Fuel 158 (2015) 672–683

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

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

Sandro Dal Secco *, Olivier Juan, Myriam Louis-Louisy, Jean-Yves Lucas, Pierre Plion, Lynda Porcheron

EDF R&D, 6 quai Watier, 78400 Chatou, France

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.

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 3 June 2015
Accepted 5 June 2015
Available online 13 June 2015

Keywords:
CFD modelling
NO_x emissions
Corrosion
Industrial boiler
Pulverized coal combustion
Genetic algorithm

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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* Corresponding author. Tel.: +33 1 30877036.
E-mail address: sandro.dal-secco@edf.fr (S. Dal Secco).

http://dx.doi.org/10.1016/j.fuel.2015.06.021
0016-2361/

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 $+30^\circ$ (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.

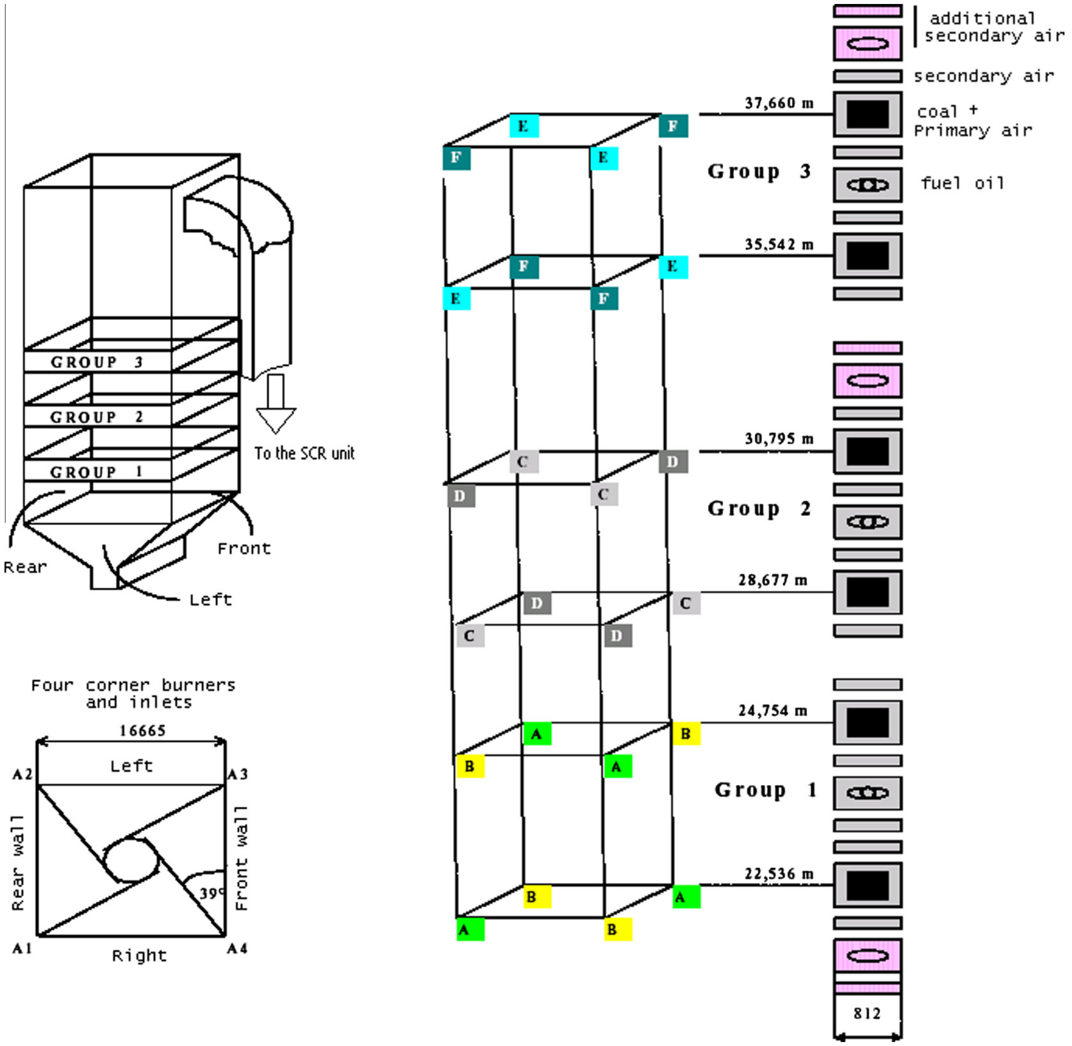

Fig. 1. Schematic of the 600 MW boiler.

For this study, we will assume that a given coal is used and that the boiler is operated at full load and at a given excess air. However, even with a specified coal load and an excess air imposed by/for thermal efficiency considerations, many parameters have to be adjusted: coal distribution in mills and burners, vertical tilt of the burners, and air staging through the on–off position of the different dampers. Due to the large number of parameters involved, the use of a CFD tool is particularly well-suited to this kind of problem since many numerical experiments can be conducted at low cost.

3. CFD modelling

3.1. Coal combustion model

The three-dimensional CFD software Code_Saturne [13] developed at EDF is a general-purpose code. This code provides an adequate framework for the development of coal combustion and has been successfully used in a large number of industrial applications [14–16]. In the pulverized-coal combustion version of Code_Saturne, conservation equations are formulated for mass, momentum, energy and other conservative quantities related to coal combustion. The pulverized coal particle size distribution is represented by a discrete number of particle size classes determined by the measured fineness distribution. Conservative equations are solved for each particle size group. The turbulence of the gas-particle mixture is predicted by means of a standard k–ε eddy viscosity model. The combustion model takes into account the particle's pyrolysis and the heterogeneous combustion of the char (Fig. 3).

The raw coal is assumed to devolatilize according to two competing reactions (Kobayashi model – Fig. 4) leading to two different volatile compounds (light and heavy volatiles) [17].

Y_1 and Y_2 are stoichiometric coefficients relative to the two reactions. The kinetics of the reactions is described applying a simple Arrhenius approach:

$$k_i = A_i \cdot \exp^{\left(-\frac{E_i}{RT}\right)} \quad i = 1,2$$

where A_i represents a temperature independent pre-exponential factor, E_i the activation energy and T the particle temperature.

