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FLAMELESS OXYFUEL SLAB REHEATING EXPERIENCES[1]

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Abstract
Recent developments in flameless oxyfuel heating technology have been demonstrated to significantly enhance existing reheating furnace performance. By installing flameless oxyfuel boosting burners or the new REBOX®HLL technology reheating furnaces can be upgraded with limited capital investment compared to other alternatives. The results from flameless oxyfuel installations in slab reheating furnaces ranging from 40 to 340 tonnes/hour will be presented. Typically these new performance enhancement systems can be installed during a normal operating schedule with little or no lost production. Start-up at SSAB Borlänge took only one day as the REBOX® HLL technology continues to use the existing air-fuel burners. Also, potential risk relating to implementing REBOX® HLL technology is minimized because it enables flexibility in operating techniques (in response to fluctuating fuel cost, availability and production requirements) and is essentially reversible.
Key words: Flameless; Oxyfuel; Reheating; Increased throughput.

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1 INTRODUCTION

Since early 1990 Oxyfuel in reheating furnaces has successfully been employed. Today more than 120 furnaces are in operation using REBOX® Oxygen technologies from Linde.
The existing technologies are:

- REBOX® All Oxyfuel (all air-fuel burners are replaced with Oxyfuel burners)
- REBOX® Oxyfuel Boosting (New flameless Oxyfuel burners are installed as add ons/parallel with the existing air-fuel burners)
- REBOX® HLL (most of the combustion air in the existing air-fuel burners is substituted with oxygen)

Depending on the furnace size, condition, and design and the goal for revamping, different technologies may be best suited for each specific case. For large slab reheat furnaces it is often beneficial to make a partial conversion to oxygen-assisted heating, in order to provide an optimal solution given operating goals and capital and infrastructure constraints.
Over the past five years, 30 flameless oxyfuel systems have been installed at 15 steel mills located throughout the world. Compared with air-fuel technology, the effectiveness of the flameless oxyfuel technology has been shown to result in reduction of specific fuel consumption of up to 50%, and significantly shortening heat cycle time resulting in increased throughput capacity in a range from 10% to 50%. In a furnace operating with 100% flameless oxyfuel, the specific energy intensity could be below 1 GJ/tonne or 0.86 mmBtu/ston (i.e., 25% lower than the best available performance for air-fuel technologies). This paper discusses experiences from installations of flameless oxyfuel technology in slab reheating furnaces, along with important developments and results. We will discuss the installations of REBOX® HLL technology in the 300 tonnes/hour walking beam reheat furnaces at SSAB's Borlänge mill and the 250 tonnes/hour walking beam reheat furnace at Outokumpu´s Tornio mill. By applying different techniques of oxygen boosting or full conversion into flameless oxyfuel heating in walking beam slab reheating furnaces, combustion and heat transfer efficiency were improved significantly and scale losses and emissions of CO_2 and NO_X were substantially reduced.

2 OXYFUEL TECHNOLOGY

When an air-fuel combustion technology is applied in a steel reheat furnace, the burner flame contains nitrogen from the combustion air. A significant amount of the fuel energy is therefore used to heat this nitrogen: approximately eight molecules of N_2 from combustion air per molecule of CH_4 (in the case of natural gas as the fuel). The hot nitrogen leaves through the stack, resulting in energy losses. By using industrial grade oxygen to avoid the nitrogen ballast, however, not only is the combustion itself more efficient but also is 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, which is normal for all types of oxyfuel burners. Another result is that the concentration of the highly radiating products of combustion, CO_2 and H_2O, is increased in the furnace atmosphere. For heating furnace operations, these two factors lead to a higher heating rate, fuel savings, and lower CO_2 emissions

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(Tables 1 and 2). For continuous heating operations, it is also possible to efficiently and economically operate the furnace at a higher temperature at the front end of the furnace. This will further increase the potential throughput of any furnace unit. Oxyfuel combustion technology allows for installation of compact equipment, such as combustion system pipes, flow trains, controls and a flue gas handling system, without the need for recuperative or regenerative heat recovery solutions. Combustion air blowers and related low frequent noise problems are also eliminated.

