Oxyfuel Solutions in Reheat furnaces for Higher Throughput with Less Emissions

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Short abstract

Most steel producers need solutions for higher production throughput in their reheat furnaces and annealing lines. The goals are to improve utilisation of investments in existing rolling mills and forge shops, to facilitate the possible restructuring of business and to better manage peak volume demand as well as additional throughput capacity for repair and maintenance activities. Not only do such solutions need to be cost–effective, they must also comply with ever-stricter requirements for emissions of gases such as CO_2 and NO_x.
If the nitrogen ballast is removed from the combustion and heat transfer process by replacing the air with industrial grade oxygen, furnace throughput can be boosted by up to 50%, and fossil fuel consumption and CO_2 production can be cut by 50%. The result is powerful and easy to install oxyfuel systems with reduced maintenance. NO_x levels are also low, as there is no nitrogen in the combustion process, furnace control is good and the flame temperature of staged and flameless oxyfuel burner technology is lower.

Keywords

Oxyfuel, reheat, heating, annealing, furnace, combustion, emissions, CO_2, NO_x, flameless

Introduction

There is a continuous quest for more production capacity and flexibility in reheat furnaces and annealing lines. The cost added to the final product should be low as there is little capital available for investment and competition is fierce. The authorities also impose strict controls and legislation with reduced levels of emissions, taxes and emission rights, all of which add to the cost of the final product.

- What is a cost-effective solution to all of these requirements?

Our search for the answer takes us back to the basics of combustion. The three prerequisites for combustion are fuel, oxygen and ignition. Oxygen is naturally present in air, as it makes up 21% of the atmosphere, but what would be the effect of also replacing the 79% not taking part in the combustion process itself, the nitrogen ballast, with oxygen? What about heat transfer considerations? How should oxyfuel technology be applied and what happens to the emissions?

This paper discusses the use of oxyfuel combustion and its implementation in reheat furnaces and annealing lines with important developments and results. An emphasis is placed on the opportunities for providing higher throughput but with reduced emissions.

More production capacity for a lower total cost

Any business should be expanding and growing to at least cover the rate of inflation but most importantly of all to win business and market share. In steel production, this growth is not evident and there has been a protracted period of excess production capacity which is not always situated in ideal locations. Operations at one or more production sites are increasingly being concentrated to better utilise investments made in equipment and staff at rolling mills or forge shops and suddenly a gap has opened up in the production capacity required which must be bridged. The lack of capacity and flexibility also hampers efficient planning and the production of peak volumes or the management of sudden production stoppages, which are not uncommon in rolling mills and forge shops.

The advanced product development of today's steel grades tends to require longer and more complex heating procedures, sometimes repeated several times. This requires more heating capacity and flexibility to produce a vast range of products.

Most producers would like to find solutions which do not involve buying a new furnace or extending their existing one, establishing a backup stockpile or introducing an additional work shift, often a less efficient and thus rather costly solution.

One early step to boost production throughput was the enrichment of combustion air, to a total oxygen content of 21-30 %. This was actually a positive spin-off from the need to reduce the consumption of and dependency on fossil-based fuels during the oil crisis of the 70s. The application of oxygen showed that with limited investment and in fast projects, it was possible to boost output capacity in existing furnaces.

Further increases in throughput, more fuel savings, and an emerging concern for environmental issues were the key factors driving developments at AGA (a member of Linde, Gas Division) during the 80s and the 90s for applications of oxyfuel-based solutions in reheat furnaces and annealing lines. Oxyfuel implies any type of fuel, gaseous or liquid, combusted with industrial grade 90-100% oxygen. The development work was mostly carried out in close co-operation with customers, resulting in industrial scale oxyfuel installations.

Oxygen – 50 years of use in modern steel making

The increasing use of oxygen in modern steel-making began over 50 years ago with the Basic Oxygen Furnace (BOF). The use of oxygen in iron-making is now commonplace with the extensive use of oxygen in blast furnaces. The benefits of using oxygen in steel-making have however been recognised since 1856 when Sir Henry Bessemer referred to the possibilities of 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 of large-scale oxygen production. It was not until after the Second World War that large volumes of oxygen began to be used in steel-making, particularly through the BOF process.

