DEVELOPMENT OF A LOW-NO$_X$ BURNER FOR NATURAL GAS AND HEAVY OIL COMBUSTION

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ABSTRACT

The results of the testing and optimization of a low-NO$_X$ burner are presented. The final objective of the study is the development of a burner suitable for natural gas and heavy oil firing in large boilers. Two experimental series are conducted. In a first stage, optimized designs are developed by means of an extensive testing in a semi-industrial-scale laboratory furnace, providing a detailed knowledge of the behavior of the burner. The performance of a prototype up to 20 MW(t) is evaluated in an industrial boiler, confirming the conclusions obtained at reduced scale.

KEYWORDS

Low-NO$_X$ burner, natural gas, heavy oil, air-staging, fuel-staging

1. INTRODUCTION

Low-NO$_X$ burners are one of the most extensively used NO$_X$ control technologies, both for retrofitting applications and for new plants. Those devices yield NO$_X$ reductions typically in the range 30-50% at a moderate cost [1,2], so that they are particularly convenient when extremely low emissions are not required. An additional advantage is that they can be combined with other control technologies (reburning, flue-gas treatment, ...) to achieve very low NO$_X$ levels and/or to reduce their implementation and operation costs.

The present paper describes the performance of a low-NO$_X$ burner (designated as TENOX) suitable for natural gas and heavy oil firing. It is the result of a collaboration project among an electricity generating company (Térmicas del Besós, S.A.), a burner manufacturer (Proyce, S.A.) and a research laboratory (LITEC).

The project comprises two experimental series. In the first place, a model of the TENOX burner has been extensively tested at a semi-industrial scale (0.3-0.35 MW(t)). That investigation allows a systematic development process, yielding also a detailed knowledge of the behavior of the burner. A second experimental programme has been conducted in the auxiliary boiler of the Foix power plant (Térmicas del Besós, S.A.). A prototype of the TENOX burner suitable for thermal inputs up to 20 MW(t) has been tested in order to check the validity of the conclusions obtained at the pilot scale.

2. EXPERIMENTAL FACILITIES

The tests are conducted in the LITEC experimental furnace, which is represented in Figure 1. The combustion chamber is cylindrical and vertically oriented, with the flow moving downwards. The total length is 3.5 m and the inner diameter is 820 mm in the flame section. The furnace is formed by eleven annular segments, the roof and the convergent exit section. All these elements are refractory lined and externally cooled by separate water jackets, with independent measurements of the flow rate and the exit water temperature. Wall thermocouples installed at each segment provide the axial profile of the surface temperature. In order to approach thermal similarity [3], the furnace is designed to reproduce the temperature history of the flame gases in large boilers.
The burner and the auxiliary controls (igniter and flame monitor) are fitted onto the furnace roof. A detailed schematic of the burner is shown in Figure 2. The most relevant features as well as the adjustable settings are summarized below.

Natural gas is injected at two different points. **Primary gas** is fed through a central injector aligned with the burner axis (No. 21 in Figure 2) which can be placed at different axial distances relative to the burner exit. It has an adjustable exit area, so that fuel injection velocity can be varied. **Secondary gas** is injected through 16 nozzles distributed around the air ducts (No. 22). The 16 fuel jets are slightly directed towards the center, at an angle of 15° to the axial direction. The gas distribution between the two lines is controlled by external pressure regulators.

The configuration for heavy oil combustion is very similar to the one shown in Figure 2, where the gas injector at the tip of the central gun is replaced by a steam-assisted atomizer. Since no simultaneous gas and oil firing is performed, the peripheric gas injectors are not used when burning heavy oil.
The combustion air enters the burner from a cylindrical plenum chamber. An adjustable flow distribution valve (No. 15) divides the total flow rate between two air registers. The primary air exits through the inner duct (No. 5). A part of the exit is blocked by a swirler fitted on the central fuel gun (No. 1), so that a fraction of the primary air emerges as a rotating flow. The blockage ratio and the design of the swirler can be varied, allowing a broad range of primary air swirl numbers. A "low-swirl" and a "high-swirl" version with primary swirl numbers $S_1=0.3$ and $0.7$, respectively, have been tested. Secondary air is fed through the outer duct (No. 3). Twelve adjustable vanes provide a variable secondary swirl level.

Exhaust gases are analyzed for $O_2$, $CO$, $CO_2$, UHC, NO/NOx, $SO_2$ and $N_2O$ using gas sampling probes and individual on-line analyzers. Solid emissions are determined in heavy oil combustion by a particle sampling probe operated under isokinetic conditions. Particle samples are also analyzed in a Scanning Electron Microscope for the study of their size distribution and morphology.

