production, subject to strict norms of emission of harmful substances and efficient use of equipment.

Keywords: Computational fluid dynamics, Combustion, Pollutant Emission, Furnace design and operation.

I. Introduction

In the last years or using computers Fluid Dynamics – has become a more and more reliable tool to check the structure of industrial furnaces and power plants [1-3]. Computational experiments have been carried out for different coal particles sizes on the base of program FLOREAN for modeling of flows, heat transport, combustion and formation of pollutants. This program complex has been adapted for power objects of Kazakhstan and allows carrying out a wide range of computational experiments. Numerical experiment has consisted of several stages: the description of physical model of the phenomena; mathematical model for the described process; the development of the numerical method and algorithm; program testing; the solution of physical task, analysis and results processing; the comparison of obtained results with data of physical experiment.

II. MATHEMATICAL MODEL

A three–dimensional computational fluid dynamics code was used to analyze the performance of different boilers with pulverized coal combustion at different operation modes. The main objective of this study was to show a number of possibilities of this threedimensional furnace modeling as an effective method for design, optimization and problem solving in power plant operation.
Consequently, the FLOREAN – code was used to predict thermal and hydrodynamic aspects of flue gases mixing in the near wall region and inside the furnace. In the case of Over Fire Air (OFA) technology the simulations show that effective mixing between flue gases and over fire air is of essential importance for CO reburning and low NOx emissions.
Program FLOREAN is based on the numerical solution of the Reynolds averaged balance equations for mass, species, energy and momentum [4]. It predicts gas flows, species

concentrations, temperature fields due to combustion, radiation and convective heat transfer and the pollutant formation and destruction in furnace chambers.

The transport by diffusion of each value is calculated by an effective exchange coefficient, based on the effective viscosity and the empirical Prandtl–Schmidt number. The mean flow equations are closed by the *k*- *e* turbulence model.

The changes of the concentrations of the flue gas components and the fuel due to the combustion are taken into account in the source/sink terms appropriate sub models. In addition, in the source/sink term the heat balance takes into account the energy release due to the combustion reactions and the significant heat transfer due to radiation using a six flux radiation model by Lockwood etc [5].

The energy balance is written as follows:

$$\frac{\delta}{\delta x_i}\left(\rho U_i h\right)=\frac{\delta}{\delta x_i}\left\{\frac{\mu_{eff}}{\Pr}\left(\frac{\delta h}{\delta x_i}\right)\right\}+S_{comb}+S_{rad} \tag{1}$$

The right hand side of the energy equation contains the source term S_{comb} due to the combustion of volatiles, char and formed carbon monoxide. The source/sink term due to radiation is calculated using the six–flux model of Lockwood and Shah [6]. It is mentioned that radiative heat exchange is one of the three basic ways of heat exchange and some researcher successfully couple computer methods and radiative heat exchange phenomena [7].

In many practical combustion processes, the fuels are liquids or solids, which have to be evaporated, and/or gasified usually prior combustion. The additional consideration of a phase change leads to more complex heterogeneous combustion processes than combustion processes in the gas phase. In FLOREAN, models for combustion of heavy fuel oil and different coal types are included.

Coal Combustion Model. The coal particle size distribution is modeled through different mean diameters. During the combustion, process the coal particle diameters changes. The change depends on the coal type e.g. swelling coal. At the end ash and unburnt carbon is left.

The coal combustion model is divided into five sub models for drying, pyrolysis, combustion of volatiles, carbon monoxide and residual char. The drying model considers the heat necessary for evaporating the moisture content. The pyrolysis model is usually a first order reaction model; more models that are detailed are available. Three different reactions between char and flue gas are considered.

The oxidation of the char to carbon monoxide or carbon dioxide and the reduction of carbon dioxide at the surface of the char particle to carbon monoxide. The model incorporates the different effects of oxygen and carbon dioxide diffusion to the particle surface and in the pores and the kinetics of the chemical reaction at the surface as a function of temperature and particle diameter.

The Eddy Dissipation Model according to Magnusson et al is used to predict the combustion of the volatiles and the carbon monoxide formed during char combustion. Gaseous fuels are treated like volatiles.

In the case of coal combustion, the two-phase flow can be treated using the Eulerian or the Lagrangian approach to calculate the flow pattern of the solid phase.

