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ABSTRACT

The present article describes the main aspects of the fundamental research carried out to evaluate and develop the most appropriate computer tools needed to help coal power plant operators to improve heat rates and limit NOx emissions. Work has specially focused on:

- Analysis and experimentation of new systems for characterising and monitoring the operation of boilers.
- Use of cutting-edge mathematical algorithms and development of new computer tools finally implemented into the optimisation system.
- Development of a brand new philosophy behind the modelling process.

The system is currently installed at Compostilla Power Station, belonging to ENDESA. Thanks to the recommendations of this novel approach, heat rate has been reduced over 1% and NOx emissions over 30%.

Keywords: software, optimisation, combustion
1 Introduction

At present, the majority of industrial facilities are equipped with control systems which, on the one hand, supply a great deal of information on what is happening in the plant, and, on the other, assure correct operation and production. However, these systems do not, in general, allow optimisation of the used resources. A better use of these resources would mean higher economic benefits for the companies and would favour the conservation of the environment.

In this context, and taking into account the increasing competitiveness among power plants, INERCO, a Spanish engineering and consultancy firm, has been researching a new approach to optimisation and developing a software package, named CESAR-SIRE; This system can help plant operators to improve heat rates and limit NOx emissions. This research has been carried out with the collaboration of ENDESA, the leading electric company in Spain, and AICIA, a research centre linked to the University of Seville. It has also been partially financed by the ECSC.

The work has focused not only on the evaluation and development of the most appropriate computer tools for the optimisation process, but also on the analysis and experimentation of new systems for characterising and monitoring the operation of boilers.

This article describes the main aspects of the research carried out to develop this system and its characteristics, with particular emphasis on the following aspects:

- General structure of the system.
- Activities related to the characterisation and monitoring of the plant.
- Philosophy behind the modelling process.
Mathematical and computer tools implemented.

Finally, the article describes the results obtained by the application of CESAR-SIRE at a full-scale Spanish power plant and INERCO’s future plans in the field of optimisation.

2 General structure of the system

The design of this new system is based on a new approach that has taken into account the following limitations of most optimisation programs (8):

- In general, from the modelling point of view, normally there is neither a profound previous characterisation of the facilities nor an adequate instrumentation to monitor the behaviour inside the boiler.

- With regard to the quality and response time of these systems, it should be noted that the optimisation and training process is not usually dynamic, and in addition there is no information on the quality and reliability of the recommendations obtained.

Additionally, the development of this type of system for a boiler is especially complex, for two reasons:

- In this type of facilities, an appropriate model requires the manipulation of a very high number of variables.

- In anticipation of future ecotaxes on emissions, optimisation should consider not only energy-related aspects, but also environmental aspects, which may have a negative effect on the plant economy.
These problems have already been resolved by other optimisation programs, namely:

- Gnocis, the EPRI/PowerGen neural network-based system
- Ultramax, the Pegasus system based on Bayesian networks

Now, INERCO proposes a new philosophy which relies on furnace specific monitoring systems and the computer architecture shown in Figure 1. According to this structure the system has a module known as CESAR (Figure 2), which is responsible for on-line calculation and monitoring, and which provides a reliable assessment of the unit’s performance. This module receives information from:

- operation signals,
- coal analysis,
- emission measurements and
- classifiers and dampers positions,

and from monitoring systems and instrumentation specifically installed for the optimisation process. The use of these specific measurement systems is one of the novelties of the new optimisation approach proposed by INERCO.

The CESAR module also includes an operating signal quality assurance system and the program libraries necessary for calculating the local and global parameters of the plant.

The other module in the system is SIRE (Figure 3). It advises plant operators on decision-making for optimised boiler settings. It receives information from CESAR or another similar
system and allows joint on-line optimisation of the performance/NOx equation for any boiler operating condition.

3 Prior activities related to the characterisation and monitoring of the plant

One of the main problems faced by optimisation systems is the suitability to the specific characteristics of the plant. In fact, the wide experience INERCO has in off-line optimisation programmes shows the need to apply this type of software only after having a prior in-depth characterisation of the plant operation (7).

To solve this problem, INERCO planned the development of a system based on previous information obtained from an off-line boiler optimisation programme. For this reason, before the adjustment and installation of the software, it was necessary to carry out a parametric test campaign to obtain a combustion diagnosis of boiler baseline conditions and an appropriate characterisation of all of the significant operating variables. This campaign included:

- A detailed study of the plant topology, including information on any operational and design peculiarities, fuel characteristics and available monitoring, instrumentation and software levels.
- An analysis of the operating parameters of the boiler, adapting the calculations needed to determine them.
- Analysis and study of operating modes.

