



# Fuel Savings and Reduced Emissions: Experience From 80 Oxy-fuel Installations in Reheat Furnaces

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**D**uring the 1970s, heavily increasing energy prices sparked the first interest in reducing the consumption of and dependency on fossil fuels in steel reheat furnaces and annealing lines. Industrial-grade oxygen was

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**Since 1990, Linde Gas has applied oxy-fuel solutions in 80 furnaces in rolling mills, forge shops and annealing lines. Results have shown substantial reductions in fuel consumption and emissions, along with more uniform heating and increased throughput.**

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simply added to the combustion air to cut fuel consumption, although emission results were sometimes poor.

More energy-efficient heating processes and further reductions in emissions were the key issues during the 1980s, resulting in Linde's first 100 percent oxy-fuel installation in 1990 at Timken in the U.S. The new millennium focuses on even lower total costs and faces strict emission controls by legislation.

This article discusses the use of oxy-fuel combustion and its implementation in reheat furnaces and annealing lines, along with important developments and results. Emphasis is placed on the opportunities for reducing both fuel consumption and emissions. The commercial viability of the oxy-fuel application is further demonstrated using important references from a list of more than 80 installations completed since 1990.

## Oxygen — 50 Years of Use in Modern Steelmaking

The increasing use of oxygen in modern steelmaking began more than 50 years ago with the basic oxygen furnace (BOF). The use of oxygen in ironmaking is now commonplace, with the extensive use of oxygen in blast furnaces. The positive aspects of using oxygen in steelmaking were first recognized in 1856, when Sir Henry Bessemer referred to the possibilities of using oxygen in his patent for the Bessemer process. Unfortunately, large volumes of oxygen could not be produced at the time. Carl von Linde changed all this in early 1900 with his patents for large-scale oxygen production. However, it was not until after World War II that large volumes of oxygen began to be used in steelmaking, particularly in the BOF process.

The benefits of using oxy-fuel combustion in steelmaking applications such as boosting in electric arc furnaces and the preheating of vessels (e.g., ladles and converters) are all well documented: reduced fuel consumption, longer furnace life, shorter cycle time and so on. Some examples are indicated in Figure 1.

However, the beneficial results in these applications are still limited compared to the use of oxy-fuel for applications relating to the semifinished steel itself (i.e., in downstream processing in hot rolling, forging and annealing operations). Here, large volumes of steel are heated to high, precisely controlled temperatures in reheat furnaces and annealing lines.



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## Oxy-fuel Combustion Has No Nitrogen Ballast

Only three things are required to start and sustain combustion: fuel, oxygen and sufficient energy for ignition. The combustion process is most efficient if fuel and oxygen can meet and react without any restrictions. In practical heating applications, however, it is not sufficient to consider only efficient combustion; the heat transfer aspect must also be considered.

Oxygen diluted with 78 percent nitrogen and 1 percent argon (i.e., the air that we breathe) will not give optimum conditions for combustion and heat transfer. The nitrogen will be heated in the combustion process, and the energy transferred to the nitrogen must be recovered in order to save fuel<sup>1</sup> (Figure 2).

Heat is transferred to a solid product surface by convection, conduction and radiation. Heat transfer into the product occurs by conduction only. This implies that the product surface (which changes over time when heated), geometry and material, as well as the internal geometry of the furnace, are important.

For even and efficient heating, the gas composition and flow pattern inside the furnace are also of importance. Oxy-fuel combustion has a much higher partial pressure with respect to the two combustion products, CO<sub>2</sub> and H<sub>2</sub>O, compared to air-fuel. This improves heat transfer. As 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 transfer conductivity and the heat capacity of CO<sub>2</sub> and H<sub>2</sub>O are higher, but also because they are both high-heat-radiating 3-atomic gases.

