Cost Reduction in Coal Fired Power Stations through Optimisation of Milling Systems

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ABSTRACT
This paper presents the methodology and results of the milling optimisation programme developed in several ENDESA pulverised coal (p.c.) power units. The scope of this programme includes the optimisation of the operation of different pulveriser designs (bowl and ball), consuming diverse coal types.

The ultimate objective of this programme is to reduce the operating costs and environmental impact of coal-fired power plants, in order to face out the increasing competitiveness of the electricity sector. In this sense, optimisation of milling systems has been revealed as one of the most effective strategies, since these systems consume around 1% of the energy produced in a thermal unit and are not normally fully optimised. Apart from this direct benefit, the control and adjustment of milling systems improves boiler efficiency and NO\textsubscript{X} emissions, providing also more stability and flexibility to boiler performance.

This approach for the optimisation of p.c. fired power stations has allowed to reduce pulverisers maintenance requirements, improve boiler performance and achieve overall reductions in unit heat rate of up to 1%.

Key words: optimisation, milling, monitoring, costs.

BACKGROUND
The present economic context for electricity generation of a thermal nature demands improved competitiveness. Given the cost of fuel, which is from 50% to 70% of the total, the most immediate way to achieve this higher competitiveness is by increasing the energy efficiency of the installations (Otero et al. (1999)).

This necessity has produced a prompt effect on fuel selection, acquisition and consumption, forcing operators to switch to fuels and operation conditions quite far from design ones. In addition, these installations must comply with more restrictive legislation concerning pollutant emissions.

As it is known, unit performance and generation of pollutants in industrial boilers depends largely on the correct distribution of fuel and air in the furnace. The existence of critical areas with an inappropriate air/fuel ratio will negatively affect these extremely important parameters. Widely used measures for controlling NO\textsubscript{X} emission are reductions of this ratio (Smith et al. (1992)) or the substitution of traditional burners by a new generation of low-NO\textsubscript{X} burners, resulting in combustion conditions to be characterised in detail.

This scenario, of changing operating conditions and procedures, suggests the development of a global optimisation approach far from the common routines currently applied in power stations. In this respect, it is also of note the up to now limitations about the adequate characterisation of milling system performance in p.c. power plants. This is particularly significant taking into account the direct effect of pulveriser adjustment on combustion optimisation.

OBJECTIVES OF THE OPTIMISATION PROGRAMME
General objectives are listed below:

- To improve the relationship between capacity, coal size distribution and electric consumption of milling systems, taking into account the ease of maintenance.
- To optimise the electric consumption of mills by means of modifications on working conditions, selection and re-design of elements, etc.
- To optimise the layout of primary air/coal feeding lines and the regulation of the fans, in order to reduce electric consumption and improve fuel distribution.
- To analyse the implementation of equipment for on-line measurement of air/coal flow to burners, as well as control of pulverised coal size distribution.
- To optimise the combustion and the net heat rate through the modification of coal size distribution, taking into account the characterisation aforementioned.
- To identify critical parameters having a decisive influence on mill performance.

These objectives could be summarised in the following goals:

- To develop an appropriate methodology for monitoring main parameters concerning air/coal supplies to burners.
- To optimise the distribution of coal and primary air between burners, correcting inherent imbalances due to design arrangement.
- To conciliate and evaluate the effects of the optimisation programme on boiler performance (efficiency, NO\textsubscript{X} emissions, and power consumption of auxiliary plant).

METHODOLOGY
Structure of the Optimisation Programme
Levels involved in the optimisation programme are shown in Figure 1. Optimisation of the milling systems could be achieved through different routes. The scope of the optimisation programme should include testing campaigns aimed to determine the appropriate adjustments for operation parameters. Nevertheless, in order to obtain worthwhile results, this optimisation programme must also involve activities focused on improving existing monitoring and software capabilities.
Scope of the Optimisation Programme

To achieve the mentioned objectives, the following activities have been undertaken:

a) Development of measurement procedures and advanced reference equipment for milling system characterisation and monitoring. Specific guidelines for the measurement of air supplies, coal flow and coal size distributions have been developed. Theoretical models and specific manual measurement methodologies for air systems have been considered to characterise primary air mass flow to each burner. In addition, meticulous coal sampling and quality assurance procedures have been defined to evaluate fuel mass flow and coal size distribution supplied to boiler. In this sense, it is normal to encounter in power stations imbalances of up to 30% in coal supplies to different burners (Rodríguez (2000)), which has an extremely negative effect on boiler performance and safety (Vetter and Gauntlett (1984)), nitrogen oxides emissions (Cañadas et al. (1997)), localised slagging and auxiliary power consumption. Evaluation and correction of these imbalances demand the development of improved monitoring equipment.

