

INCREASED EFFICIENCY IN HEATING: STATE-OF-THE-ART OXYFUEL COMBUSTION

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ABSTRACT

Increased throughput and flexibility, reduced fuel consumption and decreased emissions of greenhouse gases are the main reasons the use of oxyfuel based melting and heating become increasingly popular.

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 23-24%. In 1990 AGA converted the first furnace to operation with 100% oxygen, i.e. full oxyfuel combustion. For the past 20 years AGA (Member of The Linde Group) has been pioneering the use of oxyfuel in this field. The technology is used in iron, steel, aluminium, copper and glass manufacture. As of today, Linde has made more than 115 furnace installations of its REBOX[®] oxyfuel solutions in reheating and annealing. Linde has not only the experience from all these installations, but is also a forerunner in combustion technology development in this area.

New demands and challenges from the industry have been met by a continuous development work. As a result, in parallel to the conventional oxyfuel – for example widely used to boost melting in electric arc furnaces – there are today established very interesting technologies. Among those, the most important ones seem to be flameless combustion and direct flame impingement. These new technologies not only fulfil the existing needs with astonishing results, they also open up for completely new areas of application.

The paper describes the state-of-the-art of oxyfuel technology, including references from steel and non-ferrous production.

INTRODUCTION

Combustion is all about fuel, oxygen and ignition. Air contains only 21% oxygen, the remaining 79% is ballast, practically nitrogen. In combustion processes all this ballast is negative; it does not take part in the combustion, but has to be heated up, consuming unnecessary extra fuel. The ballast also has to be transported by electrical blowers, through oversized ducting and burners, in long furnaces and flue gas systems that are much larger in size than with using only oxygen. This has a negative impact on the capital requirements and using air will substantially increase the production of NO_x.

OXYFUEL COMBUSTION

It is a fact that only 3 things are needed to start and sustain combustion, namely oxygen, fuel and energy that is sufficient for ignition. Nitrogen is not one of them.

When firing 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: 8 molecules of N₂ per molecule of CH₄. 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.¹

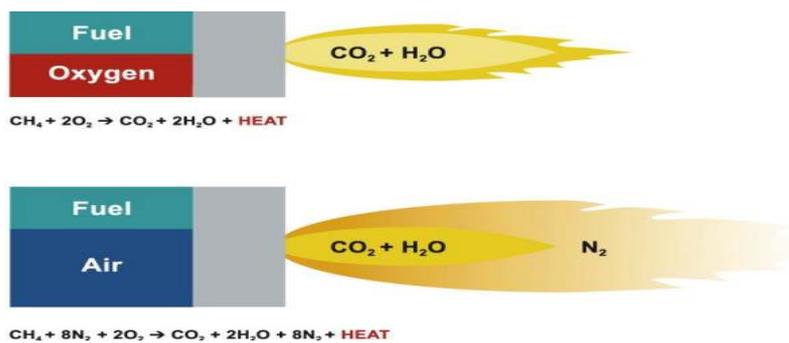


Figure 1. Due to its basic features, oxyfuel combustion provides energy savings, increased production and lowered emission.

The combustion process itself will be most efficient if fuel and oxygen can meet and react without restrictions. 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.

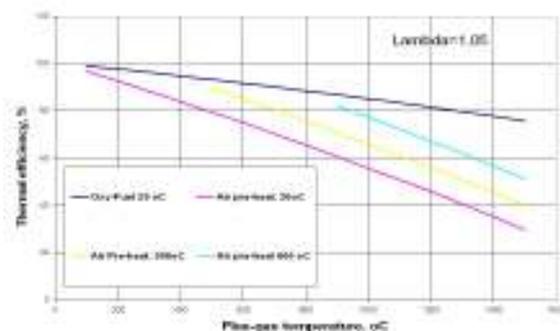


Figure 2. Comparison of overall thermal efficiency when using airfuel and oxyfuel.

