

## **Substantial Reduction of Fuel Consumption, CO<sub>2</sub> and NO<sub>x</sub> Emissions When at Same Time Increasing Production Capacity**

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### **Abstract**

Heating and melting with oxyfuel have been used in the steel industry for decades, however, mainly in the areas of scrap melting and vessel preheating. Since 1990 Linde has been pioneering the use of oxyfuel heating in reheat furnaces and annealing lines, and made more than 110 furnace installations of its REBOX<sup>®</sup> oxyfuel solutions.

Increased throughput and flexibility, reduced fuel consumption and decreased emission (much less CO<sub>2</sub> and NO<sub>x</sub>) are the main reasons the use of oxyfuel based heating become increasingly popular.

In parallel to the conventional oxyfuel there are today established very interesting technologies; one of the most important ones being flameless oxyfuel combustion. This technology has been proven to deliver outstanding results, in reheating, annealing and vessel preheating.

In addition to the great advantages of conventional oxyfuel, flameless oxyfuel provides even higher production rates, excellent temperature uniformity and very low NO<sub>x</sub> emissions. The first installations of flameless oxyfuel took place in 2003. Today more than 30 furnaces have been equipped with flameless oxyfuel.

The results can be summarized as:

- Capacity increase by up to 50%
- Fuel savings of up to 50%
- Reduction of CO<sub>2</sub> emission by up to 50%
- Reduction of NO<sub>x</sub> emission (guaranteed level below 70 mg/MJ)

The paper describes the state-of-the-art of flameless oxyfuel heating technology, including results from several installations, and discusses their future very interesting possibilities to make the steel production more effective.

## Introduction

In heating, the largest impact on fuel and CO<sub>2</sub> savings is achieved by replacing air-fuel combustion with oxyfuel combustion. [1] The oxyfuel combustion offers clear advantages over also state-of-the-art air-fuel combustion, e.g., regenerative technology, in terms of energy use, maintenance costs and utilization of existing production facilities. Oxyfuel combustion is a very good example of how an already well established and proven technology can make great contributions to reduce fuel consumption and CO<sub>2</sub> emissions if implemented further. If all the reheating and annealing furnaces would employ oxyfuel combustion, the CO<sub>2</sub> emissions from the world's steel industry would be reduced by 100 million tonnes per annum.

Linde's experience from converting furnaces into all oxyfuel operating shows energy savings ranging from 20% to 70%. It should be noted that the total energy saving is actually greater than what could be read on the meter at the furnace, the energy needed to bring the natural gas, for example, to its used in the furnace is of course also saved. 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 tonnes per hour, increased. In 1990 Linde converted the first furnace to operation with 100% oxygen, that is, full oxyfuel combustion, at Timken in USA.

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, by the use of industrial grade oxygen, then not only is the combustion itself 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<sub>2</sub> and H<sub>2</sub>O, 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<sub>2</sub> emissions and – if the fuel contains sulphur – lower SO<sub>2</sub> emissions. Today's best air-fuel solutions need at least 1.3 GJ for heating a tonne of steel to the right temperature for rolling or forging. When using Linde's REBOX<sup>®</sup> the comparable figure is below 1 GJ, a saving of 25%, cf. Table 1. 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.

Table 1. Comparison of energy needs for reheating of steel using air-fuel (with and without recuperation) and oxyfuel. AF = air-fuel; \* = including waste heat recuperation.

REBOX<sup>®</sup> is Linde's trademark for oxyfuel solutions in reheating and annealing. [2]

Recuperator		AF No	AF Yes	REBOX <sup>®</sup> No
Enthalpy in steel	kWh/t	200	200	200
Transmission losses	kWh/t	10	10	10
Flue-gas enthalpy	kWh/t	290	140*	50
Flue-gas temperature	°C	1,200	850	1,200
Air preheating	°C	20	450	20
Thermal efficiency	%	42	60	80
<b>Energy need</b>	<b>kWh/t</b>	<b>500</b>	<b>350</b>	<b>260</b>

Two features of oxyfuel combustion process need to be addressed: the increase in flame temperature and the subsequent potential of thermal NO<sub>x</sub> forming. It is important to note that NO<sub>x</sub> 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<sub>x</sub> emissions to meet environmental regulations.

Flameless oxyfuel – faster and more uniform heating, ultra low NO<sub>x</sub>

As previously mentioned, a key parameter in achieving low NO<sub>x</sub> is reduction of flame temperature. Below a temperature of approximately 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' 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, yet containing same amount of energy. See Figure 1. 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<sub>x</sub> and to achieve more homogenous heating of the steel. Low NO<sub>x</sub> emission is also important from a global warming perspective; NO<sub>2</sub> has a so-called Global Warming Potential that is 296 times that of CO<sub>2</sub>.

