# Flameless oxyfuel combustion for increased production and reduced $CO_2$ and $NO_x$ emissions

*Flammenlose Oxyfuel-Verbrennung steigert Produktion und reduziert $CO_2$- und $NO_x$-Emissionen*

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Since 1990 The Linde Group has been pioneering the use of oxyfuel heating which is by now common practice in the steel industry. Increased throughput and flexibility, reduced fuel consumption and decreased emissions of $CO_2$ and $NO_x$ are the main reasons why the use of oxyfuel-based heating has become increasingly popular. In parallel to the usage of conventional oxyfuel, flameless oxyfuel combustion has proved to offer great advantages. Since 2003, more than 30 furnaces within the steel industry have been equipped with this innovative technology – with outstanding results.

*Seit 1990 ist die Linde Group ein Pionier bei der Anwendung von Oxyfuel-Verfahren, die mittlerweile in der Stahlindustrie Verwendung finden. Erhöhte Kapazität und Flexibilität bei reduziertem Brennstoffverbrauch und verringerten Emissionen – besonders von Kohlendioxid und Stickoxiden – sind die Hauptgründe für die steigende Beliebtheit dieser Technik. Neben der konventionellen Oxyfuel-Technik hat sich die flammenlose Oxyfuel-Verbrennung als besonders leistungsfähig erwiesen. Seit 2003 wurden mehr als 30 Stahlwerke mit dieser innovativen Technologie ausgerüstet – mit hervorragenden Ergebnissen.*



Prompted by rapidly rising fuel prices in the 1970s, ways of reducing fuel consumption in reheat and annealing furnaces were first considered within the steel industry. This laid the foundation that led to the use of oxyfuel solutions in rolling mills and forge shops. In the mid-1980s Linde began to equip the first furnaces with oxygen-enrichment systems. These systems increased the oxygen content of the combustion air to 23 – 24 %. The results were encouraging: fuel consumption was reduced and the output, in terms of t/h, increased. In 1990 Linde converted the first furnace to operation with 100 % oxygen, that is, full oxyfuel combustion, at Timken in the USA. For the past 17 years Linde has been pioneering the use of oxyfuel in this field. Today, more than 110 such furnaces are in operation, figure 1.

**1**
A look through the door into the flameless oxyfuel-fired rotary hearth furnace at ArcelorMittal Shelby
Blick durch die Tür in einen flammenlosen, Oxyfuel-befeuerten Drehherdofen bei ArcelorMittal Shelby, USA

### From conventional oxyfuel to flameless oxyfuel combustion

In an air-fuel burner the burner flame contains nitrogen from the combustion air. A significant amount of the fuel energy is used to heat up this nitrogen. The hot nitrogen leaves through the stack, creating energy losses. When avoiding the nitrogen ballast,

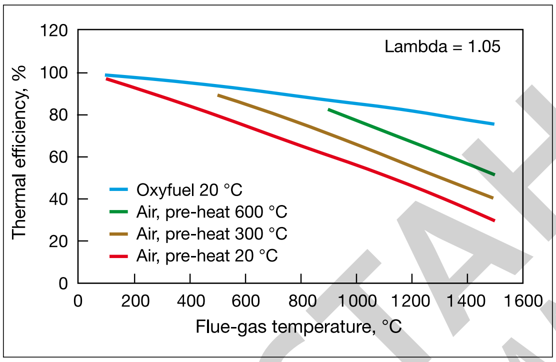
| Recuperator | | AF No | AF Yes | Rebox No |
|---|---|---|---|---|
| Enthalpy in steel | kWh/t | 200 | 200 | 200 |
| Transmission losses | kWh/t | 10 | 10 | 10 |
| Flue-gas enthalpy | kWh/t | 290 | 140 [1)] | 50 |
| Flue-gas temperature | °C | 1 200 | 850 | 1 200 |
| Air preheating | °C | 20 | 450 | 20 |
| Thermal efficiency | % | 42 | 70 | 80 |
| Energy need | kWh/t | 500 | 350 | 260 |

AF: air-fuel; [1)] including waste heat recuperation.