The heterogeneous combustion of the char particle is modelled using a global reaction rate taking into account the kinetics of CO formation and the diffusion of oxygen at the particle surface (internal diffusion is neglected). A simple reaction equation describing this heterogeneous combustion process is given by: $C(s) + \frac{1}{2}O_2 \rightarrow CO$. Char combustion reaction is supposed to occur after all volatile matter has been released. The reaction rate is limited by external oxygen diffusion. The particle burns at constant density whereas the flame front propagates towards the centre of the particle leaving a solid product (ash) behind. This concept is

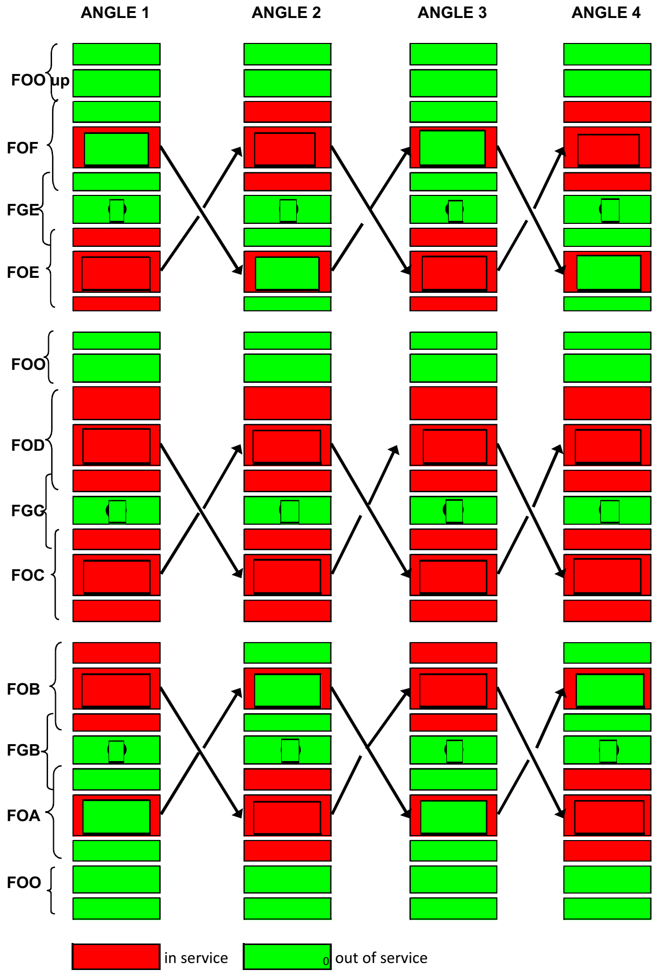

Fig. 2. Coal and air register arrangement at the corners of the boiler.

known as the shrinking core approach. In this context, the evolution equation for the mass of char inside the solid fuel particle is expressed by:

$$\frac{dm_{char}}{dt} = -S_p K_g p^n_{O_2,\infty}$$

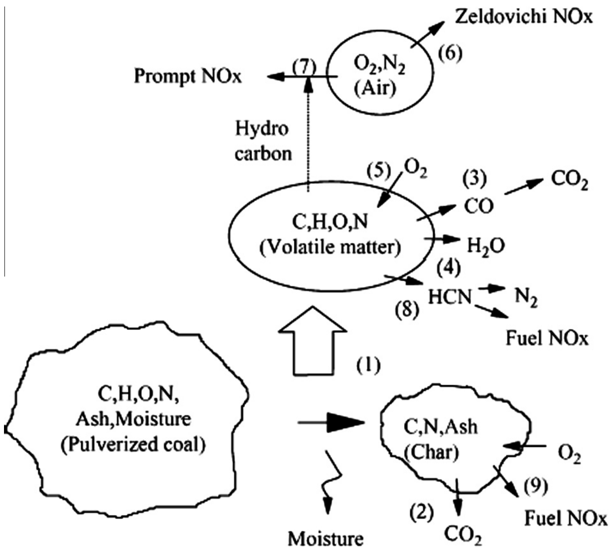

Fig. 3. Concept of pulverized coal-combustion (according to Kurose et al. [21]).

where K_g is the global reaction rate given by $\frac{1}{K_g} = \frac{1}{K_d} + \frac{1}{K_c}$ K_c is the reaction rate of the chemical reaction and K_d the diffusion rate of oxygen in the gas flow through the boundary layer surrounding the solid fuel particle. S_p represents the effective particle area where the combustion reaction is taking place and is given by: $S_p = \pi(1 - \alpha_{ash})d^2_{p,char}$ with α_{ash} the ash content of coal and $d_{p,char}$ the diameter of the char core. $p^n_{O_2,\infty}$ is the partial oxygen pressure in the bulk phase, and n the apparent reaction order. A simple Arrhenius approach is applied to describe the kinetic of this reaction whereas a temperature independent pre-exponential factor A_c and the activation energy E_c have to be provided:

$$K_c = A_c \cdot \exp^{\left(-\frac{E_c}{RT}\right)}$$

The modelling of combustion in the gas phase takes into account the presence of three different fuels: light and heavy volatiles and CO released during char burnout. Combustion-turbulence interaction is modelled with the help of a Probability Density Function, in terms of the mean mixture fractions of the different fuels and their variance.

For radiation, the P1 model was used [18] with local absorption coefficients depending on the gas-phase composition (in terms of CO_2 and H_2O) and the volumetric concentration and size of the particles.

In order to estimate the NO_x emissions, a simplified model based on De Soete [19] and Zeldovich et al. [20] mechanisms was used with standard reaction rates. In the De Soete model, we assumed HCN to be the only intermediate in the formation of NO. The HCN release rate is assumed to be proportional to the particle's burning rate.

3.2. Calculation domain and mesh

The mesh is structured and contains 470,000 cells (Fig. 5). The mesh is refined near the burners where the combustion processes actively take place. The heat exchangers have been taken into account by prescribing for each of them a pressure drop and a heat exchange derived from operating conditions.

3.3. Boundary conditions on the walls

In the absence of accurate data, we assume a uniform temperature on the boiler's walls. The wall temperature is the temperature of the water-wall metal tubes and is estimated to be constant and equal to 400 °C at full load. The walls of the boiler are assumed to be optically grey, with an isotropic and emitting reflection and uniform radiosity. The wall luminance is calculated as follows:

$$L(x,S) = \left(\varepsilon\frac{\sigma T^4}{\pi}\right) + (1-\varepsilon)\frac{I}{\pi}$$

where ε is the wall emissivity, I the incident flux at the wall and T the wall temperature. For all the simulations, the emissivity of the walls is assumed to be constant and equal to 0.7. However, above the first heat exchangers, the walls are considered to be black bodies.

