SUCCESSFUL USE OF FLAMELESS OXYFUEL IN REHEAT FURNACES AND LADLE PREHEATING

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Abstract
For decades the benefits oxyfuel combustion have been clearly demonstrated. Compared to air-fuel it delivers a much more efficient heating; faster, decreasing the fuel consumption, and producing less emissions of CO₂ and NOₓ.

In addition to the great advantages of conventional oxyfuel, flameless oxyfuel provides even higher production rates, excellent temperature uniformity and very low NOₓ emissions. Linde introduced flameless oxyfuel in 2003. As of today, more than 30 reheat furnaces and 20 preheating stands have been equipped with flameless oxyfuel. The smallest ladles where it has been viably applied are only 1 tonne.

Flameless oxyfuel further improves heat distribution uniformity, which actually also decreases the fuel consumption; compared to air-fuel, the fuel consumption could be reduced by 25-60%. It leads to ultra low NOₓ emission even at high levels of ingress air, which is extremely important. The end results could also include lower scaling losses in reheating, improved steel quality, and less refractory wear in ladle preheating.

An additional advantage is that it can be use low calorific gases as fuel. For efficient use of fuels containing below 2 kWh/Nm³ (7-7.5 MJ/Nm³), for example blast furnace top gas, use of oxyfuel combustion is an absolute requirement.

There are today also a technology that combines air-fuel and flameless oxyfuel, creating a semi flameless combustion without replacing the air-fuel burners. A large such installation is in operation in 300 tph walking beam furnaces at SSAB in Sweden.

The paper describes how flameless oxyfuel works, where it has been applied and presents results that have been achieved at installations in several countries.

INTRODUCTION
Oxyfuel solutions deliver a unique combination of advantages in reheat and annealing. Thanks to improved thermal efficiency (about 80% compared with 40-60% for air-fuel), the heating rate and productivity are increased and less fuel is required to heat the product to the desired temperature, at the same time saving on CO₂ and NOₓ emissions. Linde has made more than 120 installations in reheat and annealing furnaces and galvanizing lines, employing conventional oxyfuel, direct flame impingement oxyfuel, and flameless oxyfuel. In summary the results include:

- Throughput capacity increase of up to 50%
- Fuel savings of up to 50%
- Reduction of CO₂ emissions by up to 50%
- Reduction of NOₓ emissions
- Reduction of scaling losses
In heating, oxyfuel combustion offers clear advantages over state-of-the-art air-fuel combustion, for example regenerative technology, in terms of energy use, maintenance costs and utilization of existing production facilities. If all the reheating and annealing furnaces would employ oxyfuel combustion, the CO₂ emissions from the world’s steel industry would be reduced by 100 million tonnes per annum.

But also in vessel preheating, oxyfuel, and in particular flameless oxyfuel, shows great benefits. A very good economic outcome has been obtained from ladle and converter preheating using flameless oxyfuel.

Linde’s experience from converting furnaces and vessel preheating stands into all oxyfuel operating shows energy savings ranging from 20% to 70%, excluding savings in energy needed to bring the natural gas from its sources to the combustion point. In the mid 1980s Linde began to equip the first furnaces with oxygen-enrichment systems. These systems increased the oxygen content of the combustion air to 23-24%. The results were encouraging: fuel consumption was reduced and the output, in terms of tonnes per hour (tph), increased. In 1990 Linde converted the first furnace to operation with 100% oxygen, that is, full oxyfuel combustion, at Timken in USA. Today there are more than 120 reheat furnaces and annealing lines using Linde’s REBOX oxyfuel solutions. During the last years flameless oxyfuel have been employed.