In turn, this process made it possible to propose the additional on-line and off-line monitoring systems and instrumentation needed to improve boiler monitoring levels.
Figure 4 shows several examples of advanced monitoring systems implemented in an arch-fired boiler. These systems were installed on the basis of recommendations obtained from an off-line diagnosis carried out on one of the boilers of Compostilla II Power Station, belonging to ENDESA. As can be seen in the figure, the boiler was equipped with monitoring systems for the furnace, coal and air supplies and flue-gas at the boiler outlet.

1. With respect to the furnace monitoring, the off-line combustion diagnosis showed that the flame height in this type of boiler had considerable influence on plant performance and NOx emissions. In order to characterise the type of flame, two infrared pyrometers were installed, one in the ash hopper and the other at the end of the radiant area, thanks to which the computer system could detect the effects derived from this situation.

2. Another element-influencing performance was the imbalance level of gas distribution inside the boiler. Information on in-furnace imbalances was supplied by a novel monitoring system which allows the identification of local malfunctions at each burner. This information can be sent to the optimisation system for the evaluation of their effect on the overall plant performance.

3. In addition, it was shown that imbalances in air and coal supplies had an especially negative effect on the boiler performance.

Information on coal supply imbalances was obtained by a novel semi-automated pulverised coal sampling system, which provides reliable information on the coal flow to each burner.

To detect airflow imbalances, a windbox monitoring system based on fluid dynamic models was used. Taking into account that air supplies are not usually on-line determined in power
stations, these models allow CESAR-SIRE to predict the airflows to the furnace depending on the damper position.

4. Finally, to monitor the combustion flue-gas flow, meters were installed to determine the carbon in-ash and gas distribution at the boiler outlet.

A conclusion of the characterisation and adjustment phase is that without it, it would have been virtually impossible to determine what was really happening in the plant. Taking into account that the potential optimisation degree is directly related to the boiler available information, it can be stated that the performance of the computer optimisation system would have been very much lower without the described previous activities.

4 Philosophy behind the modelling process

During the development of the project, one of the fundamental aims was to design a system that could be automatically adapted to any boiler operating condition. This objective has been attained thanks to a new modelling philosophy based on the use of different partial sub-models and the calculation of reliability indices.

Firstly it is necessary to classify the measured and calculated variables in three levels:

- Collateral variables. They are not controllable by the operator but characterise the surrounding conditions of the plant, i.e. climate, market load demand, fuel characteristics, etc.
- Operating variables. They can be managed by the operator in order to optimise the operation of the plant. Examples are oxygen in the boiler (excess air), air distribution, etc.
- Target variables or functions. This group includes energy performance, NOx emissions and other target functions to be optimised: performance with a limit on emissions and the cost of the performance-ecotax equation due to emissions.

Taking into account this classification, the system makes use of different models based on different collateral variable ranges.

In other words, if we consider a bidimensional example (Figure 5) with the coal volatile content and the imbalance level as the normalised behaviour variables, there is no way we could find a single model to simulate all the possible boiler conditions with the same acceptable reliability level. To avoid this problem, the modelling approach divides the overall boundary into smaller sub-models just defined in those areas where the boiler has been operating, generating new sub-models as the boiler begins to operate in new regions of the control boundary. Additionally, all the creation and selection process is automatic and it is controlled by an uncertainty index, which is continually computing the suitability of each model to the facility conditions, and a control expert system which evaluates when a new sub-model must be created depending on the number of new tests detected in a new operating region.

Another novel aspect within the new modelling approach is its ability to dynamically monitor the optimisation process reliability. If we consider one of the models formerly defined by the behaviour variables, there will probably be an irregular distribution of the testing values. In Figure 6, this distribution has been shown by means of black dots. The variation between an actual value and the predicted value will be different depending on its location on the model boundary. In order to evaluate this difference, the system is continuously computing an index that reports on the differences of the model used at any time. Areas without dots will have low index values and therefore low reliability predictions must be expected. This index also informs the
training system about the need to make additional tests and criteria to select the ideal boundaries for testing.

In conclusion, thanks to these indices and the mentioned novel modelling approach, CESAR-SIRE has become an optimisation system with the following adaptability characteristics:

- Any boiler operating condition can be simulated simply by adding new partial models.
- The system is easily re-trainable simply by adding specific tests to the old or new models. This training process is controlled by on-line reliability indexes.
- The system can be applied directly to other boiler designs. In order to be adapted to a new facility design, CESAR-SIRE only requires an appropriate prior characterisation of the new plant.