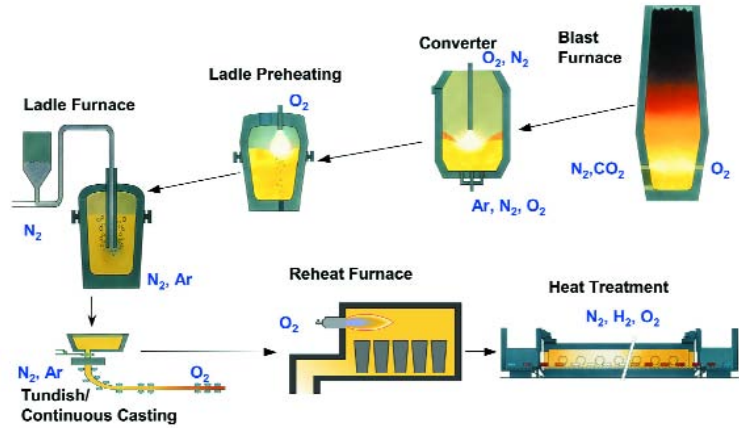
The flow pattern in an oxy-fuel furnace is advantageous compared to that of air-fuel. Exhaust gas volume is reduced by 70–80 percent because no nitrogen is present and because of the fuel savings. Thus, the residence time of the gas will be longer, with more time to transfer heat to the product. The product is in fact immersed in a gaseous exhaust fluid of CO<sub>2</sub> and H<sub>2</sub>O, a moist ambience with a higher heat transfer capacity.

When comparing an oxy-fuel furnace with an air-fuel furnace, both set at the same furnace temperature, the material reaches the setpoint value faster in the oxy-fuel furnace. This is because of the gas properties.

## Lower Specific Fuel Consumption and Reduced Exposure to Fluctuating Fuel Prices

The available heat from oxy-fuel combustion is greater than that from air-fuel. The available heat is greater, as less energy is lost to the flue gases. This directly implies lower specific

Figure 1

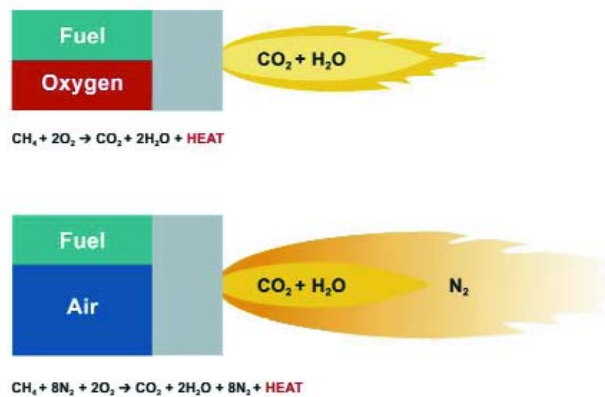


There are currently around 50 options for the beneficial use of industrial gases at integrated steel mills. Oxygen is widely recognized for its benefits and practicality.

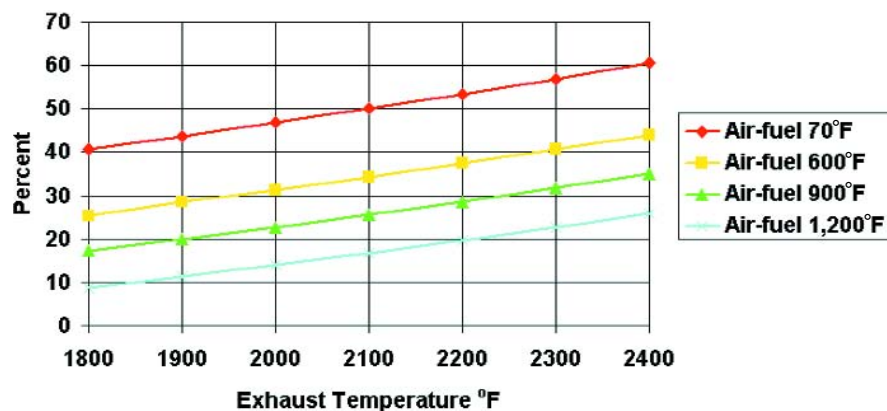
fuel consumption, as indicated in Figure 3. Actual energy savings will vary depending on fuel type, existing combustion ratio and combustion air temperature. Reductions in flue port size and radiation losses are factors that also have an impact on savings.<sup>2</sup> Fuel savings are normally in the range of 25–50 percent, depending on the status and previous heating technology used, but can be less than 0.77 mmBtu/ton steel. Oxy-fuel installations eliminate the need for combustion air fans and flue gas ventilators, resulting in further energy savings.