These procedures have converged in the definition of the EMIR technology, enabling an accurate characterisation of air/coal ratio imbalances in coal pipes. This technology entails an optimisation of the operating procedure for coal sampling carried out simply by the application of the reference Standards: ISO 9931 (“Sampling of powdered coal driven in systems of coal of direct fire”), ASTM D 197-87 (“Standard test method for sampling and fineness test of pulverised coal”) and ISO 10780 (“Measurement of velocity and volume flowrate of gas streams in ducts”).

Characterisation of air/coal supplies to boiler is an extremely delicate activity requiring an important level of specialisation and experience to obtain valid results and avoid adoption of wrong decisions based on inaccurate measurements, if appropriate tools are not available.

The application of the EMIR technology has been based on the development of automatic coal-to-burners sampling equipment: EMIR II (Figure 2). Sampling procedure carried out with this reference system entails an optimisation of the reference procedure defined by current Standards (ISO, ASTM), by means of a severe control of all sampling parameters having a significant influence on coal/air mass flow and coal size distribution.

- Inclusion of an additional dust filter enabling a higher efficiency in coal sampling.

Optimisation of conventional reference methods has been focused on the following aspects:

- Automation of the sampling procedure reducing to the minimum operating error and stringently controlling sampling parameters, resulting in significant repeatability increase (Figure 3).
- Optimisation of sampling period (4 minutes).
- Optimisation of nozzles diameter (5 mm).
- Cyclone heating during sampling period avoiding agglomeration phenomena affecting coal size distribution results.

Figure 2 – Coal/air flow to burners characterisation by EMIR II

- Increase of measurement points within sampling section reducing roping effects (coal segregation phenomena, Figure 4) due to flow disturbances and optimising coal mass flow representativeness.
- Severe control of isokinetic conditions. Air/coal sampling separated from isokinetic conditions could lead to serious mistakes and misconceptions that would not help to solve possible imbalances or operating problems (Figure 5).

Figure 3 – Comparison Non Optimised ISO 9931 Method – EMIR Technology

Figure 4 – Measurement points and coal segregation phenomena

Figure 5 – Influence of isokinetic conditions on mass of coal sampled
Coal sampling without considering a meticulous control of the above mentioned parameters, especially isokineticness, can result in deviations from the real value over 14% for the coal mass flow and up to 13% for coal size distribution. 

b) Development of specific testing campaigns. Improvement programmes applied to milling systems by plant operators are not usually as beneficial as expected. The development of an optimisation programme involves the design of testing campaigns specifically prepared for identifying critical improvement elements and corrective actions to be undertaken. All the parameters implicated in mill operation must be controlled and registered, and exhaustive characterisation of mill performance and effects on combustion has to be carried out.

Development of these testing campaigns should be carried out according to the factorial analysis methodology and considering three sequential levels:
- Initial diagnosis of milling system.
- Tests of parametric sensitivity.
- Long term confirmation tests.

The objective of the initial diagnosis is to determine the reference conditions which will be used as the basis of comparison throughout the optimisation process. At the same time possible imbalances or malfunctions are identified. Tasks developed within this level aim at the characterisation of typical values of air and pulverised coal flow to burners, including pulverised coal size distribution, by using manual measurement methods. In addition, essential direct results are obtained by means of the following activities:
- Validation of existing instrumentation.
- Correlation of process signals (air or coal flows) with manual measurements.
- Base case characterisation and imbalances identification for stable conditions in the milling system obtained by manually controlling mill operation.

Second set of tests, tests of parametric sensitivity, aims at the identification of mills optimum settings by modifying the main operating parameters identified in previous stages of the optimisation programme.

Finally, objectives of long term tests are to assess the modifications of long term variation parameters on mills performance, to consolidate definitive results confirming that optimum conditions are maintained properly and to evaluate the effects of mills optimum settings on combustion conditions.

c) Implementation of advanced software for operation optimisation. In a following stage, integrated with developed advanced monitoring, specific software tools for providing on-line reliable evaluation of unit performance have been developed. The improvement of existing monitoring and its integration with appropriate control software tools entails a valuable development line already considered within the scope of the optimisation programme.

As a final stage of this methodology, implementation of specific software for advising plant operators in the decision-making process of establishing optimised adjustments has been considered.