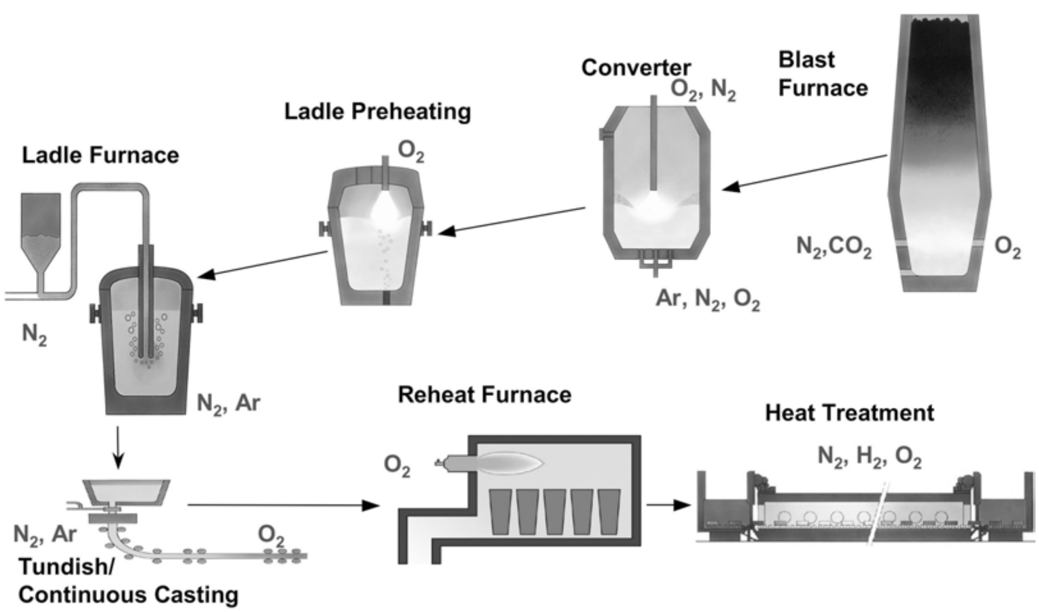


Fig. 1. There are currently around 50 options for the beneficial use of industrial gases at integrated steel mills. Oxygen is widely recognised for its benefits and practical use.

The benefits of using oxyfuel combustion in various steel-making applications such as boosting in Electric Arc Furnaces and the pre-heating of vessels, e.g. of steel ladles, converters and tundishes, are all well known: reduced energy consumption, longer furnace life, shorter cycle time, etc.

The beneficial results in these applications are however still limited compared to the use of oxyfuel for applications relating to the semi-finished 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.

Oxyfuel 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 taken into consideration.

Oxygen diluted with 78% nitrogen and 1% 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 later the energy transferred to the nitrogen must be recovered in order to save fuel, Fig 2. [1].

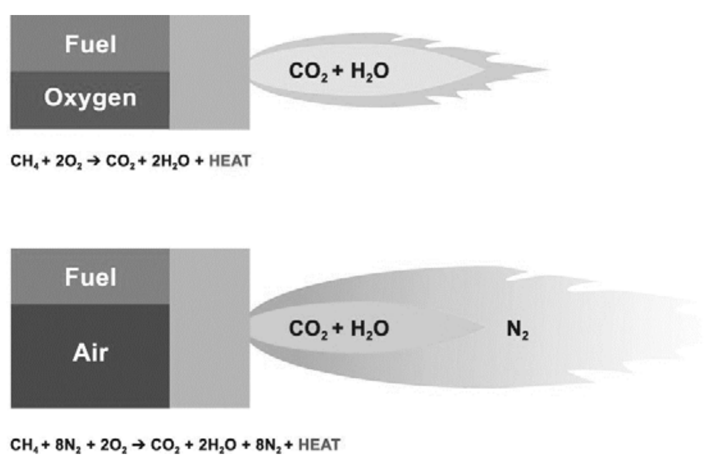


Fig. 2 Oxyfuel combustion loses no heat to the nitrogen in the combustion and flue gases. Avoiding the nitrogen ballast also drastically reduces the physical size of burners, furnaces and flue gas ducting as well as no need for recuperators or electrical ventilation fans.