Fuel Oil Combustion Model. Three phases of droplet combustion are considered:

Heating phase: heat from the gas phase causes the droplet surface to heat up. Much of the energy is convected into the droplet until the entire droplet is approaching the boiling temperature.
Fuel evaporation stage: Fuel evaporates into the gas phase and a combustible mixture is formed; the droplet diameter decreases in time. The droplet evaporation model includes heat and mass transfer. Usually the continuous gas phase is at a higher temperature than the fuel droplets.
Combustion phase: The oil combustion model uses the Eddy Dissipation Model for the combustion of evaporated combustible species in the gas phase.
The changes of the concentrations of the flue gas components and the fuel due to the combustion are taken into account in the source/sink terms.
Chemically Reactive Species (Combustion). Five gaseous Species are considered: oxygen, volatile matter, carbon monoxide and final combustion products consisting of carbon dioxide and water vapour. Three solid species char, coal and ash are taken into consideration. The mass balance of each species k is as follows:

$$\frac{\delta}{\delta x_i}\left(\rho U_i m_k\right) = \frac{\delta}{\delta x_i}\left\{\frac{\mu_{eff}}{Sc}\left(\frac{\delta m_k}{\delta x_i}\right)\right\} + S_k \quad (2)$$

with m_k being, the mass fraction of species *k*. *Sc* is the Schmidt number and S_k the source/sink term due to the reaction.

III. RESULTS OF CFD STUDIES

Kazakhstan has huge stocks of power resources, sufficient for covering own needs and export to other regions, both in a natural, and in the form of electric power. About 3.3% of world industrial stocks of coals are concentrated in Kazakhstan. More than 70% of the electric powers in Kazakhstan are generated in Thermal Power Plants.
FLOREAN has been applied for the calculation of a furnace chamber of Aksu power station fired with low grade coal of Ekibastuz (Kazakhstan). It has to be emphasized that in Kazakhstan thermal power plants predominantly use bituminous and sub–bituminous coals from Ekibastuz, Karaganda, Kuuchekinsk.
Coals from these basins have almost the same characteristics. All Kazakhstan coals are considered low rank. The moisture content varies from 5 to 40% and the high ash content is up to 55%. The volatile matter content reaches up to 28%. High ash content results in high fly ash contents in flue gases, which reach up to 60-70g/m^3 for high ash coals.
Figure 1–3 show a firing system with 12–swirl burners, which are all in operation. The nozzles are located opposite to each other in two layers, 6 nozzles in each. In order to intensify the ignition process the air is fed to the chamber in such a way that oxygen, it contains comes into reaction gradually.
The fuel in the layers is distributed equally, that caused the symmetrical flow fields (Fig.2 and Fig.3). Recirculating regions are formed close to the walls and four strong recirculating regions are formed in the corner regions at the burner levels (Fig.2).

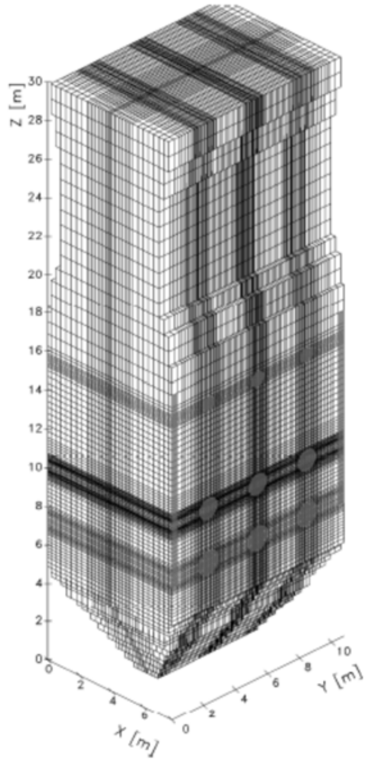


Fig. 1 – Finite volume discretization grid of the furnace of the PK39 steam generator

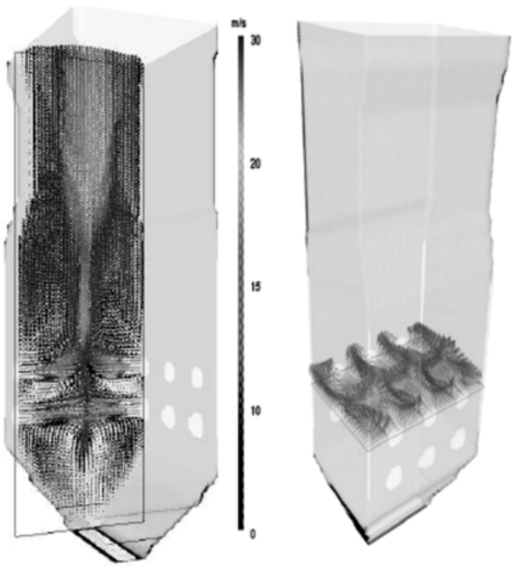


Fig. 2 - Velocity distribution in the vertical mean cross section during coal combustion at 100% load

Temperature distributions in the furnace for full load operation (with coal and oil combustion) are presented in the Fig. 3.