ENERGY EFFICIENCY

In an air-fuel burner the burner flame contains nitrogen from the combustion air. A significant amount of the fuel energy is used to heat up this nitrogen. The hot nitrogen leaves through the stack, creating energy losses. When avoiding the nitrogen ballast, by the use of industrial grade oxygen, then not only is the combustion itself more efficient but also the heat transfer. Oxyfuel combustion influences the combustion process in a number of ways. The first obvious result is the increase in thermal efficiency due to the reduced exhaust gas volume, a result that is fundamental and valid for all types of oxyfuel burners. Additionally, the concentration of the highly radiating products of combustion, CO₂ and H₂O, is increased in the furnace atmosphere. For heating operations these two factors lead to a higher heating rate, fuel savings, lower CO₂ emissions and – if the fuel contains sulphur – lower SO₂ emissions, Today’s best air-fuel solutions need at least 1.3 GJ for heating a tonne of steel to the right temperature for rolling or forging. When using Linde’s REBOX oxyfuel solutions the comparable figure is below 1 GJ, a saving of 25%, compare Table 1.

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

<table>
<thead>
<tr>
<th></th>
<th>Air fuel</th>
<th>AF w recu</th>
<th>REBOX®</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enthalpy in steel</strong></td>
<td>kWh/t</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td><strong>Transmission losses</strong></td>
<td>kWh/t</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Flue-gas enthalpy</strong></td>
<td>kWh/t</td>
<td>290</td>
<td>140*</td>
</tr>
<tr>
<td><strong>Flue-gas temperature</strong></td>
<td>°C</td>
<td>1200</td>
<td>850</td>
</tr>
<tr>
<td><strong>Air preheating</strong></td>
<td>°C</td>
<td>20</td>
<td>450</td>
</tr>
<tr>
<td><strong>Thermal efficiency</strong></td>
<td>%</td>
<td>42</td>
<td>60</td>
</tr>
<tr>
<td><strong>Energy need</strong></td>
<td>kWh/t</td>
<td>500</td>
<td>350</td>
</tr>
<tr>
<td><strong>Energy need</strong></td>
<td>GJ/t</td>
<td>1.8</td>
<td>1.26</td>
</tr>
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</table>

*after recuperation
For continuous heating operations it is also possible to economically operate the furnace at a higher temperature at the entry side of the furnace. This will even further increase the possible throughput in any furnace unit. Oxyfuel combustion allows all installation pipes and flow trains to be compact without any need for recuperative or regenerative heat recovery solutions. Combustion air-blowers and related low frequency noise problems are avoided.

**FLAMELESS OXYFUEL**

In recent years ‘flameless combustion’ has been employed. The expression communicates the visual aspect of the combustion type, that is, the flame is no longer seen or easily detected by the human eye. Another description might be that combustion is ‘extended’ in time and space – it is spread out in large volumes, and this is why it is sometimes referred to as ‘volume combustion’. Such a flame has a uniform and lower temperature, yet containing same amount of energy, see Figure 1.

In flameless oxyfuel the mixture of fuel and oxidant reacts uniformly through flame volume, with the rate controlled by partial pressures of reactants and their temperature. The flameless oxyfuel burners effectively disperse the combustion gases throughout the furnace, ensuring more effective and uniform heating of the material even with a limited number of burners installed – the dispersed flame still contains the same amount of energy but is spread over a greater volume. The lower flame temperature is substantially reducing the Low NO\(_x\) formation. Low NO\(_x\) emission is also important from a global warming perspective; NO\(_2\) has a so-called Global Warming Potential that is almost 300 times that of CO\(_2\). Figure 2 illustrates the increased efficiency achieved with flameless oxyfuel. Also, the use of low calorific fuels has been emphasized lately, for example using blast furnace top gas.

Oxyfuel burners have always been powerful and compact, and 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. Furthermore, flameless oxyfuel combustion not only adds further advantages, but opens up for new applications, all supporting a substantially decreased environmental impact.