The next result is that the concentration of the highly radiating products of combustion, CO₂ and H₂O, is increased in the furnace atmosphere. For even and efficient heating the characteristics of the gas composition and flow pattern inside the furnace will be of importance. The higher the partial pressure of the combustion products CO₂ and H₂O, the better the heat transfer properties of the gas will be, which is valid for radiation and convection as well as conduction. If the exhaust gases are not diluted with nitrogen the gas phase will take a more active part in the heat transfer process. Not only because the heat conductivity and heat capacity of CO₂ and H₂O are higher, but also because they are 3-atomic gases with ability to take part in heat transfer by radiation.

For melting and heating furnace operations these two factors lead to a higher melt or heating rate, fuel savings, lower CO₂ emissions and – if the fuel contains sulphur – lower SO₂ emissions (Table 1). For continuous heating operations it is also possible to economically operate the furnace at a higher temperature in the beginning 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 frequent noise problems are avoided.

Table 1. Comparison of typical energy needs for reheating of steel using air-fuel (with and without recuperation) and oxyfuel. AF = air-fuel; * = including waste heat recuperation. REBOX[®] is Linde's trademark for oxyfuel solutions in reheating and annealing.²

		AF	AF	REBOX [®]
Recuperator		No	Yes	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	70	80
Energy need	kWh/t	500	350	260
Oxygen production	kWh/t			25

Two features of oxyfuel combustion process need to be addressed: the increase in flame temperature and the subsequent potential of forming thermal NO_x. Conventional oxyfuel combustion can exhibit flame regions with temperatures above 2,000°C.

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 CO₂.

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.

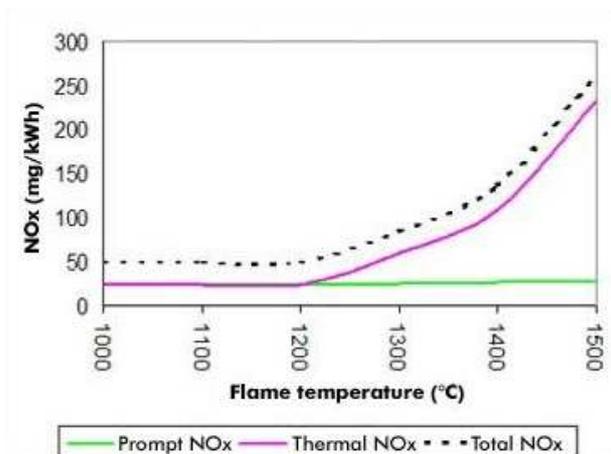


Figure 3. NO_x formation in relation to the flame temperature.³

Three things control the formation of thermal NO_x. For each of these prerequisites there are different measures that can be undertaken to minimise the formation of NO_x. Thus it is possible to formulate a strategy, including – for each of the items – the following measures:

1. 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
2. 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
3. Combustion temperature
 - Burner design

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_x emissions. However, due to authorities' continuously lower emission permit levels, further technical developments had to be taken on.

Flameless oxyfuel – faster and more uniform heating with ultra low NO_x

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:

1. Dilution of the flame by recirculating part of its flue gas to the burner, or
2. Use of separated injection of fuel and oxygen at high velocities.

The combustion occurs under a diluted oxygen concentration by mixing the furnace gases into the combustion zone. This slows down the oxyfuel combustion reactions and results in lower flame temperatures, comparable to those of air-fuel technology, which are below the point at which thermal NO_x is created.

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.