5 Mathematical and computer tools

The selection and development of CESAR-SIRE mathematical and computer tools are the result of an intensive study of the nature and limitations of the problem to be solved: the dynamic optimisation of a highly non-linear process, with numerous variables involved, whose values are not always exact (6).

Cutting-edge computer tools and mathematical techniques have been used with the aim of obtaining a product that is robust, flexible, reliable, easily adaptable to different operating conditions and which gives on-line results. With respect to the software tools, the following points are of note:
The software for presenting and obtaining results has used the most recent releases of Microsoft’s Visual Basic and C++ compilers.

SQL was used to link the system to its ORACLE databases.

With respect to programming techniques, several Component Object Modules (COM) were created. They give the system the flexibility and modularity necessary for being adapted to different conditions and allowing for a possible future expansion.

With respect to computing techniques, different artificial neural network (ANN) topologies, genetic algorithms (GA) and fuzzy logic (FL) based on expert systems were used. Other modelling and optimisation techniques were rejected for different reasons:

- Fluid dynamic and statistical methods because of their inability to operate in real time.
- Simplex because they are unable to adapt to changing situations, they are highly sensitive to noise and are incapable of modelling complex non-linear problems.

Algorithms using ANN, GA and FL were designed by INERCO given the lack of modularity and versatility of existing commercial software. In addition, they were jointly used in order to improve their potential in those aspects in which commercial products have important deficits, such as the initialisation problem or the effective convergence of the algorithms.

The following are the most remarkable aspects of the algorithms used for the design and development of the CESAR-SIRE system:

1) First of all, different neural network types have been selected to model different boiler operating conditions.
For the boiler models of the optimisation system, a back propagation network was chosen. This type of ANN allows to simulate a process using a set of representative operation tests captured and pre-processed by the system. The learning algorithm generally associated with this type of network usually presents convergence control difficulties. This disadvantage has been solved by INERCO by adding:

- A new specific random number generator.
- A new algorithm that searches for the best starting point to improve the process convergence.

In addition, self-organising maps have been used as the ideal tool for signal filtering and quality assurance. A self-organising map is able to classify a set of patterns in various groups, each characterised by some property which can not be identified by simple statistical analysis. In this way, given a particular input pattern, the network is able to decide which class it belongs to and even filter the most probable values the pattern should have depending on the assigned group.

Figure 7 shows a diagram of the signal quality assurance module designed as a part of the project. As can be seen in this figure, the model uses different ways to validate the measured and calculated signals, replacing erroneous inputs with the expected correct values. Firstly, all the measured signals are fed into a neural network, which checks if any of the values is out of the range determined by the rest of the inputs. Afterwards the signals are passed through a second statistical and coherence filter to assure their goodness. Finally, a third statistical and coherence filter is applied to the calculated values.

2) Secondly, genetic algorithms (GA) have been chosen to look for boiler optimum operating conditions, using boiler models defined by neural networks.
3) Finally, expert systems based on Fuzzy Logic (FL) have been implemented and configured to control the optimisation process, evaluating and filtering those solutions out of the boiler critical operations boundaries.

6 Results obtained and future activities in the area of optimisation

At present, the CESAR-SIRE optimisation system is installed at Compostilla II Power Station, located in the north of Spain and belonging to ENDESA. So far, the system has been operating with off-line data from test campaigns. Thanks to its recommendations, heat rate at Compostilla Power Station has been reduced over 1% and NOx emissions over 30%.

Following this off-line data acquisition period, which has permitted the final adjustment of CESAR-SIRE, on-line operation is expected to start at the end of November 2000, after linking this system to Compostilla Power Station instrumentation.

With respect to the future optimisation activities to be carried out by INERCO, it intends to develop a new closed-loop version of the CESAR-SIRE system. The final aim is to achieve the on-line adjustment of the parameters that are critical for the combustion process. In order to reach this objective, the first activity will be to identify the critical variables and the range of reliable safe values inside which the parameters will evolve automatically.

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Figure 1. General structure of the CESAR-SIRE system

Figure 2. CESAR system: efficiency losses report
Figure 3. Optimisation module of the SIRE system
1. Temperature of gases (infrared pyrometers): Detection of height of flame

2. Monitoring of imbalance levels inside the boiler

3. Coal flow measurement

4. Wind-box monitoring system: Prediction of air flow supplies into the furnace

5. Carbon in-ash and gas distribution at boiler exit

Figure 4. Specific instrumentation for optimisation

Figure 5. Model scheme. Bidimensional example
INDEX \( \downarrow \downarrow \): The model needs new tests within this area

INDEX \( \uparrow \uparrow \): The model does not need new tests within this area

Figure 6. Reliability indexes. Bidimensional example

Figure 7. Scheme of the SACS system for signal quality assurance