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NO_x REDUCTION IN ARCH-FIRED BOILERS BY PARAMETRIC TUNING OF OPERATING CONDITIONS

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Abstract

This paper presents the results of a research project whose objectives are to investigate the parametric sensitivity of boiler operation in relation with NO_x generation and heat rate, and to fine tune operating conditions to minimize NO_x emissions. The project is included in the European Coal an Steel Community Research Programme and was performed in arch-fired boilers burning low-volatile coals. Research was mainly composed of sets of in-field tests designed following the factor analysis methodology. Testing procedure included a complete survey of the experimental units operation with measurement of coal flow and size distribution to burners, furnace temperatures, in-flame gas composition profiles, and on-line boiler efficiency and unit heat rate monitoring, amongst others.

Results revealed a strong sensitivity of NO_x to operational parameters and deep differences between boilers of similar technology. NO_x emission reductions greater than 30% have been documented, exploring non-conventional boiler settings without penalizing or even increasing unit efficiency.

1. Introduction

A large proportion of the coal produced in the mining regions of the North of Spain are anthracites and other low-volatile coals. More than 3,500,000 tons/year of this coal (Volatile matter: 7.2%; N: 1.0%; Ash content: 33.5%) is burnt in the five arch-fired units of Compostilla Power Station (ENDESA).

Arch-fired furnaces (Figure 1) are designed for the industrial firing of low-volatile coals, as they provide a solution to problems arising due to the low ignitability and combustibility of these fuels. The characteristic high temperature levels and residence times of these combustion systems, as well as the higher char/volatile ratio of low-volatile coals, produce higher levels of NO_x emissions than bituminous coal firing. NO_x emissions values in the range of 1800-2000 mg/Nm^3 (d.b., 6% O_2) have been reported for different Spanish arch-fired boilers, such as Compostilla Units 4 & 5.

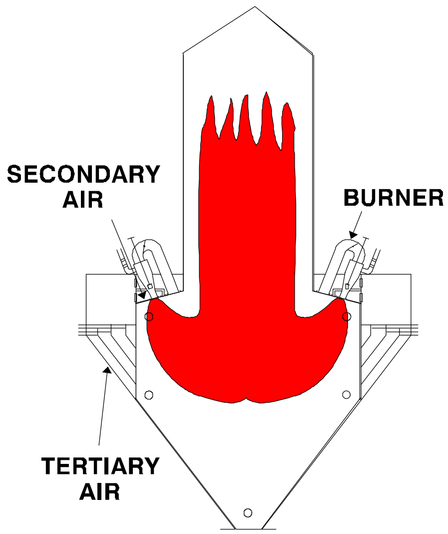

Figure 1: Arch-fired boiler

Although there is no current restriction for NO_x emissions in existing installations of this type, a limit of 1300 mg/Nm^3 (d.b., 6% O_2) is thought to be applied in the future. Commercial solutions for this oncoming problem with NO_x emissions, such as flue gas treatment using catalytic reduction systems by ammonia injection, are expensive alternatives. These techniques should therefore only be used after exhausting the possibilities of reducing NO_x emissions through the optimisation of the coal combustion process. Such primary measures should also be evaluated in terms of their possible effect on the thermal performance of boilers.

Due to the above factors, a broad-based research project on the reduction of NO_x emissions, by the use of combustion fine tuning, has been undertaken in the arch-fired Units 3, 4 & 5 of Compostilla Power Station. This project, known by the initials RNA, is included in the European Coal and Steel Community Research Programme.

2. Objectives

The main objective of the RNA Project was to determine the feasibility of approaching, or even reaching, the 1300 mg/Nm^3 NO_x limit of possible future application in Compostilla Units 4 & 5, using only combustion adjustments.

Additionally, as NO_x emissions in Compostilla Unit 3 were as low as 1100-1200 mg/Nm^3, a comparative study has been conducted in order to determine the design and performance parameters that give rise to the different NO_x formation behaviour of Compostilla Unit 3, with respect to that of the twin Units 4 & 5.

3. Tests programme

An extensive programme of in-field combustion tests, at full load and using coal of practically constant properties, has been conducted during 3 years in two different phases:

- Phase I: Trials at the "high NO_x emissions" Units 4 & 5.
- Phase II: Trials at the "lower NO_x emissions" Unit 3. Comparison with Units 4 & 5.

The methodology adopted for these trials was based on the parametric sensitivity approach, and the following schedule was drawn up for each unit:

a) Boiler instrument checking.
b) Operational modifications testing (parametric sensitivity matrix).
c) Trend confirmation testing.
d) Maximum improvement testing.