Energy management in steelmaking is taken seriously, as it reduces fuel costs and environmental impact by reducing the total CO<sub>2</sub> emissions from the production site. Low-calorific gases (such as coke oven gas, blast furnace top gas or BOF gas) can be reutilized in oxy-fuel combustion, as they can provide the flame temperatures needed in heating applications.<sup>3</sup>

Figure 2



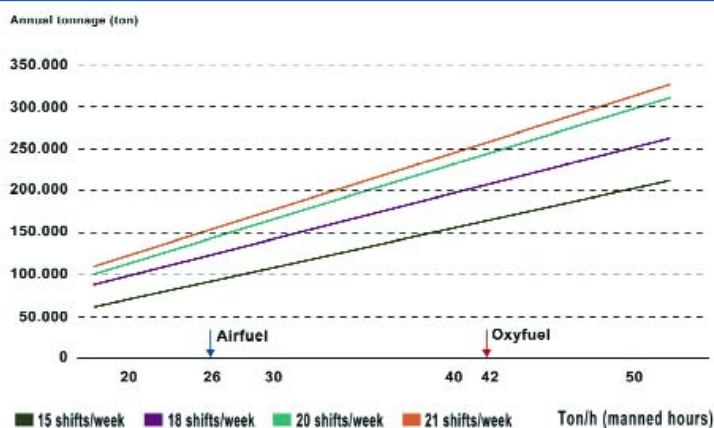
Oxy-fuel combustion loses no heat to the nitrogen in the combustion and flue gases. It drastically reduces the physical size of burners, furnaces and flue gas ducting, as there is no nitrogen present and no need for recuperators.

**Figure 3**

Calculated savings (in percent) with oxy-fuel compared with air-fuel (fuel = natural gas).

The positive heating aspect of oxy-fuel reduces throughput time, thus releasing the existing furnace for additional production capacity. Regarding energy, this can be used to concentrate production on fewer locations, with reduced standby or idle time being a secondary means of achieving energy savings.

The impact of energy costs in final product pricing can range from one- to two-digit percentage values. There is normally little opportunity to pass on rapidly increased and fluctuating fuel prices to the end-customer. This eventually reduces the profit margin in an already competitive market. Reductions in fuel consumption will have a positive effect not only on the final product price, but also on reducing possible fluctuations, ensuring more stable margins.

**Figure 4**

With oxy-fuel, 165,000 tons can be produced using the lowest shift form. This represents savings in staff and more available capacity and flexibility for peak order demands and maintenance.

## More Production Throughput and Improved Product Quality

The effectiveness of oxy-fuel in shortening the heat cycle time to increase throughput capacity was noticed at an early stage. Improvements of 50 percent are not unusual, with reported cases of capacity increases of up to 80 percent. The additional production throughput capacity can be used in various ways: to increase production with the flexibility to follow fluctuations in orders, the swift handling of peak volumes, and the planning of work and maintenance activities, thereby avoiding the need to introduce an additional shift of workers. Figure 4

shows that it is possible to achieve an annual tonnage volume of 255,000 tons with a full shift form of 21 shifts/week. Note that the diagram does not reflect the fact that the additional output achieved is not proportional to the higher cost of an additional work shift.

The heating process affects and enhances certain product properties, quality and finishes, which must be predictable and controllable and give repeatable results. The quality costs often arise from poor temperature uniformity, which makes rolling and forging sub-optimal, sometimes leading to the need to re-enter the product for a second heating sequence. It has been seen that the heating transfer properties of oxy-fuel, as discussed earlier, provide optimal conditions for fast and complete heating, thus reducing, for example, large top-to-bottom temperature variations and giving more uniform heating for better rolling or forging results.

Another important quality cost parameter concerns scale formation, which typically accounts for a 1–2 percent material loss (i.e., one ingot in every 100 or 50 is scrap). Scale formation is a function of the material properties, the oxygen content in the flue gases, furnace temperature and the heating time required. Furnace temperature and oxygen content are both controllable parameters, and here oxy-fuel facilitates an important reduction in the time of exposure during the heating operation. Customer experience and laboratory tests indicate reduced levels of scale formation and that the scales have the right properties for simple and effective scale-braking operation prior to the rolling or forging operation.<sup>4</sup>

It has also been possible to reduce or avoid certain downstream processes. One customer has reported that the surface properties improved so much with oxy-fuel that the skin-pass operation could be eliminated.<sup>5</sup>

## Minimizing Exposure to Environmental Costs

Investments to reduce and meet legislated emission levels, as well the tax paid on emissions and eventually the need to acquire emissions rights, are all significant expenses. It all comes down to another cost to be met by the producer and eventually the customer. Depending on the attitude of the company and how proactive the steel producer is, all environmental issues can create good or bad will toward customers, shareholders, employees and the community, which can indirectly affect the company's end results.