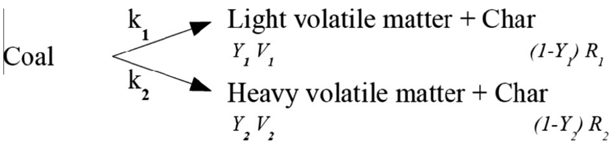

Fig. 4. Two reactions devolatilization model (Kobayashi) [17].

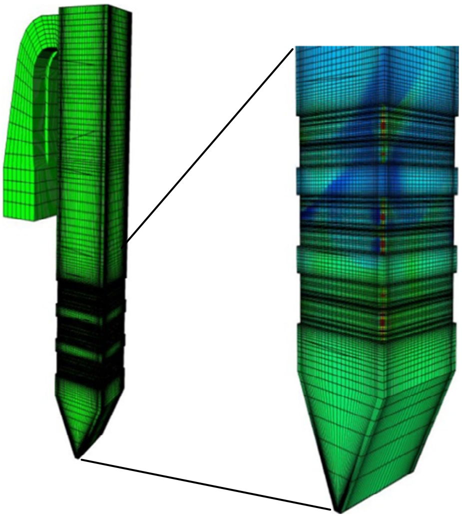

Fig. 5. Mesh used for the CFD simulations.

3.4. Coal characteristics

The fuel used for the simulations is a blend of Colombian and Russian coal which was fired during a test campaign in December 2007. The immediate and proximate analyses are provided in Table 1. The calculations assume that the size distribution of the coal particles follows a Rosin–Rammler distribution. A coal fineness including 10 particle diameters was used, with each particle size representing 10% (w%) of the distribution (Table 2). The nitrogen content is 1.7% (db) which corresponds to a moderate value, much lower than the nitrogen content of coals imported from South Africa, for example, which is usually between 2% and 2.5%. Because of its moderate nitrogen content and high volatile content, this coal can be considered rather favourable to reducing NO_x emissions.

The parameters involved in the two global competitive reaction schemes during pyrolysis of the coal particle are given in Table 3. When coal characterization on a drop tube furnace is available, the kinetic parameters of the Kobayashi scheme are determined using an optimization routine based on genetic algorithm and simplex method [22]. However, since no characterization for this particular coal has been performed, default kinetics parameters (activation energies E_1 and E_2 and the pre-exponential factors A_1 and A_2) given in Code_Saturne have been used. The stoichiometric mass coefficients Y_1 and Y_2 are derived from the coal volatile matter content. Y_1 is chosen to be equal to the volatile matter content obtained from the proximate analysis (daf basis) because this analysis is carried out at low temperature and therefore corresponds to the first reaction of the Kobayashi scheme. For the second reaction, which takes place at high temperature, it is assumed that the released hydrocarbons have a higher C/H ratio than the volatiles released at low temperature. The chosen devolatilization parameters are shown in Table 3. The Q factor is defined as the ratio between the volatile matter released at high temperature and the volatile matter obtained from the proximate analysis: $Y_2 = Q{\cdot}Y_1$. Typically the Q factor varies in the range 1.2–1.8. The value used for the simulations is assumed to be equal to an average value of 1.4.

Low-NO_x configurations may lead to high unburned carbon in fly ash if the residence time of the particles in an oxidising atmosphere is insufficient or if the oxygen partial pressure is too low. The char reactivity also plays an important role in determining the amount of unburned carbon in fly ash. Carbon in ash (or unburned carbon) is defined as the mass fraction of char in the coal particle. The unburned carbon in fly ash is averaged over the last cells before the exit of the boiler (Fig. 5) where the measurement probes are located. Because no characterization has been performed for the particular blend used in the simulations, the default kinetics for char reactivity in Code_Saturne was used (see Table 4). Therefore the calculated unburned carbon can only be considered as a qualitative value used to predict the boiler tendencies.

Table 1
Proximate and ultimate analysis of coal.

Proximate analysis	Dry basis (w%)
Volatile matter	36.8
Ash content	11.5
Total moisture (w%)	4.2
Ultimate analysis	Dry basis (w%)
C	70.9
H	4.6
O	10.8
N	1.7
S	0.5
Lower heating value db (kcal/kg)	6785

Table 2
Particle size used in the simulations.

Particle size class	Average diameter (µm)
1	1.2
2	5.4
3	11.3
4	19.0
5	29.0
6	42.1
7	60.0
8	85.8
9	128.6
10	231.9

Table 3
Devolatilization parameters.

Y_1	0.42
Y_2	0.58
E_1	$7.4{\cdot}10^4$ J/mole
E_2	$2.5{\cdot}10^5$ J/mole
A_1	$2.5{\cdot}10^5\ s^{-1}$
A_2	$1.3{\cdot}10^{13}\ s^{-1}$
Q factor	1.4

4. Genetic algorithm

4.1. The boiler settings (chromosomes)

The chromosomes used in the genetic algorithm represent all the input parameters that define the boiler settings. In the previous paragraphs we saw that even for a specified coal (full load) and a given excess air, a lot of process parameters have to be adjusted: load distribution pattern on the mills and burners, tilt of the burners and air staging (Table 5). Air staging is achieved by opening air registers of out-of-service burners (BOOS), opening auxiliary air nozzles such as the heavy fuel nozzles or the secondary air nozzles named FOO (Fig. 2). When opening or closing the air dampers, the total air flow remains constant since we assume a constant excess air and coal load, but the distribution of air inside the boiler is changed. As regards fuel staging, there is no limit on the number or mills in service or the coal mass flow rate delivered by each mill (from no coal to full capacity). The only constraint is that the sum of the coal mass flow rates delivered by in-service mills must be equal to the total mass flow rate corresponding to the full load.

Table 4
Kinetic rate parameters used for char burnout.

E_c	$6.926 \cdot 10^4$ J/mole
A_c	17.88 kg/s/m^2/atm

With respect to the vertical tilt of the burners, a discrete number of positions is allowed: −30°, −15°; 0°, +15° and +30° (angles are defined relative to the horizontal). When operating the tilting, the entire set of firing groups located on the same corner, but also on the diagonally opposite corner (Tilt 1 for corners A1/A3 and Tilt 2 for corners A2/A4 – see Fig. 1) will be moved upward or downward. However the two angles Tilt1 and Tilt2 are operated independently.