**2**

Comparison of typical energy needs for reheating of steel using air-fuel (with and without recuperation) and oxyfuel [2]

Vergleich des typischen Energiebedarfs zum Erwärmen von Stahl bei der Nutzung der Luft-Brennstoff-Befeuerung (mit und ohne Rekuperator) und der Oxyfuel-Befeuerung [2]




**3**

Comparison of overall thermal efficiency when using air-fuel and oxyfuel

Vergleich der Wärmewirkungsgrade von Luft- und Oxyfuel-Befeuerung

by the use of industrial grade oxygen, then not only the combustion itself is more efficient but also the heat transfer.

Oxyfuel combustion influences the combustion process in a number of ways. The first obvious result is the increase in thermal efficiency due to the reduced exhaust gas volume, a result that is fundamental and valid for all types of oxyfuel burners. Additionally, the concentration of the highly radiating products of combustion, $CO_2$ and $H_2O$, is increased in the furnace atmosphere. For melting and heating furnace operations these two factors lead to a higher melt or heating rate, fuel savings, lower $CO_2$ emissions and – if the fuel contains sulphur – lower $SO_2$ emissions. For continuous heating operations it is also possible to economically operate the furnace at a higher temperature at the entry (loading) side of the furnace. This will even further increase the possible throughput in any furnace unit. Oxyfuel combustion allows all installation pipes and flow trains to be compact without any need for recuperative or regenerative heat recovery solutions. Combustion air-blowers and related low frequency noise problems are avoided, figure 2.

Two features of oxyfuel combustion process need to be addressed: the increase in flame temperature and the subsequent potential of thermal $NO_x$ forming. It is important to note that $NO_x$ formation is highly dependent on the design of the oxyfuel burner, furnace specifics and the process control system. In fact, oxyfuel combustion has been used for many years to reduce $NO_x$ emissions to meet environmental regulations, figure 3.

## Lowering of $NO_x$ emissions

The legislation relating to $NO_x$ 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 $CO_2$. Bearing this in mind, development work started in collaboration with customers to find even more effective oxyfuel solutions.

Three things control the formation of thermal $NO_x$: partial pressure of oxygen, partial pressure of nitrogen, and combustion temperature, that is, $NO_x$ formation temperature. For each of these prerequisites there are different measures that can be undertaken to minimise the formation of $NO_x$. Therefore it is possible to formulate a strategy for each of these by the following measures:

– partial pressure of oxygen (ensure a well-functioning combustion and 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 (flameless combustion).

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

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combustion was an important first step to achieve reduced $NO_x$ emissions. However, due to continuing lower emission permit levels, further technical developments were needed.

### Flameless oxyfuel – faster and more uniform heating, ultra low $NO_x$

As previously mentioned, a key parameter in achieving low $NO_x$ is reduction of flame temperature. Below a temperature of approximately 1 400 °C $NO_x$ formation is limited, but above this temperature a dramatic increase in $NO_x$ 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, figure 4.

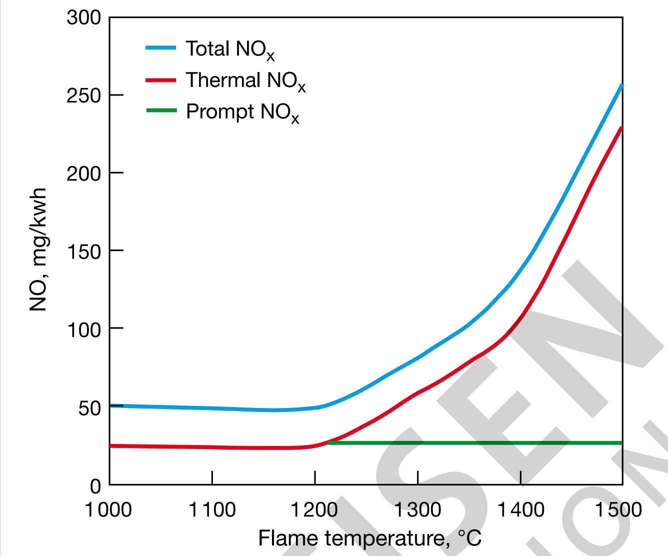
The expression "flameless combustion" communicates the visual aspect of the combustion type, that is, the flame is no longer seen or easily detected by the human eye. Another description might be that combustion is "extended" in time and space – it is spread out in large volumes, and this is why it is 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. The mixture of fuel and oxidant reacts uniformly through flame volume, with the rate controlled by partial pressures of reactants and their temperature.