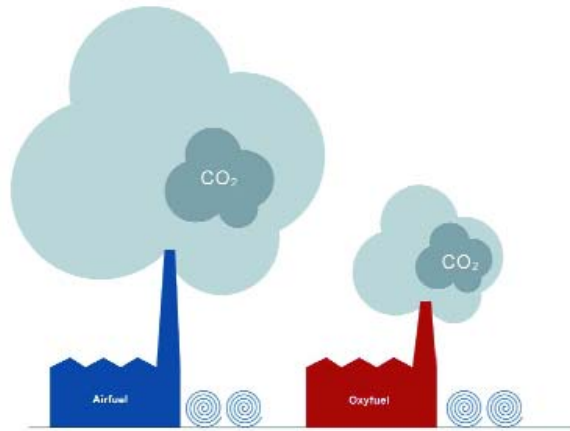
**CO<sub>2</sub> Reduced and Highly Concentrated** — The two principal routes to steel production have quite different impacts on CO<sub>2</sub> emissions. Integrated steel mills, including all upstream processes, average approximately 2 tons of CO<sub>2</sub> per ton of hot rolled plate. For minimills, the corresponding figure per ton of carbon steel (long products) is 0.5–0.6 tons of CO<sub>2</sub>.<sup>6</sup> As an example, steelmakers in Sweden today already pay a tax of \$0.015/pound CO<sub>2</sub>. They also predict that they will need future CO<sub>2</sub> emission rights, which will increase the cost of the steel product by more than \$30/ton.

Consequently, steel producers and authorities have set a target of reducing the consumption of fossil fuels, not only to cut emissions, but also to preserve limited energy resources. It has been shown that the efficient combustion and heat transfer of oxy-fuel technology can reduce the specific fuel consumption by up to 50 percent in some cases. This broadly corresponds to an equivalent reduction in fuel-borne emissions such as CO<sub>2</sub>, SO<sub>x</sub> and particulates (Figure 5).

An indirect benefit of oxy-fuel combustion stems from the highly concentrated CO<sub>2</sub> levels. This makes it of interest in the application of sequestration techniques. The CO<sub>2</sub> cleaning technology currently available cannot yet make such solutions viable for exhaust gases from iron and steel production.<sup>3</sup> Such technology may soon be available, or appropriate applications may alternatively be found for low-grade CO<sub>2</sub>, particularly within the steel industry itself.

**Getting Down With NO<sub>x</sub>** — The formation of NO<sub>x</sub> originates from the presence of free nitrogen in the atmosphere together with available oxygen, as in conventional air-fuel combustion (so-called thermal NO<sub>x</sub>), or as a result of the nitrogen contained in the fuel during combustion with oxygen. However, the level of nitrogen in fuel is almost negligible. In oxy-fuel combustion, NO<sub>x</sub> levels can be high because of the high combustion temperature, poor pressure control and the extensive