A more detailed investigation of the natural gas flame has been performed for a few selected cases in order to gain further insight into the relevant phenomena. Measurements include the velocity field in isothermal flow and the spatial distribution of temperatures inside the combustion chamber. Gas temperatures are obtained using bare wire thermocouples with a diameter of 70 µm. The flow field is investigated by means of a Hubbard probe and a five-hole Pitot tube. The Hubbard probe is used to detect the location of the reverse flow zones. The velocity field and the spatial distribution of static pressure of the isothermal combustion air flow are obtained with the five-hole tube positioned according to the previously-established flow direction.

Some experiments have been conducted in a large-scale single-burner boiler using natural gas. A prototype based on the above described burner has been built and operated at thermal inputs in the
range 7-17 MW. The results are compared with those obtained for the burner previously installed in the boiler. The dimensions of the combustion chamber are 8 m x 2.2 m x 3.2 m (length, width, height), and the burner is installed horizontally. The concentrations of O₂, CO and NOₓ in the flue gases are determined using a portable analyzer. NOₓ values are confirmed in some selected cases with measurements following the USEPA standard.

3. NATURAL GAS FIRING

3.1 Pilot Scale Experiments

Characterization of the flame

Figure 3 represents the velocity field obtained in isothermal flow. A flow rate of 340 Nm³/h is injected, with a fraction of 84% being fed through the primary air register. Primary air swirl number is 0.3 in this case.

A low velocity region develops along the axis of the furnace. Even though it is out of the probed area, a small recirculation zone can be visually noticed in the wake of the central injector. Two phenomena are responsible for that effect. In the first place, the primary swirler and the fuel nozzle cause a blockage around the axis and the primary air emerges as an annular jet. On the other hand, the swirler creates a swirling motion that causes the jet to spread radially creating a positive pressure gradient. As a consequence, the air flow is decelerated along the axis, even creating a recirculating flow [4]. Even though the swirling motion of the air fraction going through the swirler is high, the global swirl number of the primary air is rather low and a very short recirculation zone is created. Nevertheless, the low velocity core plays an important role in flame stabilization under some burner conditions. Downstream, the axial velocity profiles become gradually more uniform as the annular jet develops.

An external recirculation zone is detected near the walls as a consequence of the confined nature of the flow and of the sudden expansion created at the burner exit. The main effect is the entrainment of combustion products, that get mixed with the air flow issuing from the burner.

![Figure 3 - Velocity field in isothermal flow.](image-url)
The spatial distribution of temperature inside the furnace is displayed in Figure 4. The measurements have been performed under the following conditions:

- Gas flow rate, $Q_g = 24.7 \text{Nm}^3/\text{h}$; Primary fuel fraction, $Q_{g1} = 37.6\%$
- Air flow rate, $Q_a = 284 \text{Nm}^3/\text{h}$; Primary air fraction, $Q_{a1} = 84\%$
- Flue gases: $[O_2] = 3\%$; $[CO] = 4 \text{ppm}$; $[NO_x] = 36.5 \text{ppm}$

The temperature distribution shows two different zones within the flame. A narrow, high temperature region appears close to the burner due to the combustion of the primary fuel injected through the central nozzle. The maximum flame temperature (1595 °C) is detected inside this zone. A much colder flow (down to 400 °C) can be seen around the hot core. It mainly consists of fresh air with some proportion of combustion products transported backwards through the external recirculation zone. A steep gradient is measured between the inner flame and the outer cold stream, displaying changes up to 800 °C within a radial distance of 1 cm. As the primary fuel is depleted, a temperature decay occurs due to heat transfer to the walls and dilution by recirculated products.

The secondary fuel is fed through the peripheric injectors with a near-axial direction and it comes into contact with the primary flame after some length from the burner exit. That distance is around 15 cm, as estimated by visual inspection and corroborated by the temperature map. Figure 4 shows a steep increase in the diameter of the 1400 °C isoline at that distance.

![Figure 4 - Temperature distribution inside the furnace.](image-url)
The secondary flame is characterized by a much larger volume and a more uniform temperature distribution than the primary zone. Peak values are also lower than in the previous case, with a maximum temperature of 1557 °C. Gas temperatures are in the range 1400-1500°C over most of the secondary flame. Those features are thought to be the consequence of several effects:

- The secondary fuel is injected from 16 points with a near-axial direction, so that the fuel is distributed over a large region.
- A good mixing must take place between the secondary fuel, the combustion air and the products for the primary flame. First of all, the fuel must cross the combustion air jet before coming into contact with the primary flame. On the other hand, the distribution of secondary natural gas into 16 jets, together with the long distance between the injection point and their burning, provide an excellent way to obtain a homogeneous air/fuel mixture.
- At the point where the secondary fuel ignites, a significant amount of combustion products has been entrained. The gases from the primary flame are injected along the axis; products from downstream regions are transported backwards through the external recirculation zone. Such effects cause a dilution of the fresh air/fuel mixture resulting in lower flame temperatures.