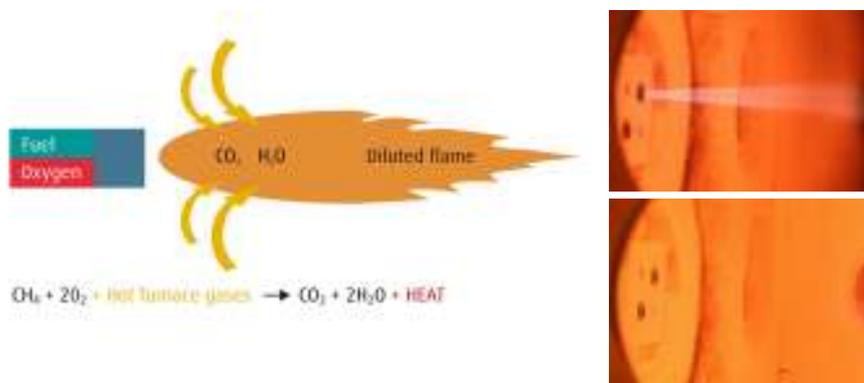


Figure 4. In flameless oxyfuel combustion the flame is diluted by the hot furnace gases. This reduces the flame temperature to avoid creation of thermal NO_x and to achieve more homogenous heating. The top-right photo shows the hot oxyfuel flame coming from the burner on the left. The bottom photo shows flameless combustion – a diluted and almost transparent flame.

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.⁴ Trials in 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 of furnaces. Conventional oxyfuel and regenerative air-fuel technology created similar NO_x levels.⁵

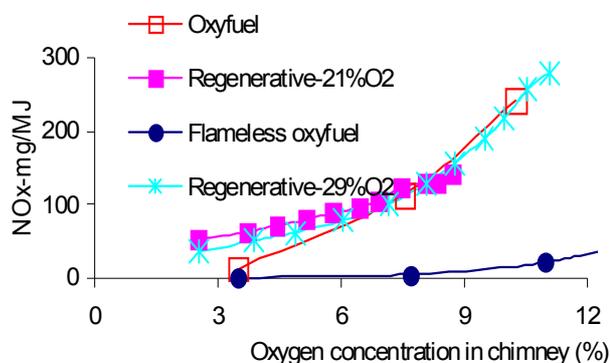


Figure 5. Emissions for conventional oxyfuel are comparable to regenerative air-fuel technology, whereas flameless oxyfuel remains almost insensitive to ingress air.⁵

As a result of the intense development work flameless oxyfuel combustion has now been used for many years to reduce NO_x emissions to meet environmental regulations.

Power in a small package

Flameless oxyfuel burners

Oxyfuel burners have always been both powerful and compact. 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.



Figure 6. The photo to the left shows a 3 MW, self-cooled ceramic flameless oxyfuel burner. To the right is a compact 5 MW water-cooled flameless oxyfuel burner displayed. Both are equipped with an integrated UV cell and a pilot burner. The reference object is a matchbox.

There seems to be an increasing need to also be able to combust low calorific fuels. For fuels containing $<2 \text{ kWh/m}^3$, use of oxygen is a must. Also here flameless oxyfuel can be successfully employed. At integrated steel mills use of blast furnace top gas ($<1 \text{ kWh/m}^3$), alone or in combination with other external or internal fuels, is becoming increasingly important. Low calorific fuels, e.g., blast furnace top gas, not only has a low energy density meaning that large volumes have to be transported, the situation is further accentuated by the fact that they, as frequently being flue-gases, have a low pressure that is costly to increase.

Direct Flame Impingement

Direct Flame Impingement (DFI), where oxyfuel flames directly heat the moving metal, is a patented solution within Linde's REBOX[®] solutions portfolio. The main benefits of DFI oxyfuel are:

- Drastically higher heat transfer resulting in higher capacity and less fuel consumption
- Compact and powerful unit for easy retrofit
- Providing possibility to modify surface conditions