Industrial Scenarios for Tests Development

The development of a wide-scale optimisation programme requires covering a broad spectrum of technological configurations. This point is considered to be a key factor for the successful execution of the optimisation programme and for obtaining worthwhile results. In this sense, different ENDESA pulverised coal units have been considered, with significant differences in coals consumed (bituminous, anthracite and lignite), boiler design (arch, tangential, front-wall), milling system design (bowl and ball pulverisers, adjustable and non adjustable classifiers) and operating/maintenance conditions.

The main development of the general optimisation programme has been achieved through preliminary stage. Similarly, the most relevant methodological results obtained in this stage are currently being applied to bowl mills, as a way of extending the optimisation approach.

Specific strategies for the optimisation of each utility have been developed through milling system performance improvement.

RESULTS

Ball Milling System Optimisation

Preliminary characterisation of baseline conditions. Practical aspects of milling system operation for achieving an adequate combustion development are basically associated with a well-balanced coal and air distribution to burners. In this sense, coal and air distribution must be within the range of ±5% ±10% burner to burner in order to ensure a balanced combustion process (Storm (1993)). Malfunctions in normal operation of milling systems, regulation of air flow and maintenance policies are normally associated with an unbalanced coal and air distribution, and therefore to a lack of combustion efficiency (Schleijting (1995); Vetter and Gauntlett (1984)).

The identification of these typical imbalances in 4 ENDESA p.c. units (Units 1 to 4) with double-ended ball tube mills has been carried out. Base-reference situations and capabilities of optimisation of the different milling systems selected have been identified by means of these preliminary diagnoses, constituting an essential first step for the later optimisation of these systems.

Initial characterisation of primary air systems (primary airflow distribution, pressure drops, capacity of regulation, etc.) and pulverisers performance (coal production, size distribution, power consumption) has been carried out in the aforementioned units. This work has been developed through both theoretical approach (empirical modelling of air systems) and experimental approach (manual measurements of primary air and pulverised coal to burners).

a) Theoretical approach. Modelling of primary air system with real operating data has been carried out at Unit 1. Fluid-dynamic studies of primary air flows and pressure drops in ducts and flow regulation elements have been undertaken for normal operating conditions of this unit (full load (330 MW), 5 mills in service and typical impulsion conditions of Draft Forced Fans and Primary Air Fans).

Within this analysis the possibilities of regulation/reduction of pressure drops in ducts and the optimisation of ducts layout have been evaluated. Besides, the capabilities of regulation and control of Primary Air Fans (P.A.F.) and Force Draft Fans (F.D.F.) and revamping necessities have also been assessed.

As a result of this analysis the following adjustments strategies for reducing pressure drops and decreasing auxiliary consumption have been established:
- Adjustments of fan operation have been proved as the best air flow regulation strategy, using air dampers as compensation elements. This control strategy enables a reduction of pressure drops at air dampers, reaching electric savings of up to 110 kW.
- Effective regulation capacity of air dampers has been established for damper openings between 40% and 60%.
- Existing fans (Primary Air and Forced Draft Fans) were working far from design conditions. Replacement of the existing fans by others with design conditions closer to real operating conditions has been evaluated. This substitution enables an increase in fans efficiency of up to 20% (from 50% to 75% for F.D.F. and from 60% to 80% for P.A.F.), with reductions in power consumption of up to 900 kW.
- Possibility of replacement of Forced Draft Fan engine was evaluated for an extra efficiency increase of 5% in this utility (substitution from 740 rpm engine to 600 rpm engine). Potential power consumption reductions are up to 110 kW.

As a general result of this approach, the optimisation of primary airflow systems at ball mills p.c. units has been proved essential for the later optimisation of overall milling system operation. In particular, potential reductions in fans power consumption of over 10% were identified by the application of these measures to the specific design and operating conditions of Unit 1. Additional reduction of fans power consumption of up to 25% could be obtained in this utility by revamping of Primary Air Fan and Forced Draft Fan.

b) Experimental approach. Different preliminary tests have been carried out at Units 1 to 4, establishing normal operating conditions of primary air and milling systems and identifying typical imbalances and capabilities of optimisation. In particular, manual measurements of primary air and pulverised coal flows...
Specific primary air tests defined with this scope have been carried out. As a result of these trials, existing airflow measurement systems have been validated and calibrated. In this sense, correlation between primary air control signals (%) and real air flow obtained by manual measurement (Nm/h) were established for a reliable on-line characterisation of the distribution of mill air in these Units (Figure 6).

![Figure 6](image)

**Figure 6 – Calibration of primary air flow measurement systems (Unit 3)**

Important differences in air mass flow for the same control signal were determined between mills. Differences of up to 50% were identified.