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

For efficient and even heating, the gas composition and flow pattern inside the furnace are of importance. Oxyfuel combustion has a much higher partial pressure as regards the two combustion products, CO_2 and H_2O, compared to airfuel. 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_2 and H_2O are higher but also because they are both high heat-radiating 3-atomic gases.

The flow pattern in an oxyfuel furnace is advantageous compared to airfuel. Exhaust gas volume is reduced by 70-80% 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_2 and H_2O, i.e. a moist ambience with a higher capacity to transfer heat.

When comparing an oxyfuel furnace with an airfuel furnace, both set at the same furnace temperature, the material reaches a set point value faster in the oxyfuel furnace. This is because of the gas properties.

Oxyfuel - powerful yet simple to install

The fact that oxyfuel combustion does not have to take the non-productive nitrogen ballast into account implies both practical and cost-effective solutions as regards the application of the technology as well as maintenance. There is no longer any need for large burners or combustion air ducts, often requiring electrical blowers. Oxyfuel burners are compact and easy to retrofit in an existing furnace, either for boosting or for full 100% oxyfuel application, see Fig. 3. A modern water-cooled flameless oxyfuel burner with a 2.5 MW power rating, integrated UV and pilot burner weighs 10-20 kg. The compact burners are easily installed and accessible for inspection and maintenance.

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

The application of oxyfuel in an existing furnace, previously equipped with airfuel, increases the production capacity, so 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.

As regards the design of new reheat and annealing furnaces, oxyfuel technology facilitates more compact furnace designs for the same output capacity as an airfuel furnace.

Fig 3, The 2 MW oxyfuel burner on the left in the photograph was installed for a boosting application next to the 0.5 MW airfuel burner in a pusher furnace.

It is the know-how of customer processes that has been acquired, requirements imposed by authorities and technical breakthroughs that have advanced the development of oxyfuel combustion. New oxyfuel burner technology such as staged and flameless combustion and direct flame impingement applications (DFI) is now available but of equal importance are correct measurement, efficient control and new regulation models and a thorough understanding of furnaces.

Flameless oxyfuel – ultra-low NO_x and large furnaces

The legislation relating to NO_x emissions is strict and the permissible emission levels are constantly being reduced. Against this background, development work was started in collaboration with customers to find even better oxyfuel solutions. The work also aimed at finding more rugged and simpler installations for implementation as well oxyfuel-based solutions viable in larger furnaces such as catenary and walking beam furnaces.

A key parameter to achieving low NO_x is to reduce the flame temperature. Below a temperature of 1425°C, NO_x formation is limited, but above this temperature a dramatic increase in NO_x occurs. One way of reducing the flame temperature is to use the principle of flameless combustion. This has been known for many years but it has only recently been industrially exploited.

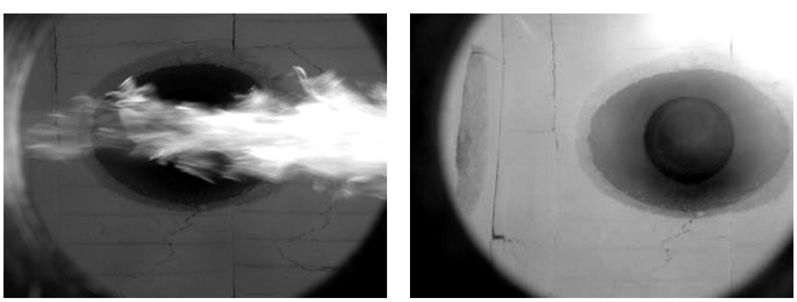


Fig 4. The photograph on the left shows a conventional oxyfuel flame, whilst the right-hand photograph shows the same burner in flameless mode; i.e. an invisible volume combustion.