In each test, a broad characterisation of boiler performance was made, by measuring or monitoring the following items, amongst others:

a) Temperature distribution within the furnace (60 measurement points).
b) Gas composition (NO, NO_x, O_2, CO) above the burner arch (24 measurement points).
c) Gas composition (NO, NO_x, O_2, CO) and temperature at the outlet of the economizer (using a grid of 32 measurement points).
d) Emission levels of NO, NO_x, O_2 and CO.
e) Coal fineness and flowrate to burners.
f) Fuel-oil support.
g) Excess oxygen.
h) Air damper positions.
i) Fly ash carbon content.
j) Coal analysis.
k) Desuperheating spray flows.
l) Boiler efficiency and unit heat rate.

Besides this, modelling of the windboxes of Units 4 & 3 has been performed, in order to establish the relationships between air dampers openings and actual air flowrates through them.

4. Discussion of experimental findings

4.1 Scope

The operating modifications tested during commercial operation of the boilers consisted of variations to several different parameters. These included excess air, secondary and tertiary air dampers openings, fuel-oil support, distribution of active burners, positioning of straightening vanes, and combustion air temperature. Other factors such as the degree of boiler slagging were also taken into consideration.

Although results obtained within this Project reveal significant effects of most of the above mentioned operating modifications[1], this paper will only focus on the relevant trends determined for excess air, secondary and tertiary air dampers openings and fuel-oil support at Compostilla Units 3, 4 & 5.

4.2 Phase I: Trials at Units 4 & 5

4.2.1 NO_x Emissions. The main findings obtained in Units 4 and 5 of Compostilla P.S. are shown below, in relation to the operating conditions that brought about a significant fall in NO_x emissions. More specifically, the distribution of air fed into the boiler, which determines the type of flame obtained, and the excess air are especially important factors in the generation of NO_x. Likewise, the influence of eventual fuel-oil support has been established.

Figure 2 details the results for Compostilla Unit 4 of the most important cases in terms of NO_x emissions. The percentages of change in comparison with reference data are shown in parentheses. This figure illustrates the possibility of achieving the limit of 1300 mg/Nm^3 NO_x, using only primary measures. Results produced in the identically designed Unit 5 are very similar.

It must be underlined that the general tendencies shown by the figures recording overall emission of NO_x in the different trials, were fully confirmed by local measurements made directly above the burners, using probes especially designed for this purpose.

- ***Type of flame (excess air).*** One of the most important results of the studies undertaken in Units 4 and 5 of Compostilla P.S. was that two types of flame were identified (short and long). These were caused by differing relative proportions of secondary and tertiary air fed into the boiler (Figure 1). The qualitative difference between these types of flame arises due to the finding of a substantial modification

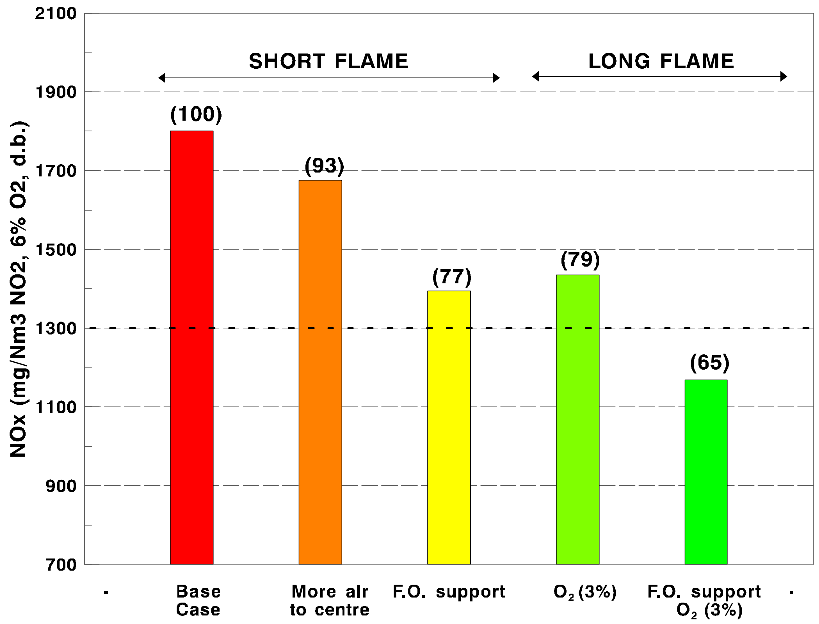

Figure 2: NOx emission results in outstanding cases (the limit of 1300 mg/Nm³ NOx of possible future application is