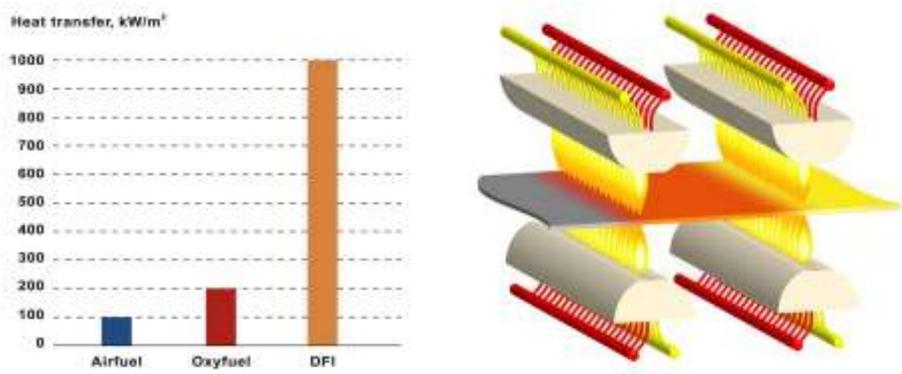


Figure 7. DFI oxyfuel unit, shown in a principle sketch to the right, has a high thermal efficiency of around 80%, higher than electrical pre-heaters, and the very high ability to transfer heat to the material.

Use of DFI reduces the specific fuel consumption while delivering a significant capacity increase. In a galvanising line, for example, additional benefits include improved zinc adhesion and surface appearance; this is due to DFI's effective pre-cleaning properties, leaving both strip and furnace rolls cleaner than before.

RESULTS IN STEEL AND NON-FERROUS PRODUCTION

Many practical cases from production have shown that oxyfuel is a rewarding but also demanding technology. It takes more than oxyfuel burners in a furnace to reach the results that are possible and many factors are influencing the performance of such an installation. For instance furnace pressure control and furnace atmosphere control are two out of many important factors that are important and can be difficult to realize in furnaces that are designed for air-fuel combustion, especially in certain furnace types.

As of today, Linde has made more than 115 furnace installations of its REBOX[®] oxyfuel solutions in reheating and annealing. This in-house furnace and process engineering know how has made Linde a world leader in oxyfuel applications – today Linde can deliver turnkey projects with short implementation time and guaranteed performance.

Since the first flameless oxyfuel installation in 2003, this technology has proven to surpass the already and earlier recognised important benefits of conventional oxyfuel combustion. The results can be summarized as follows:

- More uniform heating for improved downstream processing
- High heat flux with thermal efficiency for increased capacity and flexibility, and shorter heating cycles
- Reduced specific fuel consumption
- Ultra low emissions of NO_x even with ingress air

The following are examples of applying oxyfuel in industrial scale operations.

Electric arc furnaces

The most frequent use of oxyfuel combustion in the steel industry is in the electric arc furnace (EAF), to enhance the melting process. Most of the modern EAFs are today

equipped with oxyfuel burners, frequently using so-called coherent jet technology, i.e., including the possibility to inject high-velocity oxygen through the centre of the flame. For EAFs, conventional oxyfuel is used as it provides the feature of substantially raised flame temperature; the higher the flame temperature, the faster the scrap melting.

Non-ferrous, aluminium industry

With the increasing demands for non-ferrous metals, increasing the throughput of existing melting furnaces represents a challenge for the aluminium industry. Producers also need to constantly improve process yields, cut fuel consumptions and reduce emissions of greenhouse gases.

Flameless oxyfuel combustion technology is uniquely designed for the challenges that exists within the aluminium industry. After implementation of the flameless combustion system the overall results have been more homogenous heating and melting, enabling not only a higher power input and thus higher melt rates, but also reduced formation of dross and NO_x emissions. Also, as some customer cases have proved, it is possible to maintain the level of production with less energy and reduced emissions of greenhouse gases.

Reheating and annealing

Outokumpu Stainless, Sweden, walking beam and catenary furnaces

In 2003, a walking beam furnace in Degerfors was rebuilt and refurbished in a 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.⁶



Figure 8. Outokumpu Degerfors Works increased their 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 accumulate production volumes from another site.

At 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 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. Flameless oxyfuel burner installation at Outokumpu Nyby.

At Avesta Works, stainless sheets are hot-rolled in the Steckel mill and cold-rolled in the Z-high mill. Here can we also find the world's largest oxyfuel fired furnace, 39 MW. The refurbishment included a 10 m extension, yet production capacity was increased from 75 to 150 t/h. 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; stepwise it is now being converted from conventional oxyfuel to flameless oxyfuel.