Temperature distributions in furnace volume for full load boiler operation with coal combustion are given on Figure 3 in the shape of temperature isosurfaces. It has seen that zone of maximum temperatures are concentrated in the center of the fire-chamber on the level of the burners.

The penetration of the over fire air jets into the furnace can be seen in the velocity (Fig.2) and temperature (Fig.4) distribution. A significant increase of the flue gas temperature arises along the jets induced by the carbon monoxide combustion. Calculated data show good agreement with experimental data (Fig.4).

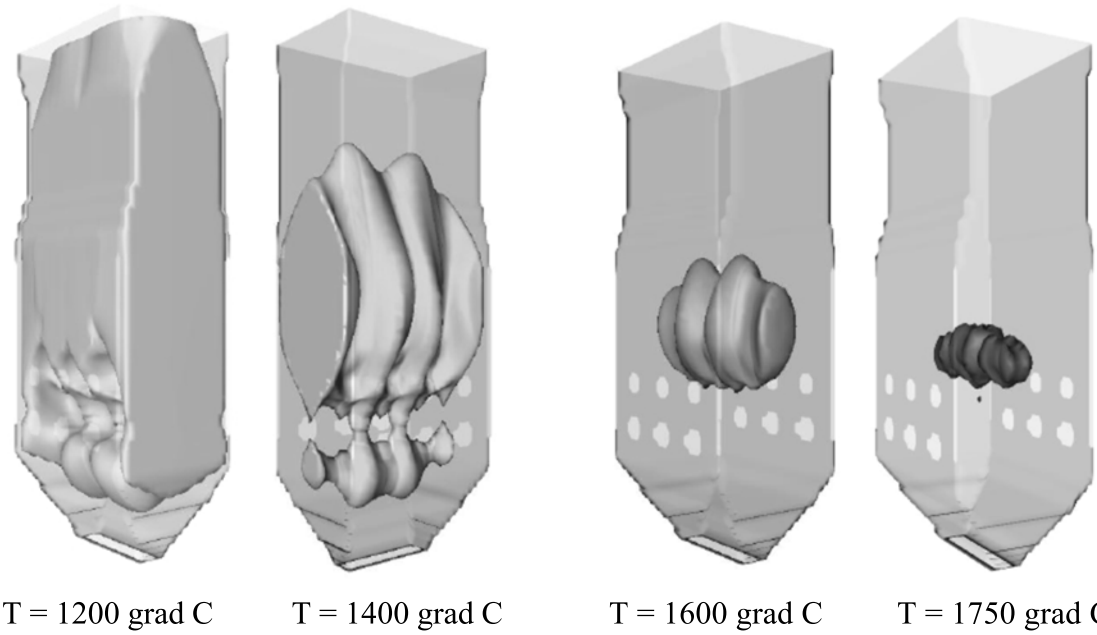


Fig. 3 - Temperature isosurfaces

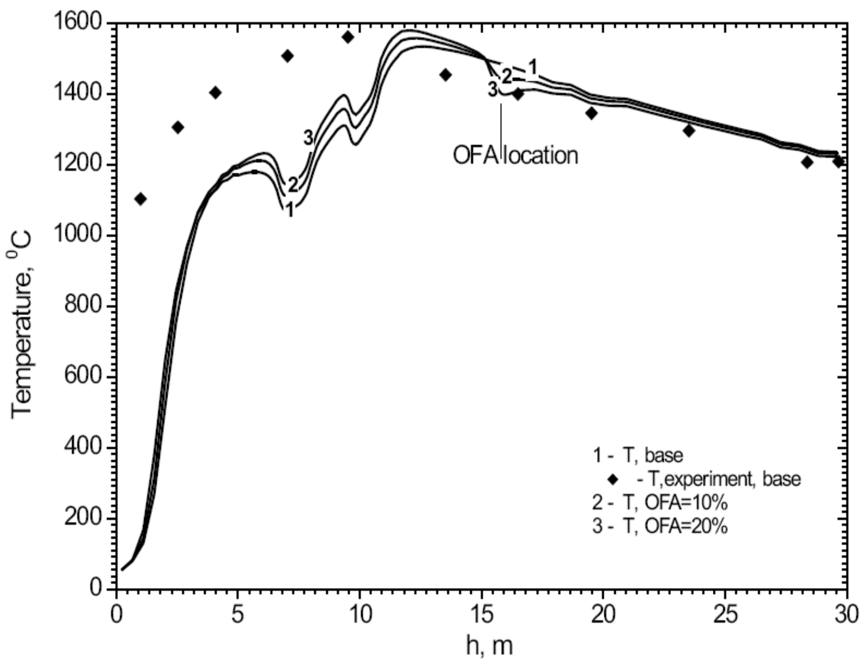
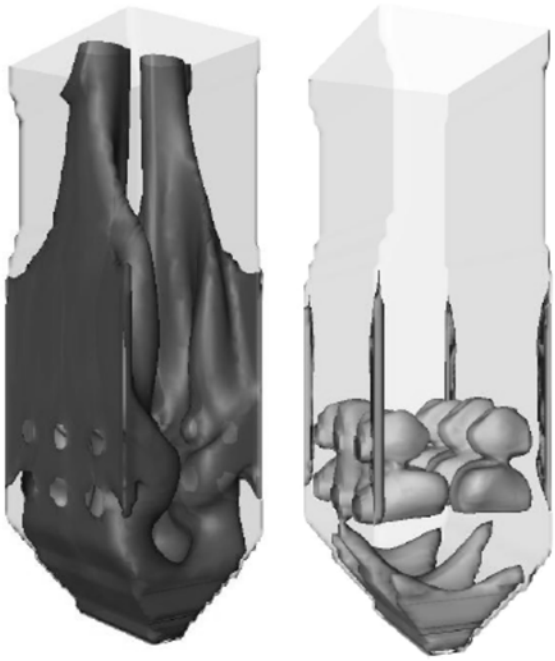


Fig. 4 – Simulated temperature distribution over furnace height during coal combustion at 100% load compared with experiment