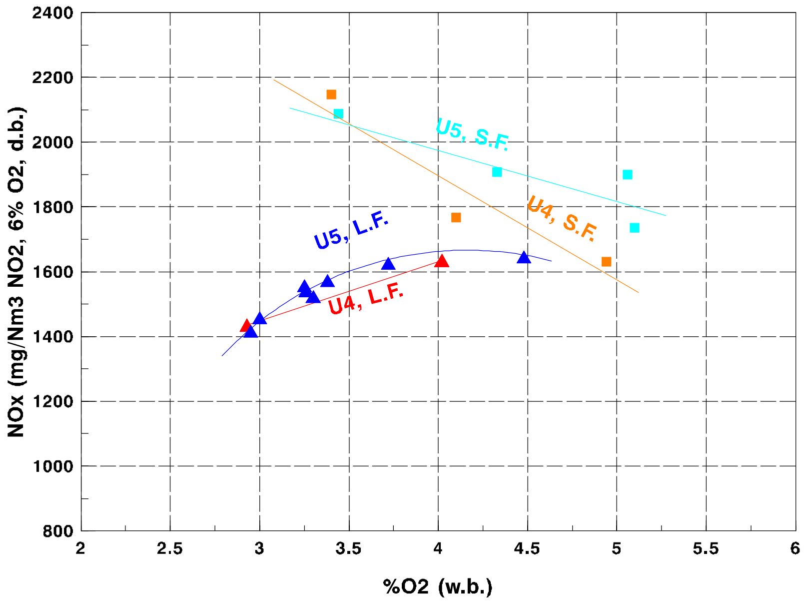

Figure 3: NOx/ O2 general relationships for short and long flames (Units 4 & 5)

in the causal relationship between the formation of NO_x and the operational oxygen level (Figure 3).

In fact, when the ratio between secondary air (S.A.) and tertiary air (T.A.) is low, as occurs with the air settings used in the past in the above-mentioned boilers (the base condition), an inverse dependence between concentrations of NO_x and O_2 is observed, i.e., less NO_x is formed when oxygen levels are higher.

This condition is associated with raising of the flame due to a greater flow of tertiary air. This gives rise to shorter and more intense flames (short flame), where combustion occurs with a less stratified supply of oxygen, i.e., with a greater initial mix of air and coal. The generation of NO_x is thereby controlled by temperature. This means that when an increase of excess air occurs, the flame cooling effect prevails over those deriving from higher local concentrations of oxygen, which brings about a net reduction in the formation of nitrogen oxides.

In this sense, correlations between the average temperature within the furnace and excess air have therefore been established. Variation coefficients of 40º C for each 1% change in excess oxygen are obtained. The cooling effect deriving from an increase of 1% in operational oxygen excess may be evaluated according to the ratios calculated between variations in NO_x and the average temperature in the furnace. A reduction of around 300 mg/Nm^3 in NO_x is produced, clearly demonstrating the importance of this factor in the formation of nitrogen oxides in this boiler type.

On the other hand, when the S.A./T.A. ratio is higher, the flame tends to occupy the lower part of the furnace, and therefore becomes longer, making the combustion process less intense, and with an increasingly stratified supply of oxygen. NO_x generation comes to be controlled by the influence of local concentrations of oxygen, i.e., by the stoichiometry of the oxidisation/reduction reactions involved in the formation of nitrogen oxides, to the detriment of the thermal control associated with variations in excess air.

Thus, in this case (long flame), an increase in excess air gives rise to an increase in the generation of nitrogen oxides. This is the opposite of the situation when a short flame is formed. The overall tendencies in the NO_x/O_2 ratios shown in Figure 3 are supported by the measurements made at the level of the arch of burners, as shown in Figure 4.

These two flame types, which may be identified at a macroscopic level by the structure of the temperature profiles measured in the furnace, therefore present a

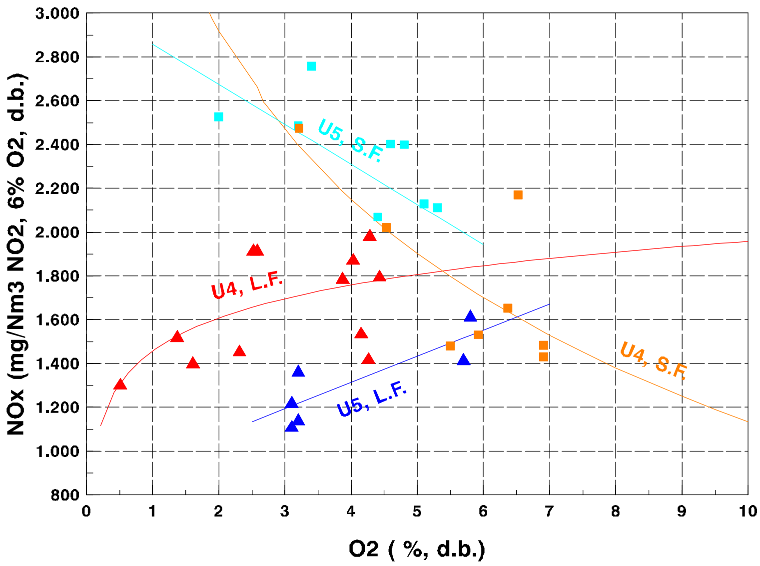

Figure 4: NOx / O2 burners arch relationships for short and long flames (Units 4 & 5)

