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Using a genetic algorithm and CFD to identify low NO_x configurations in an industrial boiler

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HIGHLIGHTS

- A genetic algorithm has been coupled with CFD simulations of a 600 MW boiler.
- The genetic algorithm was able to automatically generate innovative boiler settings.
- Correlations between operating parameters and boiler output data were obtained.
- A target function helped to achieve low-NO_x configurations with low corrosion risk.
- The predicted NO_x emissions are consistent with levels measured in the boiler.

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ABSTRACT

This paper focuses on a computational intelligence approach used for minimizing NO_x emissions in a 600 MW tangentially-fired pulverized-coal boiler. Genetic Algorithms (GA) were used to correlate operating parameters to significant output data predicted by CFD simulations of the boiler. The operating parameters include the opening or closing of air dampers, changing the coal distribution through mill selection and feed rate and vertical tilting of the burners. A target function was introduced to estimate for each boiler settings defined by given operating parameters, the costs associated with corrosion on the water-wall tubes, heterogeneous heat flux distribution along the walls, unburned carbon in fly ash and NO_x emissions. The GA was able to automatically generate innovative boiler configurations among thousands of CFD calculations performed. The target function allowed the search space to be explored to establish configurations offering a good compromise between NO_x reduction and the cost associated with corrosion in particular. Moreover, the predicted NO_x emissions from the GA model are consistent with the NO_x levels measured during test campaigns.

1. Introduction

Tangentially-fired pulverised-coal boilers are widely used for industrial coal combustion because they ensure thorough mixing inside the furnace and almost uniform heat flux to the boiler walls. However, like other pulverised-coal technologies, these boilers may face various issues such as significant amounts of unburned carbon in fly ash, slagging and corrosion to the walls and an increase in NO_x emissions, especially when operated in conditions that are substantially different from those recommended by the manufacturer. NO_x emissions in particular are an important issue since nitrogen oxides resulting from coal combustion participate to the formation of acid rain and photochemical smogs, which lead to severe air pollution. The control and reduction of NO_x emissions from coal combustion has become an important concern although their contribution to overall emissions is relatively low compared to those from transportation. As a consequence, governments around the world and international organizations, which support policies to limit air pollution, have established restrictive legislation. In recent years great efforts have been made to reduce NO_x emissions from combustion processes. The approaches used to control NO_x emissions involve primary measures and secondary measures. Primary measures concentrate on preventing the formation of NO_x during the combustion stage whereas secondary measures intend to reduce NO_x after its formation. Secondary measures, such as $DeNO_x$ facilities, had to be introduced in order to comply with environmental restrictions, but primary measures to prevent NO_x formation have been developed in the past and are still undergoing investigation.

Several technologies including burner design modification, air/fuel staging, overfire air (OFA) operation, flue gas recirculation,

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low-NO_x burners and reburning systems have been used to reduce and control NO_x emissions. The main objective of these technologies is to minimise the reaction temperature and the contact between nitrogen from the fuel and oxygen present in the combustion air, while creating a fuel-rich area where NO_x can be reduced to N_2 [1–7]. Since NO_x emissions are strongly related to complex physical and chemical processes such as turbulence, combustion (pyrolysis, homogeneous and heterogeneous oxidation), heat transfer, radiation, and NO_x formation/destruction mechanisms, understanding these complex processes is a prerequisite to reducing NO_x emissions.

In the case of this study concerning EDF 600 MW corner-fired utility boilers located in France, SCR (Selective Catalytic Reduction) units have been installed to decrease NO_x emissions below a concentration set by the European environmental regulation. In addition, the air/fuel staging technique which is a low cost technique since it requires no material modification, has been successfully tested on the different 600 MW units. With this technique, the lower NO_x concentration in the flue gas reduces the amount of NH_3 that needs to be injected into the SCR unit. In this air-staged combustion process, the oxygen concentration in the combustion zone is reduced and additional air is introduced above the lean combustion zone to complete the burning of the char particles. Air can be injected at different levels in the 600 MW boiler, either through a large number of openings (oil support burners, additional air nozzles) or by using the burner-out-of-service (BOOS) technique. As regards fuel staging, this also offers many possibilities, since it is possible to change the number of mills in service and/or the amount of coal delivered by each mill.