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. A comparison of the results from the installations at Ovako’s Hofors Works shows the difference in reality, see Figure 2.

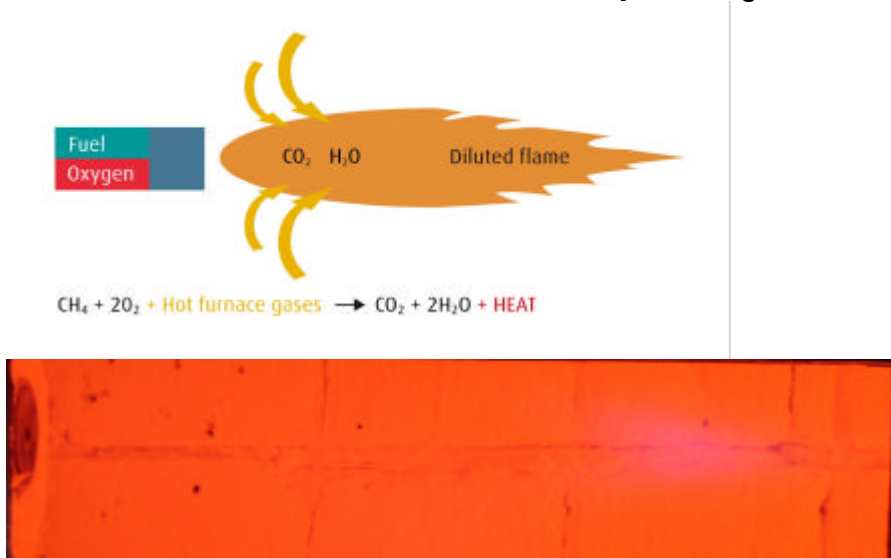


Figure 1. In flameless oxyfuel combustion the flame is diluted by the hot furnace gases. This reduces the flame temperature to avoid creation of thermal NO<sub>x</sub> and to achieve more homogenous heating of the steel. The photo shows flameless oxyfuel with a diluted and almost transparent flame. [3]

With the low flame temperatures of flameless oxyfuel, formation of thermal NO<sub>x</sub> is avoided. This was confirmed in an investigation carried out by the Royal Institute of Technology in Stockholm, Sweden. [4] Trials in a pilot-scale furnace showed that even with large volumes of ingress air entering the furnace NO<sub>x</sub> levels remained low. This is a typical problem for old and continuous type furnaces. Conventional oxyfuel and regenerative air-fuel technology created similar NO<sub>x</sub> levels, higher than flameless oxyfuel.

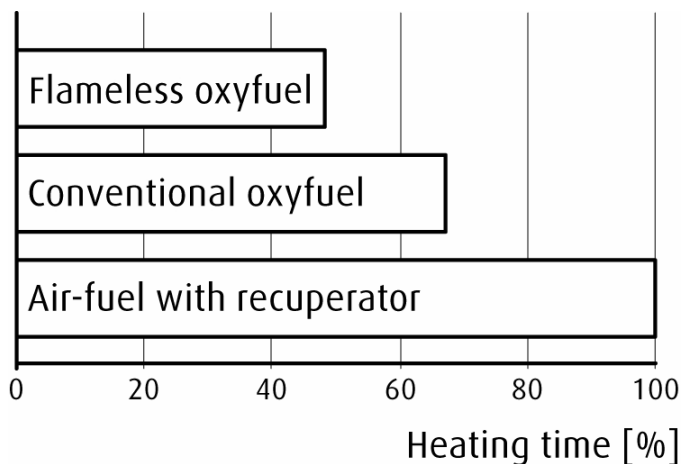


Figure 2. Comparison of total heating time at Ovako’s Hofors Works using different combustion technologies. [5]

### **Also for Low calorific Fuels**

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

Today there are 115 reheat furnaces and annealing lines using Linde's oxyfuel solutions. During the last years flameless oxyfuel have been employed. Such flameless oxyfuel installations are either up and running or under installation at the following steel companies: ArcelorMittal, Ascométal (SeverStal), Böhler-Uddeholm (Voestalpine), Cosipa, Dongbei Special Steel, Outokumpu, Ovako, Scana Steel and SSAB. Below is presented examples from installations in France, Sweden and USA.

#### **Ascométal, France, soaking pit furnaces [6]**

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, a turn-key delivery in 2005-2007 converted 9 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 tonne heating capacity each. The results include 50% more heating capacity, 40% fuel savings, NO<sub>x</sub> emission reduced by 40%, and scale formation reduced with 3 tonne per 1,000 tonne heated.