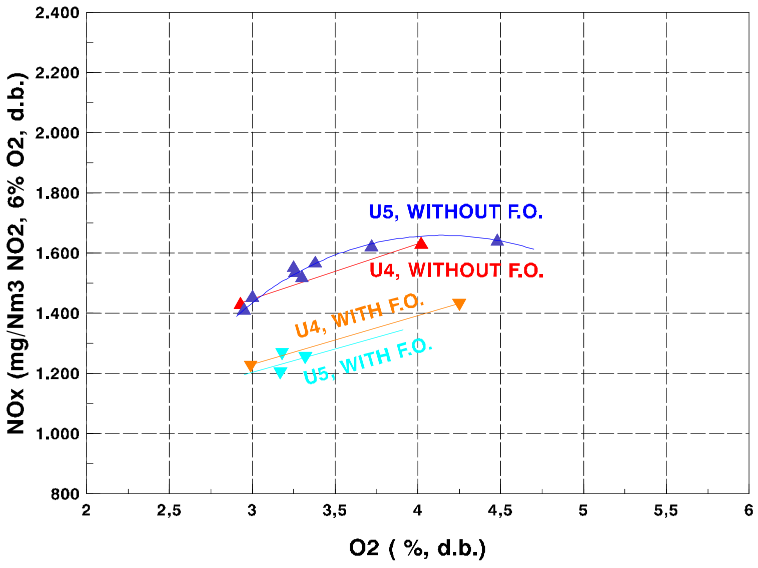

Figure 5: NOx / O2 general relationships for cases with and without F.O. Support (Units 4 & 5, long flame)

form of behaviour that is contrary to the basic operating parameter of total feed air. As it is stated below, this fact is related to the influence of NO_x reduction, in each case, over unit heat rate.

Additionally, it was found that the conditions leading to the lowest NO_x generation corresponded to long flame type situations, attaining values of approximately 1400 mg/Nm^3 (d.b., 6% O_2). This is equivalent to a reduction in these emissions of 20% in comparison with the initial basis (1800 mg/Nm^3) (Figure 2).

On the contrary, reducing the generation of NO_x without changing the flame from the short type, using increases in the excess of overall operational oxygen or the airflow supplied to the boiler centre, only gives rise to improvements of approximately 7%.

x ***Fuel-oil support.*** Important reductions in NO_x emissions were found in the two experimental boilers when fuel-oil support at central burners was employed in long flame type situations (Figure 5). Minor fuel-oil support (7 tons/h) together with a reduction in the excess of oxygen, implicated a fall of NO_x emissions to around 1200 mg/Nm^3 (Figure 2). This is equivalent to a 35% net reduction of this parameter.

These facts may be explained on the basis of the following factors:

- An increase in the temperature of the initial zone of the flame, which produces a greater devolatilisation. The literature on this subject states that the fraction of volatile nitrogen has a lower degree of conversion to NO_x under stratified combustion conditions, such as those existing in arch boilers.

- Fuel-oil combustion consumes the available oxygen in the first zone of the flame, creating an area rich in reducing substances in which the coal nitrogen and thermal NO tends to produce molecular nitrogen.

- A decrease in the average nitrogen content of the fuel (coal + fuel-oil) due to the lower content of the fuel-oil (approximately 0.3 - 0.5%), which is markedly lower than that of the coal used in Compostilla P.S. (1.4 - 1.6%).

Fuel-oil support was found to be most effective in these units when it took place in the central area of the boiler. This is explicable due to the greater formation of NO_x in this region, because of its higher temperature levels, which make reduction more probable.

Figures 6 and 7 show the correlations obtained at the level of the arch of burners in Unit 4 both with and without fuel-oil support, depending on type of flame. Thus when fuel-oil support is being used, the NO_x/O_2 ratio is found to be direct for both types of flame, i.e., the lowest concentrations of NO_x are attained for the lowest levels of excess oxygen.

This fact could be explained by the creation of more strongly reducing zones in the initial areas of the flame, thereby increasing the relative importance of local stoichiometry in relation with NO_x production. Another possible explanation of this phenomenon could be increased devolatilisation of fuel nitrogen, this fraction being very sensitive to local levels of oxygen respecting its conversion into molecular nitrogen.

NO_x emissions are found to be lower for short flames as the flow of supporting fuel-oil is increased. It may be observed that the degree of reduction decreases progressively towards an asymptotic value (Figure 6).