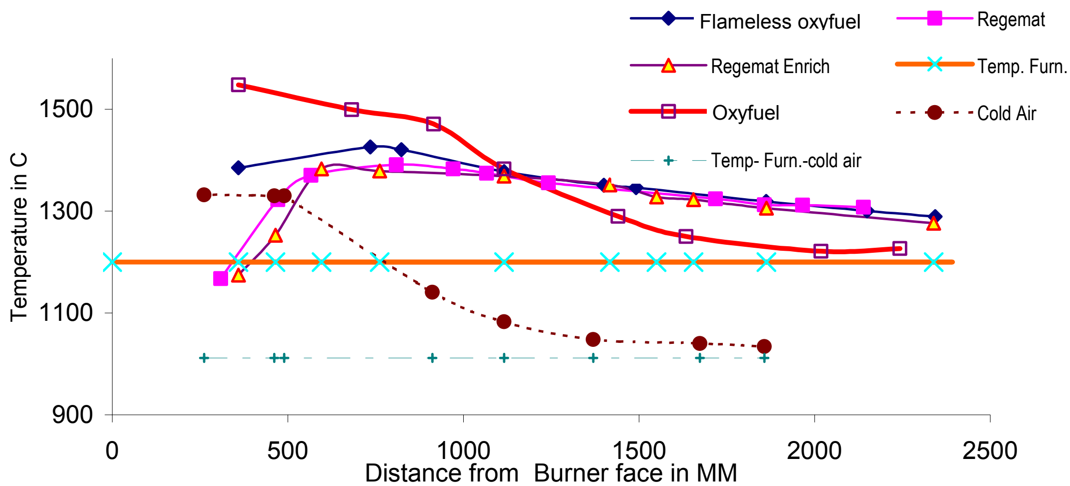


Fig. 5 Flameless oxyfuel maintains a lower temperature than a conventional oxyfuel flame. No temperature peaks can be seen [2].

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, see Fig. 4. 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, Fig. 5.

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 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 mainly dictated by temperature [3].

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 with a limited number of burners. It has also been shown, as in Fig. 6, that flameless oxyfuel technology is insensitive to air ingress, which is a great benefit in old and continuous type furnaces.

Since 2003, two full-scale applications have been installed using flameless oxyfuel burner technology. Both are found within the Outokumpu Stainless group, one being a walking beam furnace and the other a continuous annealing line. Outokumpu required increased production throughput in existing furnaces while local authorities stipulated even lower levels of NO_x emissions.

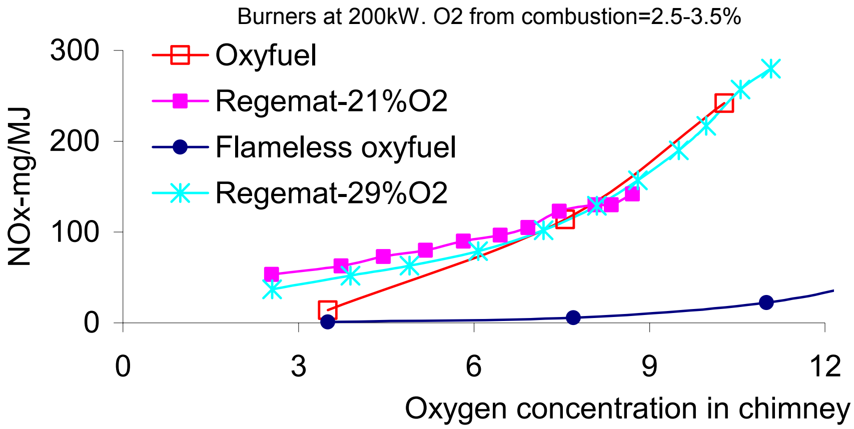
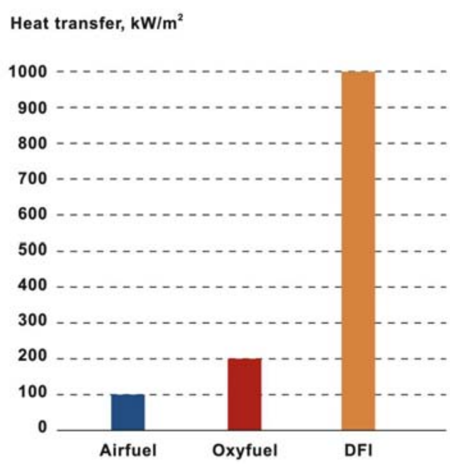


Fig 6. Emissions of NO_x from oxyfuel combustion are comparable to regenerative airfuel burners, whereas flameless oxyfuel is almost insensitive to air ingress into the furnace [2].

