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Numerical prediction of processes for clean and efficient combustion of pulverized coal in power plants

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ABSTRACT

Coal-fired power plant technologies should provide higher efficiency of energy conversion, reduction of pollutants emission, operation of facilities in a wide range of loads and efficient utilization of variable quality fuels. In order to achieve these tasks, mathematical modeling is regularly used worldwide for optimization of boiler operation. Reduction of pollutants emission is the task of greatest concerns. Among the most important pollutants are oxides of nitrogen and sulfur. Combustion process modifications for NO_x control and sorbent injection for SO_2 control are cost-effective clean coal technologies, used either standalone or with other methods. An in-house developed computer code was applied for simulation of processes in the 350 MW_e boiler furnace, tangentially fired by pulverized lignite. Predictions suggested optimal combustion organization providing the NO_x emission reduction of up to 20–30%, with the flame position improvement. Boiler thermal calculations showed that the facility was to be controlled within narrow limits of working parameters. SO_2 reduction by injection of Ca-based sorbent particles into the furnace was simulated for different operation parameters. Such a complex approach enables effective evaluation of alternative solutions, considering emissions, flame position and efficiency of furnace processes and the boiler unit.

1. Introduction

Growing demand for electric power generation leads to further increase in the use of fossil fuels, like coals of different quality. Due to combustion of coals in large power plants significant amount of pollutant gasses, such as nitrogen and sulfur oxides, are released into the atmosphere. The following aims of coal-fired power plant technology development can be identified: higher efficiency in energy transformation process, reduction of pollutants emission, operation of facilities in a wide range of loads, as well as efficient utilization of variable quality and low heating value fuels. Different regulations and directives concerning emission reduction exist, effectively forcing plant operators to invest into development and implementation of new technologies. Regarding emission reduction, the Electric Power Industry of Serbia is to apply the regulations of the European Union Directive 2010/75/EU, considering the limitation of emissions from large combustion plants. In forthcoming period significant investments are planned in order to improve emission reduction while retaining or even increasing power plants efficiency. Mathematical models are often used in analysis and process optimization prior to any other steps [1–14], often in conjunction with measurements.

Among the most important pollutants are oxides of nitrogen, so considerable research efforts focus on modeling NO_x formation/destruction and predicting NO_x emission [2–5,7,8,15,16]. Nitrogen oxides consist of nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O) and other oxides of less influence. N_2O emissions are not typically significant within pulverized coal combustion systems. NO and NO_2 are collectively referred to as NO_x. Total nitrogen emission from power plant boilers of the Electric Power Industry of Serbia was 58,030 tons per year in 2008. This emission is within corresponding limiting values, however more rigid limits (2010/75/EU) are to be set from 2016 on. Primary measures for NO_x control (tuning of the combustion/aerodynamics parameters) offer a simple and cost effective means of NO_x emission reduction (up to 60%) [16], whereas secondary measures based on the flue gas post-combustion clean-up, are considerably more expensive.

Abbreviations: OFA, Overfire air; CFD, Computational fluid dynamics; FSI, Furnace sorbent injection; PSI cell, Particle source in cell; SIPSOL, Strongly implicit procedure solver; SIMPLE, Semi-implicit method for pressure-linked equations; FEGT, Furnace exit gas temperature; LHV, Lower heating value.

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In numerical simulations of NO_x reduction done by other authors different furnace shapes and sizes can be seen. Some authors simulated tangentially-fired furnaces, with burners placed in furnace corners [1,2,8], or along the screen walls [1]. Others performed simulations of wall fired furnaces [3–5]. Most authors predict production and destruction of NO only [3,5,8,13,14], since it is most abundant NO_x compound in flue gases from coal combustion. In most NO simulations prompt NO is neglected, while thermal NO and fuel NO are considered [3–5,13,14]. In their simulations authors mostly tried to verify some of the primary methods for NO_x reduction and to optimize the combustion process. Multiple stage combustion showed good NO_x reduction [3–5]. Some authors examined influence of new burners on NO_x reduction [3,13], while some investigated overfire air (OFA) systems.

NO in combustion originates from three main processes: thermal NO, fuel NO and prompt NO; the most significant is fuel NO (typically accounts for 75–95% of total NO [16,17]) which comes from nitrogen present in fuel. Contribution of thermal NO becomes significant only at higher flame temperatures, greater than 1600 K–1800 K [16]. Prompt NO is formed from the attack by hydrocarbon fragments on molecular nitrogen in the flame zone. It is significant only in extremely fuel-rich flames, therefore it is neglected in the present model.