The possibility of balancing primary airflow distribution to boiler was evaluated by means of the correction of the existing control strategies with the implementation of the primary air correlations obtained for each pulveriser. Modifications in primary air control loops were carried out in Unit 1, obtaining significant improvements in primary air distribution.

Contrary to other grinding systems, in double-ended ball tube mills, firing performance is not controlled via mill feeder but via the air flowing through the mill, and therefore coal throughput is directly related to primary airflow to the mill. In this sense, reliable procedures for on-line identification of coal mass flow through primary airflow characterisation were developed. Correlations between coal mass flow and inlet primary airflow were obtained for each mill tested. Proportional and direct correlation between coal and air were determined for the specific milling conditions of the tests, resulting in high correlation indexes (Figure 7).

![Figure 7](image)

**Figure 7 – Coal mass flow vs. primary air flow correlation (Unit 3)**

This feature implies that the air/coal ratio leaving the grinding chamber for a specific ball pulveriser always remains constant, whenever milling conditions do not change (linings, wear, ball recharge, coal characteristics, etc.) (Gehrke and Fontanille (1991)). However, substantial differences in these relationships between mills of the same unit were detected. Important differences in coal mass flow between mills were identified within these tests for the same primary air regulation per pulveriser (associated with normal combustion control strategies usually implemented in ball mills power plants).

Typical maximum imbalances (deviation from average value) detected in air and coal distributions between mills for Units 1 to 4 at full load stable operation are shown in Figure 8. Differences of up to 30% and 50% have been identified for coal flow and air/coal ratio between mills. These imbalances were directly related to the aforementioned discrepancies between the theoretical balanced control strategy and the real performance of air and milling systems existing in the tested units.

In addition to this general analysis of mill performance, individual burners analyses for each mill were carried out. In this sense, great differences were detected in coal mass flow between burners of a same mill, identifying maximum imbalances of up to 50% (Figure 8).

![Figure 8](image)

**Figure 8 – Typical coal and air imbalances in ball milling systems**

Pulverised coal size distributions were also determined within these preliminary tests. Four different particle sizes were measured for coal sampled from ducts to burners (325, 200, 170 and 100 mesh), and corrections according to International Standards and adjustments to Rosin-Rammler were carried out. Differences of up to 10% through 200 mesh were detected between burners.

The contrasted influence of these air and coal imbalances on auxiliary consumption should be remarked on. Effects on specific mill power consumption (kWh/t), directly related to mill production, have been evaluated. Differences between mills with initially the same performance of up to 27% have been identified.

These preliminary diagnoses have additionally allowed the identification of unbalanced combustion conditions for normal operation of the 4 industrial pulverised coal units selected. High capacity of combustion optimisation was identified in these utilities through air and milling systems adjustments.

Identification of critical parameters. Based on results of preliminary characterisation tests, a great deal of tests were defined and carried out in 4 industrial p.c. units (Units 1 to 4) for the identification of the fundamental parameters that condition ball mills performance. More than 250 milling tests were developed for two different double-ended ball mill designs with two different classifier system designs (adjustable and non adjustable). Through these trials main operating and maintenance parameters for grinding adjustments in ball mills have been identified. Evaluation of the effects of these critical parameter modifications on mills performance has been carried...
out, determining the influence on coal size distribution, coal mass flow, airflow requirements and power consumption.

With the aforementioned scope, the tests that were developed can be classified in two different stages: parametric sensitivity tests and long-term tests.

a) Parametric sensitivity tests. More than 150 short-term tests have been developed in order to identify critical parameters of the operation of ball pulverisers. On the basis of design and operational specifications of these types of pulverisers, specific tests were carried out for the evaluation of the effect of the following fundamental parameters on mill performance:

- Type of fuel consumed: moisture and grindability (i.e., Hardgrove Grindability Index).
- Primary air flow to the mill.
- Temperature of inlet primary airflow.
- Pressure of inlet primary airflow.
- Classifier adjustments.
- Mill coal level.
- Mill outlet airflow temperature (air-coal mixture).
- Mill outlet airflow pressure (air-coal mixture).
- Differential pressure of primary air-coal flow inside the mill.
- Speed of raw coal feeder.

An accurate methodology based on parametric sensitivity analysis for each mill was applied. In this sense, parameters were initially modified one-to-one, with the rest of the mill operating variables remaining constant. Modifications on mills operation were developed withdrawing the mill to be tested from the general control loop.

Parameters that have been proved to have a more relevant influence on mill performance (pulverised coal flow and size distribution, and mill power consumption) can be summarised as follows:

- Coal characteristics: moisture and grindability (Hardgrove Grindability Index).
- Primary air temperature to the mill.
- Classifier adjustments.
- Primary air flow to the mill.