It is interesting to note that the flame structure deduced from the temperature map is quite different from what could be inferred from the global operation parameters. If the characteristics of the primary flame are estimated from the ratio between the primary air and fuel streams, an average stoichiometric ratio of 2.5 is obtained. Thus, if a good mixing between both flows is assumed, the primary flame would display low temperatures due to the high excess air (fuel-lean core), and a very low NO formation would be obtained. On the contrary, the measurements demonstrate that the peak temperatures occur in that zone, resulting in a high NO formation.

Influence of Operational Parameters

A thorough investigation of the influence of the different burner settings has been conducted in order to select the most convenient regimes for a low NOx operation. The equipment displays a broad range of stable combustion, while allowing significant variations in flame shapes and NOx levels. Carbon monoxide emissions are always below 10 ppm, even for oxygen levels lower than 1 %. Experiments are performed at thermal inputs in the range 0.3-0.35 MW. Some of the most relevant results are summarized in what follows.

The distribution of natural gas between the primary and secondary nozzles proved to be one of the key parameters in the behavior of the burner. Figure 5 shows the NOx emissions as a function of the percentage of fuel through the central injector. Those results illustrate the typical evolution obtained in many different experimental series. A maximum NOx appears at Qgi in the range 40-60 %. As Qgi increases, the NOx emission shows a slight decrease. A much sharper reduction is obtained for lower primary fuel flow rates. Those results can be explained in the light of the flame structure previously presented.

For Qgi under 60%, the flame can be divided into two different zones. An intense flame appears due to the burning of the primary fuel in an oxygen-rich environment, displaying the highest temperatures. The NOx formation rate is expected to be high in that region. The secondary fuel burns over a large volume where temperatures are lower than in the primary flame. Gases in that region are diluted by combustion products from the primary region and from the external recirculation zone. As a consequence, the average NOx formation rate is expected to be much more limited inside the secondary flame. Thus, the NOx emission is the result of the contributions of the two flame regions, and the final value will depend on their relative importance.
Figure 5 - Influence of fuel distribution and air preheat temperature on NO\textsubscript{X} emissions (gas firing).

Figure 6 - Influence of fuel and air distributions on NO\textsubscript{X} emissions (gas firing).
The visible flame shape displays also a significant dependence on the fuel distribution parameter, $Q_g1$. At intermediate values of $Q_g1$, a short and intense flame attached to the burner is obtained. In those cases, the products from the primary flame are a significant fraction of the total flow and the highest NOx levels are obtained. As $Q_g1$ approaches 100%, the fuel exit velocity exceeds a critical value beyond which the flame becomes detached from the burner displaying a vertex stabilized in the central low velocity wake. In that case, the primary flame is no longer a short intense flame, and its NOx formation potential diminishes.

As $Q_g1$ decreases below 40%, the separation between the primary and the secondary flames becomes more apparent. The fraction of products from the secondary region increases and the final NOx emission is reduced. With very low primary fuel flow rates, the primary flame acts mainly as a pilot flame for the ignition of the secondary fuel. Below a certain value of $Q_g1$ the combustion becomes unstable and further improvements in pollutant emissions are not possible.

Figure 5 shows a significant increment of NOx concentration when combustion air is preheated to 250°C. Nevertheless, the higher flame temperatures promote the ignition in the secondary flame and lower primary fuel fractions are possible. As a consequence, minimum emissions are very similar to the ones obtained in the cold air experiments.

Figure 6 represents the NOx emissions as a function of the air and fuel distributions. The three curves display similar trends, but they are displaced to the left as the primary air fraction decreases. Also, peak NOx levels are reduced for lower $Q_g1$. It was not possible with the described configuration to attain air-staged conditions, i.e., to maintain a fuel-rich primary zone by delaying the mixing with the secondary air stream. Below a certain level of primary air (which depends on air preheat temperature, secondary swirl, ...) a stable flame cannot be obtained.