4.2.2 Collateral effects of reductions in NO_x. The measurement of NO_x emissions must be accompanied by checking of the effects of modifications on flyash carbon content and, with greater exactitude, on boiler efficiency and unit heat rate.
In general, the hypothesis that any action aimed at reducing the production of NO_x would produce a fall in boiler efficiency was widely accepted, this being due to an increase in the amount of ash unburnt. Although this hypothesis was supported by observations made during different experimental programs, it was found to be incorrect for Units 4 and 5 of Compostilla P.S., in the light of the results obtained.

In fact, the change from the usual boiler conditions (as the base case) to the final condition (with or without fuel-oil support) does not only bring about a significant reduction in NO_x emissions (from 20 to 35%), but is also accompanied by improvements in unit heat rate, in spite of a slight increase in ash carbon content.

These facts are shown in Table 1, where the most relevant results of trials with a short flame are presented (when NO_x production is optimised by supplying more air to the centre of the boiler) and final results using long flame with and without fuel-oil support.

Thus, although the levels of unburnt carbon increased about 0.8% under final conditions with a long flame, in net terms there was a 0.3% increase in boiler efficiency. This improvement in boiler performance is basically caused by a decrease in the volume of fluegas, due to the lesser excess air used in the final

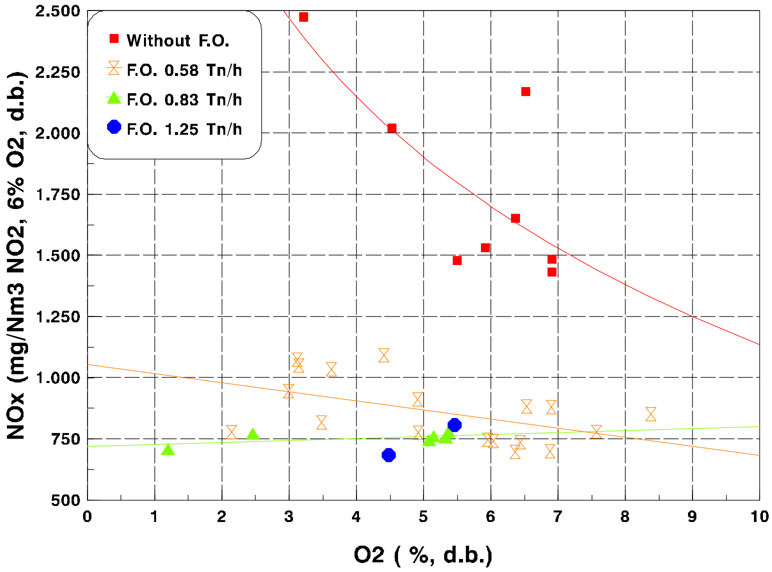

Figure 6: NOx / O_2 burners arch relationships for different F.O. Support flowrates (Unit 4, short flame)

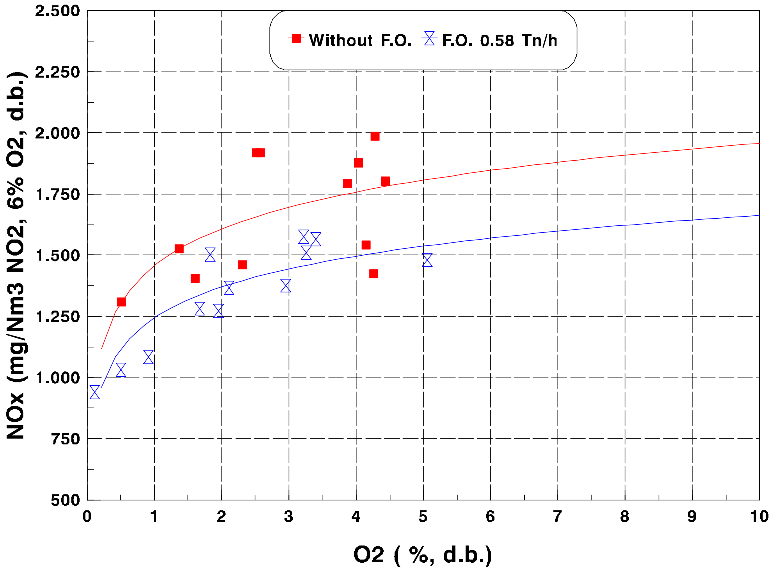

Figure 7: NOx/ O_2 burners arch relationships for cases with and without F.O. support (Units 4, long flame)

conditions (as was pointed out above, NO_x levels are decreased on reducing the supply of combustion air for a long flame type).

The use of a lower excess of air also gives rise to a reduction in auxiliary power consumption, which also has a positive effect on unit heat rate.
In this context, making a greater use of heat transfer in the water walls, for long flame types, brings about a drastic reduction in desuperheating spray flowrates, which in turn leads to an improvement in turbine performance and the supply of higher quality steam to the latter.