The first two parameters, closely related to grinding conditions, are directly defined by unit operating conditions and external imperatives, and therefore cannot be continuously modified for on-line milling condition adjustments. Nevertheless, characterisation of the effect of these variables on ball mills performance must be taken into consideration for the definition of the best adjustment strategies at each grinding condition.

Specific tests for the characterisation of milling conditions under the modification of these grinding variables have been carried out in Units 1 to 4. Some of the main results achieved in this sense, and that should be remarked on, are:

- A reduction in the Hardgrove Grindability Index (H.G.I.) of the fuel fed to the mill has been proved to cause a decrease in coal flow with a non-significant effect on coal size distribution. Reductions of up to 10% of mill production were detected for the modification of the type of fuel consumed from high H.G.I. (60, coal) to low H.G.I. (35, coke).
- An increase of raw coal moisture seems to cause a light benefit in coal size distribution (increase in coal fineness), with a non-significant effect on coal mass flow. Necessities of primary airflow highly increases with coal moisture, due to the requirement of coal drying.
- Primary air temperature to the mill has been proved to have a significant effect on both coal flow and particle coal size distribution. Results of these tests are presented in Figure 9. As a consequence of temperature rise a significant increase in coal fineness, with a higher requirement of primary air flow to keep the mill coal mass flow constant. Variations detected in this sense depend on the mills where tests have been developed, since milling conditions (wear, coal, primary air temperature, etc.) vary from mill-to-mill. In Figure 10 results of tests for three different blades positions (open: 45%; medium: 60%; closed: 65%), carried out in mill 1 of Unit 1 are presented. With the modification of classifier positions from 45% to 65% up to a 5% increase in passing through 200 mesh (from 90% to 95%) and 0.8% reduction on 100 mesh (from 1% to 0.2%) were obtained. A 15% increase of airflow requirements was produced for keeping coal mass flow in a typical mill production of 27 t/h (w.b.).

The other two parameters presented with significant influence on mill performance (classifier adjustments and primary air flow) have been proved to enable on-line effective adjustments of milling operation, both in coal flow and particle size distribution. The influence of classifier adjustments on mill performance was evaluated through several tests in which blades positions were modified (closed / open) and primary air flow was varied for the different classifier positions tested. As a general tendency of these tests, closer classifier positions have been proved to cause a significant increase in coal fineness, with a higher requirement of primary air flow to keep the mill coal mass flow constant. Variations detected in this sense depend on the mills where tests have been developed, since milling conditions (wear, coal, primary air temperature, etc.) vary from mill-to-mill. In Figure 10 results of tests for three different blades positions (open: 45%; medium: 60%; closed: 65%), carried out in mill 1 of Unit 1 are presented. With the modification of classifier positions from 45% to 65% up to a 5% increase in passing through 200 mesh (from 90% to 95%) and 0.8% reduction on 100 mesh (from 1% to 0.2%) were obtained. A 15% increase of airflow requirements was produced for keeping coal mass flow in a typical mill production of 27 t/h (w.b.).

Furthermore, replacement of non-adjustable classifiers by adjustable ones of higher efficiency was carried out in mills of Unit 1. In Figure 10 data from trials with non-adjustable classifiers (previous classifiers) are also presented. Significant improvements in coal size distribution per mill (up to 10%) were achieved by the substitution of the non-adjustable classifiers by the adjustable ones (a value that varies from mill-to-mill).

Feasibility of replacement of the non-adjustable classifiers by adjustable ones in all the mills of Unit 1 was evaluated under normal operation of this utility. Mill pressures, before and after the substitution of classifiers, are shown in Figure 11 as a
pressure drops for the same primary air flow conditions. Nevertheless, higher classification introduced by these new systems produced higher rejection of coal per mill, increasing not only coal fineness but also primary air flow, and thereby pressure drops for high classifier adjustments (i.e. 65% of blades positions).

The substitution of classifiers produced a reduction in pressure drops for the same primary air flow conditions. Nevertheless, higher classification introduced by these new systems produced higher rejection of coal per mill, increasing not only coal fineness but also primary air flow, and thereby pressure drops for high classifier adjustments (i.e. 65% of blades positions).

Therefore, operating conditions of the unit were modified as a consequence of the classifier substitution. Different adjustments in mills and boiler operation were assessed and a new operating point was established. Total power consumption of fans did not significantly change for the same coal requirement in this new situation, but with higher capacity of coal fineness regulation by classifier adjustments. This higher capability of milling regulation enabled not only to optimise coal size distribution for an efficient combustion, but also to give the flexibility for the implementation of milling optimisation strategies based on both ball recharges and classifier adjustments.