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

**AWARD WINNING USE IN REHEATING**

For the use of flameless oxyfuel in reheating and annealing, three recent installations are worth special mention:

- Use of REBOX HLL technology, which creates a type of flameless oxyfuel without replacing the existing air-fuel burners, for slab reheating in a 300 tph walking beam furnace at SSAB in Sweden.
- The AIST Energy Achievement Award winning flameless oxyfuel installation in a rotary hearth furnace at the seamless tube mill of ArcelorMittal Shelby in the USA. Here the energy savings compared with air-fuel exceeded 60%.
- The new state-of-the-art annealing furnace for stainless steel wire applying REBOX DST (Direct Solution Treatment) at Dongbei Special Steel Group in China. The flameless combustion here uses a low calorific fuel with an energy content of 1.75 kWh/Nm$^3$ (6.3 MJ/Nm$^3$).

Flameless oxyfuel installations for reheating and annealing could be find at the following steel companies: ArcelorMittal, Ascométal, Böhler-Uddeholm, Usiminas, Dongbei Special Steel, Outokumpu, Ovako, Scana Steel and SSAB. Here follows some examples from those installations.

Linde has carried out flameless oxyfuel installations at two sites belonging to the bearing steel producer Ascométal in France, which is part of the Severstal Group. At Fos-sur-Mer, a turnkey delivery in 2005-2007 converted nine soaking pit furnaces into all flameless oxyfuel. The delivery included a combustion system with flameless burners, furnace upgrade, new flue gas system, flow train, and a control system. The furnace sizes are 80 to 120 tonne heating capacity each. The results include 50% more heating capacity, 40% fuel savings (compare Figure 3), NO$_X$ emission reduced by 40%, and scale formation reduced with 3 tonne per 1,000 tonne heated. In a second and similar project in France in 2007-2008, four soaking pit furnaces at the Les Dunes plant were also converted into all flameless oxyfuel operation.
Fig 3. The diagram shows total average fuel consumption in the 13 soaking pit furnaces at Ascométal, Fos-sur-Mer. 2001-2004 was all air-fuel combustion. The first conversion into oxyfuel took place in 2005. In 2007 nine out of 13 furnaces were operated with all oxyfuel. The average fuel consumption per tonne was reduced by 100 kWh or 10 Nm$^3$ of natural gas.

20 OXYFUEL INSTALLATIONS AT OUTOKUMPU

Linde has made a total of 20 installations at Outokumpu’s sites in Sweden, in reheating, annealing and preheating. In 2003, a walking beam furnace in Degerfors was rebuilt and refurbished in a Linde turnkey project with performance guarantees, see Figure 4. 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.

At the Nyby plant, there are two catenary furnaces, originally installed in 1955 and 1960 respectively. The catenary furnace on the first annealing-pickling line, for hot or cold rolled strips, was converted to all oxyfuel operation in 2003. Requirements for increased production combined with stricter requirements for low NO$_X$ 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 and NO$_X$ levels below the guaranteed level of 70 mg/MJ.
At Avesta we find the world’s largest full oxyfuel fired furnace, 40 MW. The old 24 m catenary furnace had a 75 tph capacity, but the requirement was to double this whilst at same time meeting strict requirements for emissions. The refurbishment included a 10 m extension, yet production capacity was increased to 150 tph. The conversion involved the removal of air-fuel burners and recuperators and the installation of all oxyfuel. The oxyfuel technology used involved staged combustion. The conversion reduced fuel consumption by 40%, and NO\textsubscript{X} levels are below 65 mg/MJ. This furnace is an example of another route to flameless; having been converted from conventional oxyfuel to flameless oxyfuel last year and resulting in an additional 50% reduction of the NO\textsubscript{X} levels.

50% FUEL SAVINGS AT ARCELORMITTAL

There have been several successful installations in rotary hearth furnaces. One is found at ArcelorMittal Shelby in Ohio, USA. In 2007, Linde delivered a turnkey conversion of a 15-metre diameter rotary hearth furnace at this seamless tube producer. It included combustion system with flameless burners, furnace upgrade, new flue gas system, flow train, and a control system. The former air-fuel fired furnace was converted in two steps, first using oxygen-enrichment for a period of time and then implementation of the flameless oxyfuel operation. Excellent results have been achieved, meeting all performance guarantees. These included >25% more throughput, 50% fuel savings compared with oxygen-enrichment, NO\textsubscript{X} emission <70 mg/MJ, and 50% reduced scale formation. Pictures of the furnace, before and after the installation, are shown in Figure 5.