Figure 5

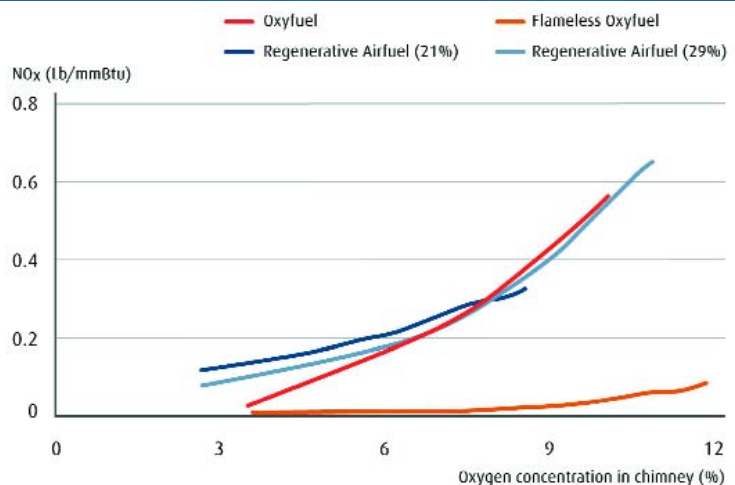


At equivalent production output, oxy-fuel reduces specific fuel consumption by 30 percent, corresponding to the same reduction of CO<sub>2</sub>. Exhaust flue gas volumes are reduced 70–80 percent. Total air-fuel power input of 34 mmBtu/hour (with preheated air at 660 °F) is equivalent to 23 mmBtu/hour with oxy-fuel.

leakage of air into the furnace. However, all of these parameters are controllable and have been a focal point in the development of oxy-fuel burners, application, control philosophies and furnace designs at Linde for more than 25 years. Figure 6 shows how conventional oxy-fuel results in NO<sub>x</sub> levels similar to regenerative-type air-fuel burners and how flameless oxy-fuel is almost insensitive to any ingress of air into the furnace.

Sweden has some of the toughest regulations on emissions of NO<sub>x</sub> in Europe. Legislated levels are at 100 or 150 mg/MJ (0.2324 or 0.3486 pound/mmBtu) depending

Figure 6



Burners at 0.7 mmBtu/hr · O<sub>2</sub> from combustion = 2.5 – 3.5%

Results from tests in a pilot-scale furnace. Emissions of NO<sub>x</sub> from oxy-fuel combustion are comparable to regenerative air-fuel burners, whereas flameless oxy-fuel is almost insensitive to air ingress into the furnace.<sup>9</sup>

**Table 1****Calculated Equivalent NOx Emission Levels for Oxy-fuel Compared to Air-fuel**

Measurement	Air-fuel	Calculated equivalent oxy-fuel
Concentration (ppm)	171	2,120
Emissions of NO <sub>2</sub> over time (lb./hr.)	7.94	7.94
Emissions of NO <sub>2</sub> from energy used (lb./mmBtu)	0.2324	0.3462
Dry exhaust (scfh)	390,937	31,459
Wet exhaust (scfh)	466,142	81,962
NO <sub>2</sub> for the steel produced (lb./ton)	0.325	0.325
Energy to steel heated (mmBtu/ton)	1.154	0.773
Power installed (mmBtu/hr.)	34	23
Leak air (scfh at 3% excess oxygen)		4,526.8
	At 3% excess oxygen	

on fuel type. However, customers require suppliers to fulfill the level of 70 mg/MJ (0.1627 pound/mmBtu), which has become the industry standard. Figure 6 shows that even lower emission levels could be achieved with new flameless oxy-fuel technology developed by Linde.

Oxy-fuel combustion reduces the amount of NOx produced, but the concentration appears high. This is due to the absence of nitrogen in the combustion process and thus much smaller flue gas volume. In Table 1, at identical production output with a constant emission of 7.94 pounds NO<sub>2</sub>/hour, the calculated equivalent emission concentration (ppm) values for oxy-fuel are higher. For this reason, the emission of NOx is better expressed as produced NOx (pounds) in relation to energy consumed (mmBtu) or the volume of steel produced (tons), as described in Table 1. These oxy-fuel values are not actual, since they are typically much below 0.3462 pound/mmBtu.

The correct measurement equipment must also be used, as traditional analysis tools cannot measure the high concentration of CO<sub>2</sub>.

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### Oxy-fuel — Powerful Yet Simple to Install

The fact that oxy-fuel combustion does not have to

take the nonproductive nitrogen ballast into account implies both practical and cost-effective solutions in regard to the application of the technology as well as maintenance. There is no longer any need for large burners or combustion air ducts, which often require electric blowers. Oxy-fuel burners are small in size and easy to retrofit in an existing furnace, either for boosting or as a 100-percent oxy-fuel application. In a boosting application, oxy-fuel burners either replace some air-fuel burners or are additionally mounted, as in Figure 7, next to existing air-fuel burners. The objective is to give an extra capacity boost or reduce temperature differences in the material heated. A modern, water-cooled, flameless oxy-fuel burner with a 8.5 mmBtu/hour

power rating, integrated UV and pilot burner weighs 20–45 pounds. The space-efficient burners are easily installed and accessible for inspection and maintenance.