Table 1: Comparison of energy needs for reheating of steel using air-fuel (with and without recuperation) and oxyfuel employing best techniques of each kind. REBOX® is Linde´s trademark for oxyfuel solutions in reheating and annealing

	Metric	Air Fuel	Air Fuel With recuperation	REBOX ALL Oxyfuel	REBOX HLL
Enthalpy to steel	**kWh/ton**	200	200	200	200
Transmission losses	**kWh/ton**	10	10	10	10
Skid cooling losses	**kWh/ton**	30	30	30	30
Flue gas enthalpy	**kWh/ton**	231	113	39	46
Flue gas temperature	**°C**	1000	1000	900	950
Air preheating	**°C**	20	450	20	400
Thermal efficiency	**%**	51	68	86	84
Energy need	**kWh/ton**	471	353	279	286
Energy need	**GJ/ton**	1,70	1,27	1,00	1,03

Table 2: Comparison of energy needs for reheating of steel using air-fuel (with and without recuperation) and oxyfuel employing best techniques of each kind. REBOX® is Linde´s trademark for oxyfuel solutions in reheating and annealing

	US	Air Fuel	Air Fuel with recuperarion	REBOX ALL Oxyfuel	REBOX HLL
Enthalpy to steel	**mmBtu/ton**	0.62	0.62	0.62	0.62
Transmission losses	**mmBtu/ton**	0.031	0.031	0.031	0.031
Skid cooling losses	**mmBtu/ton**	0.093	0.093	0.093	0.093
Flue gas enthalpy	**mmBtu/ton**	0.72	0.35	0.12	0.14
Flue gas temperature	**°F**	1832	1832	1652	1742
Air preheating	**°F**	68	840	68	750
Thermal efficiency	**%**	51	68	86	84
Energy need	**mmBtu/ton**	1.46	1.09	0.86	0.89
Energy need	**GJ/ton**	1.70	1.27	1.00	1.03

3 FLAMELESS OXYFUEL

In conventional oxyfuel combustion, the relatively high flame temperature creates a potential for forming thermal NO_X. It is important to note that NO_X formation is highly dependent on the design of the oxyfuel burner, furnace specifics and the process control system. In fact, oxyfuel combustion has been used for many years to reduce NO_X emissions to meet environmental regulations [1]. Although only oxygen is used in the conventional oxyfuel combustion process, NO_X is produced as a result of the

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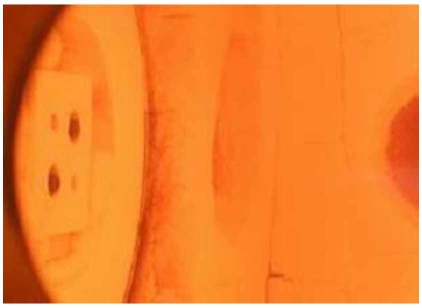
high flame temperature and the ingress air. To lower the peak temperature and improve the flame conditions, the introduction of so-called staged combustion was an important first step to achieve reduced NO_X emissions. However, due to regulatory authorities' continuously lower emission permit levels, further technical developments were required. Conventional oxyfuel combustion can exhibit flame regions with temperatures above 3600°F. One way to reduce the flame temperature is to use the principle of "flameless combustion". This technology has been around for many years. However, only recently has it been exploited industrially.



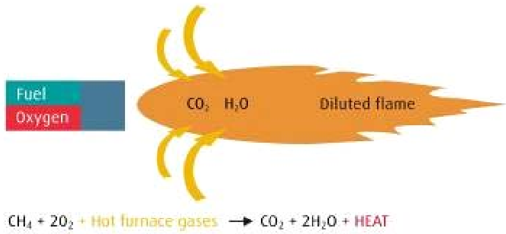


Figure 1: In flameless oxyfuel combustion the flame is diluted by the hot furnace gases. This reduces the flame temperature to avoid creation of thermal NO_X and to achieve more homogenous heating of the steel. The photograph shows flameless oxyfuel combustion with a diluted and almost transparent flame.

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). Another description might be that combustion is "extended" in time and space because it is spread over a large volume. This is the reason it is sometimes referred to as "volume combustion". Such a flame has a uniform and lower temperature, yet contains a high amount of energy.

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 load [2]. The dispersed flame contains the same amount of energy but is spread over a greater volume – with a limited number of burners installed. Figure 2 shows the results of many years of operation at Ovako's Hofors Works [3].

Typically, NO_X is a problem for old and continuous type furnaces. Use of conventional oxyfuel and regenerative air-fuel technology that is much more sensitive to furnace air in-leakage creates higher levels of NO_X than flameless oxyfuel. However, with the low flame temperatures of flameless oxyfuel [4], formation of thermal NO_X is minimized and NOx formation is relatively insensitive to air in-leakage. This was confirmed in an investigation carried out by the Royal Institute of Technology in Stockholm, Sweden. Trials in pilot-scale furnace showed that, even with large volumes of ingress air entering the furnace, NO_X levels remained low. This has been proved further in several additional industrial installations.