4.2. Principle of the algorithm

We have used the ParadisEO [23] library developed by INRIA (*Institut National de Recherche en Informatique et Automatique*) to implement the genetic algorithm. This library provides a simple and flexible environment to experiment on the crossover/mutation/selection steps. For the selection step, we use the Evolutionary Programming Stochastic Tournament method already implemented in ParadisEO (each individual competes against n opponents and the best score survives). As for crossover and mutation steps, these are carried out as follows. Each individual is a direct representation of the coal boiler's configuration parameters: binaries for the air nozzles (open/closed), integers for the burners' vertical tilt, and continuous values for the burners' load. Because we have to post-process the chromosomes, modifying some gene values to fulfil physical constraints (e.g. constant global coal load, mandatory opening of in-service burner air nozzles), we have implemented a simple one-gene exchange crossover procedure. Combined with mutations, it leads to satisfactory variability in the successive populations. The mutation step is two-fold: first the gene that will undergo the process is randomly selected, and second its value is changed depending on the gene type: swap for binary, random assignment for others. The effectiveness of a genetic algorithm typically relates to both the population size and the number of generations that are created. Due to the significant amount of time required to evaluate all the individuals in the population, we chose to limit the population size to around 50, which seemed a good trade-off between evaluation time and diversity. Finally, the fitness of an individual is obtained by running Code_Saturne and then combining six physical/chemical indicators (combustion efficiency through O_2 and CO concentration in the flue gas, unburned carbon, NO_x emissions, surface prone to corrosion risk, and thermal flux on the walls) into a single economic value: the cost function.

4.3. The cost function

The following indicators are obtained from the CFD simulations. The total cost (expressed in Euros) is obtained by simply adding up the respective estimated costs associated with each indicator.

Table 5
Parameters involved in the genetic algorithm.

Parameter	Value
Air/heavy fuel nozzles	On/Off
Coal mass flow rate/mill	From 0% to 100% capacity (full range operation)
Tilt angle corners A1/A3 (Tilt1)	−30°, −15°; 0°, +15°, +30°
Tilt angle corners A2/A4 (Tilt2)	−30°, −15°; 0°, +15°, +30°

4.3.1. O_2 concentration in flue gas

The theoretical concentration value is 4.6 (vol.%) assuming that combustion is complete. We assume that a maximum fluctuation of 0.5% around this value is acceptable. However, anything above this fluctuation level means the combustion process is very poor, and a strong financial penalty is therefore applied to the cost function.

4.3.2. CO concentration in flue gas

A high CO concentration in the flue gas is a sign of incomplete combustion. Since carbon monoxide is considered a hazardous air pollutant, a strong penalty will be applied for levels above 100 ppm@6%O_2 in the flue gas.

4.3.3. NO_x emissions

The Cordemais and Le Havre boilers were equipped with SCR (Selective Catalytic Reduction) in 2008. The efficiency of this device is close to 80% which is sufficient to comply with the 2008 European regulation for Large Combustion Plants. However, reducing NO_x concentrations below 200 mg/Nm^3@6%O_2 using primary measures combined with the use of the SCR for the 600 MW boilers has several advantages. Firstly, because in that case exemptions have been granted by Europe for smaller power plants to emit above the national emissions ceiling, provided they run for a limited amount of hours per year[1]. The second reason is that reducing NO_x concentrations in the flue gas will reduce ammonia consumption and extend the lifetime of catalysts. Furthermore it will help to ensure compliance with the future 2016 Industrial Emissions Directive that will lower NO_x emissions ceilings. Therefore the cost function takes into account a penalty in the case where NO_x emissions after the SCR (assuming an 80% efficiency) are above 200 mg/Nm^3@6%O_2. In the case where NO_x concentrations are below this value, the cost will be reduced using an estimate of the ammonia and catalyst savings.

4.3.4. Water-wall corrosion

Coal-fired power plant boiler water-wall tubing experiences gradual wall loss from the fireside as a result of corrosion. Under normal conditions, typical wastage rates are quite low (less than 0.25 mm/year). However, when using low-NO_x combustion systems to comply with regulations, reducing zones are created in the lower part of the furnace. Under such reducing conditions, wastage rates are much higher and can reach up to 1 mm/year. The influencing factors are varied and sometimes difficult to assess: the nature of the gaseous medium adjacent to the material, the metal temperature, the possible presence of ash deposits forming a barrier between the metal and the gas, the heat flow through the structure and erosion by the particles.

Steam generator water-tube boilers are particularly affected by this phenomenon because they carry water at a high temperature range and are exposed to the flow of exhaust gases. In pulverized coal plants, corrosion is generally attributed to sulphur or chlorine products from the fuel. Low-NO_x combustion configurations induce reducing atmospheres coupled with lower temperature sintering and melting of ash in some parts of the boiler. In power plants using coals with high chlorine or sulphur contents, these configurations increase the propensity to create corrosive deposits of sulphur and chlorine free radicals.

A work programme sponsored by the EPRI (Electric Power Research Institute) has been carried out by PowerGen UK [24,25] to investigate the influence of operational and fuel variables on the fireside corrosion rates of power station boiler tubing, using a

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[1] Exemptions will not be granted after 2016 in accordance with the 2016 IED (Industrial Emissions Directive).

1 MWth combustion test facility. A series of predictive equations were derived from the metal loss data relating furnace wall corrosion rate to surface metal temperature and local combustion environment.

From these experiments the authors derived a correlation for metal loss exposed to either oxidising or reducing conditions:

$$M = 6 \cdot 10^{5}\left(\sqrt{t0 \cdot K_{po}} + \sqrt{tr \cdot K_{pr}}\right)e^{-\frac{123500}{RT}}$$

where M is the metal loss in µm, K_{pr} and K_{po} are corrosion rates respectively under reducing and oxydising conditions in cm^2/s, $t0$ and tr are the corresponding times in hours during which the sample is exposed and T is the metal temperature.

The corrosion rates are expressed in terms of the metal temperature $T(K)$ and CO concentration for reducing conditions:

$$K_{pr} = 5 \cdot 610^{-5}\sqrt{\%\mathrm{CO}}\,e^{-\frac{98000}{RT}}$$

$$K_{po} = 3 \cdot 6910^{-3}\,e^{-\frac{123500}{RT}}$$

These equations can be used to estimate metal loss alternatively exposed to oxidising and reducing conditions.

Fig. 6 gives an example of metal loss after a period of four months for three cases with different metal exposure: oxidising, reducing (CO = 3%) and alternate (two months under oxidising conditions and two months under reducing conditions). These results are in line with what is generally observed for EDF pulverized-coal boilers. The cost associated with the metal loss will depend on the wastage rate. It will be based on the cost of a coating in the areas where the wastage will be higher than 50 µm per year and below 1 mm per year. The cost will be increased if the metal loss is higher than 1 mm per year because of the need to use a more efficient and more expensive coating.

