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CFD study of harmful substances production in coal-fired power plant of Kazakhstan

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In this paper a study of physical and technological processes that occur during combustion of high-dust fuel in the combustion chamber of Kazakhstan's boiler unit. Computational experiments were obtained the distribution of concentrations of harmful dust and gas emissions during the combustion of high-ash coal in the combustion chamber. The main purpose of the present work is to study different possibilities to improve the performance of the coal-fired furnace. Different influences which lead to decrease in pollutant emissions have been analysed.

Keywords: coal-dust torch, combustion, thermal power plant, heat and mass transfer, pollution

INTRODUCTION

It is fair to say that the ability to use fire is an important factor in ushering the dawn of civilization. Today our dependence on the service of fire is almost total, from heating and lighting our homes to powering the various modes of transportation vehicles. Useful as it is, fire can also be menacing and sometimes deadly. Wild land and urban fires cause tremendous loss of property and lives every year; the noxious pollutants from automotive and industrial power plants poison the very environment in which we live; and the use of chemical weapons continues to be an agent of destruction with ever greater efficiency. Combustion is certainly one branch of science that affects almost every aspect of human activities [1].

Heat transfer problems pertaining to the combustion in industrial furnaces are of great importance to the engineering designer of boilers and steam generators. In most industrial flame applications, the achievement of high heat transfer rates is a main target and is desirable.

Pulverized coal combustion is the most commonly used method in the coal-fired power plants and it will continue to be important way for electricity production due to large stocks of coal worldwide. Since coal is a natural resource that depends on many factors, parameters and conditions it has variable properties and composition.

Pulverized coal combustion in industrial furnaces is a quite complex process and involves many physical and chemical sub-processes. Hence a proper description for the dynamic, thermal and reactive behaviors of pulverized air-coal flows is essential for a better prediction of combustion and pollutant emission formation in a coal-fired furnace.

Using of different types of coals combined with some modifications of the combustion furnaces and equipment can be a cost-effective way of improving combustion behavior and lowering pollutant emissions from power plant. Comprehensive modeling of pulverized coal combustion has become a commonly used tool for designing and optimization.

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.

EXPERIMENTAL DETAILS

Description of furnace

The computer simulation is performed for furnace chambers of Kazakhstan Power Plants. The case-study boiler PK-39 with swirl burners in boxer-firing system is installed at Aksu Thermal Power Plant (Fig.1). The unit generates a nominal steam capacity of 475 t/h and electrical output of 160 MWe. Twelve swirl burners are placed in two layers: three in each layer on the front and rear wall of the furnace. The nominal-load operating

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conditions (all burners operating) of the furnace are given in Table 1. Existing distribution of coal particle sizes is represented by using five different size classes of pulverized coal.

Table 1. Summary of the furnace operation parameters

Steam generating capacity,	Total air,	Coal flow rate,	Excess air	Load,
t/h	kg/s	kg/s		MWe
475	157	24.32	1.18	390
Coal composition				
W	Ash	C	H	O	N	S
0.07	0.41	0.79	0.05	0.13	0.015	0.015

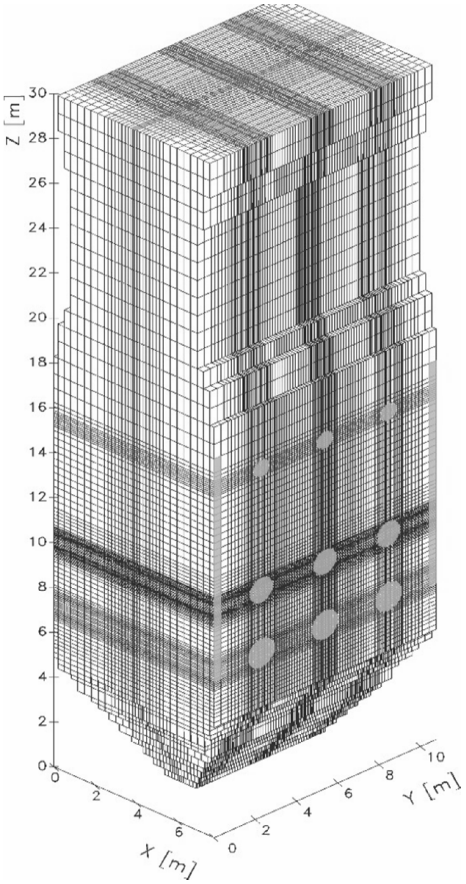

Fig.1. Scheme of the furnace PK-39

Mathematical model

Program FLOREAN is based on the numerical solution of the Reynolds averaged balance equations for mass, species, energy and momentum [1-3]. 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-ε 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 by 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. [4]. The energy balance equation is written in terms of the enthalpy.