Figure 10. Flameless oxyfuel burner installation at Outokumpu Avesta Works.

Ascométal, France, soaking pit furnaces

Flameless oxyfuel installations have been made at two sites belonging to the bearing steel producer Ascométal, part of the Severstal Group. At Fos-sur-Mer, a turnkey delivery in 2005-2007 converted 9 soaking pit furnaces into all flameless oxyfuel. The results include 50% more heating capacity, 40% fuel savings, NO_x emission reduced by 40%, and yield improvement – scale formation was reduced with 3 tonne per 1,000 tonne heated.⁷

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

ArcelorMittal, Shelby (OH), USA, rotary hearth furnace

In 2007 a rotary hearth furnace for billet reheating was converted on a turnkey basis. The formerly air-fuel fired furnace was equipped with flameless oxyfuel technology. The conversion was made in two steps: first using oxygen-enrichment for a period of time and then implementation of the all flameless oxyfuel operation. Excellent results have been achieved, fulfilling the performance guarantees, including 25% increased reheating capacity and 50% reduced fuel consumption (from enrichment, 65% compared with air-fuel),. Moreover, the temperature uniformity improved, producing better piercing results. The scale formation was reduced by 50%, and the emission levels of NO_x and CO₂ were significantly minimized.⁸



Figure 11. A look through the door into the flameless oxyfuel fired rotary hearth furnace at ArcelorMittal, Shelby.

DFI - Use in stainless steel strip annealing

In 2002 the first installation of a compact DFI oxyfuel unit took place. It was at Outokumpu's Nyby site in Sweden. It resulted in the possibility to increase the production by 50% without extending the furnace length. It should be noted that this furnace already was all equipped with oxyfuel combustion.

DFI - Galvanising and other coating lines

Recently the REBOX[®] DFI solution was installed at ThyssenKrupp Steel's (TKS) galvanising and aluminising line in Bruckhausen, Germany. This installation was Linde's second of its kind at TKS.

The results at the metal coating line in Bruckhausen are equally good as that at the galvanising line in Finnentrop, which was the first DFI installation for TKS.⁹ At Finnentrop it has resulted in a production increase of 30%, from 82 to 105 t/h. Oxyfuel not only effectively heats – contributing to a reduction of fuel consumption – but also cleans, thus eliminating the need for the 25 m pre-cleaning section. Besides this, it made it possible for ThyssenKrupp to pre-oxidise steel strips in a precise and controlled manner.



Figure 12. A DFI unit is replacing part of the dark-zone in Finntrop boosting output 30%.

Vessel preheating

At Acerinox, Spain, 90 tonne 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. Preheating from about 900°C up to 1,175°C takes about 1 hour.



Figure 13. Ladle drying and preheating with flameless oxyfuel at Acerinox, Spain.

Another installations sites are at Outokumpu Stainless Avesta and Tornio Works, Sandvik Steel, Ovako Hofors and Kanthal where ladles and converters of different sizes are dried and/or preheated with flameless oxyfuel burners.

CONCLUSIONS

Oxyfuel combustion is used all over the world for practically any process with a high demand on productivity, product quality, operational accuracy, flexibility and environment. The utilization of new technology seems to depend on where the first references are established, productivity and environmental demand and where sufficient know-how and support is available close to the process itself.

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 and more uniform heating and reduced 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.

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 air-fuel, which have been well known for years. In the commercial installations, from 2003 and onwards, it has been clearly proven flameless oxyfuel has taken this a step further, with even higher production rates, decreased fuel consumption, thus reduced emission and uniform heating. The fuel savings have been varying depending on the technology used before conversion to oxy-fuel. But in all cases the fuel savings have been major even if the energy needed to produce oxygen is taken into consideration, especially per ton of produced product.

The use of DFI oxyfuel has just started. However, it does not require much imagination to see that it will be become largely used, not only for strip heating relating to annealing and coating of different kinds. A technology that has 10 times the heat transfer than the one in use, is waiting to be fully exploited.

ACKNOWLEDGEMENT

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