4.3.5. Heat fluxes on the walls

Heat flux homogeneity along the boiler walls is important in order to ensure a uniform heat exchange between the hot flue gases and the boiler's tubes. When applying air staged configurations, it is expected that the flame will be concentrated on the lower part of the boiler, and therefore the heat fluxes due to flame radiation may display some high peaks on the water-wall tubes. This may cause early evaporation of the water inside the tubes, a change in the heat transfer coefficient and a local increase in the metal temperature. This high temperature can in turn lead to metal creeping and possible water leaks due to tube failure. In order to take into account the possible influence of radiation on the partial replacement of water-wall tubes, we define a heterogeneity index related to the heat distribution on the walls of the boiler. This index is based on the average and standard deviation of the heat flux compared to the baseline values. In the case of strong heterogeneity, a penalty corresponding to a forced outage will be applied when the index is greater than a given value.

4.3.6. Carbon in fly ash

The cost associated with unburned carbon in fly ash relates to ash recycling. Ash recycling is possible if the percentage of carbon in ash is lower than 7%.

4.4. The numerical experiments

To compute chemistry and fluid dynamics, Code_Saturne is run on an 8-core machine for approximately 14 h per individual at the time of this study. This significant running time presented an obstacle for a large population and given the number of generations. To overcome this difficulty, we divided the execution of Code_Saturne over a fifty-two 8-core node cluster which was equivalent to reducing the average evaluation time to fifteen minutes per individual. To avoid unnecessary re-evaluation, we built a database of all the chromosomes that have already been assessed. We started from an initial population of fifty-two individuals reflecting best-practice and standard configurations. We ran the genetic algorithm for fifty generations (several weeks of computation) on a constant population. As a result, we obtained several interesting boiler settings minimising the global economic cost (the genetic algorithm was stopped because no significant improvement in cost was observed on the last generations).

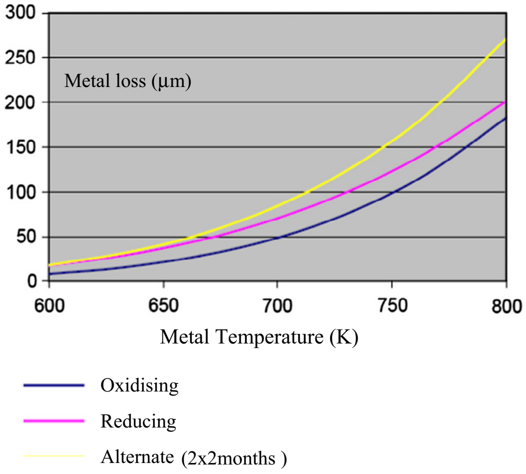

Fig. 6. Metal loss for a total duration of 4 months as a function of temperature and exposure conditions.

5. Results

5.1. Some individuals from the last generation

Among the thousands of CFD calculations performed, it should be noted that none of them led to flame extinction or even very poor combustion. The O_2 concentration in the flue gas has always remained close to the theoretical value corresponding to almost complete combustion. We will see in Section 5.3 that this result relates to the choice of char reactivity. Table 6 displays the results for some individuals from the last generation with large NO_x abatement compared to the baseline configuration. Most configurations with high NO_x reduction are obtained using four mills distributing coal on the lower and middle group only (mills A, B, C and D) and with no vertical tilting of the burners (horizontal injection). To achieve substantial NO_x abatement, a sufficient number of air nozzles must be opened to create air-staged combustion with a reduced oxygen area near the in-service burners, so that during devolatilization fuel-nitrogen is released in an oxygen-depleted atmosphere. Some configurations, like individual No. 962 which corresponds to a deep staged configuration, lead to a particularly high NO_x reduction (Table 6). However, the cost associated with corrosion is also particularly high for this case. The configuration corresponding to individual No. 610 allows substantial NO_x reduction with a very limited cost associated with corrosion. If we check the CO concentration (which is a marker of the corrosion risk under reducing conditions) near the walls of the boiler (Fig. 7), we observe high levels of CO for individual No. 962. This configuration is very favourable to NO_x abatement but at the same time it generates a high corrosion risk for the boiler walls. Individual No. 610 should be preferred over No. 962 because although the NO_x reduction is lower, the balance between ammonia savings and corrosion cost is largely in favour of this moderately staged configuration.

Table 6
Genetic algorithm: results for some individuals from the last generation.

Individual No.	Mills used	Coal mass rate (kg/s)	Burner tilt angle[a]	Opened air registers	NO_x ($mg/Nm^3@6\%O_2$)	NO_x abatement (%)	Corrosion cost (k€/year)	Unburned carbon (%)
1072	A	14.3	0°	FOF; FOE 2/4[b]; FOO up; FGE 2/4[b]; FOO mid[c] 1/3[d]	437	−53	39.6	0.8
	B	7.7						
	C	19.3						
	D	19.3						
1042	A	14.9	0°	FOE; FOF; FOO up	454	−51	16.7	0.7
	B	8.6						
	C	19.3						
	D	17.8						
610	A	7.1	0°	FOE 1/3[d]; FOF; FOO up 1/3[d]	557	−40	4.8	0.4
	B	14.9						
	C	19.3						
	D	19.3						
962	A	14.9	0°	FOE; FOF; FOO up; FGE	430	−54	60.8	0.8
	B	8.7						
	C	19.3						
	D	17.7						
190	A	11.1	0°	FOE; FOO up; FGE 2/4[b]	605	−35	8.7	0.4
	B	7.4						
	C	17.1						
	D	15.4						
	F	9.6						
346	A	14.9	−15°	FOE; FOO up	644	−31	4.8	0.4
	C	19.3						
	D	19.3						
	F	7.1						

[a] The same tilt angle is applied to all burners.
[b] The registers are opened only on two diagonally opposite corners A2/A4.
[c] FOO mid stands for additional secondary air nozzle from the middle group (Group 2).
[d] The registers are opened only on two diagonally opposite corners A1/A3.

Note that the pattern of the opened nozzles can be quite complex and could hardly be considered an intuitive choice. In particular, some individuals include different types of nozzles which may be opened only at two corners of the boiler. The genetic algorithm here has definitely helped to identify unusual settings.

Although the configurations involving four mills in the lower and middle group (A, B, C, D) are most favourable to NO_x reduction, some configurations involving five mills like individual No. 190 are also good candidates since they offer noticeable NO_x reduction with negligible corrosion risk. Individual No. 346 is a much more standard configuration with one mill feeding the lower group, two mills for the middle group and one mill for the upper group. Even with a standard configuration this result shows it is possible to achieve a good compromise between NO_x reduction and corrosion risk.