Direct Flame Impingement – extreme heating in limited space

Direct Flame Impingement (DFI), where an oxyfuel flame directly heats a moving strip of metal, has proven to be the most effective way of increasing heat transfer (kW/m^2), see Fig. 7. The principle is taken from preheating metal surfaces by torching prior to welding.



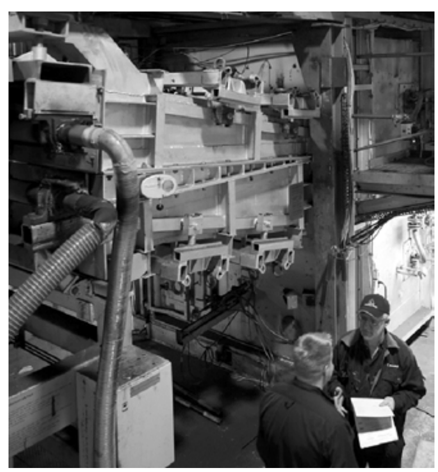


Fig*. 7 Heat transfer is much higher when the flame is in contact with the object to be heated. The photograph shows the compact DFI unit of 4 MW, which boosts throughput capacity by 50% in a catenary furnace at Outokumpu Stainless.*

The customer's request was to boost production capacity by 50% in a catenary furnace already equipped with oxyfuel, without extending the length of the furnace. A compact unit was designed for retrofitting on the entry side of the furnace, see Fig. 7, which contained 4 cassettes each with 30 oxyfuel burners, giving a total of 120 burners and a total power of 4 MW.

Lowered specific cost per tonne steel produced

As mentioned above, it was the search for reduced fuel consumption and the high cost of fuel during the oil crisis which initially sparked the interest in applying additional oxygen to the combustion process. Fuel savings, with full oxyfuel application, are in the range 25-50%, reaching levels below 250 kWh/tonne heated steel.

Energy management in steel-making is taken seriously, as it reduces costs and environmental impact by lowering the total CO_2 emissions from the production site. Low caloric content gases, such as coke oven gas, blast furnace top gas or BOF gas can be reutilised in oxyfuel combustion, as it can provide the flame temperatures needed in heating applications [4].

The focus is however now on how the efficient oxyfuel combustion can be used to shorten the heat cycle time in order to increase throughput capacity. Improvements of 50% are not unusual with reported cases of capacity increases of up to 80%.

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, avoiding the need to introduce an additional shift of workers, see Fig. 8. Remember that the diagram does not reflect the extra costs implied when adding an additional work shift. The diagram shows that it is now possible to achieve an annual tonnage volume of 230,000 tonnes with a full shift form of 21 shifts/week.