There also seems to be an increasing need to combust Low Calorific Fuels [5]. For fuels containing less than 2 kWh/m^3(193 btu/cf), use of oxygen is a must. Flameless oxyfuel can be successfully employed for this application. At integrated steel mills, use of blast furnace top gas (less than 1 kWh/m^3) (97 btu/cf), alone or in combination with other external or internal fuels, is becoming increasingly important. Low Calorific Fuels, such as blast furnace top gas, not only have a low energy density, which

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requires that large volumes have to be transported [6]; they have a low pressure that is costly to increase.

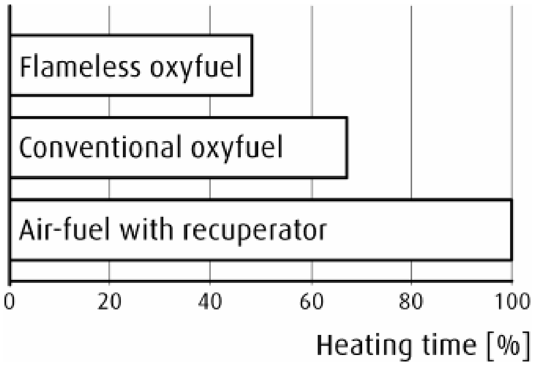

Figure 2: Comparison of total heating time at Ovako's Hofors Works using different combustion technologies.

For the past 20 years, Linde has been pioneering the use of oxyfuel in reheating and annealing furnaces. To date, Linde has installed 120 of its REBOX® technical solutions and 30 flameless oxyfuel systems in steel mills around the world. Currently, these installations are either up and running or in the process of installation at a total of 15 production sites among the following steel companies: Acerinox, ArcelorMittal, Ascométal (Severstal), Böhler-Uddeholm (Voestalpine), Usiminas, Dongbei Special Steel, Kanthal, Outokumpu, Ovako, Sandvik, Scana Steel, SSAB, and others.

4 REBOX® HLL AT SSAB, BORLÄNGE, SWEDEN

SSAB is global niche producer of high strength steel with a leading market position because of its productivity and its innovative solutions that help increase the competitiveness of its customers. SSAB's production capacity in Sweden and the USA totals more than six million tonnes.

SSAB's mill at Borlänge, Sweden, produces sheet coil products. The size of the slabs is 11,000 mm (36 ft) long by 1,500 mm (59 in) wide by 220 mm (~9 in) thick. The reheating takes place in two 37 meter (121 ft) long by 12 meter (39 ft) wide walking beam furnaces (see comparison in Figures 4 and 5) heating slabs from 20°C (68ºF) to 1230°C (2246°F). Designed maximum capacity was 300 tonnes/hour per furnace and the mill produces 2.8 million tonnes of hot rolled coils per year. Oil and propane are used as fuels in the furnaces. The air-fuel combustion system uses a recuperation system to preheat air to 400-550°C (752-1022°F).

The new installation at SSAB uses the REBOX® HLL technology, which creates a type of flameless oxyfuel without replacing the existing air-fuel burners. By reducing the air flow and substituting high velocity oxygen injection into the combustion, great benefits can be achieved. Approximately 75% of the oxygen needed for the combustion is supplied with this technique. For full oxyfuel combustion the flue gas volumes are less than 25% of that of air-fuel combustion at the same firing rate. For REBOX® HLL technology the flue gas volumes are about 35% of that of air-fuel combustion.

It is important to emphasize that the REBOX® HLL technology continues using the existing air-fuel burners. This means that installation of this technology is rather easy

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because it does not include any replacement of burners or installation of additional burners, which minimizes the installation complexity and down time. Also, the existing air-fuel system, at any time, can be brought back into operation as is was before the REBOX® HLL technology was employed. This eliminates any potential risk relating to implementing the REBOX® HLL technology because it enables operating technique to be flexible and optimized in response to fluctuating fuel cost and production requirements.

Following is a summary of achieved results from walking beam istallations using REBOX® HLL and/or flameless oxyfuel boosting:

- Emissions of NO_X have been reduced by up to 45%
- Fuel consumption has been decreased by 25%, with similar reductions in SO_2 and CO_2 [7,8] emissions
- The use of flameless oxyfuel technology has demonstrated no negative impact on the surface quality
- Flameless combustion has demonstrated a positive impact on the temperature uniformity of the slabs.
- Production throughput has been increased by 15-30%
- The ideal heating curve suggested by the control system has been achieved more closely
- There has been a reduction in smoke emanating from the furnace, greatly improving the plant working environment

Figure 3. Burner Installation at SSAB

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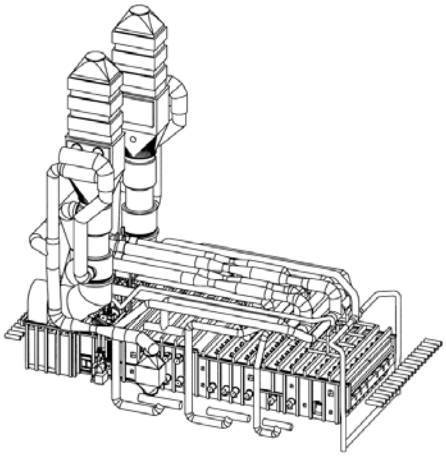

Figure 4:Walking beam furnace at SSAB, Borlänge, Sweden.