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.

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 submodels 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 detailed models 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. [5] 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.

NOx formation model

Within the combustion of fossil fuels, nitric oxide is built up through different reaction paths. The main reactions are the oxidation of molecular nitrogen (thermal NO–formation) and the oxidation of the fuel bounded nitrogen (fuel–NO).

Detailed kinetic models for predicting fuel NO with 29 elementary reactions are used, for example, by Lendt [6]. In the case of three–dimensional simulation, such models consume too much CPU–time. Therefore global mechanisms are used. For simulation of nitrogen oxides formation the Zel'dovich mechanism for thermal NO_x, De Soete [7] or the Mitchell-Tarbell [8] mechanisms for fuel NO_x formation are applied.

Depending on the coal type, fuel-bound nitrogen is released during pyrolysis and char burnout. It is supposed that the main gas species containing nitrogen produced during coal combustion are HCN and NH_3. In some modeling approach, volatile and char nitrogen is released only as HCN proportional to the char burnout rate [9-13].

De Soete mechanism

Recognizing the importance of HCN as a precursor to the subsequent nitrogen compound intermediates, De Soete correlated the rate of NO formation and decay with a pair of competitive parallel reactions, each first order in HCN and NH_3. HCN and NH_3 are competitively oxidized and reduced according to the following generic scheme involving four reactions:

$$R_1 = 1.0 \cdot 10^{10} \cdot X_{HCN} \cdot X_{O_2}^{o} \cdot \exp\left(\frac{-33732.5}{T}\right),$$

$$R_2 = 4.0 \cdot 10^{6} \cdot X_{NH_3} \cdot X_{O_2}^{o} \cdot \exp\left(\frac{-16111.0}{T}\right),$$

$$R_3 = -3.0 \cdot 10^{12} \cdot X_{HCN} \cdot X_{NO} \cdot \exp\left(\frac{-30208.2}{T}\right),$$

$$R_4 = -1.8 \cdot 10^{8} \cdot X_{NH_3} \cdot X_{NO} \cdot \exp\left(\frac{-13593.7}{T}\right).$$

Where $R_1 \ldots R_4$, – reaction rate, 1/s; X_{HCN}, X_{NO}, $X_{O_2}^0$ – mole fraction, mol/mol; T – temperature, K.

This model describes the gas phase reaction of HCN and NH_3 with an oxidation rate to NO and a reduction rate to N_2.

Mitchell and Tarbell model

A global model has been proposed by Mitchell and Tarbell [8], involving NH_3, HCN, NO and N_2 as N-containing species. The first reaction step is the conversion of HCN to NH_3 by an attack of an oxidizing agent.

The NH_3 forms and destructs NO within a pair of competitive parallel reactions. In their global model, Mitchell and Tarbell propose the recycling of NO back to HCN through hydrocarbons C_xH_y.

The postulated reaction rate of the NO recycling is not temperature dependent [14-17]. The suggested value of the C atom number x in the hydrocarbons is eight; the value of y is calculated from coal analysis. The H_2 − concentration is calculated from equilibrium. In addition NO is reduced by a heterogeneous reaction between NO and char particles [18].

RESULTS OF SIMULATION

Computer simulations were carried out with the aim to investigate different possibilities to improve the boiler performance, to decrease pollutant emissions and analyze different influences.

Thermal wall conductivity is dependent on several factors including accumulation of ash on the walls [19-23]. Hence, it also has significant impact to overall heat pick up of the furnace walls and thermal performance of the boiler (Fig.2).

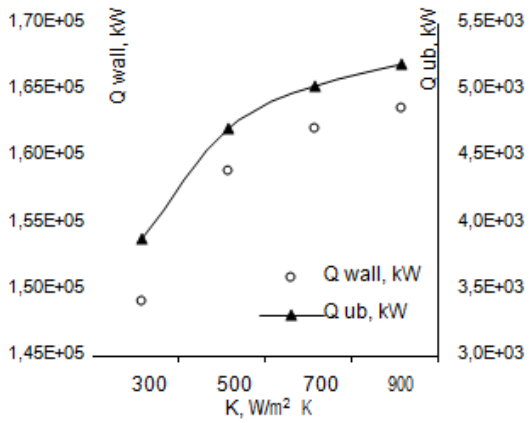

Fig.2. Influence of the wall conductivity on heat pick up of the walls and heat losses by unburned species at the furnace outlet

Fig.3 shows dependence of NO and CO emissions on the wall conductivity. It predicts that both emissions increase with increases in wall conductance.

Fig.4 shows predicted NO and CO concentrations at the furnace outlet as a function of swirling. Studies have shown that swirling of the incoming air stream which surrounds the coal stream can significantly influence the NO and CO concentrations.

