

# Invisible Flames for Clearly Visible Results

The most recent development in oxyfuel technology is flameless combustion. For some years it has been installed in furnaces and vessels, providing both more uniform heating and ultra-low NO<sub>x</sub> levels. Actually, thanks to its additional benefits, flameless oxyfuel combustion technology is what many people consider the Best Available Technique.

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It is a well-known fact that only three things are needed to start and maintain combustion: oxygen, fuel and sufficient energy for ignition. The combustion process itself would be most efficient if fuel and oxygen could meet without any restrictions. However, in practical heating applications it is not simply a question of efficient and clean combustion; heat-transfer efficiency is also extremely important. Nevertheless, it has been clearly demonstrated in practice that if oxygen (and not air) is used to combust a fuel, the heat-transfer mechanisms – convection and radiation – can be promoted at the same time, simultaneously lowering all air pollutants.

Air contains 21 % oxygen and 79 % ballast. In an air-based combustion process this ballast – practically all nitrogen – has to be heated, for which purpose a lot of fuel is needed. To overcome part of this waste of energy, bulky and expensive heat-recovery systems are often used. Flue-gas volumes are also much greater than when using oxygen alone – and this also has a negative impact on capital requirements and, moreover, will substantially increase the production of CO<sub>2</sub>. Use of oxyfuel instead of air-fuel combustion for all kinds of heating operations opens up tremendous opportunities, as it leads to fuel savings, reduces the time required for the heating process and reduces emissions. Numerous results from installations have proven this.

## 15 years of oxyfuel installations

Prompted by rapidly rising fuel prices in the 1970s, ways of reducing fuel consumption in reheat and annealing furnaces were first considered. This laid the foundation for a development that led to the use of the oxyfuel solutions in rolling mills and forge shops. In the middle of the 1980s AGA began to equip the first furnaces with oxygen-enrichment systems. These systems increased the oxygen content of the combustion air to 23 % or 24 %. The results were encouraging: fuel consumption was reduced and the output (in terms of tonnes per hour) increased. In 1990 AGA converted the



*'Pilot-scale studies and experience from installations of flameless oxyfuel confirms that the burner designs to achieve ultra low emissions of NO<sub>x</sub> are correct. We also see better heating properties in large furnaces and improved temperature uniformity', says Tomas Ekman, senior combustion specialist at AGA.*

first furnace to operation with 100 % oxygen, i.e. full oxyfuel combustion. For the past 15 years AGA has been pioneering the use of oxyfuel in this field.

The most important factor in this development has always been a thorough understanding of the customer process and the particular constraints and challenges that customers are facing. Continuous development and implementation of new burner technologies, to meet new demands, have been the keys to improvement and deeper understanding. Additionally, the importance of close cooperation with selected key customers cannot be exaggerated. These joint commitments have ensured successful implementation of new technologies, to the benefit of both parties.

The development of new oxyfuel-burner technologies in the field of reheating can briefly be summarised as follows:

- High-velocity water-cooled burners were introduced in 1990 (at Timken, USA).
- In 1994 the first ceramic burners were installed (at Ovako Hofors Works, Sweden).
- To achieve low NO<sub>x</sub> emissions, ceramic burners with staged combustion were introduced in 1997 (at Ovako Hofors Works, Sweden).
- In 2002 so-called Direct Flame Impingement (DFI) was first used on a commercial scale (at Outokumpu Stainless Nyby Works, Sweden).
- The first installations of flameless oxyfuel took place in 2003 at Outokumpu Stainless, in a walking beam furnace at Degerfors Works and in a catenary furnace at Nyby.

Recently all oxyfuel technologies for reheat furnaces and annealing lines have been packaged in a Rebox solutions portfolio, also in-

cluding control systems, engineering, project handling, revamping, commissioning and assistance agreements.

### Lowering of NO<sub>x</sub> emissions

The legislation relating to NO<sub>x</sub> emissions is strict, and permissible emission levels are constantly being reduced. It is worth noting that nitrous oxide, in addition to having many well-known adverse effects, is also one of the greenhouse gases listed in the Kyoto Protocol; its so-called global-warming potential is 230 times that of CO<sub>2</sub>. Bearing this in mind, development work has been started in collaboration with customers to find even more effective oxyfuel solutions.

Three things control the formation of thermal NO<sub>x</sub>: partial pressure of oxygen; partial pressure of nitrogen; combustion temperature, i.e. NO<sub>x</sub> formation temperature (here preferably below 1,400° C). For each of these prerequisites there are different measures that can be undertaken to minimise the formation of NO<sub>x</sub>. Thus it is possible to formulate a strategy, including – for each of the items – the following measures:

#### Partial pressure of oxygen

- Ensure a well-functioning combustion-control system
- Minimise air ingress by means of tightness and strict control of the furnace pressure

#### Partial pressure of nitrogen

- Avoid having nitrogen present in the oxidation media
- Minimise air ingress by means of tightness and strict control of the furnace pressure

#### Combustion temperature

Although only oxygen is used in the conventional oxyfuel combustion process, nitric oxide is produced as a result of the high flame temperature and the ingress air. To lower the peak temperature and improve the flame conditions, the introduction of so-called staged combustion was an important first step to achieve reduced NO<sub>x</sub> emissions. However, due to authorities' continuously lower emission permit levels, further technical developments had to be taken on.