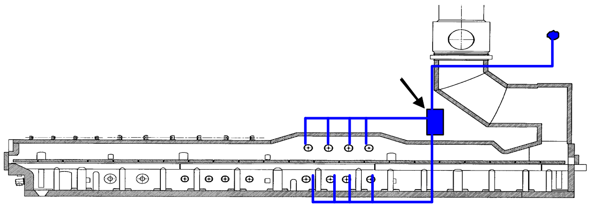

Figure 5: The original furnace equipped with recuperative air-fuel system and REBOX HLL arrangement.

4.1 The REBOX® HLL Installation

The installation of the REBOX® HLL system was made in the preheating zones (Zone 1 and 2), originally equipped with sixteen 3.8 MW (12 mmbtu/h) oil burners using recuperated combustion air of 400°C (750°F). The entire installation was done during a normal production period, using some planned maintenance stops to drill the holes into the furnace. Oxygen flow trains (Figure 6) were placed on top of the furnace to feed the zone with the required pressure and amount of oxygen. Oxygen lances connected with flexible hoses to the main supply pipings completed the installation. No changes to the original air combustion system were needed, which makes it possible to run the REBOX® HLL system "On" or "Off", dependent on the conditions and objectives at hand.

It was decided to have an operating range for the REBOX® HLL system corresponding to oxygen enrichment levels of 25% to 85%. Most of the time, the operation ran with 75% of the total oxygen coming from the high pressure oxygen system, corresponding to an oxygen enrichment level of 51%. The control system is very important because it must control both the flow of air and oxygen to the zone to achieve a correct oxygen level and desired combustion. However, due to the very fast response time of the oxygen regulation system, a correct oxygen to fuel ratio was very easy to attain at all levels of power rates. Hence, the combustion performance improved so that less excess oxygen was needed to avoid incomplete combustion and smoke generation. To provide optimum combustion efficiency, the oxygen to fuel ratio is continuously adjusted to a lower value at higher oxygen enrichment levels.

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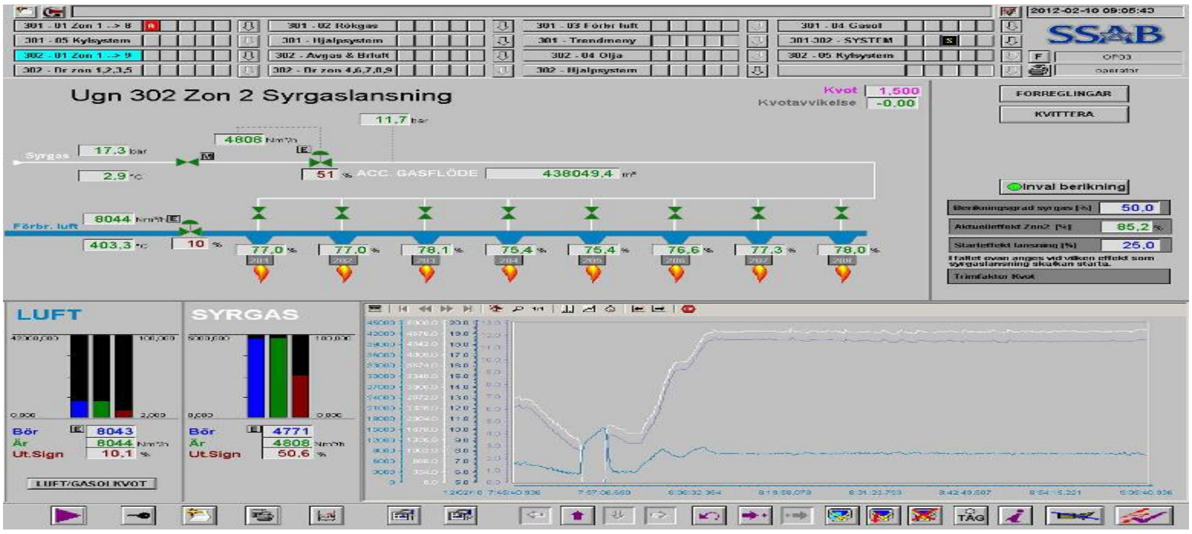

Figure 6: Operators screen.