SO_2 emission from power plants, and consequently, acid rains, are important ecological problem. 1000 MW_{th} boiler plant, burning lignite with 0.5% sulfur content, releases daily more than 150 tons of sulfuric acid. The European directive 2010/75/EU sets serious SO_2 emission limits, difficult to achieve in older plants, so investments in new technologies and modernization are necessary. Different desulfurization technologies are commercially available, varying in complexity, effectiveness and costs [18]. Most commonly used is wet scrubbing, with more than 95% of SO_2 removal efficiency, but with serious problems of waste material disposal and high investments and operational costs. On the other hand, dry flue gas desulfurizaton and furnace dry injection of solid powder reacting with SO_2, are SO_2 control technologies with lower investment, less erosion and lower energy requirements, especially for older plants which need to be retrofitted at low capital costs. Furnace sorbent injection (FSI), used standalone or in combination with other methods, might be a competitive technology, especially for combustion of coals with relatively low-sulfur content. The efficiency of this technique is up to 40%, or higher, while the investments are much lower: compared with wet scrubbers, FSI costs about 15% for entire installation. Staged FSI can lead to increase in SO_2 removal efficiency to 80–85%, while combination with NO_x air-staging could bring about considerable total savings in the system.

Different modeling approaches can be employed to describe the desulfurization reaction between the sorbent particles and the gas phase: unreacted shrinking core models, grain models (changing grain size, overlapping grain) and pore models (single pore and random pore). Description and comparison between the models were reported in Ref. [19]. A kind of shrinking unreacted core model, Borgwardt's semi-empirical model of reactions between CaO particles and SO_2, was implemented in this work.

Main motivation for this numerical study was to examine the possibility of decreasing NO_x emission by tuning different operation parameters in tangentially-fired furnace of Kostolac-B 350 MW_e boiler units. Effects of coal and preheated air distribution over the individual burners and the burner tiers, grinding fineness and quality of coal and the cold air ingress, as well as application of OFA were investigated. The analysis was done by an in-house developed submodel of NO_x formation/destruction, validated by comparison with available measurements of NO_x emission from the case-study boiler units during operation [11]. Bearing in mind that combustion modifications in boiler furnace can lead to decrease of boiler efficiency, it was essential to provide proper characteristics of flame and safe operation of the heat transfer surfaces in order to avoid unit efficiency decrease and to assure required superheated steam temperature, which was done by the boiler thermal calculations. In this study, additional goal was to investigate the possibility of reducing SO_2 emission by direct injection of calcium-based sorbent particles into the same boiler furnace. Simulations of SO_2 reduction by FSI included examination of different operating parameters, such as Ca/S molar ratio, sorbent injection ports position and the sorbent particles size.

Both NO_x formation/destruction and CaO sorbent sulfation submodels were coupled with a comprehensive 3D differential model for prediction of furnace processes, also developed in-house, previously validated against available large-scale measurements [9,10,12]. A number of CFD codes, developed by commercial companies and research organizations, are available worldwide. However, these codes are closed source, preventing modifications to core components. Reliable application of the software packages, better insight into the calculation mechanism or any alterations of the code itself require support from software developer which can become costly if developers are interested in making modifications at all. To meet specific needs of some industry users, including fast analysis, alterations in the code of commercial software would require from developer to make special version each time the change is necessary. Some codes enable user defined functions to override built in functions, but these are built around closed source and no alteration of the code execution is possible. Further, users with specific needs often do not want to go through the entire modeling process, they would rather use software made for their specific need, in our case the boiler furnace model in which they can easily change input parameters, such as preheated air and air coal–dust mixture temperatures and flow rates through the burners. All influencing variables should be made easily accessible by the user. Thus, in-house developed models and software packages can be advantageous in trying to achieve optimum usefulness of software tools for solving practical problems in the case-study boilers and other facilities.

This in-house developed software is to be used primarily by engineering staff dealing with the process analysis in boiler units. Consequently, the software incorporates trade-offs between sophistication and computational practicality. New software solutions facilitate variation of operation parameters in the case-study furnace, turning on/off individual burners, selection of data input mode, restart from previous iterations and so on, within a special user friendly interface. Data input into the NO_x and the sorbent sulfation submodels, starting the software and the convergence monitoring are also enabled through the special panels.

2. Mathematical model and computer code

Comprehensive 3D CFD in-house developed code is given in more details in Refs. [9–12]. An easy-to-use interface for introducing input data is built within the code, Fig. 1. Two-phase flow is treated by Eulerian–Lagrangian approach. Gas phase is described by time-averaged Eulerian conservation equations for mass, momentum, energy, gas mixture components concentrations, turbulence kinetic energy and its rate of dissipation. In general-index notation:

$$\frac{\partial}{\partial x_j}(\rho U_j \Phi) = \frac{\partial}{\partial x_j}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_j}\right) + S_\Phi + S_p^\Phi \quad (1)$$

with additional sources due to particles S_p^Φ, while ρ, U_j, Γ_Φ and S_Φ are gas-phase density (kg/m^3), velocity components (m/s), transport