In order to characterise the capability of regulation of these operating parameters, milling tests combining modifications on both classifier blades positions and primary air flow through the mill were developed in different mills with adjustable classifiers. Different adjustment maps were defined for each mill under constant milling conditions (Figure 12). This type of regulation brings forth the capability of improving coal size distribution by classifier adjustments and at the same time controlling coal mass flow through primary airflow requirements.

As a result of these trials, internal mill performance has been proved to be a critical parameter that should be taken into account for milling condition characterisation. In this sense, for the same global milling conditions (93 A), but with punctual ball recharge (that implies a temporal evolution of ball size distribution), a clear increase of primary air flow requirement of up to 13% has been observed for the same mill production. Nevertheless, non-substantial effects on coal size distribution have been produced by these ball recharge strategies, with light increases in coal fineness (variations below 2% for passing through 200 mesh, and far less for coal coarses). Other different types of ball recharges were also assessed in these mills. In particular, continuous ball recharges (instead of long term recharges) were used in order to achieve a more constant operation of the mills.

Specific tests were carried out for more than half a year to study mill performance under different ball-ball-charge. In these trials, continuous operation of ball mills without ball recharge was assessed, decreasing balls mass inside the mill by “natural” ball wear and reducing mill intensity consumption progressively from 106 A to 89 A.

**Figure 11** – Pressure drops for non-adjustable and adjustable classifiers (Unit 1). Icon indicates operating conditions for 27 t/h coal flow rate (w.b.)

**Figure 12** – Capability of classifiers adjustments (Unit 1)

**Figure 13** – Liners and ball recharge effects on mill performance (Unit 2; 25 t/h of coal per mill, d.b.; 93 A)

b) Long term effects tests. More than 100 tests for the evaluation of the influence of mill internals on grinding conditions of double-ended ball mills, and therefore on performance, were carried out. In particular, the effect of the following specific parameters on milling conditions were evaluated within these trials:
- Three different types of liners (1, 2, 3).
- Two different types of balls (1, 2).
- Liner wear.
- Balls wear.
- Strategy of ball recharge: punctual and progressive.
- Ball size distribution (three sizes: 50, 32 and 25 mm).

These trials were developed in ball mills of Units 2 and 3 during a long period of time. In this sense, milling conditions were periodically monitored for more than one year in order to determine the effect of the aforementioned parameters on mills performance. The main results of these trials are presented below:

- Ball size distribution inside the mill has been proved to be a critical parameter with considerable influence on mill performance, since the milling process is altered by the modification of shearing and collision components of grinding. Ball size distributions have been modified by means of different ball recharge strategies (mainly type of balls, type of recharge and ball size).

In Figure 13 primary airflow requirements and coal size distributions are presented for nominal coal mass flows of mills of Unit 2 (25 t/h, d.b.) in two different in-mill ball size distributions. The two situations presented (reference and final conditions) are associated with the same balls mass inside the mills (corresponding to 93 A of intensity), but with a difference of time between tests of 8 months (punctual recharge), which implies a wear on balls and therefore different ball size distributions inside the mills.

Results for different types of balls and liners are shown.
Variations in coal size distribution and primary air flow requirements for the maintenance of mill production at nominal value were monitored for the different balls charges tested. In Figure 14 typical mill performance under three punctual situations of balls charges (102 A, 95 A and 89 A) is presented.

As a direct result of the reduction of mill-ball-charge a decrease in coal fineness was detected. Reductions within 0.04 to 0.17% through 200 mesh per ampere were determined (Unit 3).

In addition to this, primary air flow requirements for the maintenance of mill production tended to increase when mill intensity was reduced. Increases detected in these tests were between 235 and 504 Nm/h·A, depending on the specific mill tested. Therefore, a reduction in mill intensity produced a slight increase in primary air power consumption (Figure 15). Nevertheless, total auxiliary power consumption, associated with mills and fans, was reduced, basically due to the enormous reduction produced in mill consumption (Figure 16).

Definition of adjustment strategies. Different control and adjustment strategies were defined for optimum operating points determination of ball milling systems in the selected pulverised coal units.

Due to the proved capacity of regulation that classifier adjustments and ball recharges (mill intensity) have been proved to have on mill performance, combined adjustments strategies of these two parameters have been defined.

The adjustment strategy finally defined for ball mill performance optimisation can be summarised in the following four steps:

- Identification of minimum coal fineness requirement for an efficient combustion.
- Identification of primary air fans capacity (primary air flow requirement per mill).
- Regulation of mill intensity for the optimisation of mill power consumption reduction.
- Adjustment of classifier position as compensation of mill intensity regulation, in order to attain “coal fineness – fans capacity” requirements.