From an operating point of view, the system was quite simple, the main parameters being oxygen-enrichment level and the oxygen-fuel ratio (lambda value).

The process model used for controlling the heating of slabs with REBOX® HLL technology was complemented with a gas composition factor. This reflects the better radiative properties of the products of combustion (higher concentrations of CO_2 and H_2O) resulting from the combustion having been carried out with higher oxygen concentrations in the oxidant.

During four weeks of trial in April and May 2008, the REBOX® HLL system was initially employed. The system start-up took only one day; some adjustments on control parameters were required, and, after checking temperatures and quality of the first discharged slabs, the system was allowed to run full time. Since March 2009, the REBOX® HLL system has run continuously.

Figure 7:Compact oxygen flow train installed on the walking beam furnace at SSAB - Borlänge in Sweden.

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Figure 8: Highly diluted flames created by the REBOX HLL installation at the walking beam furnace in SSAB-Borlänge in Sweden.The fuel used is heavy oil.

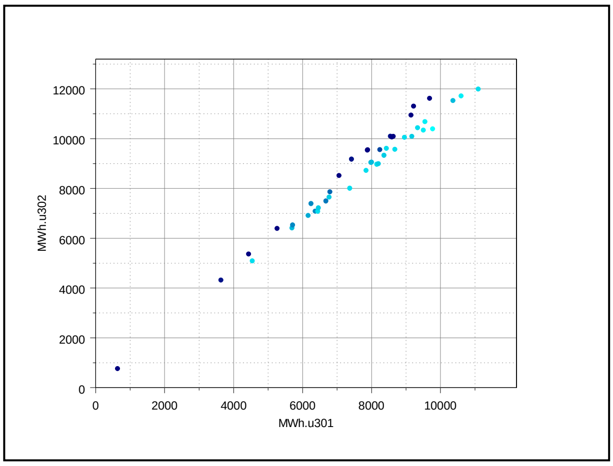
5 RESULTS

Implementation of the REBOX® HLL system in the preheating zones (Zone 1 and 2) has produced many interesting results and proven benefits.

5.1 Lower Fuel Consumption

The first obvious result is lower fuel consumption. To reach the same temperature in the zone and in the slabs as with an all air-fuel operation, the fuel consumption using the REBOX® HLL system is approximately 40% less. This is due to two main reasons: less nitrogen to heat and a higher gas radiation factor (as explained previously). As a result, the overall fuel consumption decreases as well. Figure 9 shows the weekly energy use in the HLL-equipped furnace compared to the sister walking beam furnace heating the same amount of steel slab [9]. It's obvious that more use of oxygen lowers the energy consumption with this technique. This could also be seen in the other diagram where weekly kWh/t (btu/t) is plotted against production rate (t/h).

In order to evaluate the specific energy savings from using oxygen by the REBOX® HLL method, different regressions where made. The result is a relationship that shows 2.5-2.6 kWh of energy savings per Nm^3 of industrial grade oxygen used



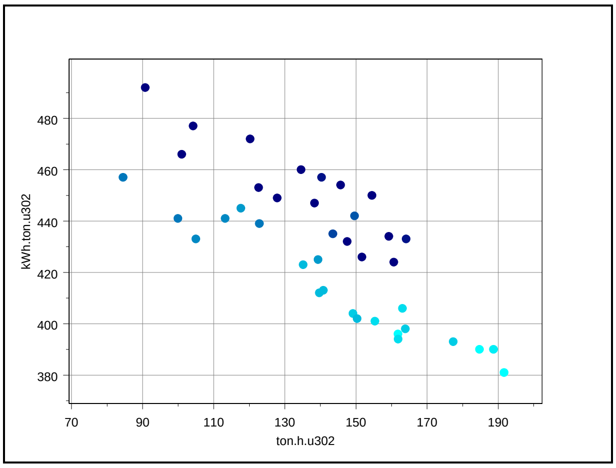


Figure 9: Fuel consumption as a function of oxygen use. The left diagram compares the two walking beam furnaces, one using air-fuel (x-axis) and one using REBOX HLL (y-axis). The right diagram shows the fuel consumption in the furnace with the REBOX HLL installation as a function of the oxygen use. In both diagrams: dark blu e=no oxygen use, light blue= oxygen up to 4000 m3/h (148,000 scfh) used.

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5.2 More Even Temperature Distribution

The temperature distribution within the zone was very even, and enhances the possibility of producing a temperature profile along the slab that is more uniform. These results are shown in Figure 8. With REBOX® HLL, from operational point of view, a new tool has been added to control the temperature distribution inside the furnace.