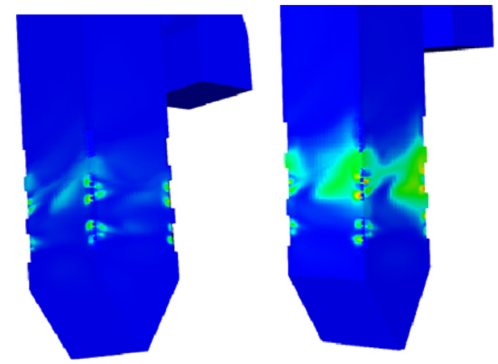
Low corrosion risk (case 610) High corrosion risk (case 962)

Fig. 7. CO concentration along the wall for two cases.

5.2. Heat flux on the water-wall tubes

In the previous paragraph we saw that most configurations with high NO_x reduction are obtained using a pattern with four mills distributing coal on the lower and middle group only, therefore concentrating the coal load towards the bottom of the boiler. However, the air-staging technique and concentrating coal in the lower part of the boiler leads to a significant increase in heat flux radiated on the ash hopper walls. Indeed, the decrease in NO_x emissions is associated with an increase in the heat flux radiated to the ash hopper walls as shown in Fig. 8.

Test campaigns have already demonstrated that positioning the coal load towards the bottom of the boiler and especially if combined with downward tilting of the burners increases the risk of having high temperatures on the metal tubes. It has also been shown that these temperature peaks were related to the arrangement of the tubes along the boiler walls. In fact, the water-wall tubes are vertical along the ash hopper walls, then spiralled in the part of the boiler above the ash hopper, leading to different tube lengths and therefore different pressure drops for the liquid–vapour mixture circulating inside the tubes. Furthermore, any increase in the average heat flux or heat flux heterogeneity received by the ash hopper will tend to increase the risk of high metal temperature.

The results obtained by the simulations show on the one hand that there is a clear correlation between the average heat flux and the variance of the heat flux on the ash hopper walls (Fig. 9), and the other hand, that when the burners are horizontal or tilted downwards, there is greater dispersion of the average heat flux and its standard deviation in the ash hopper. Conversely, when the

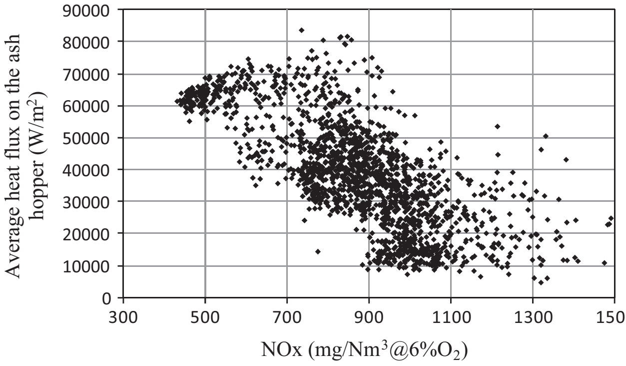

Fig. 8. Average heat flux on the ash hopper versus NO_x emissions.

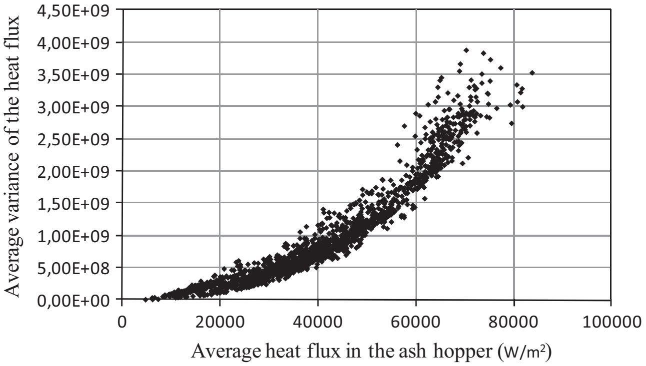

Fig. 9. Correlation between average heat flux and its variance in the ash hopper.

burners are tilted upward, it minimizes both the average heat flux and its standard deviation (Figs. 10 and 11). This result corroborates the on-site observations of more frequent peak temperatures on the water-wall tubes when the burners are horizontal or tilted downward. When those peak temperatures occur, the operator will usually tilt the burners in the upward position. According to the simulations, this lowers both the average heat flux and its variance and thus reduces the risk of metal peak temperatures. This also explains why most operators usually run this type of boiler with the burners tilted upward with an angle of approximately 20° from the horizontal.

The occurrence of peak temperatures should be higher when using low-NO_x configurations. Indeed, positioning the load in the lower part the boiler will increase the heat flux in the ash hopper. Furthermore if we consider the heat flux heterogeneity index which measures the degree of heterogeneity on all the walls of the boiler (see Section 4.3.5), we observe an increase in this index when decreasing the NO_x emissions (Fig. 12). Regarding NO_x emissions as a function of burner tilt, we can see from Fig. 13 that when the burners are tilted strongly upward (the sum of the two angles greater than 45°) the NO_x level hardly drops below 900 mg@6%O_2. Zero tilting (i.e. horizontal burners) seems to be the position most favourable to reducing NO_x emissions. This observation was also made during test campaigns: at a given load, when tilting the burners in the upward position, the NO_x emissions tend to increase.

5.3. Unburned carbon in fly ash

As far as burnout is concerned, the genetic algorithm gives a typical result i.e. an increase of unburned carbon when NO_x emissions are decreased (see Fig. 14). This is due to the limited residence time of the particles in an oxygen-enriched atmosphere when the air-staging technique is applied. Indeed in that case, a significant part of the boiler is in an oxygen-depleted environment. Note that because we have chosen a high char reactivity (default values were used in Code_Saturne), the level of unburned carbon remains low (<2%) even in deep air-staging conditions. In this instance, the level of unburned carbon always allows fly ash recycling, therefore it will not have any impact on the global cost function and thus the choice of boiler configurations. A fairly clear correlation between unburned carbon in fly ash and the unburned CO concentration in the flue gas is observed (Fig. 15). Incomplete combustion of the particles is therefore accompanied by incomplete conversion of carbon monoxide to carbon dioxide. However, due to relatively high excess air, the CO concentration in the flue gas is moderate even for deep air-staging configurations. Therefore, as with unburned carbon, there will be no penalty due to high CO levels, since the CO concentration never reaches the maximum permitted value of 100 ppm in the flue gas.