In a second and similar project in France in 2007-2008, 4 soaking pit furnaces at the Les Dunes plant, were also converted into all flameless oxyfuel operation.

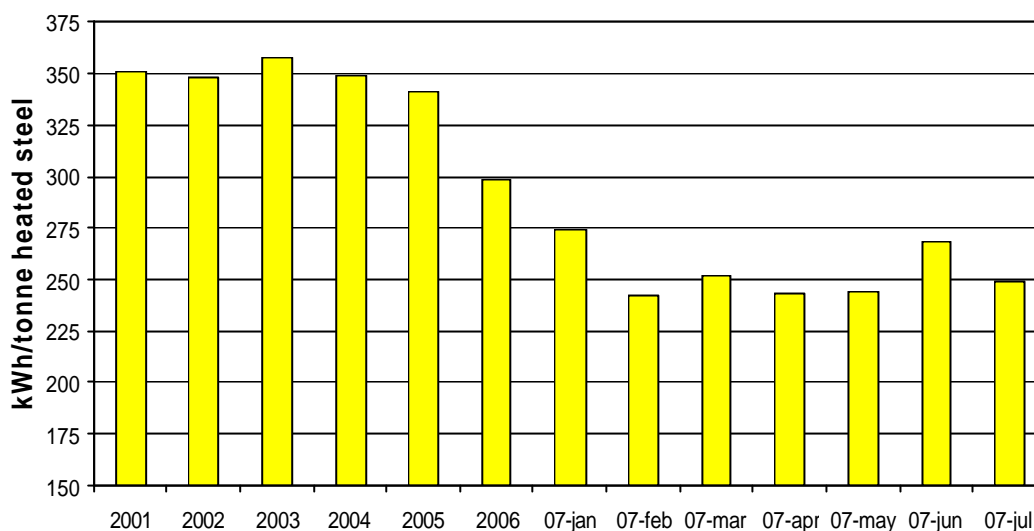


Figure 3. The diagram shows total average fuel consumption in the 13 soaking pit furnaces at Ascométal, Fos-sur-Mer. 2001-2004 was all air-fuel combustion. The first conversion into oxyfuel took place in 2005. In 2007 nine out of 13 furnaces were operated with all oxyfuel. The average fuel consumption per tonne was reduced by 100 kWh or 10 Nm<sup>3</sup> of natural gas.

### Outokumpu, Sweden, walking beam and catenary furnaces [7]

In 2003, a walking beam furnace in Degerfors 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<sub>x</sub> emissions below 70 mg/MJ.

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<sub>x</sub> 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 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<sub>x</sub> levels are below the guaranteed level of 70 mg/MJ.

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 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<sub>x</sub> 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.



*Figure 4. Outokumpu in Sweden increased its heating capacity in the existing walking beam furnace by 40-50% when implementing flameless oxyfuel. With this investment in an existing furnace plate mill could accommodate production volumes from another site.*

### **ArcelorMittal Shelby, USA, rotary hearth furnace [8]**

In 2007, Linde delivered a turnkey conversion of a 15-metre diameter rotary hearth furnace at this seamless tube producer. 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<sub>x</sub> emission <70 mg/MJ, and 50% reduced scale formation.



Figure 5. A look through the door and outside views of the REBOX<sup>®</sup> installation in a rotary hearth furnace at ArcelorMittal Shelby.

### Flue-gas volumes and CO<sub>2</sub> emissions

Use of oxyfuel combustion instead of air-fuel does not only lead reduced CO<sub>2</sub> emissions, but also to substantially lower off-gas volumes to handle. Additionally, the CO<sub>2</sub> concentration in the off-gas is high, which makes it suitable for further processing if wanted. Table 2 shows a comparison between air-fuel and Linde's REBOX<sup>®</sup> oxyfuel heating in a real case with a 200 t/h slab reheating furnace.

Table 2. Comparison of fuel consumption and flue-gas volume for a 200 t/h continuous slab reheating furnace.

		Air-fuel	REBOX <sup>®</sup>	
Natural gas	Nm <sup>3</sup> /t	40	30	-25%
Natural gas	Nm <sup>3</sup> /h	8,000	6,000	-25%
Flue-gas volume	Nm <sup>3</sup> /h	83,000	18,000	-78%

Figure 6 provides further illustration to the difference. Here it is assumed same production, e.g., steel reheating in two cases, which would require a power 10 MW if firing with air-fuel. The corresponding power when employing oxyfuel would be 6.7 MW. It is very interesting to note the difference in flue-gas volumes. Assuming the flue-gas should be further treated, it is reasonable to look at the dry gas volume. As can be read from the figure the dry flue-gas volume contains 96% CO<sub>2</sub>.