It's seen that maximum temperatures are in the center of the fire-chamber on the level of the burners. Here the intensive combustion took place. The existing of minima in presented temperature field caused by low temperature of fuel and transporting gas supplied to furnace through the burners nozzles.

Fig. 5-8 shows results of combustion products calculations for low-grade Kazakhstan hard coal power station. Concentration isosurfaces show concentration of O_2 (Fig.5) and CO (Fig.7) distribution inside of the furnace space and over furnace height.
The picture of fuel burning out is shown in Figure bellow by fields of concentration of oxygen O_2 (Fig.6) and carbon monoxide CO (Fig.8) over furnace height during coal combustion at 100% load.



c_{O2} = 0.05 kg/kg c_{O2} = 0.10 kg/kg

Fig. 5 – Oxygen isosurfaces

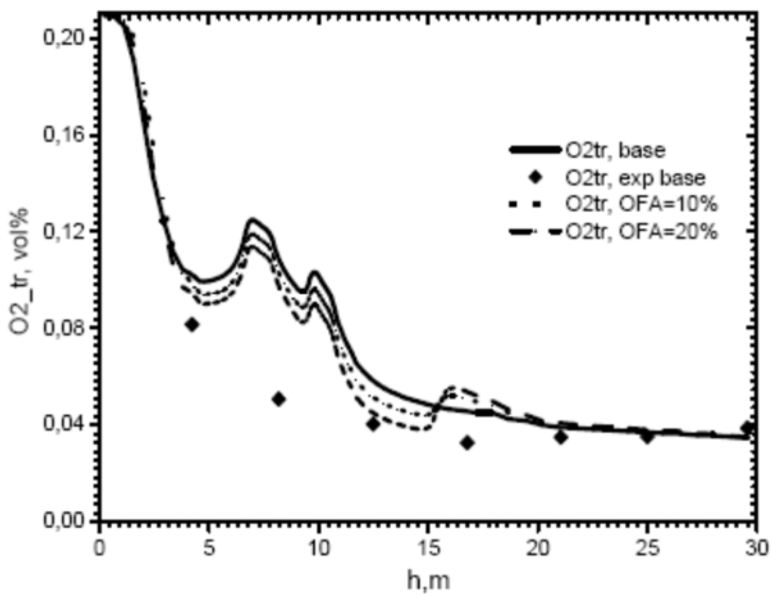
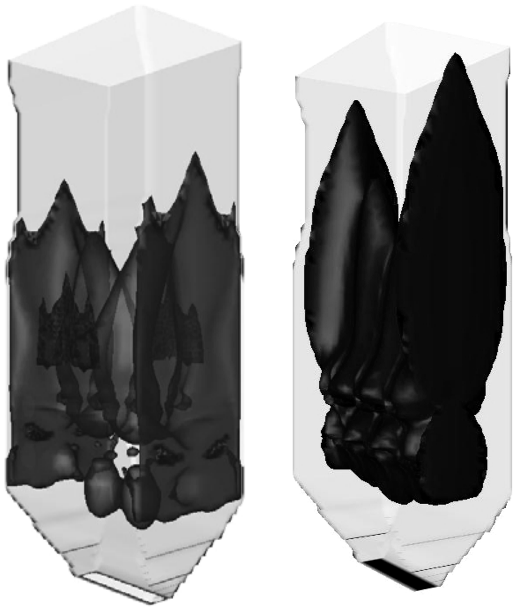