### Flameless combustion

In addition to substantially lower NO<sub>x</sub> emissions, the development work also aimed at finding more rugged installations for implementation as well as oxyfuel solutions viable in larger furnaces such as catenary, pusher and walking

beam furnaces. As mentioned, a key parameter in achieving low NO<sub>x</sub> is reduction of flame temperature. Below a temperature of 1,400° C NO<sub>x</sub> formation is limited, but above this temperature a dramatic increase in NO<sub>x</sub> occurs. Conventional oxyfuel combustion can exhibit flame regions with temperatures above 2,000° C. One way of reducing the flame temperature is to use the principle of 'flameless' combustion. This principle has been known for many years but has only recently been exploited industrially.

The expression 'flameless combustion' rather expresses the visual aspect of the combustion type, i.e. the flame is no longer seen or easily detected by the human eye. Another description might be that combustion is 'extended' in time and space – it is spread out in a large volume. This is why it is sometimes referred to as 'volume combustion'. Such a flame has a uniform and lower temperature.

There are two main ways of obtaining the 'flameless' oxyfuel combustion mode: either dilution of the flame by recirculating part of its flue gas to the burner, or use of separated injection of fuel and oxygen at high velocities. In a conventional stable-flame burner the flame is almost a field discontinuity, dependent on fluid dynamics with computational difficulties and involving complex reaction paths with abundant formation of radicals and intermediate products. The gradual, volume-distributed reaction rate typical of 'flameless' and staged combustion is more accurately controlled. The mixture of fuel and oxidant reacts uniformly through flame volume, with the rate controlled by partial pressures of reactants and their temperature.

In addition to reducing the temperature of the flame, flameless oxyfuel burners effectively disperse the combustion gases throughout the furnace, ensuring more effective and uniform heating of the material – the dispersed flame still contains the same amount of energy but is spread over a greater volume – with a limited number of burners installed.

### Oxyfuel vs airfuel study

From the existing 90 oxyfuel installations in reheat furnaces and annealing lines it is both proven and well known that oxyfuel has numerous advantages over airfuel (less fuel consumption, enables higher throughput rates, improved temperature uniformity, much smaller gas handling systems, easy retrofit, lower maintenance costs, less CO<sub>2</sub> emissions, etc., etc.). All indications from installations of flameless oxyfuel show that NO<sub>x</sub> emissions comply well

with the stipulated values. However, it was deemed of interest to perform a comparison with airfuel under the same conditions, and to focus on NO<sub>x</sub> emissions.

Thus the Royal Institute of Technology (KTH), Stockholm, Sweden carried out such a pilot-scale study in spring 2004. The purpose was to compare oxyfuel with the most modern airfuel combustion, so-called regenerative flameless technology. Tests were carried out in an 8 m<sup>3</sup> furnace.

It was shown that flameless oxyfuel combustion technology is almost insensitive to air ingress when it comes to NO<sub>x</sub> emission under normal operating conditions. The test was performed in the above-mentioned pilot-scale furnace, in which air ingress into the combustion chamber was simulated by leaking air into it in order to raise the free oxygen content in the combustion gases. The oxygen content was measured in the furnace-flue gas outlet. The flameless oxyfuel solution proved highly insensitive to air ingress, and conventional oxyfuel had similar NO<sub>x</sub> emissions to those of state-of-the-art regenerative airfuel technology. This is of great benefit, particularly in old and continuous furnaces.

'It is an obvious result that flameless oxyfuel technology produces much lower NO<sub>x</sub> emissions than the best airfuel technologies, and that the difference becomes more pronounced with increasing in-leakage of air to the furnace,' says Włodzimierz Błasiak, Professor of Energy and Furnace Technology, who led the study.

### Full-scale installations

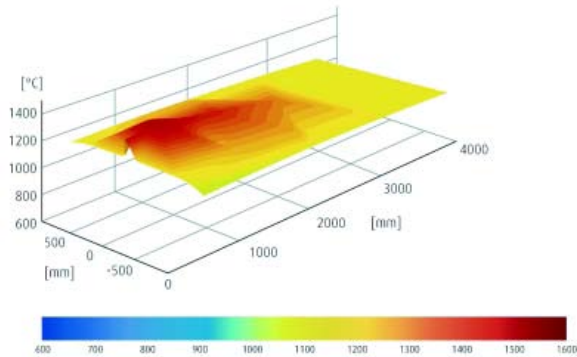
Since 2003 full-scale applications have been installed using flameless oxyfuel burner technology. This has led to the possibility of meeting the demand for increased production throughput in existing furnaces at the same time as fulfilling local authorities' stipulated lower levels of NO<sub>x</sub> emissions. Here are some examples of installations:

- Outokumpu Stainless, Degerfors, Sweden. In 2003, a walking beam furnace was converted to flameless oxyfuel by applying Rebox-S technology in an AGA turnkey project with performance guarantees. The resultant 40-50 % increase in heating capacity provided increased loading of the rolling mill.
- Outokumpu Stainless, Nyby, Sweden. 32 flameless Rebox-W burners were installed in another turnkey project, in which a catenary furnace was converted from airfuel to oxyfuel in 2003. The results include a 50 % increase in heating capacity and a 40 % reduction in specific fuel consumption.
- Ascométal, Fos-sur-Mer, France. In 2004 it was decided to take on a project to convert its pit furnaces into flameless oxyfuel using Rebox-W technology. In practice, 13 airfuel-fired furnaces are now being replaced with 9 furnaces equipped with flameless oxyfuel; the total steel output is being kept unchanged, i.e. the throughput rate is being increased by 50 %.
- Scana Steel, Björneborg, Sweden, is making heavy forgings. During the 1990s its car bottom furnaces were converted to oxyfuel, providing much faster heating and reduced

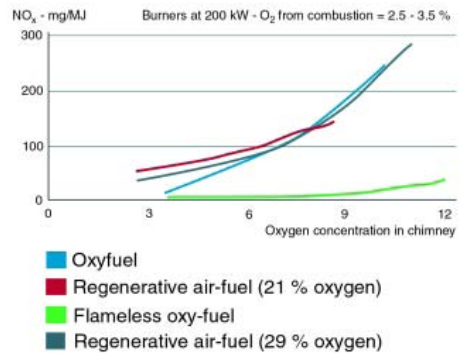


Flameless oxyfuel burner Rebox-W, mounted to the left in the photographs, firing in flame mode (<800° C) in the photograph to the left and in flameless mode (>800° C) in the photograph to the right.





Compilation of temperature measurements of flameless oxyfuel, as here from a Rebox-W burner fired at 0.15 MW to reach a furnace temperature of 1,200°C. It shows the lower and more even temperature distribution without any peaks, beneficial to achieve low emissions of NO<sub>x</sub> and uniform heating of the material.



Results from tests in a pilot-scale furnace (8 m<sup>3</sup>), NO<sub>x</sub> level as a function of the air-ingress to the furnace. Emissions of NO<sub>x</sub> from oxyfuel combustion of propane are comparable to those of regenerative airfuel burners, whereas flameless oxyfuel is almost insensitive to air-ingress.

fuel consumption. Scana Steel has now started to adopt flameless oxyfuel to add the benefits of Rebox-W.

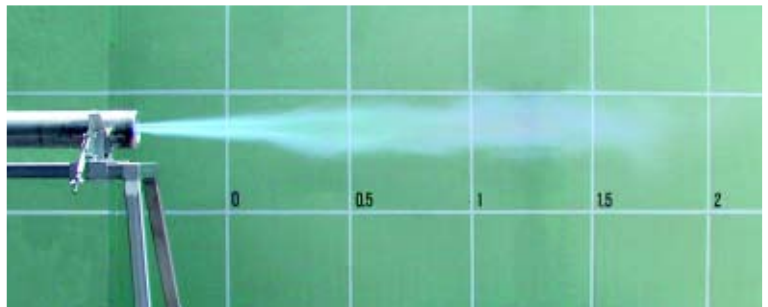
- Böhler-Uddeholm, Hagfors, Sweden, is one of the early adopters of oxyfuel in its car bottom furnaces at the forge shop; the first installation took place in 1993. To further reduce NO<sub>x</sub> and improve heating properties Rebox-W is now being installed.

Flameless oxyfuel has also been installed for preheating of ladles and converters at a number of steel mills in Sweden, including Sandvik, Outokumpu Stainless and Ovako, and several more are in progress.

### Best Available Technique

Flameless oxyfuel combustion has such major advantages that this process is likely to be installed in most applications. The advantages of conventional oxyfuel combustion are combined with those of flameless combustion to produce improved heating and reduced NO<sub>x</sub> emissions. The latter advantage is normally important in the case of large, continuously oper-

The picture shows a flameless oxyfuel burner fired in normal oxyfuel mode. This is used for initial heating of furnace from ambient to 800°C.



ating furnaces but is also relevant to other heating processes, for example the preheating of ladles.

Accordingly, it is no great surprise that many people are enthusiastic about flameless oxyfuel. To take one example, Jean-Marie Tesson, combustion specialist at Ascométal, says: 'We have compared different technologies to improve our operations, also including how to minimise emissions. As flameless oxyfuel displays such great advantages over other tech-

nologies, for us it was an obvious choice to go for this.'

The development of flameless oxyfuel combustion has been brought forward in close cooperation with steel producers, i.e. the users, to meet their needs. It builds on the many proven advantages of oxyfuel over airfuel, which have been well known for years. The recent introduction of flameless oxyfuel has taken this a step further, with very low NO<sub>x</sub> emissions and uniform heating.



The turnkey flameless oxyfuel project in the walking beam furnace at Outokumpu Stainless, Degerfors site, resulted in 40-50% more heating capacity and 25% reduced specific fuel consumption compared to the earlier airfuel burners and recuperator.

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