In addition to this, it is of note that the number of mills in service can be optimised for each particular operating condition of each utility. In this sense, the aforementioned adjustment strategy can be parameterised as a function of mills in service, reaching an optimum point of milling system and combustion process operation.

Specific boiler performance trials were carried out to evaluate the effect of different air and coal flow distributions and coal size distributions to burners on the combustion process. Capability of operation with different number of mills in service at full load was also assessed.

Cases matrix that summarises conditions of the specific tests developed in this sense at Units 2 and 3 (arch-fired) is presented in Table I. Main parameters that have been modified, as well as the different values of these modifications are shown in this table.

Capacity of the Data Acquisition Systems (D.A.S.) of these units was assessed in order to compile necessary operating and performance parameters during the trials. In this sense, different data sheets were defined. In each test the following parameters were collected from the D.A.S.s for the correct evaluation of the tested conditions:

- Mills operating conditions: primary and secondary air flow, primary and secondary air temperatures, mill outlet temperature, mill air inlet pressure, etc.
- Boiler efficiency.
- Unburnt coal losses.
- Steam attemperation flows.
- Power consumption of auxiliary systems (milling systems, P.A.F., F.D.F., I.D.F. and electrostatic precipitator).
- Unit heat rate.

<table>
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<tr>
<th>Parameters</th>
<th>Values</th>
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<td>O₂ (boiler exit section)</td>
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<td>BASE</td>
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<td>S.A. Distribution</td>
<td>BASE</td>
</tr>
<tr>
<td>T.A. Distribution</td>
<td>BASE</td>
</tr>
<tr>
<td>Horizontal distribution of air</td>
<td>BASE</td>
</tr>
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<td>Mills in service</td>
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<tr>
<td>Burners out of service</td>
<td>4 MILLS</td>
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<td>Mill Intensity (A)</td>
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<td>Hours after sootblowing</td>
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</table>

Table I – Cases matrix of optimisation tests (Unit 2 & 3)

Analysis on milling system performance and combustion development has been carried out for these situations, assessing
the effects on combustion imbalances, slagging, flames distribution and stability, boiler efficiency and NO\textsubscript{x} emissions.

Results of the tests related to the effect of milling system operation on auxiliary power consumption and combustion processes are presented below (Figure 17):

- In these utilities “5 mills in service” is the design specification for full load (350 MW) operation. Capability of full load stable operation with 6 and also 4 mills in service by means of mills operating and air distribution adjustments was demonstrated.

- Mill intensity was reduced in Unit 3 from the design value of 106 \text{A} to 89 \text{A}, for 5 and 6 mills in service. Feasibility of stable unit operation under this new situation was evaluated by continuous monitoring of mills and boiler performance. Capacity of stable operation at full and variable loads was demonstrated, with auxiliary power consumption reductions of up to 10-15%.

- Reduction in total auxiliary power consumption was achieved in Unit 2 by reducing the number of mills in operation. Reductions of up to 7% and 11% (compared to reference case with 6 mills, 103 \text{A}) were achieved for 5 and 4 mills in operation with a milling system intensity consumption of 103 \text{A} and 110\text{A}.

Due to the fact that the classifiers of these mills were non-adjustable, operation with 4 mills needed a mill intensity of 110 \text{A} in order to maintain fans capacity for the type of coal consumed (high moisture). In this sense, utilities with adjustable classifiers will have the capability of controlling primary air requirements by classifiers regulation. Therefore, in these latter systems, operation with lower mill intensity could be established, providing higher reductions in power consumption.

- Flames geometries have been proved to be significantly modifiable as a function of the number of mills in service for arch-fired boilers. In this sense, reduction of operating mills in Unit 2 (from 6 to 5 to 4) produced an increase in air-coal velocity in ducts to burners, causing longer flames (burning coal in lower furnace regions). This arrangement of combustion enabled a reduction in NO\textsubscript{x} emissions of up to 30% (650 mg/Nm\textsuperscript{3}) for the operation with 5 and 4 mills in service, and without boiler efficiency losses or even with an improvement in this parameter.

- As a result of these trials, optimum units operating conditions were defined for each number of mills in service, optimising ball recharge and air distribution to boiler. In this sense, oxygen excess was also modified in order to optimise the operation with a different number of mills in service. Improvements of units heat rate of up to 1% were reached by these adjustments.