ArcelorMittal Shelby received the AIST Energy Achievement Award for its efforts to reduce fuel consumption by nearly two-thirds in the billet reheating operation at its Shelby, Ohio, seamless tube mill. Mike Lantz, senior process engineer and oxyfuel conversion project manager for ArcelorMittal, said, “It is an honour to have received the 2009 AIST Energy Achievement Award. It recognizes ArcelorMittal’s strategic commitment to sustainability.” Jerome Granboulan, vice president of ArcelorMittal and CEO of Tubular Products, said, “As an industry leader, we focus on maintaining operational excellence while investing in projects that will strengthen our cost position and improve environmental performance.”
Fig 5. Outside view of the Rotary Hearth Furnace at ArcelorMittal, Shelby, before and after the REBOX installation. Please note that all bulky equipment and piping relating to the previously used air-fuel system have been removed as it no longer is of any use.

300 TPH WALKING BEAM FURNACES AT SSAB

At SSAB in Sweden REBOX HLL is used. The slabs are reheated in walking beam furnaces with a capacity of 300 tph per furnace, from ambient temperature to 1,230°C. The air-fuel combustion system uses a recuperation system to preheat air to 400°C. The fuel is oil, and prior to the HLL installation the consumption was 440 kWh/tonne, or 1.58 GJ/tonne.

REBOX HLL 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. 75% of the oxygen needed for the combustion is supplied with this technique. The flue-gas volume is less than 45% that of air-fuel. The system start-up took just one day. The installation in only one zone has increased the heating capacity from 300 to 320 tph.

The installation of HLL is rather easy because it does not include any replacement of burners or installation of additional burners, which minimizes the installation down time. The air-fuel system can at any time be brought back into operation as it was before. This eliminates any potential risk relating to the implementation, and it enables operation to be flexible and optimized in response to fluctuating fuel cost and production requirements.

Fig 6. Highly diluted flames created by the REBOX HLL installation at 300 tph walking beam furnaces at SSAB, Borlänge in Sweden. The fuel used is heavy oil.

Some important results from this installation are:

- No negative impact on the surface quality.
• A positive impact on the temperature uniformity of the slabs.
• The ideal heating curve suggested by the control system can be achieved more easily.
• Less smoke emanating from the furnace, greatly improving the plant environment.

Based on the results of current installation in one zone, SSAB has estimated that a full implementation would provide the following:

• A reduction of NO\textsubscript{X} emission by 45%.
• Fuel consumption can be decreased by 25%, leading to the same reductions in SO\textsubscript{2} and CO\textsubscript{2} emissions.
• Production throughput can be increased by 15-20%.

At SSAB’s Borlänge mill, an extensive REBOX\textsuperscript{®} HLL oxyfuel system has been installed. Combined with a similar but smaller system implemented there in 2009, the installation, which started up in early 2011, will represent the world’s largest oxyfuel combustion system in a reheat furnace. The first system, with 25 MW of power, was installed in one of two zones within one of the 300 tph walking beam furnaces. Following its successful operation, the technology has now be extended to that furnace’s second zone and to both preheating zones within the other furnace. The combined oxyfuel installation will allow the Borlänge plant to operate at 60-70 MW and delivers operational improvements including a 10% increase in throughput capacity, a reduction of fuel consumption by 15%, in addition to helping to decrease CO\textsubscript{2} and NO\textsubscript{X} emissions by as much as 15 and 25 percent respectively.