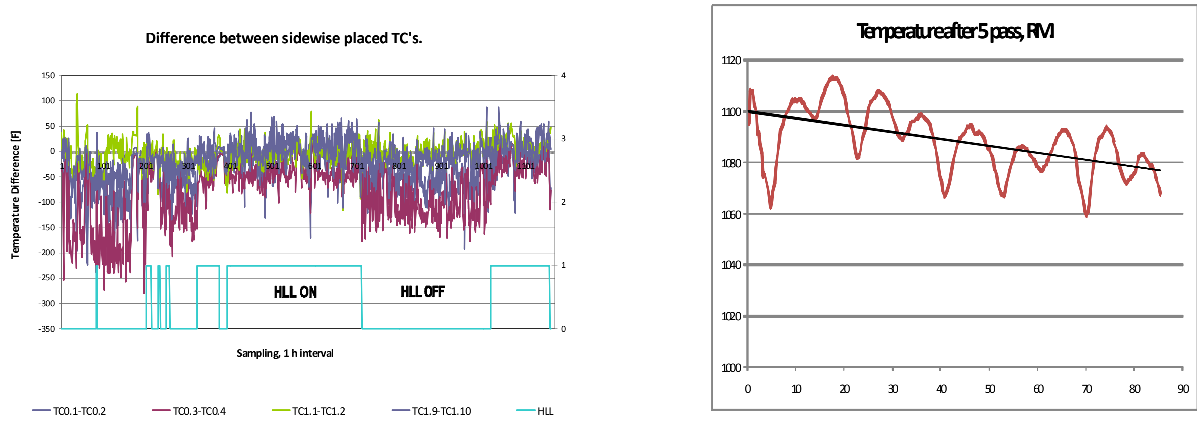

Figure 10.The left diagram shows the impact of REBOX HLL operation on the zone's deviation in temperature distribution. In the right diagram, it is presented the temperature profile along heat transfer bar after 5 passes through rougher mill.

5.3 Decreased Emissions

From an environmental point of view, there are also benefits from employing the REBOX® HLL technology: CO_2 and SO_2 emissions decrease proportional to the reduction in fuel consumption. The NO_X emissions change by REBOX® HLL technology is more difficult to characterize in general terms. It depends on the burner configuration used to apply the technology and to what you compare. In the current application, a lot of measures have been taken to lower the NO_X at the same time that the REBOX® HLL technology was implemented and began to be used. All together the NO_X emission has decreased from 117 mg/MJ (0.272 lbs per million btu) to 85 mg/MJ (0.198 lbs per million btu), which is a very low figure for the use of heavy fuel oil as fuel. When evaluating these figures, we should also consider the change of total energy input per tonne of produced steel. If taking this into account, on average the REBOX® HLL system in one zone gives an additional reduction of 7% in total NO_X per tonne of heated steel.

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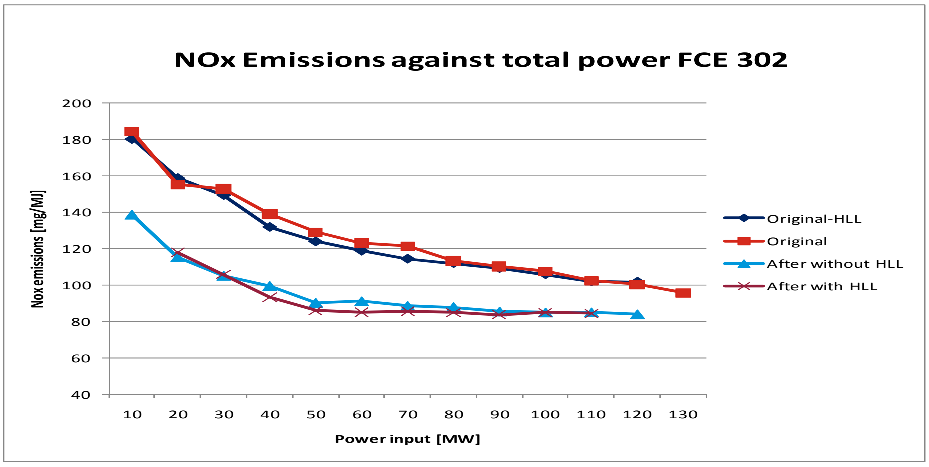

Figure 11: *NO_X emissions have been significantly decreased since the installation of REBOX HLL. "Original" means the operation in early 2009. "After"represents operation in 2010. At both time periods the furnace has been operated both with and without REBOX HLL technology.*

As mentioned earlier, it was possible to lower the oxygen/fuel ratio to provide complete combustion without producing smoke. This means that, not only is less fuel needed, less oxygen is required (compared to our earlier assumptions).