In flameless oxyfuel combustion the flame is diluted by the hot furnace gases. This reduces the flame temperature to avoid creation of thermal $NO_x$ and to achieve more homogenous heating of the steel.

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.

With the low flame temperatures of flameless oxyfuel, formation of thermal $NO_x$ is avoided. This was confirmed in an investigation carried out by the Royal Institute of Technology in Stockholm, Sweden. Trials in a pilot-scale furnace showed that even with large volumes of ingress air entering the furnace $NO_x$ levels remained low. This is a typical problem for old and continuous type furnaces. Conventional oxyfuel and regenerative air-fuel technology created similar $NO_x$ levels, higher than flameless oxyfuel, figures 5 and 6.

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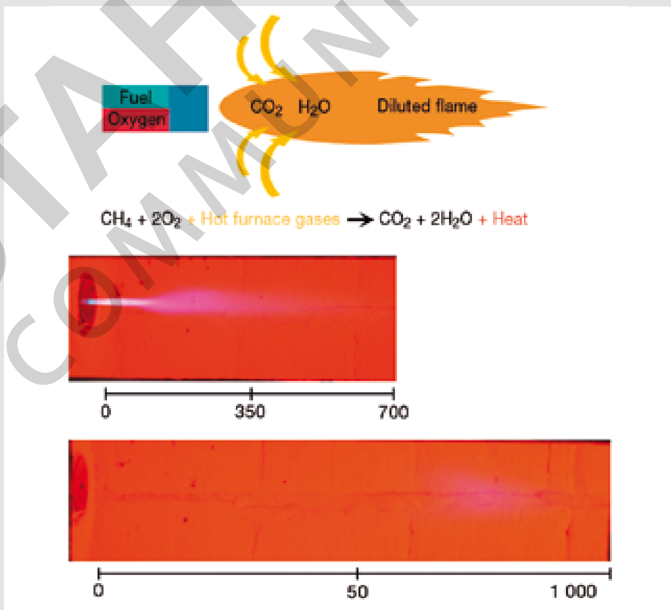
$NO_x$ formation in relation to the flame temperature

Bildung von $NO_x$ in Abhängigkeit von der Flammentemperatur

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In flameless oxyfuel combustion the flame is diluted by the hot furnace gases. This reduces the flame temperature to avoid creation of thermal $NO_x$ and to achieve more homogenous heating of the steel. A forerunner to flameless oxyfuel to solve the $NO_x$ issue is shown in the middle photo, staged oxyfuel combustion (here with 5 % primary oxygen). The lower photo shows flameless oxyfuel combustion with a diluted and almost transparent flame [5]