A second version of the burner was developed in which the primary air injection geometry was modified in order to obtain a higher swirl level ($S_t=0.7$). Figure 7 represents some results obtained with the "high-swirl" geometry. Primary air fractions can be reduced down to 35% even at $Q_g1=100\%$, allowing an effective air-staging. Figure 7 demonstrates the strong dependence of NOx on air distribution, with a minimum level around 24 ppm.

![Figure 7 - Influence of fuel and air distribution on NOx emissions (gas firing, high-swirl version).](image-url)
3.2 Full Scale Tests

The NO\textsubscript{X} emission with the gas burner previously installed in the boiler is 84 ppm (3\% O\textsubscript{2}) at 20 MW(t). This value is compared in Figure 8 with some of the results obtained with the TENOX prototype. Figure 8 also contains the results from one of the experimental series conducted in the experimental furnace. Some of the main results are:

1. The new burner reduces the NO\textsubscript{X} emissions by a factor up to 3.5 compared to the original equipment.

2. The behavior of the prototype is in excellent agreement with the results from the model burner, in spite of the large difference in size. Figure 8 demonstrates a parallel evolution in NO\textsubscript{X} emissions. Comparisons between photographs taken at the two scales also show similar flame configurations.

Some of the data points in Figure 8 for the TENOX burner were obtained at 10 MW(t) due to operation constraints of the power plant. However, the results display only a minor influence of the firing rate (less than 10\% between 8 and 16 MW(t)) and the conclusions are considered valid. Additional tests are in progress in order to explore other configurations of the burner.

4. HEAVY OIL FIRING

In heavy oil operation, the central gas gun is replaced by an oil barrel fitted with a steam-assisted atomizer. The operation parameters are similar to those for natural gas firing with the exception that fuel staging has not been tested. Additional variables in this case are the nozzle design and the oil and steam injection conditions. The combustion air is preheated to 250 °C in all the tests in order to simulate the conditions in industrial burners. Around 250 different tests were conducted at a constant thermal input of 0.33 MW. Only a brief summary of the results is presented here.

Figure 9 shows the strong influence of the air-staging degree on NO\textsubscript{X} emissions for different cases. As the primary air flow rate decreases, conversion of fuel nitrogen to N\textsubscript{2} is promoted due to the gradually fuel-richer conditions. It is apparent from Figure 9 that the slope of the curves display significant variations depending on the other test parameters. In most cases, the NO\textsubscript{X} emission displays a
minimum for values of $Q_{A1}$ between 30 and 50%. That point coincides with the conditions at which the flame becomes detached from the burner exit. As a consequence, the efficiency of the air staging decreases and further increments in secondary air flow rate lead to higher NOX emissions.

The optimization of the nozzle design and of the oil and steam injection conditions provide an efficient means to achieve very low NOX levels. Figure 10 represents the minimum emissions obtained through the testing of four different atomizers, for the two burner versions. The effective spray angle is one of the main differences among the four designs, being gradually reduced from atomizer A to D. The tests confirm the results obtained in a previous investigation [5] suggesting that smaller injection angles can yield, under certain conditions, a reduction in NOX emissions without a rise in particulate matter.

The testing of the TENOX burner at pilot scale yielded a minimum NOX level of 134 ppm (3% O2). Particulate emissions at low-NOX operation of the burner are lower than 150 mg/Nm³. CO is below 15 ppm for oxygen levels down to 1%.

![Graph showing influence of air distribution on NOX emissions in different experimental series (oil firing).](image)

**Figure 9** - Influence of air distribution on NOX emissions in different experimental series (oil firing).

## 5. SUMMARY

A new low-NOX burner for natural gas and heavy oil firing has been tested and optimized at two different scales. The main results of the study are summarized in the following:

- In-flame measurements in the laboratory furnace provide a detailed knowledge of the flame structure, and allows the identification of the phenomena responsible for the reduction in NOX emissions.

- Two different burner geometries for natural gas operation have been developed at the semi-industrial scale. One of them (low-swirl version) uses fuel-staging and yields a minimum NOX emission of 26 ppm. The second configuration (high-swirl version) is based on air-staging, giving a minimum of 24 ppm.

- A combination of air-staging and atomizer design optimization leads to a minimum NOX emission of 134 ppm in heavy oil operation.
A 20 MW(t) prototype of the TENOX burner was tested in an industrial burner, yielding a minimum NO\textsubscript{x} emission of 24 ppm with natural gas. This level means only 28% of the emissions obtained with the burner previously installed in the same boiler.

The full-scale tests confirm the conclusions obtained at the reduced scale in respect to both NO\textsubscript{x} emissions and flame configuration. Therefore, the use of a semi-industrial furnace has proved to be an excellent tool in the development of combustion equipment for large boilers.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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