The REBOX HLL technology creates a type of flameless oxyfuel without the need to replace existing air-fuel burners. By reducing the air flow within the combustion process and substituting the majority of the air with oxygen, which is delivered via high velocity injection, combustion is greatly improved. Additionally, the flue-gas volume produced from this oxygen-enhanced mixture is less than 55 percent of that of air-fuel alone. The benefits for the end user include increased throughput capacity, improved temperature uniformity, decreased fuel consumption and reduction of NO\textsubscript{X} and CO\textsubscript{2} emissions. As no alternative or additional burners are required, which minimises the installation downtime, the legacy air-fuel system can also be reinstated at any time. This mitigates potential risk associated with the implementation and allows for optimal and flexible operations in order to respond to fluctuating fuel costs and production requirements.

LADLE AND CONVERTER PREHEATING

Flameless oxyfuel brings very strong advantages in preheating of vessels. Flameless oxyfuel delivers a simple, compact and low weight installation as compared to an air-fuel system with a recuperator or regenerative solution. It is seen as the best available technology for heating and not only allows for ultra low NO\textsubscript{X} emissions, but brings extended refractory life through more uniform temperature distribution. The first installation took place in 2003. Today more than 15 installations of flameless oxyfuel are in operation, two recent cases are found at Outokumpu at Tornio, Finland and SKF at Katrineholm, Sweden.

In 2008 flameless oxyfuel preheating was installed at Outokumpu’s 90 tonnes ferrochrome converter. The 2.5 MW flameless oxyfuel system is used for drying and preheating of the converter, and provides the Tornio Works with greater energy efficiency, lower fuel consumption, and reduced emissions CO\textsubscript{2} and NO\textsubscript{X}.

“It is Outokumpu’s policy to follow and implement technology that decreases fuel consumption and CO\textsubscript{2} and NO\textsubscript{X} emissions. Linde’s flameless oxyfuel system is a compelling technology that fulfils this need. Outokumpu will continue to utilise technologies that increase output while saving energy and reducing emissions,” said Outokumpu’s Mauri Kauppi.

At SKF a similar type of flameless oxyfuel technology was installed last year, but for preheating ladles. And the size is here completely different; the ladles are for 1 tonne of steel. Six ladle preheating stands were
equipped with OXYGON® flameless oxyfuel preheating systems. This installation shows that a new energy saving and environmentally friendly technology also can be viable in a smaller scale production.

Fig 7. Ladle preheating stations using flameless oxyfuel for preheating of 1 tonne ladles at SKF at Katrineholm, Sweden.

SUMMARY

Oxyfuel provides an overall thermal efficiency in the heating of 80%, air-fuel reaches 40-60%. With flameless oxyfuel, compared to air-fuel, the energy savings in a reheating furnace are at least 25%, but many times 50% or even more. It is possible to operate a reheating furnace with fuel consumption below 1 GJ per tonne. The corresponding reduction in CO₂ emissions is also 25-50%. Savings in terms of NOₓ emissions are substantial. Flameless oxyfuel combustion has major advantages over conventional oxyfuel and, even more, over any kind of air-fuel combustion. The improved temperature uniformity is a very important benefit, which also reduces the fuel consumption further.

In more than 120 installations, Linde’s REBOX oxyfuel solutions enable rolling mills, forge shops, annealing operations and metal coating lines to increase furnace throughput and improve operational flexibility, heating performance and temperature uniformity while reducing scale formation and cutting fuel consumption.

With oxyfuel it is possible to increase the throughput rate by up to 50%. This can be used for increased production, less number of furnaces in operation, increased flexibility, etc. It is also of interest when ramping up production; two furnaces can cover the previous production of 2.5-3 furnaces, meaning possibility to post start-up of the third furnace and, additionally, resulting in decreased fuel consumption. Increased capacity can also be used to prolong soaking times. Thanks to the reduced time at elevated temperatures, oxyfuel leads to reduced scale losses, at many installations as high as 50%.

But also in vessel preheating, oxyfuel, and in particular flameless oxyfuel, shows great benefits. A very good economic outcome has been obtained from ladle and converter preheating using flameless oxyfuel.

As of today, more than 30 reheat furnaces and 20 preheating stands have been equipped with flameless oxyfuel. The smallest ladles where it has been viably applied are only 1 tonne.