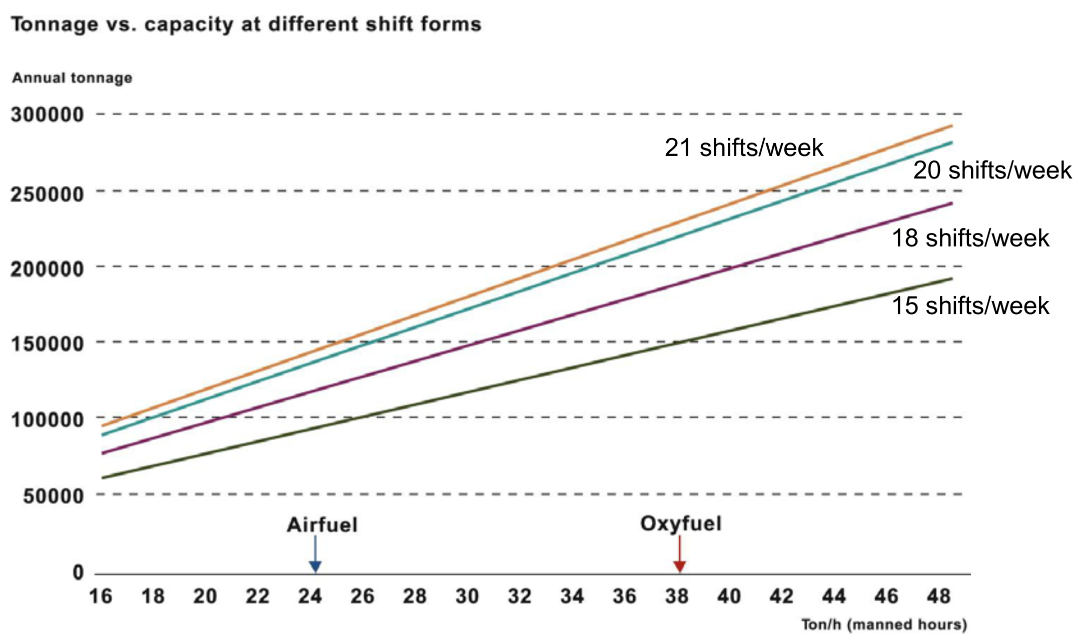


Fig. 8. With oxyfuel, 150,000 tonnes can be produced using the lowest shift form. This represents savings in staffing costs and increases available capacity and flexibility for peak order demands and maintenance activities.

The heating process affects and enhances certain properties, quality and finishes of the product, which must be both 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 oxyfuel, as discussed earlier, provide optimal conditions for fast and complete heating, reducing for example large top-bottom temperatures sometimes encountered.

Another quality cost parameter concerns scale formation, which typically accounts for a 1-2% loss of material, i.e. every 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 oxyfuel 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 rolling or forging operations [5]. It has also been possible to reduce or eliminate some downstream processing. One customer reports that the surface properties improved so much with oxyfuel that the skinpass operation could be eliminated [6].

Minimising exposure to environmental costs

Investments made to reduce and meet legislated emission levels, as well as the tax paid on emissions and eventually the need to acquire emission rights are all significant costs. Depending on the attitude and pro-activeness of the steel producer, all environmental related issues have the possibility of creating good or bad will towards customers, shareholders, employees and the community, which can indirectly affect the result of the company.

The two principal routes to steel production account for quite different impacts on CO_2 emissions. Integrated steel mills, including all upstream processes, average approximately 2 tonnes of CO_2 per tonne of hot rolled plate. For mini-mills, the corresponding figure per tonne of carbon steel (long products) is 0.5-0.6 tonne of CO_2 [7]. As an example, steelmakers in Sweden today are already paying a tax of €0.027/kg CO_2. They also predict that they will need future CO_2 emissions rights which will increase the cost of the steel product by more than €30/t.

Consequently, authorities have set a target of reducing the consumption of fossil fuels not only to cut emissions but also to preserve existing, limited energy resources. It has been shown that the efficient combustion and heat transfer of oxyfuel technology can reduce the specific fuel consumption by up to 50% in some cases. This broadly corresponds to the same reduction of fuel-borne emissions such as CO_2, SO_x and particulates.