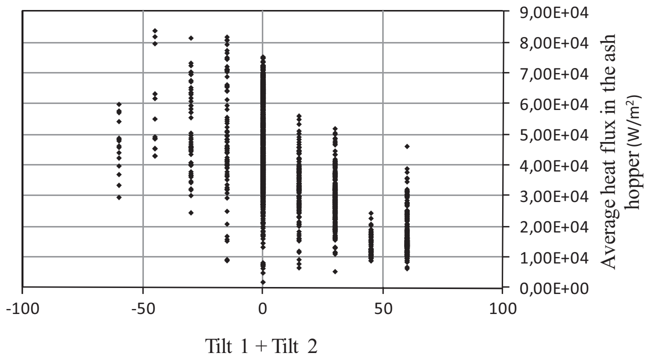

Fig. 10. Average heat flux on the ash hopper walls versus the sum of vertical tilt angles (Tilt 1 for corners A1/A3 and Tilt 2 for corners A2/A4).

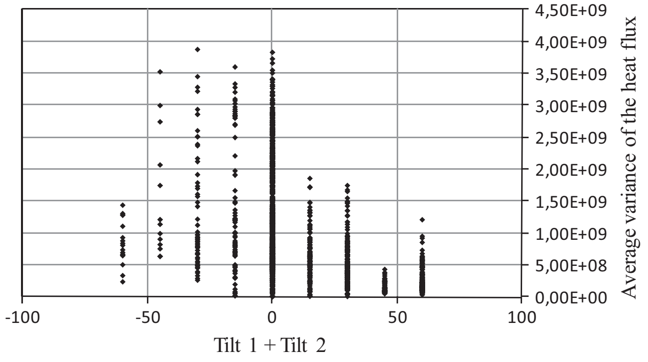

Fig. 11. Variance of the heat flux on the ash hopper versus the sum of vertical tilt angles (Tilt 1 for corners A1/A3 and Tilt 2 for corners A2/A4).

5.4. Corrosion on the water-wall tubes

In Section 5.1, we saw that some configurations lead to a dramatic NO_x reduction. However the cost associated with corrosion in that case is often also particularly high. Nevertheless, some other configurations offer very substantial NO_x abatement without being penalised by the corrosion cost.

Fig. 16 presents the correlation between NO_x emissions and corrosion cost. It shows that if we want to achieve NO_x emissions well below 500 mg@6%O_2 in most cases an industrial coating will be needed to protect part of the walls from corrosion. For values

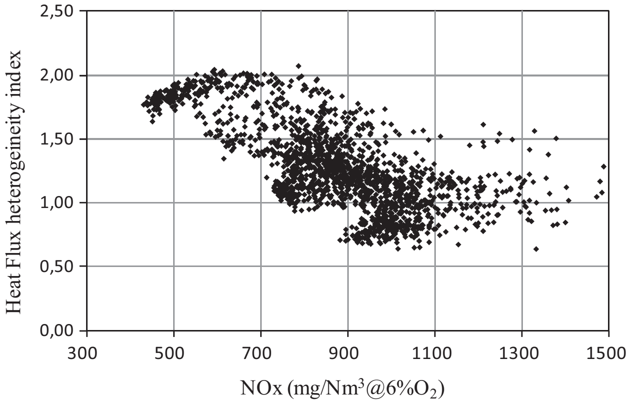

Fig. 12. Heat flux heterogeneity index versus NO_x emissions.

above 500 $mg@6\%O_2$ but below 600 $mg@6\%O_2$ for instance, a large number of individuals can be found offering a low corrosion cost, meaning that wastage rates should remain quite low. These configurations show that it is possible to achieve a good compromise between NO_x reduction and corrosion risk.

5.5. Comparison of the simulations with results obtained during on-site measurement campaigns

Some of the results of tests carried out during different measurement campaigns are reported here. The tests performed in January 2012 relate to Cordemais Unit 4 (Table 7) while tests carried out in April 2011 concern Le Havre Unit 4 (Table 8).

These trials were designed to implement and test a number of low-NO_x configurations simulated with Code_Saturne. In order to estimate the corrosion risk, probes were used to monitor the near wall atmosphere (CO and O_2 concentrations). The configurations tested are not strictly identical to the simulations achieved using the genetic algorithm. In particular, the coals used during these tests are two different USA coals whereas for the simulations we assumed the boiler was fed with a blend of Colombian and Russian coals. Despite these differences a number of similar trends between simulation and tests are observed.

First of all the results confirm that when the burners are tilted upwards the NO_x level remains high (see Section 5.2). Testing in January 2012 (Table 7) helped highlight the role played by the burners' vertical tilt on NO_x emissions. It was found that for a given boiler configuration, tilting the burners upward leads to a significant increase in NO_x emissions. For example, for an ACDE mill configuration, while it is possible to obtain a reduction of almost 40% when the burners are horizontal or tilted slightly downward, when they are positioned at the maximum upward tilt angle (+30°) the NO_x abatement is only 5%. For an ABCD mill configuration, the difference is even more sensitive since the reduction is 60% when the burners are almost horizontal (+6°) and only 20% when they are geared up to the top. Therefore, the tests carried out have confirmed the adverse effect of the upward direction of burners on NO_x emissions, a trend already identified by the genetic algorithm (Fig. 13).

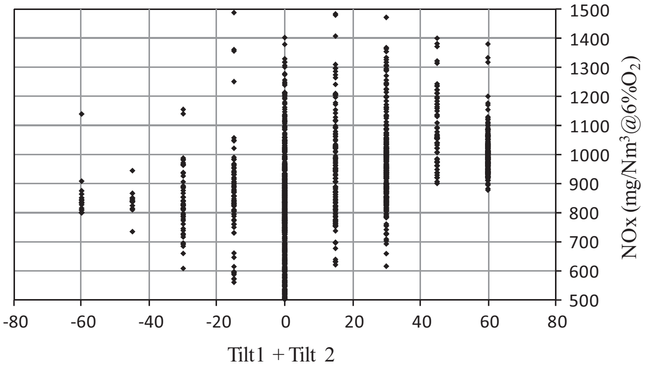

Fig. 13. NO_x emissions versus the sum of vertical tilt angles (Tilt 1 for corners A1/A3 and Tilt 2 for corners A2/A4).

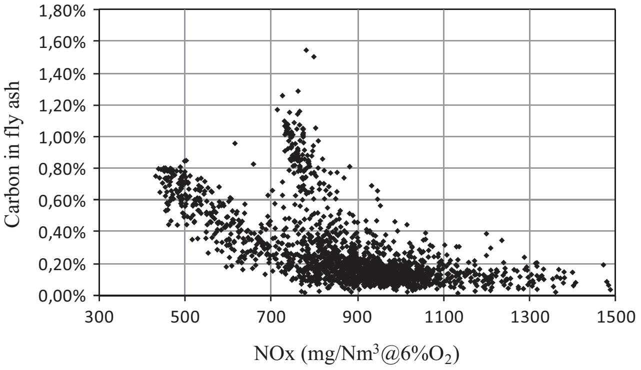

Fig. 14. Carbon in ash versus NO_x emissions.