5.4 Increased Throughput

Productivity increase has not been completely validated but the possibilities have been indicated. Due to the production logistics of the rolling mill, with two parallel furnaces of nearly the same capacity having to feed the hot mill at the same pace, an increased capacity for one furnace can not be easily accommodated. However, it was obvious that with the REBOX® HLL system, the heating rate increased and the potential to increase the tonnage throughput is substantial. For example, no limitations which normally are present, such as low pressure of combustion air or not enough heating provided occurs when using HLL operation. Simulations show that a productivity increase of 14% is achievable with the REBOX® HLL technology installed and operating in only two furnace zones. However, a higher productivity rate is not the only benefit that comes with higher heating capacity. Increased soaking time and a more flexible production unit for use as a stand-alone furnace are also significant advantages [10].
In Table 3 the achieved results could be seen as well as the reference values without any use of oxygen.

Table 2: Actual results of the REBOX HLL installation in the walking beam furnace no302

	Air- fuel	**REBOX HLL Zone 1&2**
Conversion to HLL of total installed power (HLL/Total)	0/152	50/152
Fuel consumption at 140 t/h [kWh/t] [btu/t]	448	376 (-16%)
NO_X [tonnes/year] at 1.6 million tonnes production	304	186*
Max oxygen consumption [Nm3/h] [scfh]	-	10,000
Production limit [t/h]	300	340

**Includes other NO_X reducing measures.*

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6 REBOX® HLL AT OUTOKUMPU STAINLESS, TORNIO, FINLAND

Outokumpu Stainless Tornio Works is one of the leading stainless steel plants in the world. In the end of 2011 Linde and Outokumpu installed REBOX® HLL in both preheating zones of the number 2 Walking Beam furnace. After detailed evaluations and simulations, Linde delivered the system as a turn-key supply, including performance guarantees.
The furnace is fired with a mixture of liquefied propane gas and CO gas from the Ferrochrome furnaces on site. The oxygen is supplied from an AGA/Linde ASU via pipeline. The furnace preheats hot and cold slabs before hot-rolling.
In the successful performance test, heating capacity increased from 250 to >300 ton/h and at the same time specific energy consumption was reduced by ~30 kWh/ton (~0.1 mmbtu/ton). The capacity may be used for increased production when production demand is high or conversely only one furnace is utilized when order activity is reduced, saving even more energy.
The NOx emission was reduced from an already very low level by 5-10%.

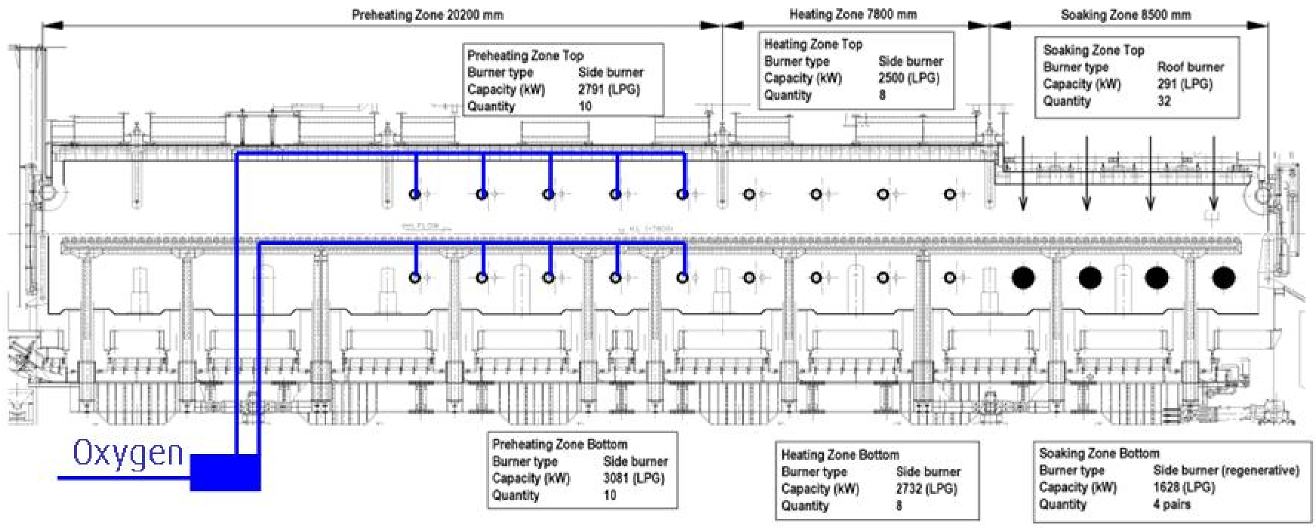

Figure 12: Walking beam furnace at Outokumpu, twenty Rebox-HLL lances installed in the preheat zone.