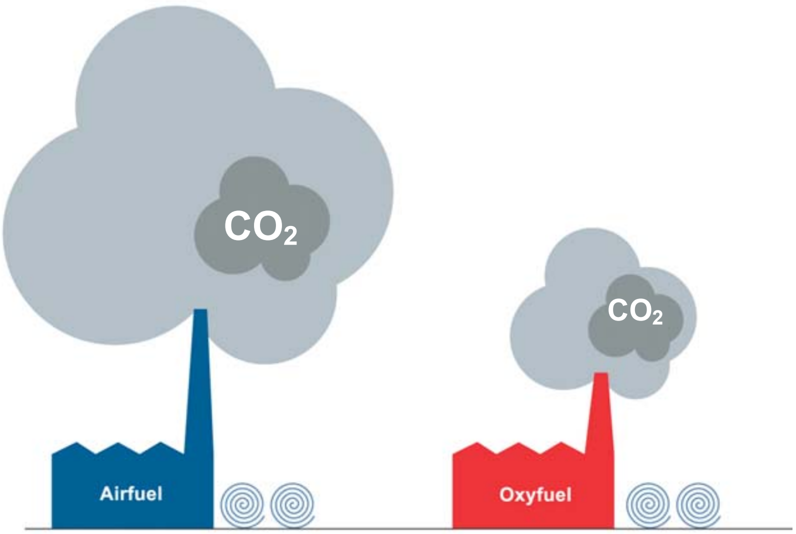


Fig. 9. At equivalent production output, oxyfuel reduces specific fuel consumption by 30%, corresponding to the same reduction of CO_2. Exhaust flue gase volumes are reduced 70-80%. 10 MW with preheated air at 350° C corresponds to 6.7 MW with oxyfuel.

A more recent interesting aspect of oxyfuel combustion stems from the highly concentrated CO_2 levels. This makes it of interest in the application of sequestration techniques. The CO_2 cleaning technology currently available cannot yet make such solutions viable for exhaust gases from iron and steel production [4]. Such technology may however soon be available or appropriate applications may alternatively be found for low grade CO_2, particularly within the steel industry itself.

The formation of NO_x originates from the presence of free nitrogen in the atmosphere together with available oxygen, as in conventional airfuel combustion, so-called thermal NO_x, 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 oxyfuel combustion, NO_x levels can be high because of the high combustion temperature, poor pressure control and the extensive leakage of air into the furnace. All these parameters are however controllable and have been a focal point in the development of oxyfuel burners, application, control philosophies and furnace designs for over 25 years. The diagram presented earlier in Fig. 6 shows how conventional oxyfuel results in NO_x levels similar to regenerative type airfuel burners and how flameless oxyfuel is almost insensitive to any ingress of air into the furnace.

Oxyfuel combustion reduces the amount of NO_x produced but the concentration appears high. This is due to the absence of nitrogen in the combustion process and thus much smaller exhaust volumes.

Measurement	Airfuel	Oxyfuel
mg NO2/nm3	350	4352
ppm	171	2120
kg NO2/h	*3,6*	*3,6*
mg NO2/MJ	100	149
Dry exhaust nm3/h	10277	827
Wet exhaust nm3/h	12254	2152
kg NO2/ton	*0,134*	*0,134*
kWh/ton	373	250
Power MW	10	6,7
Leak air nm3/h*		119*
	*at 3% excess oxygen**	

Table 1 The table expresses the calculated equivalent NO_x levels for oxyfuel. The oxyfuel values are not to be seen as actual since they are typically below 150 mg/MJ. They are high due to the absence of nitrogen and the drastically reduced exhaust volumes.

In Table 1, at identical production output with a constant emission of 3.6 kg/hour, the equivalent emission concentration values for oxyfuel are high (ppm, mg NO_2/nm^3). The absence of nitrogen and the low exhaust volumes are the reason for such high values. For this reasons expressing the emissions of NO_x is better expressed as produced NO_x (mg) in relation to energy consumed (MJ) or the volume of steel heated (ton).

Swedish legislation on NO_x is 100 or 150 mg/MJ depending on fuel type. However customers do require suppliers to fulfil the level of 70 mg/MJ. The diagram in Fig. 6 shows that even lower levels could be achieved with new flameless oxy-fuel technology developed by Linde.

The correct measurement equipment must also be used, as traditional analysis tools cannot measure the high concentration of CO_2.

Oxyfuel – challenging but rewarding

Presented below are some examples of the more than 80 oxyfuel installations implemented by Linde Gas since 1990. More information on these cases and others can be found at www.linde-gas.com/rebox.