A great benefit is the fact that bulky exhaust gas ducts and recuperators, and the associated electric ventilation fans, are no longer required. Scrubbers and other flue gas cleaning systems can also be eliminated, thus reducing both installation costs and maintenance.

In regard to the design of new reheat and annealing furnaces, oxy-fuel technology facilitates more compact furnace designs for the same output capacity as an air-fuel furnace. The application of oxy-fuel in an existing furnace, previously equipped with air-fuel, increases the production capacity, avoiding the need to extend the furnace or purchase an additional unit. This is of considerable interest, as material logistics, production line setup and the floor space available within an existing rolling mill or forge shop are normally both expensive and time-consuming to increase or alter.

The knowledge of customer processes, the requirements imposed by authorities and recent technical breakthroughs have driven Linde's development of oxy-fuel combustion, not only in terms of burner technology, but also in terms of correct measurement, efficient control systems and new regulation models, as well as a thorough understanding of furnaces.

### Oxy-fuel — Challenging but Highly Rewarding

The following are examples from more than 80 oxy-fuel installations implemented by Linde Gas since 1990.

**Figure 7**

The compact 6.82 mmBtu/hour oxy-fuel burner was installed for a boosting application next to the 1.7 mmBtu air-fuel burner in a pusher furnace.

**The Timken Co., U.S.** — In 1990, Timken was the first to commission a 100-percent oxy-fuel installation in their soaking pits, used to heat bearing steel ingots prior to rolling. They have benefited from a 63 percent reduction in specific fuel consumption, 74 percent less flue gas emissions, and heating time reduction from 5 hours to 2.5–3 hours. Scale has also been reported as easy to remove.

**Böhler-Uddeholm, Sweden** — A 52 percent reduction in specific fuel consumption was achieved since the installation of oxy-fuel in five car-bottom furnaces at Böhler-Uddeholm. The first installation took place in 1993. These furnaces heat 8- to 77-ton ingots prior to forging. The heating time could be reduced by 25–50 percent with improved surface quality and reduced scale formation.

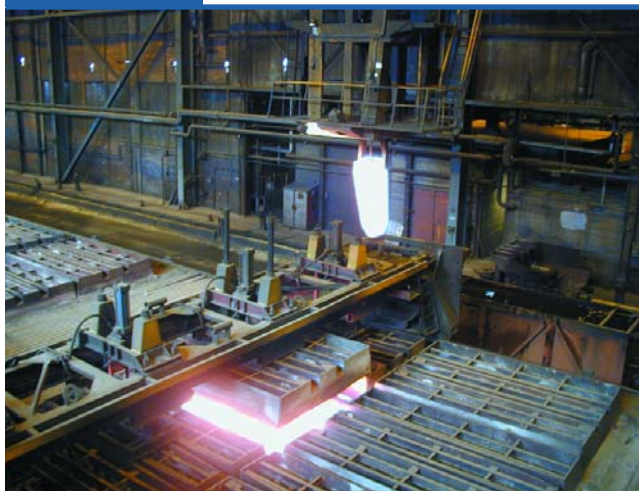
**Ovako Steel, Sweden** — Since 1994, the SKF subsidiary Ovako Steel has used oxy-fuel in a total of 42 pit and rotary hearth furnaces. This has increased throughput capacity by 35 percent, creating flexibility in production rates, shift forms and maintenance planning. Fuel consumption and CO<sub>2</sub> emissions are down by 35 percent. A new rotary hearth furnace was commissioned in 1998, incorporating oxy-fuel for maximum performance.<sup>7</sup> A photograph of the Ovako operations is shown in Figure 8.

**North American Forgemasters, U.S.** — Since 1999, NAF has been using oxy-fuel in six box furnaces for heating ingots prior to forging. Energy consumption for oxy-fuel was 56 percent less than in the air-fuel furnace with the same charge and heat cycle. NO<sub>x</sub> emissions for the oxy-fuel furnace were about 50 percent of air-fuel NO<sub>x</sub> emissions. A 10 percent increase in the heating rate was measured with the oxy-fuel furnace, which is likely due to faster ramp to temperature setpoint.