Table 1: General data from the most important tests in Unit 4

Case	Short flame (air to centre)	Long flame (final condition, without F.O.)	Long flame (final condition, with F.O.)
% O_2 (v/v, w.b.)	4.28	2.93	2.99
% NO_x (mg/Nm^3, 6% O_2, d.b.)	1675*	1435	1223
% ash unburnt	3.22	4.07	4.02
Boiler efficiency (%)	**87.67**	**87.97**	**87.90**
Water walls efficiency (%)	59.09	67.24	66.34
Desuperheating spray flowrate (lb/h)	101,700	19,300	22,600
Unit heat rate (kcal/kWh)	**2429.48**	**2408.34**	**2411.05**

* 1800 mg/Nm^3 in the case of a non-optimised short flame (base case)

This therefore constitutes a clear demonstration of the possibility of attaining reductions in the emissions of NO_x from anthracite burning boilers by around 30%, while also offering substantial improvements to the economic balance of unit performance (approx. 20 kcal/kWh). The said results are obtained by abandoning the operational solution traditionally adopted, which involves combustion conditions that are optimised respecting the production of unburnt.

4.3 Phase II: Trials at Unit 3

4.3.1 Design and operating differences. Compostilla Unit 3 has performed very differently, with respect to Units 4 & 5, in terms of NO_x emissions over time. In this sense, an extensive study of the design and operating differences of Units 3 & 4 have been performed with the following main results (Figure 8):

- Unit 3 (330 MW) presents a proportionally larger distance between front and rear walls than Unit 4 (350 MW). This determines a greater specific furnace volume for that boiler.

- Refractory lining surfaces have a lower extent in Unit 3.

- Unit 3 typical coal fineness is 95% through 200 mesh, due to the new classifiers installed in this plant, whilst Unit 4 coal size is around 88% through 200 mesh.

- In Unit 3 only 2 adjustable vertical levels of tertiary air are used, whereas Unit 4 has 3 levels of tertiary air. Vertical distance from burners tips to the upper T.A. level is 3.5 m in Unit 3, and only 1.5 m in Unit 4.

- Tertiary and secondary air distribution is substantially different in these units. As it can be noted in Figure 8, the S.A./T.A. ratio, obtained from windbox modelling, is much lower in Unit 3 for the base case. Additionally, Unit 4 presents a larger proportion of S.A. supplied through the vents.

4.3.2 Effects of modifications in air distribution. Tests campaign udertaken in Unit 3 has produced very important results in order to characterize NO_x formation and heat rate fine tuning in this boiler. Nevertheless, this paper will only emphasize those results which allow a comparison with the combustion patterns of Unit 4 (similar to those of Unit 5).

In this sense, the most relevant effect determined in Unit 3 is that produced through the modification of the S.A./T.A. ratio. Table 2 and Figures 9 and 10 show comparisons of Units 4 & 3 performance when varying this ratio.