However, it is not easy to understand how the boiler will react to a given air or fuel staging configuration due to the large number of input parameters associated with a particular boiler setting. The behaviour of a coal boiler is complex, the response to the numerous input parameters highly non-linear and there is no simple relation between input parameters and output data. Given the number of possible configurations, finding settings to optimize NO_x reduction without compromising the boiler's material safety would require a huge number of calculations. A step-by-step modification of input parameters through trial and error is a very time-consuming process because for each set of parameters a CFD simulation has to be performed. An optimization method was therefore needed that would explore the search space extensively, could enumerate a scattered population of potential solutions and could use CFD modelling to evaluate any boiler setting. This and a previous work by Risio et al. [8] led us to consider genetic algorithms [9]. The capacity of genetic algorithm to handle heterogeneous populations, yet comply with safety rules, was an important characteristic in identifying unusual settings that minimize pollutant formation.

In the field of coal optimization studies, the use of genetic algorithm is mostly restricted to experimental data. For a problem similar to ours, Hao et al. [10] have combined genetic algorithm and neural networks using NO_x and O_2 measurements on a 600 MW boiler to search for an optimum solution to achieve low NO_x emissions. The input parameters include OFA distribution pattern, secondary air distribution pattern, coal quality and burner nozzle tilt angle. Although the results of these studies are consistent with experimental data, the method is limited by the cost of the many measurements required. However, some recent work combining CFD and genetic algorithm can be found in literature. Salahi [11] has used automated multi-objective optimization including NO_x and CH_4 using CFD simulation of a coal combustion reactor. Liu and Bansal [12] have used non-dominated sorting genetic algorithm-based multi-objective optimization to decrease slagging inside a coal boiler furnace. However, to our knowledge, there has never been such an intensive use of CFD combined with genetic algorithm to simulate pulverized-coal combustion as in this study. For any individual or boiler setting (thousands of possibilities), we have used the Computational Fluid Dynamics software Code_Saturne, a finite volume tool developed at EDF R&D to evaluate the quality of the boiler configuration in terms of combustion, unburned carbon, NO_x emissions, area of the boiler walls prone to corrosion risk, and thermal flux distribution on the walls.

2. The 600 MW corner-fired boilers

2.1. Description of the boiler

EDF operates three 600 MW tangentially-fired pulverized-coal units located in France. Two of them are sited in Cordemais (units 4 and 5) and one is based in Le Havre (unit 4). A schematic representation of the furnace and burners is shown in Fig. 1. The total height is about 80 m and the boiler has a 16.6 m × 16.6 m cross section. Coal injection is performed at the corners of the boiler (A1 to A4) at three different levels (Group 1, Group 2 and Group 3). At each level, four firing groups (one at each corner) fed by two mills are used. In order to operate at full load, four mills are usually used out of a total of six available (named A to F). Each mill distributes pulverized coal to four burners belonging to the same firing group, but not on the same horizontal plane. The burners are directed tangentially towards a virtual cylinder in the centre of the furnace to create a swirling vortex in the combustion chamber to improve mixing. Fig. 2 shows the arrangement of the 12 firing groups at each corner of the boiler. Each firing group is equipped with two coal burners and their associated secondary air nozzles (FOA to FOF, named according to the corresponding mill) located just above and below the primary air nozzle through which the pulverized coal enters the boiler, a heavy fuel oil nozzle (named FGB for the lower level, FGC for the middle level and FGE for the upper level) and additional secondary air nozzles named FOO. In particular, the nozzles located on top of the upper firing groups (named FOO up) can be opened to simulate close coupled OFA, since their location is just above the highest burners. It should be noted that heavy fuel oil injection is performed only during the ignition phase. However after start-up, these nozzles can be used to inject secondary air. Injections of air and pulverized coal are performed at a fixed angle of 39° from the boiler walls to obtain a stable vortex. The firing groups can be vertically tilted to shift the position of the flame from −30° (maximum downward tilt angle) to +30° (maximum upward tilt angle). Air nozzles are opened in opposite pairs, therefore if one nozzle at one corner is opened, the same type of nozzle in the diagonally opposite corner will also be opened. It should be noted that the secondary air inlets associated with the burners can be opened even if the corresponding burner is out of service (BOOS).

2.2. Assumptions used in this study

For a given load, the total coal mass flow is known (depending on the coal heating value) and the total air mass flow is calculated assuming a given excess air. The total air mass flow is adjusted so that the O_2 concentration in the flue gas near the economiser meets a given value depending on the boiler load. The air distribution between the different nozzles depends on the position of the dampers. The air dampers of the different air nozzles (primary air, secondary air and air through the oil nozzles) can only operate in on–off mode so for a given total air mass flow rate, the actual flow rate through an open port depends on the total number of opened air ports. As regards the coal mass flow rate for one mill, it is assumed that it is evenly distributed among the four associated burners.