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Numerical modeling of repowering of a thermal power plant boiler using plasma combustion systems

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ABSTRACT

In this study, numerical analyses of repowering of a thermal power plant boiler using plasma combustion systems were performed. In order to reduce the energy consumption of the power plant, fuel-oil burners were disassembled and plasma combustion systems were installed on the surfaces of the boiler. The integration procedure, design data, and boundary conditions were given in detail. Superheater, economizer and tubes (dome) were modeled as porous media and the pressure losses of each section were compared with design data. The power plant was modeled according to the design parameters using the Thermoflex commercial software, in order to find the heat loads of each boiler section. These results were used as input data in CFD (Computational Fluid Dynamics) code. ANSYS Fluent was used for numerical analyses. Temperature contours, velocity vectors, and isosurfaces of temperature in the furnace were compared. According to the results, the integration of the plasma combustion systems to the boiler slightly decreases the velocities at the inlet of each domain. Additional energy from the plasma combustion system has no reverse effect in the case of overheating, especially for convective surfaces.

1. Introduction

Sustainable production of energy with increasing demand profile is one of the main problems of energy engineers. Coal is the main fuel source with a percentage of 26.8% in total energy demand [1]. In recent years, many research activities have been carried out to decrease the harmful effects of coal combustion in terms of global warming. Most of the coal-fired thermal power plants, operating around the world have major efficiency or availability problems due to ageing. Repowering of these thermal power plants is of great importance to offset the increasing energy demand. Repowering can be defined as increasing the installed capacity, net electric efficiency, and decreasing the emissions per installed capacity of an existing thermal power plant. Generally, a gas turbine is added to the cycle in repowering applications. Feedwater heating, hot windbox, and parallel repowering are the three of the most commonly implemented repowering methods. In thermal power plants, repowering reduces CO_2 emissions per installed capacity [1,2]. The most important parameter in repowering applications is the expected life of the components. Therefore, a detailed life expectancy analysis has to be carried out before repowering. Plasma combustion system application in thermal power plants is another repowering method in order to decrease emissions for existing thermal power plants.

Fuel-oil burners are generally in use in thermal power plants for the startup operation and flame stabilization. Plasma activation of coal particles instead of using fuel-oil burners promotes more effective and environmentally friendly combustion [3,4]. Plasma systems are also used for combustion stabilization [5] in utility boiler furnaces. Plasma combustion systems can be used to promote early ignition and enhanced stabilization of a pulverized coal flame. In addition, plasma combustion systems reduce the harmful emissions originated from coal combustion [6]. Ignition of coal by plasma requires less energy compared to the case of using fuel oil or natural gas in thermal power plants for startup and flame stabilization [7–9]. It is explained by additional crushing of coal particles by plasma, production of free radicals, and acceleration of chemical reactions of oxidation. Kanilo et al. [7] showed that using microwave plasmatrons instead of fuel oil burners reduce equivalent energy consumption by 90% in the startup. During the plasma activation, part of the coal/air mixture is fed into the plasmatron, where plasma flame with high energy content induces gasification of coal and partial oxidation of the char carbon. Carbon is mainly

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oxidized to carbon monoxide at the inlet of the furnace which can be easily ignited. Messerle et al. [8] numerically modeled a thermal power plant boiler with CINAR ICE and PLASMA-COAL 1D code.

CFD (Computational Fluid Dynamics) analysis of a tangentially fired thermal power plant boiler with different turbulence models [10,11], gas temperature deviation in the upper furnace area [12,13], unburned carbon and NO_x formations [14,15], the effect of the over-fire air on NO_x formation [16], and operating conditions [17–19] can be found in the literature. Constenla et al. [20] numerically investigated 350 MW_e tangentially fired pulverized coal furnace in order to predict the flow characteristics with real operating conditions. Zhou et al. [21] used two-fluid-trajectory model to simulate 3D gas particle flows and coal combustion in a tangentially fired furnace. They offered a grid system rotated by an angle to reduce the computation time. Numerical and experimental results were compared to validate the TFT (Two Fluid Trajectory) model. The combustion behavior of coals has to be identified in order to design the combustion zone [22–25]. Bar-Ziv et al. [26] developed a tool for the prediction of the firing behavior of any coal in a specific boiler. The tool tested for 550 MW opposite-wall and 575 MW tangential-fired utility boilers. A method also developed for fouling and slagging behavior and determining the emissivity of the fly ash in a 50 kW test facility. Numerical modeling of co-firing of biomass and coal enables to discover the combustion problems for non-spherical particles [27–29]. Karampinis et al. [30] investigated co-firing lignite and biomass in a large scale utility boiler. Non-spherical form of the biomass particle, which influences the drag coefficient, devolatilization, and combustion characteristics, was taken into account. Retrofitting of oil burners for biomass injection was suggested. NO_x formation in tangentially fired burners was also numerically modeled. Staging combustion [31], various coal types, firing configurations, and boiler sizes and types [32] were investigated numerically. Oxy-fuel combustion systems [33–36] are of great interest due to CO_2 capture potential. Zhang et al. [37] compared gray and non-gray WSGGM (weighted-sum-of-gray-gases models) in oxy-coal furnaces. Non-gray WSGGM is used for both air and oxy-fuel combustion. Particle radiation and gas radiation were compared and non-gray WSGGM with weighting factors for particle radiation was suggested. Habib et al. [38] investigated the characteristics of the oxy-fuel combustion in a gas-fired water tube boiler for different oxygen inlet percentages. Ash recycling and re-burning [39], furnace sorbent injection [40], slagging and fouling prediction [41], and ash deposition were also investigated. Taha et al. [42] modeled ash deposition for co-combustion of MBM (meat and bone meal) and coal in a tangentially fired boiler. Ash deposition on the heat exchange surfaces was modeled on the basis of ash viscosity. In addition, Vuthaluru and Vuthaluru [43] used numerical model to investigate ash related problems in a large scale tangentially fired boiler. Additive injection was found to be one of the effective methods to overcome ash deposition with the optimum location of burner ports.