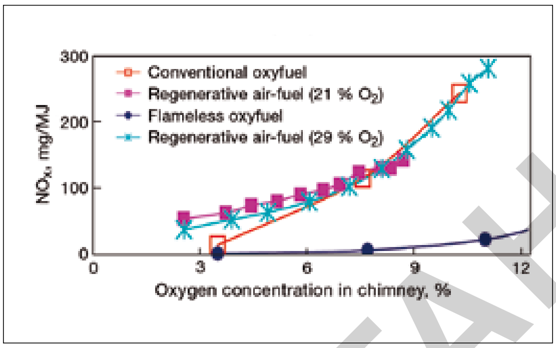
Bei der flammenlosen Oxyfuel-Verbrennung wird die Flamme mit den heißen Ofenabgasen vermischt. Dadurch wird die Flammentemperatur reduziert, die Bildung von thermischem $NO_x$ verhindert sowie eine homogene Erwärmung des Stahls erreicht. Das Vorstadium der flammenlosen Verbrennung zur Reduzierung der $NO_x$-Probleme (mit 5 % Primärsauerstoff) wird im mittleren Foto gezeigt. Das untere Foto zeigt die vollständige flammenlose Verbrennung mit der vermischten und annähernd transparenten Flamme [5]

### Power in a small package, also for poor fuels

Oxyfuel burners have always been powerful and compact, and the new generation of flameless oxyfuel burners has maintained its compact design to facilitate exchange of already installed oxyfuel burners and for easy retrofit of air-fuel installations.

There seems to be an increasing need to combust low calorific fuels. For fuels containing below 2 kWh/m$^3$, use of oxygen is an absolute requirement. Flameless oxyfuel can be successfully employed here. At integrated steel mills the use of blast furnace top gas (<1 kWh//m$^3$), alone or in combination with other external or internal fuels, is becoming increasingly important.

Low calorific fuels like, for example, blast furnace top gas, not only have a low energy density meaning that large volumes have to be transported, the situation is further accentuated by the fact that, as frequently being flue-gases, they have a low pressure that is costly to increase, figure 7.




6

Emissions for conventional oxyfuel are comparable to regenerative air-fuel technology, whereas flameless oxyfuel remains almost insensitive to ingress air [6]

Die Emissionen der konventionellen Oxyfuel-Technik sind vergleichbar mit denen regenerativer Luftbefeuerung, während sie bei flammlosem Oxyfuel kaum auf den Luftzustrom reagieren [6]

### Examples of installations

Linde has undertaken over 30 installations of flameless oxyfuel at more than a dozen different sites. Below are some examples of these installations and what has been achieved is described briefly. Most of the installations relate to reheating and annealing, but some are also employed for preheating of vessels.

**Walking beam and catenary furnaces at Outokumpu.** In 2003, a walking beam furnace in Degerfors, Sweden, was rebuilt and refurbished in a Linde turnkey project with performance guarantees. It entailed replacing the air-fuel system (including recuperator) with flameless oxyfuel, and installation of essential control systems. The resultant 40 – 50 % increase in heating capacity provided increased loading of the rolling mill, reduction of over 25 % in fuel consumption and $NO_x$ emissions below 70 mg/MJ, figure 8.

At the Nyby plant, there are two catenary furnaces, originally installed in 1955 and 1960 respectively. The catenary furnace on the first annealing-pickling line, for hot or cold rolled strips, was converted to all oxyfuel operation in 2003. Requirements for increased production combined with stricter requirements for low $NO_x$ emissions led to this decision. The furnace, 18 m long, was equipped with flameless oxyfuel burners. The total power input, 16 MW, was not altered when converting from air-fuel to oxyfuel, but with oxyfuel the heat transfer efficiency increased from





7

The photo to the left shows a 3 MW, self-cooled ceramic flameless oxyfuel burner. The photo to the right shows a compact 5 MW water-cooled flameless oxyfuel burner. Both are equipped with an integrated UV cell and a pilot burner. The reference object in the photos is a matchbox

Links ein selbstkühlender, keramischer flammloser Oxyfuel-Brenner mit 3 MW; rechts ein kompakter, wassergekühlter Typ mit 5 MW. Beide sind mit einer integrierten UV-Zelle und Pilotbrenner ausgestattet; zum Größenvergleich dient eine Streichholzschachtel

46 to 76 %. The replacement of the air-fuel system, combustion blowers and recuperators resulted in a 50 % increase in heating capacity without any increase in the length of the furnace, a 40 % reduction in specific fuel consumption, $NO_x$ levels are below the guaranteed level of 70 mg/MJ, figure 9.