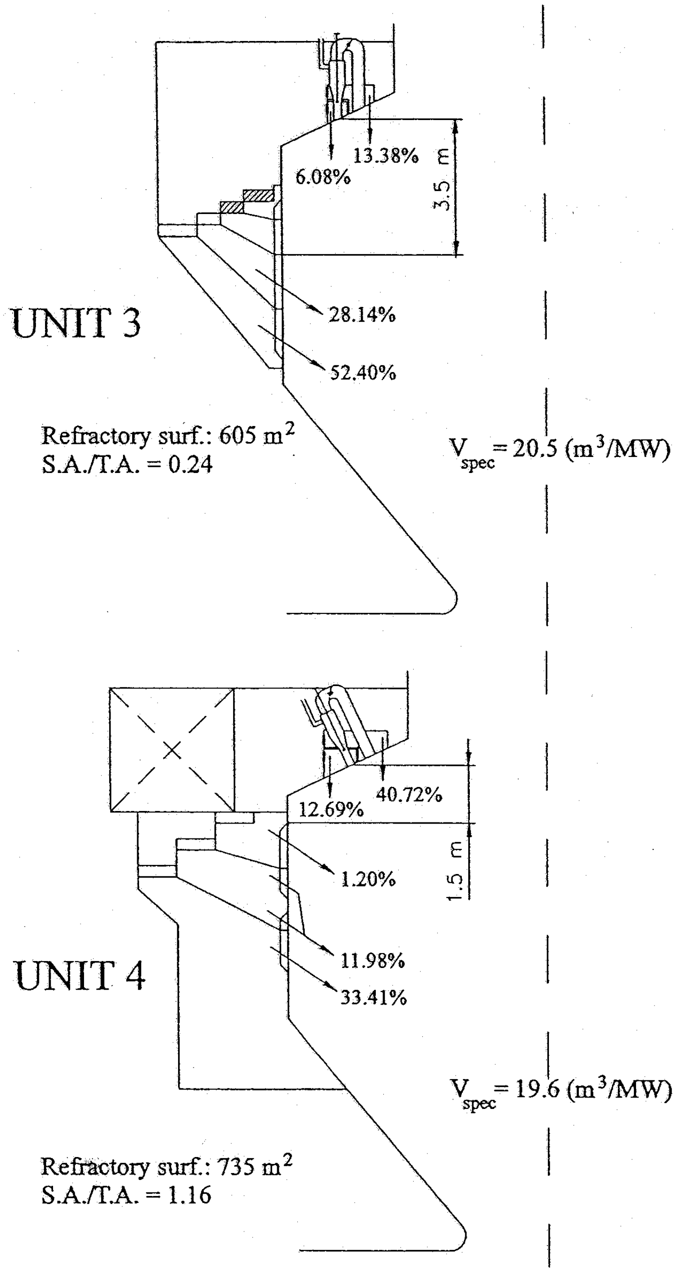

Figure 8: Furnace design and air distribution patterns for base cases (Units 3 & 4)

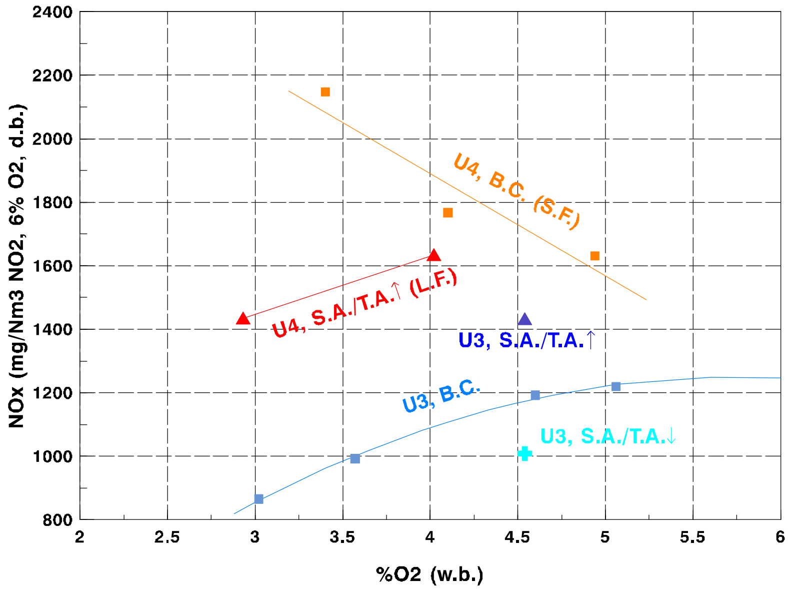

Figure 9: NOx / O_2 general relationships for Units 3 & 4 when modifying the S.A./T.A. Ratio (B.C.: base case; S.F.: short flame; L.F.: long flame)

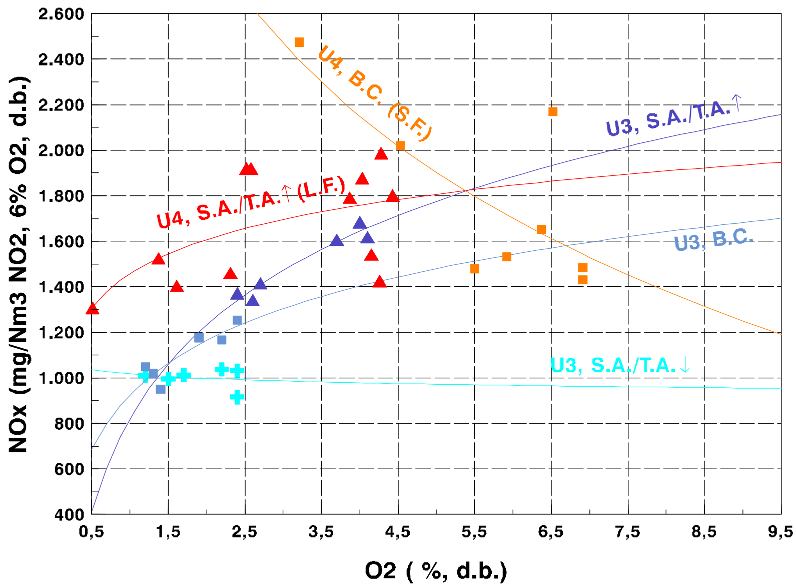

Figure 10: NOx/ O_2 burners arch relationships for Units 3 & 4 when modifying the S.A./T.A. Ratio (B.C.: bases case; S.F.: short flame; L.F.: long flame)

Table 2: Comparison of performance data from most significant tests with variation of the S.A./T.A ratio (Units 4 & 3)