**Outokumpu Stainless, Sweden** — In 2001, a catenary furnace for annealing stainless steel strip at Avesta works was refurbished. Production throughput was raised from 82 to 165 tons/hour. Staged combustion oxy-fuel burners with a total power of 133 mmBtu/hour were installed, making it one of the largest oxy-fuel installations of its kind. Fuel consumption was reduced by 40 percent compared with the previous operation using air-fuel burners and recuperators.

In 2003, Linde Gas refurbished the existing walking beam furnace at the Degerfors works. The complete turnkey project included the rebuilding and refurbishment of the existing furnace, the application of flameless oxy-fuel technology and the installation of essential control systems during a 25-day stoppage.

**Figure 8**



At Ovako Steel, ingots are heated to 2,200°F in oxy-fuel converted pit furnaces prior to downstream hot rolling.

Performance was guaranteed, with a production increase of 30 percent, reduced fuel consumption, lowered NO<sub>x</sub> emissions and improved temperature uniformity.

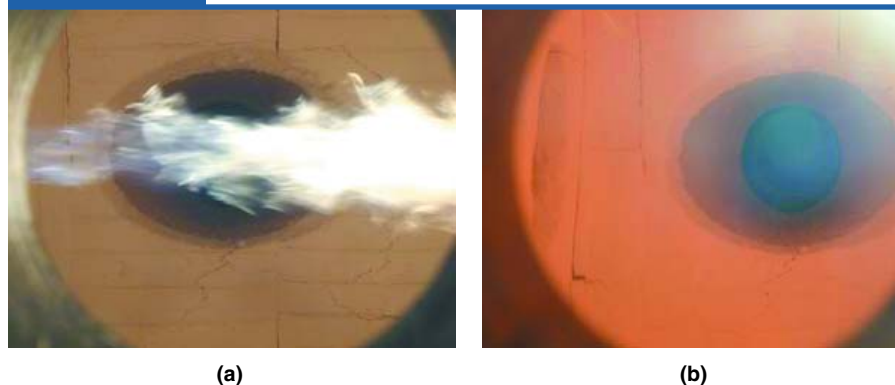
## Recent Developments

**Flameless Oxy-fuel — Ultralow-NO<sub>x</sub> and Large Furnaces** — The legislation relating to NO<sub>x</sub> emissions is strict, and permissible emission levels are constantly being reduced. Against this background, development work was begun in collaboration with customers to find even more effective oxy-fuel solutions. The work also aimed at finding more rugged installations for implementation, as well as oxy-fuel solutions viable in larger furnaces such as catenary, pusher and walking beam furnaces.

A key parameter in achieving low NO<sub>x</sub> is the reduction of flame temperature. Below a temperature of 2,600°F, NO<sub>x</sub> formation is limited, but a dramatic increase in NO<sub>x</sub> occurs above this temperature. One way of reducing the flame temperature is to use the principle of flameless combustion. This principle has been known for many years, but it has only recently been industrially exploited.

The term *flameless combustion* expresses the visual aspect of the combustion type, i.e., the flame is no longer seen or easily detected by the human eye (Figure 9b). A more accurate definition would be that combustion is diluted by different means and thus spread out in a large volume, which some scientists refer to as volume combustion, resulting in a lower flame temperature.

The solution of diluting the combustion and flame uses either dilution or the injection of fuel and oxygen at high velocities separated from each other. In a conventional stable flame burner, the flame is almost a field discontinuity, depends on fluid dynamics with

**Figure 9**

(a) A conventional oxy-fuel flame, and (b) the same burner in flameless mode (i.e., invisible volume combustion).

computational difficulties, and involves complex reaction paths with abundant formation of radicals and intermediate products. The gradual, volume-distributed reaction rate typical of flameless and staging combustion is more accurately controlled. The mixture of fuel and oxidant reacts anyway, irrespective of proportion, without support of a flame front and with kinetics dictated mainly by temperature.<sup>8</sup>

In addition to reducing the temperature of the flame, flameless oxy-fuel burners effectively disperse the combustion gases throughout the furnace, ensuring more effective and uniform heating of the material with a limited number of installed burners. Figure 6 showed that flameless oxy-fuel technology is insensitive to air ingress when it comes to NO<sub>x</sub> emission. The test was performed in a pilot-scale furnace where ingress air 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 flue. The flameless oxy-fuel solution proved to be almost insensitive to the air ingress, and con-

ventional oxy-fuel had similar emissions of NO<sub>x</sub> as state-of-the-art regenerative air-fuel technology. This is of great benefit, particularly in old and continuous furnaces.