Preliminary characterisation of baseline conditions. Tests at 4 different pulverised coal power units have been developed in order to determine base milling conditions (primary air and coal interrelations), capabilities of optimisation of these systems and critical parameters with significant effect on bowl mills performance.

In particular, manual measurements of primary air and pulverised coal flows have been carried out according to the specific sampling tools defined within this optimisation programme (coal sampling methodologies and procedures, and specific coal sampling equipment, EMIR II).

Specific primary air tests have been developed for the validation and calibration of the existing airflow measurement systems (correlation between primary air control signals (%) and real air flow obtained by manual measurement (Nm\textsuperscript{3}/h)).

Coal mass flows under different operating conditions were determined by manual measurements. Correlations between coal mass flow and r.p.m. feeder control signal (%) were obtained for each mill. Proportional and direct correlations between real value and control signal were determined for this specific mill design, resulting in high correlation indexes (Figure 18).

As a result of this determination, air/coal ratios leaving the grinding chamber for this specific pulveriser design have been proved to be variable with mill production. In this sense, the highest air/coal ratios have been determined for low mill operation (low mass flow), decreasing with mill production. Variations of these ratios with mill operation have also been established, being different for each unit. Furthermore, substantial differences in these relationships between mills of the same unit were detected.

Differences of up to 47% and 50% have been identified for coal flow and air/coal ratio between mills. Air/coal ratio average values vary from 4 to 1.8. These typical imbalances are far from the optimum values (1.7 to 2.1) specified by different bibliographical references (Scott (1995); Smith (1992)).

Related to individual burners analysis per mill, high differences were detected in coal mass flow between burners of a same mill, identifying maximum imbalances of up to 38%.

Pulverised coal size distributions were also determined within these preliminary tests. Differences of up to 16% and 23% were detected for fine particles (through 200 mesh) between mills and between burners of a same mill.

Identification of critical parameters. On the basis of design operational specifications of these types of pulverisers and on results of preliminary characterisation tests, a great deal of tests are being carried out for the evaluation of the effect of the following fundamental operating parameters on bowl mill performance (coal mass flow, coal size distribution and power consumption):

- Type of fuel consumed: moisture and grindability (Hardgrove Grindability Index).
- Primary air flow to the mill.
- Temperature of inlet primary airflow.
- Pressure of inlet primary airflow.
- Classifier adjustments.
- Mill pressure drops.
- Mill outlet flow temperature (air-coal mixture).
- Mill outlet flow pressure (air-coal mixture).
- Pressure of primary air-coal flow inside the mill.
- Speed of raw coal feeder.
- Grinding pressure.

By means of these tests, important results relating to efficient adjustments of milling conditions for bowl mill design are being obtained, evaluating the optimum operational and maintenance points of these systems.

New technologies based on vibration analysis of mill performance are being developed at present. Feasibility of application of these technologies to bowl mills diagnosis are also being evaluated, defining and carrying out different specific tests at those full-scale power plants.

CONCLUSIONS AND PROSPECTS

The optimisation programme described in this paper has enabled to develop a solid general methodology for the improvement of mill operation in coal-fired power plants. The main results and achievements of this optimisation programme can be summarised as follows:

- Development of a specific technology and reference equipment (EMIR II) for a more accurate and easier characterisation of coal and air supplies to the boiler.
- Definition of a precise quality assurance system for validation of results obtained by the aforementioned technology.
- Evaluation of reference or manufacturer’s adjustments for the milling/air system maintenance and operation. These references have been proved to be far from the optimum conditions in most of the cases analysed. Optimum settings for milling systems have been demonstrated to be highly specific at each overall operating condition. Particularly, these adjustments need to be assessed in cases of significant modifications on coal supplies, mill maintenance state, or boiler load profiles.
- In the specific cases studied, reductions in mill energy consumption of up to 10% have already been achieved, with potential reductions in fan consumption of over 25%. Furthermore, reductions in unit heat rate of up to 1% have been reached by milling and boiler adjustments, with significant reductions in NOx emissions (up to 30%).
- A general strategy for the continuous optimisation of milling system operation has been defined, combining the joint monitoring and control of the milling and combustion processes, and providing higher operation flexibility.

Additionally, the following new approaches for on-line characterisation, diagnosis and control of milling process are also being carried out, as a complement to the optimisation activities already presented:

- Development of novel coal flow regulation devices of low pressure loss and limited maintenance.
- Development of specialised software tools for milling system optimisation, by providing on-line reliable evaluation and advice to plant operators.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the collaboration of the other INERCO, AICIA and ENDESA personnel involved in activities resulting in this paper. This work has been carried out with a partial financial grant from the European Coal and Steel Community.

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