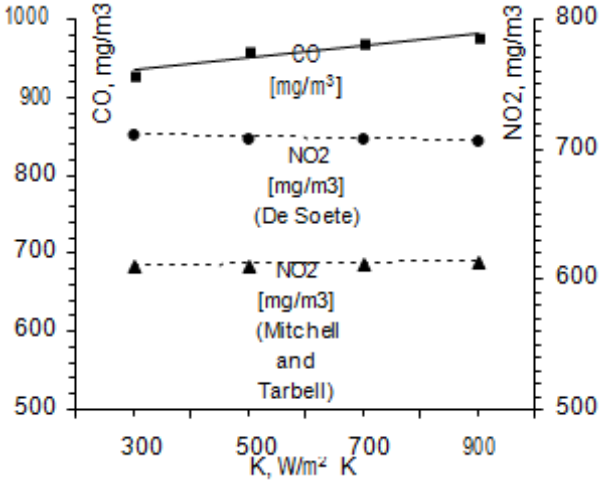

Fig.3. Influence of the wall conductivity on NO_2 and CO concentration at the furnace outlet

These variations in NO and CO result principally from difference in mixing process, when the swirling incoming air results in sufficient mixing to promote earlier ignition, hence the extent of mixing of the coal and air has a significant impact on the volatile N-containing species conversion to NO.

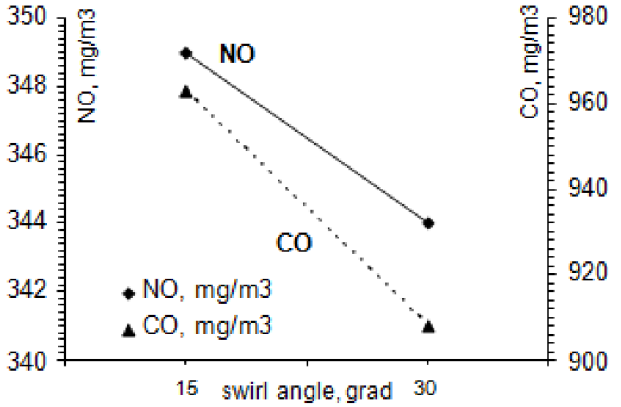

Fig.4. Influence of the incoming air stream swirling on NO and CO concentration at the outlet

To reduce NO emissions air staging was used. The penetration of the over fire air jets into the furnace can be seen in the velocity distribution (Fig.5). A significant increase of the flue gas temperature arises along the jets induced by the carbon monoxide combustion.

Temperature distributions in the furnace for full load operation (with coal and oil combustion) are presented in the Fig.6 and Fig.7. It's seen that the zone of maximum temperatures is concentrated in the center of the fire-chamber on the level of the burners.

The minima in the presented temperature field are caused by the low temperatures of fuel and transporting gas supplied to the furnace through the burner nozzles. Calculated data show good agreement with experimental data (Fig.6) [24].

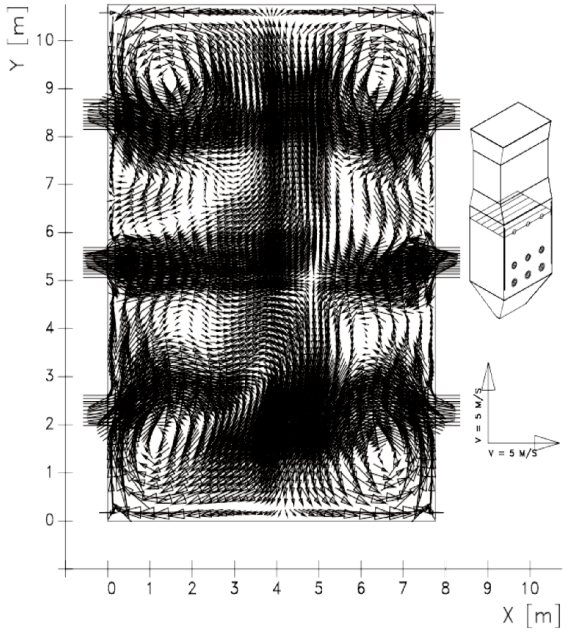

Fig.5. Velocity distribution in the level of the OFA jets during coal combustion at 100% load