Accordingly it can be concluded that using oxyfuel instead of air-fuel in reheating would lead to the following benefits relating to energy and CO<sub>2</sub> emission:

- Fuel savings of up to 50%
- Reduction of CO<sub>2</sub> emissions by up to 50%
- A flue-gas volume that is 75-85% smaller and having a CO<sub>2</sub> content of 95% (dry)

This small flue-gas stream with a high CO<sub>2</sub> content should be very suitable for cleaning, storage and sequestration.



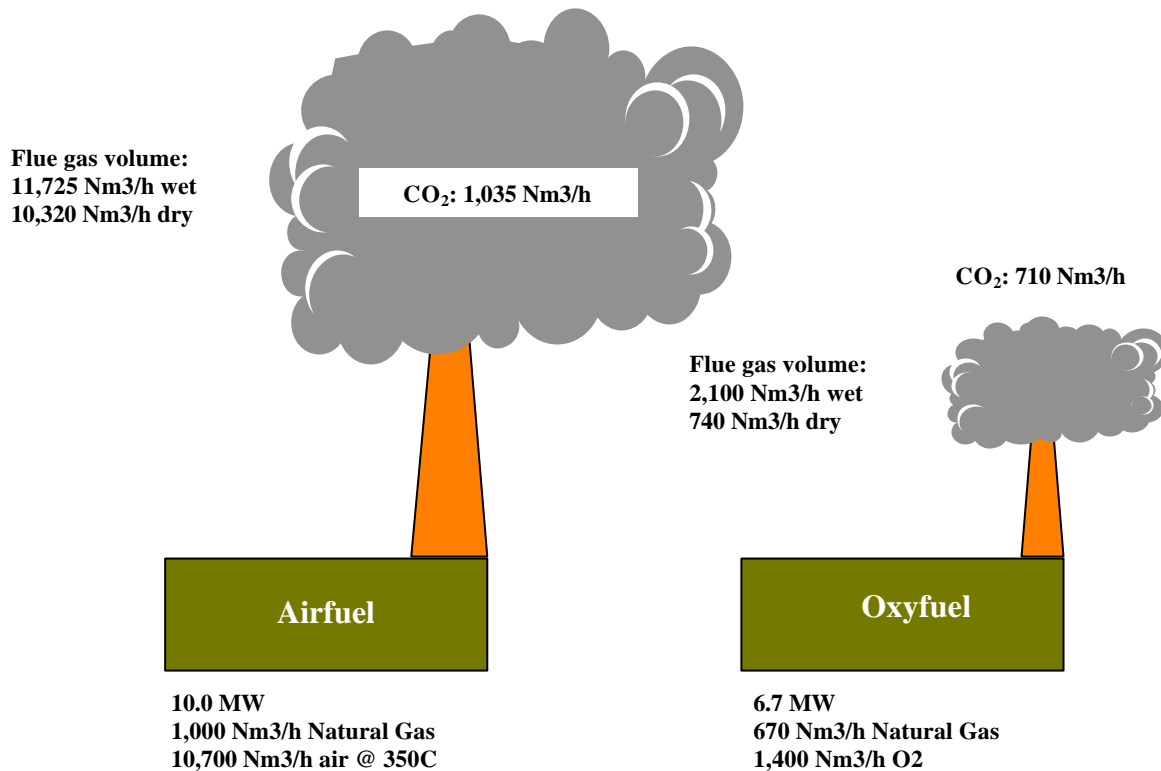


Figure 6. The picture compares two cases. The required power is 10 MW if firing with air-fuel, which is the baseline. The corresponding power when employing oxyfuel would be 6.7 MW. For these two cases, which are assumed to give the same heating results, the flue-gas volumes and compositions, respectively, are indicated.

It is of course appropriate to comment on the CO<sub>2</sub> emissions relating to oxygen production. However, it is clearly shown that this impact is much smaller than what could be saved from employing oxyfuel combustion in the heating. [9]

## Conclusions

Flameless oxyfuel combustion, as applied within Linde's REBOX<sup>®</sup> solutions, has major advantages over conventional oxyfuel and, even more, over any kind of air-fuel combustion. [10] Oxyfuel gives an overall thermal efficiency in the heating of 80%, air-fuel reaches 40-60%. With flameless oxyfuel, compared air-fuel, the energy savings in a reheating furnace are at least 25%, but many times 50% or even more.

The corresponding reduction in CO<sub>2</sub> emissions is also 25-50%. If all the reheating and annealing furnaces would employ oxyfuel combustion, the CO<sub>2</sub> emissions from the world's steel industry would be reduced by 100 million tonnes per annum.

With oxyfuel it is possible to increase the throughput rate – which can be used for increased production, less number of furnaces in operation, increased flexibility, etc. – by up to 50%.

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