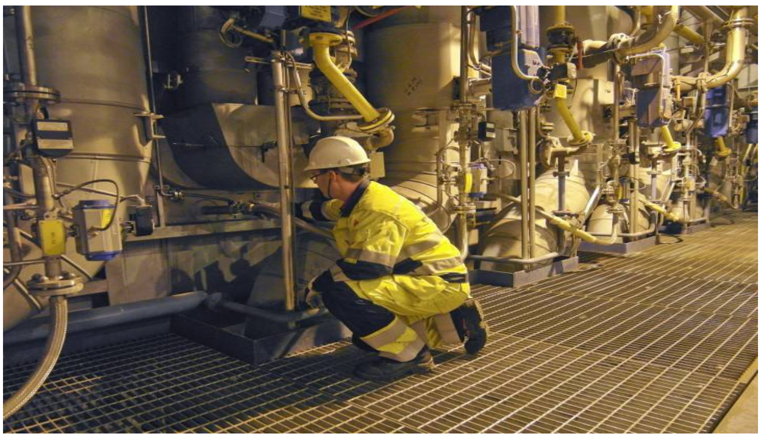

Figure 13: Rebox-HLL lances installed below existing burners at Outokumpu.

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7 REBOX® ALL OXYFUEL, OUTOKUMPU STAINLESS, DEGERFORS, SWEDEN

In 2002, Outokumpu decided to meet changing market demands by increasing capacity in the hot-rolled plate mill at their Degerfors site by 30% at the same time fulfilling strict environmental legislation.
In 2003, a 120,000 ton/year capacity walking beam furnace (Figure 14), in Degerfors was rebuilt and refurbished in a turnkey project with performance guarantees. The elements of REBOX® oxyfuel solution entailed:

- Turn key project with performance guarantees
- Replacement of recuperative air-fuel system with oxyfuel flameless burners
- Modified heating zone for improve heating profile
- Removal of the recuperative flue gas system and replacement with active damper for active furnace pressure control
- New combustion system with the state of the art control and heating profile modeling


Figure 14: Outokumpu in Sweden increased its heating capacity in the existing walking beam furnace by >35% when implementing flameless oxyfuel.

The fulfilled performance guarantees followed with ongoing results of >35% increase in heating capacity (Figure 13), provided an increase in loading of the rolling mill, and a reduction of over 30% in fuel consumption. The environmental requirements were by far exceeded by achieving NO_X emissions significantly below 70 mg/MJ.

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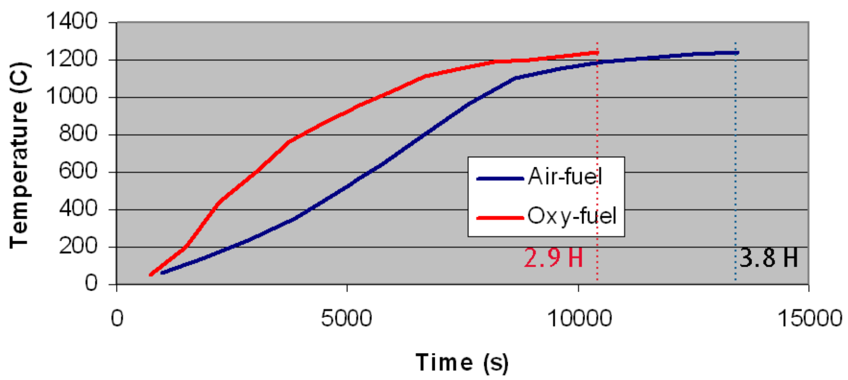

Figure 14: Comparision of heating curves at Outokumpu, Degerfors, before and after conversion to flameless oxyfuel operation. Slab thickness is 166 mm.

8 SUMMARY

REBOX® Flameless oxyfuel is a proven and leading combustion technology, which provides substantial benefits for slab and billet reheating in continuous reheat furnaces.

REBOX® Flameless oxyfuel technology is known as an attractive solution not only for improvement of heating efficiency and to increase steel reheating capacity, but also to significantly reduce emissions to the environment and improve the quality of the product.

The successful results from REBOX® industrial installations of flameless oxyfuel in 30 furnaces, demonstrates clear advantages over other alternatives.

REBOX® HLL provides a lower capital cost, less invasive method to enhance production flexibility, increase capacity, improve energy efficiency and allows higher production outputs with fewer furnaces. The producer is able to operate the REBOX® HLL system in a flexible manner to achieve the desired objectives given the current mill, cost, and market conditions.

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