At the Avesta Works, stainless sheets are hot-rolled in the Steckel mill and cold-rolled in the Z-high mill. At Avesta Works we also find the world's largest oxyfuel-fired furnace, 40 MW. The old 24 m furnace had a 75 t/h capacity, but the requirement was to double this whilst at the same time meeting strict requirements for emissions. The refurbishment included a 10 m extension, yet production capacity was increased to 150 t/h. The conversion involved the removal of air-fuel burners and recuperators and the installation of all oxyfuel. The oxyfuel technology used involved staged combustion. The conversion reduced fuel consumption by 40 %, $NO_x$ levels are below 65 mg/MJ. This furnace is an example of another route to flameless; having been converted from conventional oxyfuel to flameless oxyfuel last year.

8

Outokumpu in Sweden increased their heating capacity in the existing walking beam furnace by 40 – 50 % when implementing flameless oxyfuel. With this investment in an existing furnace, the plate mill could accumulate production volumes from another site

Outokumpu steigerte die Wärmekapazität im vorhandenen Hubbalkenofen in Schweden nach der Installation von flammenlosen Oxyfuel-Brennern um 40 – 50 %. Mit dieser Investition am vorhandenen Ofen konnte das Grobblechwalzwerk zusätzlich Material aus anderen Werken verarbeiten

**Soaking pit furnaces at Ascométal.** Linde also undertook flameless oxyfuel installations at two sites belonging to the bearing steel producer Ascométal, part of the Severstal Group. At Fos-sur-Mer in France, a turn-key delivery in 2005 – 2007 converted nine soaking pit furnaces into all flameless oxyfuel. The delivery included a combustion system with flameless burners, furnace upgrade, new flue gas system, flow train, and a control system. The furnace sizes are 80 to 120 t heating capacity each. The results include 50 % more heating capacity, 40 % fuel savings, $NO_x$ emission reduced by 40 %, and scale formation reduced with 3 t per 1 000 t heated, figure 10.

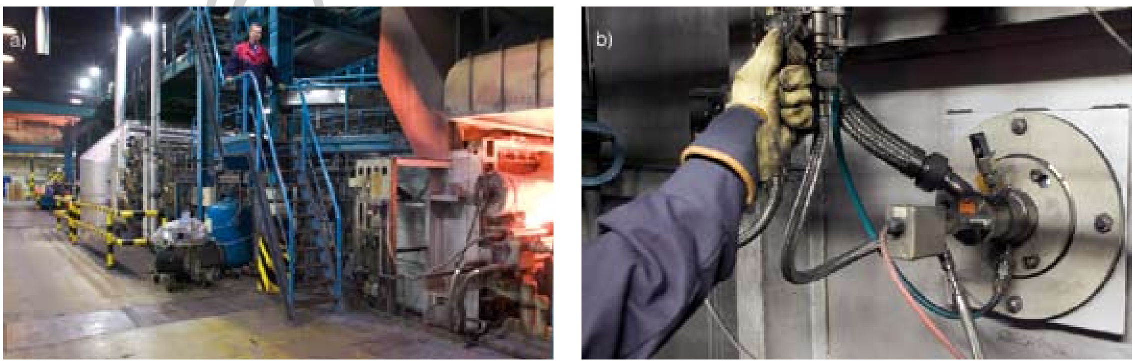
In a second and similar project in France in 2007 and 2008, four soaking pit furnaces at the Les Dunes plant were also converted into all flameless oxyfuel operation.

**Rotary hearth furnace at ArcelorMittal Shelby.** In 2007, Linde delivered a turnkey conversion of a 15 m diameter rotary hearth furnace at this seamless tube producer in the USA. It included combustion system with flameless burners, furnace upgrade, new flue gas system, flow train, and a control system.

The former air-fuel fired furnace was converted in two steps, first using oxygen-enrichment for a period of time and then implementation of the flameless oxyfuel operation.