Fig. 6 – Simulated oxygen distribution over furnace height during coal combustion at 100% load compared with experiment

In the model for combustion products, formation three different reactions between char and flue gas are considered. The oxidation of the char to carbon monoxide or carbon dioxide and the reduction of carbon dioxide at the surface of the char particle to carbon monoxide.
The model incorporates the different effects of oxygen and carbon dioxide diffusion to the particle surface and in the pores and the kinetics of the chemical reaction at the surface as a function of temperature and particle diameter.
Due to the CO reactions also at lower temperatures, CO concentration is further reduced in the gas path after the furnace outlet.



$c_{CO} = 5 \cdot 10^3$ mg/Nm³ $\qquad$ $c_{CO} = 2 \cdot 10^3$ mg/Nm³

Fig. 7 – Carbon monoxide isosurfaces

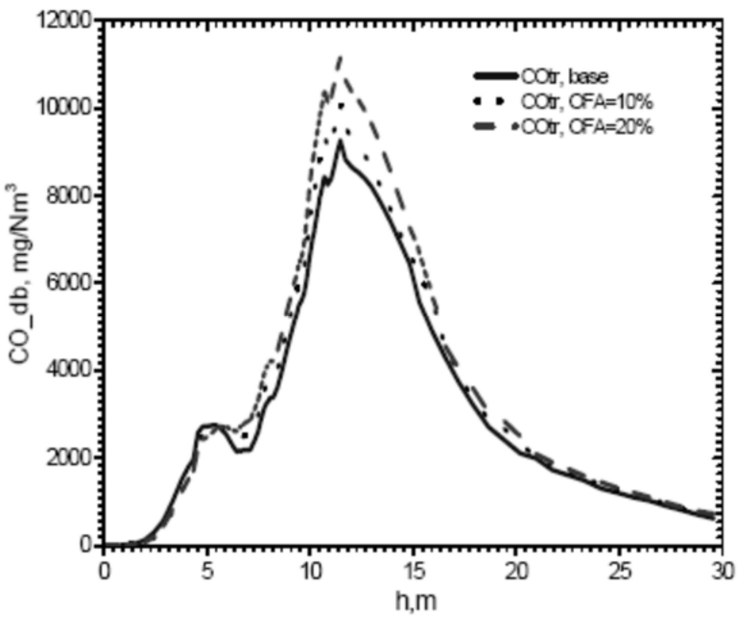


Fig. 8 – Simulated carbon monoxide distribution over furnace height during coal combustion at 100% load

IV. CONCLUSION

By means of the 3D CFD tool FLOREAN numerical simulations have been carried out to predict gas flow, species concentrations, temperature fields due to combustion, radiation and convective heat transfer and the pollutant formation and destruction in furnace chambers of Kazakhstan Power Plants.

The purpose of the presented research was to investigate numerically the characteristics of reacting flows and heat transfer due to oil and coal turbulent combustion in large-scale boiler furnaces. The data resulting from the present study allow an improved understanding of combustion processes and provide detailed description of furnace performance.

Results from CFD simulation can be useful for engineers to choose an appropriate burner and furnace design, to reduce pollutant emissions, as well as to optimize furnace operation.

V. REFERENCES

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