Ovako Steel, Sweden

Since 1994, the SKF-subsidiary Ovako has used oxyfuel in a total of 42 pit and rotary hearth furnaces. It has increased throughput capacity by 35%, creating flexibility in production rates, shift forms and maintenance planning. Fuel consumption and CO_2 emissions are down by 35%. A new rotary hearth furnace was commissioned in 1998, including oxyfuel for maximum performance [8].

Edelstahlwerke Buderus, Germany

In 2000, four oxyfuel burners were installed for boosting in a pusher furnace, Fig 3. Productivity was increased by 11% whilst maintaining the desired set-point temperature, which had previously caused some ingots to require a second heat sequence. Even after boosting of the capacity, adding extra power to the furnace, the fuel consumption per tonne of produced steel was reduced by 9%.

Outokumpu Stainless, Sweden

In 2001, a catenary furnace for the annealing of stainless steel strip at the Avesta works was refurbished. Production throughput was raised from 75 to 150 t/h. Staged combustion oxyfuel burners with a total power of 39 MW were installed, probably making it the largest oxyfuel installation in its kind. Fuel consumption was lowered by 40% compared with the previous operation using airfuel burners and recuperators.

Outokumpu Stainless, Sweden

In 2003, the Degerfors works ordered an upgrade of the existing walking beam furnace. The complete AGA (member of Linde) turnkey project included the rebuilding and refurbishment of the existing furnace, the application of flameless oxyfuel technology and the installation of essential control systems during a 25-day stoppage. Performance was guaranteed, with a production increase of 30%, reduced fuel consumption, lowered NO_x emissions and improved temperature uniformity.

Conclusions

Combustion is all about fuel, oxygen and ignition. Leaving the nitrogen ballast out of the equation not only improves the combustion process but also the more important heat transfer aspects, as no heat is lost to the nitrogen which must be recovered later. All three aspects of heat transfer are promoted: convection, radiation and conduction. The answer lies in the gas properties of oxyfuel combustion; the product to be heated is immersed in a gaseous fluid containing highly radiating 3-atomic CO_2 and H_20. This also has benefits as regards the simple installation of the compact and powerful oxyfuel burners, the removal of large airfuel burners, bulky combustion air ducting, ventilator fans, recuperators and exhaust piping.

The efficient heat transfer of oxyfuel reduces the heating time required, which increases throughput capacity by up to 50% in existing furnaces without increasing staffing requirements. The improved utilisation of past investments in production equipment and staff is a key issue for reducing total costs. The additional capacity also creates more flexibility for managing peak orders, sudden production stoppages and efficient maintenance planning.

While boosting throughput capacity, oxyfuel also has environmental benefits. The consumption of fossil fuels is reduced by 30-50%, having the corresponding impact on CO_2. Further reduction of CO_2 and fuel is possible through the use of low caloric energy forms, as acceptable flame temperatures can be achieved with oxygen.

Emissions of NO_x are reduced, as the nitrogen ballast is not part of the combustion process and as a result of careful furnace design, effective pressure control and oxyfuel burners such as staged combustion and the new flameless type. The latter enables the flame temperature to be reduced, is insensitive to air ingress and gives excellent heating properties in large furnaces.

Oxyfuel is no longer simply a well-known means of improving steel-making. Since 1990, Linde has proven in more than 80 installations the viability of oxyfuel technology in creating effective total cost solutions in applications for reheat furnaces and annealing lines.

Furnace type	Process	Material	No
Box	**Annealing**	Stainless steel	2
	Forging	Alloy steel	6
		Carbon steel	3
Car bottom	**Forging**	Tool steel	8
Catenary	**Annealing**	Stainless steel	4
Pusher	**Rolling**	Mixed	1
		Structural steel	1
Roller hearth	**Annealing**	Stainless steel	1
	Rolling	Carbon steel	2
		Copper	1
Rotary hearth	**Rolling**	Alloy steel	1
		Bearing steel	2
Soaking pit	**Rolling**	Bearing steel	42
		Bearing/Alloy steel	3
		Mixed	1
		Stainless steel	8
Walking beam	**Rolling**	Stainless steel	1

Table 2 Since 1990, Linde has commissioned over 80 oxyfuel installations in batch and continuous type furnaces.

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Notes

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