Excellent results have been achieved, meeting all performance guarantees. These included >25 % more throughput, 50 % fuel savings (from enrichment), $NO_x$ emission <70 mg/MJ, and 50 % reduced scale formation.

**Vessel preheating.** At Acerinox, Spain, 90 t ladles are dried and preheated with a 2 MW flameless oxyfuel burner. When drying the ladles from cold status to the final temperature of 1 175 °C an average thermal efficiency of 84 % is reached. The preheating normally starts at about 900 °C in the incoming ladles, and after about 1 hour 1 175 °C is achieved.

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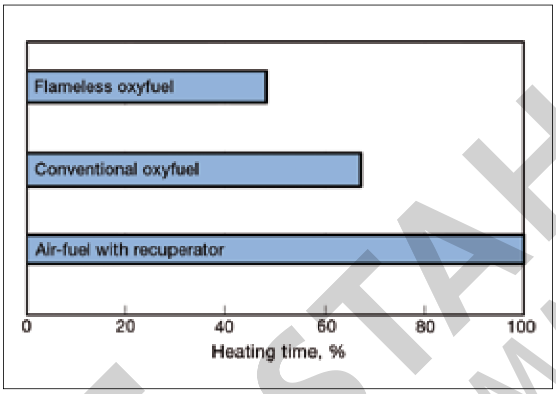
Flameless oxyfuel burner installation at Outokumpu, Nyby

Installation eines flammlosen Oxyfuel-Brenners bei Outokumpu in Nyby

**10**
An ingot is lifted out of one of the pit furnaces at the Fos-sur-Mer plant
Entnahme einer Bramme aus einem der Tieföfen im Ascométal-Werk in Fos-sur-Mer




**11**
Comparison of total heating time at Ovako Hofors Works using different combustion technologies
Vergleich der gesamten Aufwärmzeit bei der Nutzung verschiedener Verbrennungstechnologien, Werk Ovako, Hofors

At Outokumpu, Avesta, Sweden, 90 t ladles have been preheated with a 1.5 MW flameless oxyfuel burner since 2004. At Sandvik, Sweden, an 80 t AOD converter has been preheated with a 1.4 MW flameless oxyfuel burner since 2003. The flameless oxyfuel system replaced an old 6 MW air-fuel burner system. The heating time was reduced from 13 h to 10 h, that is, a reduction in fuel consumption of >80 % and, at the same time, a heating time reduction of 23 %. Flameless oxyfuel is also successfully employed for vessel preheating at Ovako and Kanthal. Outokumpu at Tornio, Finland, is the latest operation choosing this technology.

## Summary

Flameless oxyfuel combustion has such major advantages that this process is likely to be installed for most applications. The advantages of conventional oxyfuel combustion are combined with those of flameless combustion to produce improved and more uniform heating and reduced $NO_x$ emissions. The latter advantage is normally important in the case of large, continuously operating reheat and annealing furnaces but is also relevant to other heating processes, for example the drying and preheating of ladles and other vessels.

A very good example of the impact of flameless oxyfuel can be found at Ovako's Hofors Works in Sweden. The first use of oxyfuel in reheating operations dates back to 1994, and since then a large number of soaking pits and rotary hearth furnaces have been converted to conventional oxyfuel. However, in 2006, flameless oxyfuel began to be used, and installations with conventional oxyfuel were then converted to flameless operation. In addition to further decreasing the total heating time by 15 %, the flameless oxyfuel also delivered more uniform heating, an additional fuel saving of 17 %, and 5 – 20 % less scaling, figure **11**.

The development of flameless oxyfuel combustion has been brought forward in close cooperation with steel producers, that is, the users, to meet their needs. It builds on the many proved advantages of oxyfuel over air-fuel, which has been well known for years. In the commercial installations, from 2003 onwards, it has been clearly proved flameless oxyfuel has taken this a step further, with even higher production rates, decreased fuel consumption, thus reduced $CO_2$ emission, very low $NO_x$ emission and uniform heating.

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