Case[1]	S.A./T.A. [2]	NO_x (mg/Nm^3, 6% O_2)	Desuperheating [3] spray flow	Ash unburnt (%)	Boiler effic. (%)	Heat rate (kcal/kWh)
U4. Base Case	1.16	1767	101700	3.2	87.67	2429.48
U4. Long flame	3.21	1635	29500	3.8	87.35	2423.56
U3. Base Case	0.24	1198	38.90	8.3	85.60	2498.42
U3. S.A./T.A.↑	0.41	1441	14.50	5.9	86.61	2463.05
U3. S.A./T.A.↓	0.21	1014	42.60	9.2	85.07	2526.29

[1] Oxygen excess: U4: 4,1% ; U3: 4,6%

[2] Flowrate ratio from windbox modelling

[3] U4 (lb/h) ; U3 (%)

The following features could be established from the analysis of these data:

- NO_x emissions are around 1700 mg/Nm^3 for Unit 4 (at 4,1% O_2), whereas these values are significantly lower for Unit 3 (1000-1400 mg/Nm^3) for an oxygen excess of 4,6%.

- S.A./T.A. ratios are much lower in Unit 3, although substantial variations in air dampers openings are applied. The combined effect of this factor and the longer distance for T.A. supply in this unit seems to produce a higher degree of combustion stratification, as it can be concluded from the lower NO_x emissions and higher ash unburnt levels for Unit 3. In this sense, refractory extension and specific furnace volume seem not be the key parameters to explain Units 3 & 4 differences, as furnace average temperatures are similar (lower variations than those determined by the slagging influence). Significant effect of other factors like coal fineness or oxygen excess might also be discarded as they would determine a contrary trend of NO_x and unburnt results.

- Increasing the S.A./T.A. ratio in both units produces a reduction in desuperheating spray flows, which positively affects to turbine efficiency and, therefore, to unit heat rate. This reduction is due to the higher heat exchange in the lower furnace.

- Increasing the S.A./T.A. ratio seems to determine a less stratified combustion process in Unit 3, as NO_x emissions are higher and ash unburnt is lower in these conditions. These relationships are the opposite for Unit 4, most likely due to the very different air supply patterns of this unit, with T.A. addition much nearer the burners tips. This fact produces short, intense, and temperature controlled flames when the T.A. flow is high (base case), whilst, for lower T.A. supplies, flames tend to ocuppy the lower furnace, with an increasingly stratified supply of oxygen.

- Increasing the S.A./T.A. ratio has a positive effect on heat rate for both units, although this influence is much lower in Unit 4, where the higher unburnt levels in this condition give rise to a penalization in boiler efficiency.

5. Economic implications

The economic implications of the results obtained in Phase I (Units 4 & 5) are very important.

The current costs of reducing NO_x levels (taking into account operating costs as well as investment write-off) to a level similar to that attained in these units (by around 30%) are approximately $400 per ton of NO_x eliminated. This cost corresponds to using primary measures according to the most recent evaluations published around the world.

If it were necessary to use secondary measures, this cost would be increased by about $2,000 per ton of NO_x eliminated.

Nevertheless, the expectations arising from the RNA Project indicate that it is possible to attain the above-mentioned reduction in NO_x emissions in anthracite - burning boilers without the need to make any additional investments, and even with a reduction in operating costs, that for Compostilla Units 4 & 5 might be evaluated in 200 $/Tn NO_x eliminated (1,400,000 $/year).

On the other hand, results obtained in Phase II (Unit 3) show the importance of air distribution design for NO_x emissions control in arch-fired furnaces. Additionally, the significant variability of NO_x emissions and unit heat rate, depending on air supply configuration, permits to operate this boiler according to different criteria: minimisation of heat rate, minimisation of heat rate for NO_x emissions below 1300 mg/Nm^3, minimisation of NO_x emissions, etc. These strategies might be decided on the base of the economic implications, in each case, of heat rate optimisation and NO_x control.

6. Conclusions

The fundamental conclusions arising from the results of the RNA Project are:

- They demonstrate the possibility of reducing NO_x emissions in arch-boilers consuming anthracites by approximately 20 - 35%, using only primary measures. This would represent for Compostilla Units 4 & 5 the possibility of achieving the 1300 mg/Nm^3 NO_x limit, without applying secondary measures.

- They demonstrate the compatibility, in some cases, of this said reduction in emissions with the attainment of noticeable improvements in units heat rate. These improvements are obtained by moving away from standard operating criteria aimed at reducing ash carbon contents to a minimum, and using long flame types of combustion and lower excess air, thereby improving the net performance of boilers and turbines.

- They also demonstrate the importance of air distribution design for NO_x control and heat rate improvement, with regard to the operating modifications to be implemented for these aims.

7. Acknowledgements

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