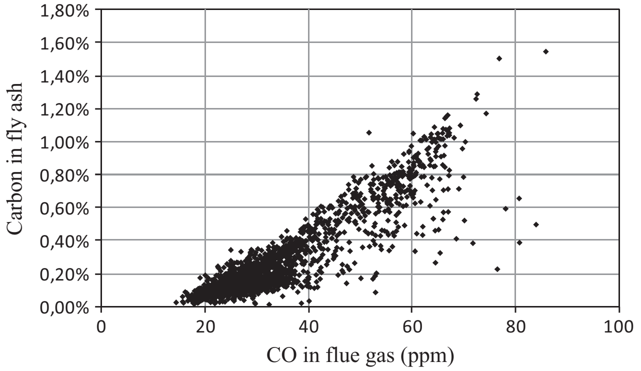

Fig. 15. Correlation between CO in flue gas and unburned carbon.

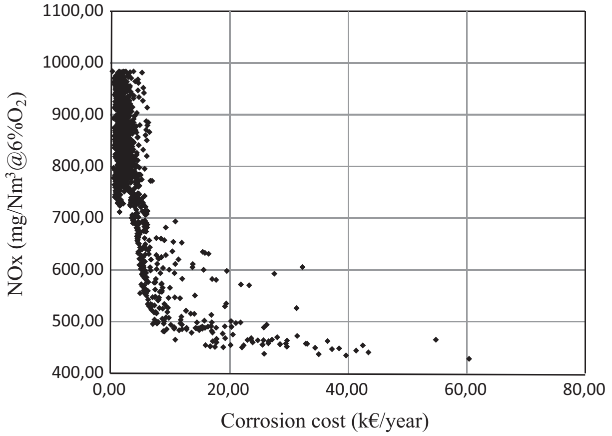

Fig. 16. NO_x emissions as a function of corrosion cost.

The boiler configuration used during the April 2011 campaign on the Le Havre 4 boiler (Table 8) with open nozzles FOO up, FOE and FGE at corners 2 and 4 is similar to individual No. 190

Table 7
Test campaign results for Cordemais 4 boiler.

Boiler	Cordemais 4					
Date	January 2012					
Coal fired	USA1					
Mills used	ACDE			ABCD		
Opened air registers	FOO up					
Burner tilt	30°	12–17°	−14° to 0°	30°	17°	6°
NO_x abatement	−5%	−30%	−40%	−20%	−50%	−60%
Carbon in ash	5%	5%	5%	5%	5%	5%
Corrosion risk	Low	Low	Low	Medium to high		

Table 8
Test campaign results for Le Havre 4 boiler.

Boiler	Le Havre 4		
Date	April 2011		
Coal fired	USA2		
Mills used	ABCDF		
Opened air registers	FOO up FGE	FOO up FGE FOE	FOO up FGE2/4 FOE
Burner tilt	+13°	+13°	+13°
NO_x abatement	−32%	−39%	−36%
Ammonia saving	−41%	−51%	−47%
Carbon in ash	4–7%	4–7%	4–7%
Corrosion risk	Low	Low	Low

simulated during the genetic algorithm (Table 6). This test shows that we can reduce 36% of the NO_x concentration compared to a baseline configuration (the simulation prediction was a 35% reduction) with a low corrosion risk (confirmed by the estimated corrosion cost given by the genetic algorithm). This trial also highlighted a 47% ammonia saving compared to the baseline configuration.

Moreover, during most trials the atmosphere near the walls has remained only slightly reducing, which prevented the risk of corrosion except in the January 2012 campaign where a deep air-staged configuration was used (mills A, B, C and D) for which high CO concentrations were measured in some parts of the walls.

Finally, during these test campaigns, the level of carbon in fly ash remained below the maximum value allowing ash recycling.

6. Conclusion

This work has been performed through close cooperation between different R&D departments, engineering department and the power plant engineers and operators. In this context, we successfully used a genetic algorithm to automatically generate innovative coal boiler configurations among thousands of CFD calculations performed. The genetic algorithm here has definitely helped identify unusual settings with quite complex opened nozzle patterns that could hardly have been found intuitively. The originality of the coupling between CFD calculations and a genetic algorithm to automatically generate at reasonable computational cost optimal boiler configurations must be emphasized here. However human expertise for the interpretation of the best results obtained is still necessary. Most configurations with high NO_x reduction are obtained using four mills distributing coal on the lower and middle group only and with a sufficient number of opened air nozzles to create air-staged combustion with reduced oxygen near the in-service burners. This type of configuration is very favourable to NO_x abatement, but at the same time it may generate a high corrosion risk for the boiler's walls. The cost function allowed the search space to be explored to determine configurations offering a good compromise between NO_x reduction and the cost associated with corrosion.

Using the database obtained from the simulations, we were able to obtain some interesting correlations between boiler settings and boiler output variables. The results corroborate the on-site observations made during test campaigns. Regarding the heat flux distribution on the water-wall tubes, the results obtained by the genetic algorithm confirm the more frequent peak temperatures on the water-wall tubes when the burners are tilted downward. As regards the NO_x emissions, one interesting result is that when the burners are tilted strongly upward, the NO_x level hardly drops below 900 mg@6%O_2. This observation was also made during test campaigns: at a given load, when tilting the burners in the upward position, the NO_x emissions tend to increase. As far as burnout is concerned, the genetic algorithm gives a typical result, i.e. an increase in unburned carbon when NO_x emissions are decreased.

A number of improvements can be made to the process described in this report. Firstly, we made the assumption that the metal water-wall tube temperature was constant throughout the boiler. Now, a thermo-hydraulic model for the tubes has been produced; it would therefore be useful to couple this module with the combustion calculation in the boiler to more accurately predict the metal temperature peaks for a particular boiler setting.

This work was carried out for a boiler at full load and for a given coal. Future work will include partial loads and the variability of fuels, since the NO_x level is highly dependent on the type of fuel used.

Finally, the cost function used here enables a simple assessment of the boiler configurations. However, estimating the associated costs can be tricky, indeed, because the cost function is global, a poor assessment on a single indicator can lead to a non-optimal solution. It would therefore be wise to replace the overall cost function with a multi-objective function able to identify solutions in several sub-search spaces.

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