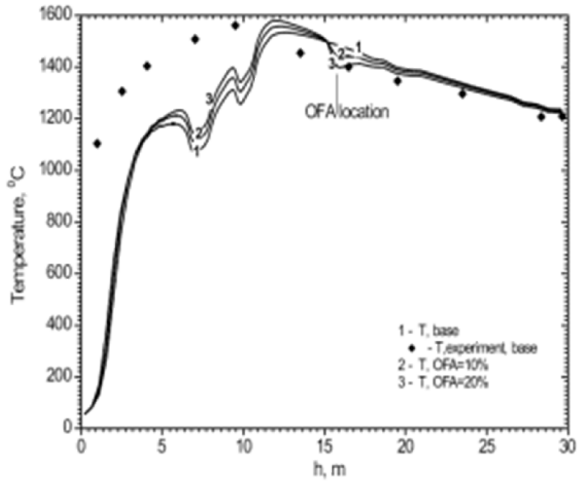

Fig.6. Simulated temperature distribution over furnace height during coal combustion at 100% load compared with experiment [24]

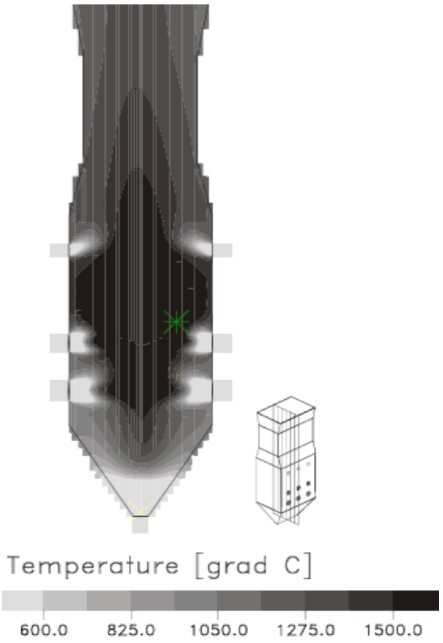

Fig.7. Temperature distribution in the middle vertical section during coal combustion at 100% load

Fig.8 shows predicted NO_2 and CO concentrations at the furnace outlet as a function of different air distribution between main burners, over fire air (OFA) and curtain air (CA) nozzles.

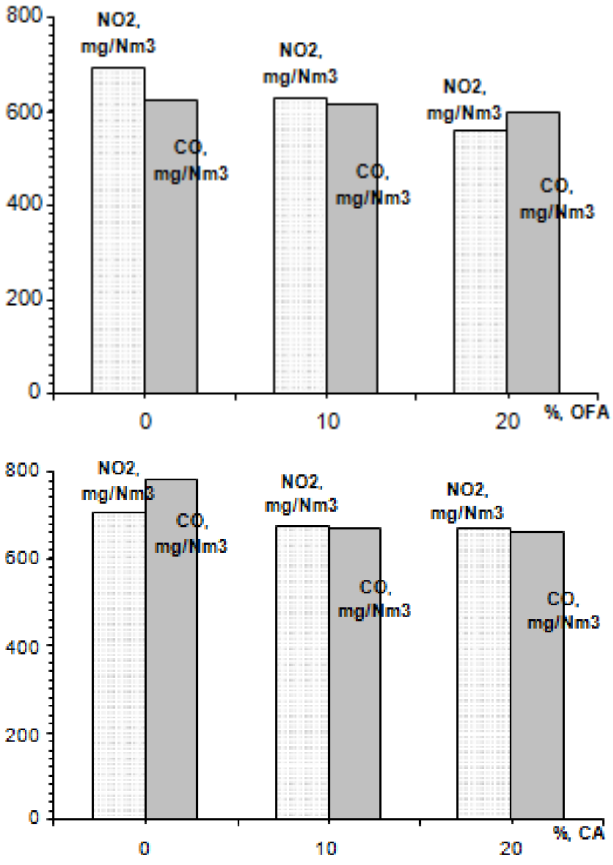

Fig.8. Influence of OFA and additional curtain air on CO and NO_2 concentrations at the outlet of the furnace PK-39-steam generator

Fig.8 shows that using the OFA-technology at the outlet of the combustion chamber observed a clear reduction in nitrogen dioxide (NO_2). However, the concentration of carbon monoxide (CO) is the same. When using a curtain air, conversely, decreasing the concentration of carbon monoxide (CO) and the concentration of nitrogen dioxide (NO_2) almost does not change.

Studies have shown that these parameters of the incoming air streams redistribution can significantly influence on the NO_x and CO concentrations. These variation in NO_x and CO emissions result principally from difference in mixing process staging of combustion in furnace and results in a significant impact on the nitrogen conversion to NO and CO formation.

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CONCLUSION

The present paper is showing the dependence of NO and CO emissions on the wall conductivity and the prediction of NO and CO concentrations at the furnace outlet as a function of swirling. Moreover, to reduce NO emissions air staging was used. It shows the effect of OFA-Technology for distribution of velocity, temperature, and concentration characteristics (NO_x and CO).

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.

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