Park et al. [44] combined a 3D CFD model and a 1D steam-water side model to simulate the effects of burner and OFA settings, firing patterns and coal blending on boiler efficiency and also pollutant formation and combustion efficiency. Zhang et al. [45] investigated Euler–Lagrange (E–L) and Euler–Euler (E–E) models in a sudden-expanding coal combustor. The results show that the conventional E–L model can predict CO_2 distribution reasonably when the number of particle trajectories is sufficient. The E–E model also gives a reasonable prediction of the trend of the CO_2 distribution, but it underestimates the amount of CO_2 because the fluctuation of particle temperature is not fully accounted for in the calculation of heterogeneous reaction rates. Drosatos et al. [46] used the macro heat exchanger model in the convective section of the boiler. Schuhbauer et al. [47] developed a detailed boiler model by coupling the fire and steam side. The combustion chamber radiation interaction with convective part was modified in order to get closer results to target values. APROS and ANSYS Fluent were coupled. Baek et al. [48] investigated the effect of the coal blending method on carbon in ash and NO_x emissions. The results show that in-furnace blending the method gives the least NO_x and carbon in ash. He et al. [49] diagnosed metal surface overheating issues in the reheater section of a boiler. Velocity and temperature distributions were obtained for different working cases in order to obtain the cause of the overheating problem. Edge et al. [50] coupled a 1D process model and a 3D CFD model in order to investigate heat flux in a natural circulation boiler. Kuang et al. [51] also investigated the overfire air angle on flow characteristics in a down-fired furnace. Liu and Bansal [52] integrated multi-objective optimization with CFD to optimize boiler combustion in a coal fired power plant boiler. Modlinski [53] numerically modeled tangentially fired boiler retrofitted with swirl burner. Vuthaluru and Vuthaluru [54] modeled a wall fired furnace for different operating conditions. Particle traces were obtained to determine the residence time in the furnace. Chui et al. [55] specified the improvement strategies for eleven selected boilers in China. Numerical models were used to increase the availability and decrease the emissions. Crnomarkovic et al. [56] investigated radiative heat exchange inside the pulverized lignite fired furnace for the gray radiative properties with thermal equilibrium between phases. Diez et al. [57] reviewed conventional lumped models and semi-empirical approaches used in the online thermal monitoring of the boilers. Online modeling techniques improved by means of integrating offline CFD predictions. Different types of plasmas for different types of combustion systems have been investigated. Positive effects of the plasma systems on combustion dynamics and kinematics were reported [58–60].

In this study, numerical analyses of repowering of a thermal power plant using plasma combustion systems were performed. Retrofitting works, boundary conditions of numerical analyses, and design parameters were given. Fuel-oil burners were disassembled and plasma combustion systems were installed on the surfaces of the boiler. The details and installation descriptions can be found in the next section. The power plant was modeled according to the design parameters using the Thermoflex commercial software in order to find the heat loads of each boiler section. Validation of the results can be found in the previous study [2]. These results were used as input data in CFD code. For numerical analyses, ANSYS Fluent was used. Superheater, tubes, and economizer sections were modeled as porous media in order to model the pressure drop in these sections. Numerical and design data pressure drop values were compared in order to validate the numerical results. Temperature contours, velocity vectors, and isosurfaces of temperature in the furnace were obtained.

2. Retrofitting works and numerical modeling

The Soma A thermal power plant began operation in 1957 and served until 2010. Currently, the installed capacity of the power plant is 44 MW_e with two units. The boiler was designed to operate with Soma lignite with a lower heating value of 3550 kcal/kg. The ultimate and proximate analyses of Soma/Eynes lignite are given in Table 1. Design data and different operating conditions of one unit are given in Table 2. Operating condition 4 is the constant maximum load of the design data. Because the coal fired power plants are operated in base load to cover the demand, it was expected to work in condition 4 during the operation. Four fuel oil burners, around the corners of the boiler, were installed for the startup and stabilization of the flame. Twelve coal burners, eight of them were in service at condition 4, were also installed around the boiler.