Since 2003, two full-scale applications have been installed using flameless oxy-fuel burner technology. These include heating in reheat furnaces and annealing lines, walking beam and pit furnaces, and a catenary furnace. This has led to the possibility of meeting the demand for further increased production throughput in existing furnaces, while at the same time fulfilling

local authorities' stipulated lower levels of NO<sub>x</sub> emissions.

### Direct Flame Impingement — Extreme Heating in a Limited Space

Direct flame impingement (DFI), where an oxy-fuel flame directly heats moving metal, has proved to be the most effective way of increasing heat transfer. The principle is taken from the reheating of metal surfaces by torching prior to welding.

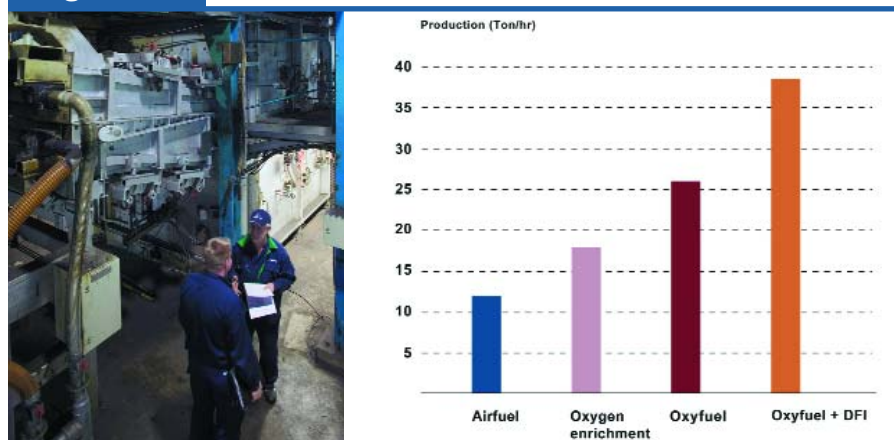
DFI is of particular interest when extreme heating is required but there are severe space restrictions. A typical example is shown in Figure 10. The customer, having a catenary furnace for strip annealing, was already equipped with oxy-fuel and wanted to increase production capacity by 50 percent without extending the length of the furnace. A compact unit was designed for retrofitting on the entry side of the furnace, which contained four cassettes each with 30 oxy-fuel burners, giving a total of 120 burners and a total power output of 13.7 mmBtu/hour.

Direct application of oxy-fuel flames onto the continuously moving material has proved to be a powerful and space-efficient solution for the existing furnace to boost capacity and to even out temperature differences in the material.

### Summary

Eliminating the nitrogen ballast in the combustion and heat transfer process by replacing the air with industrial-grade oxygen cuts fossil fuel consumption by up to 50 percent and reduces CO<sub>2</sub> levels correspondingly. Further reduction of fuel and CO<sub>2</sub> is possible through the use of low-caloric energy forms, as acceptable flame temperatures can be achieved with oxygen.

NO<sub>x</sub> levels can also be kept low, as there is no nitrogen in the oxy-fuel

**Figure 10**

The photograph shows the compact DFI unit of 13.7 mmBtu/hour, which boosts throughput capacity by about 50 percent in a catenary furnace at Outokumpu Stainless.



combustion process. Furnace control is good, and the flame temperature of modern oxy-fuel burner technology is lower.

Furnace throughput can be boosted by up to 50 percent, providing extra production capacity, which can be used to concentrate production and better accommodate peak volumes and maintenance activities. Oxy-fuel installations are powerful and space-efficient and are thus easy to retrofit in any existing furnace, requiring less maintenance compared to air-fuel systems with ventilator fans, bulky flue gas systems and recuperators.

Oxy-fuel technology is no longer simply a well-known means of improving steelmaking. Since 1990, Linde has proved in more than 80 installations the viability of oxy-fuel technology in creating effective total cost solutions in applications for reheat furnaces and annealing lines.

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