

Use of direct flame impingement oxyfuel

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In air-fuel combustion, the burner flame contains nitrogen from the combustion air; hence, 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.

Prompted by rapidly rising fuel prices in the 1970s, the steel industry began to consider methods to reduce fuel consumption in reheating and annealing. This laid the foundation for the use of oxyfuel solutions in rolling mills and forge shops (Fig. 1). In the mid 1980s, Linde first began to equip these furnaces with oxygen-enrichment systems, which increased the oxygen content of the combustion air to 23–24% (Fig. 2). The results were encouraging: fuel consumption was reduced and the output, in terms of tons per hour, increased.

In 1990, Linde converted the first steel reheating furnace in the world to operate with 100% oxygen at Timken in the USA. Since then, Linde has been pioneering the use of oxyfuel for this application. Today, the number of such installations has reached 120. Overall, the results can be summarised as:

- capacity increase of up to 50%
- fuel savings of up to 50%
- reduction of scaling losses

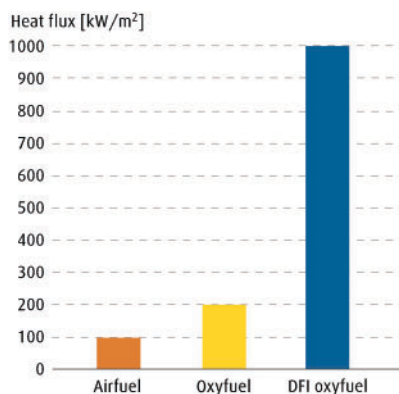
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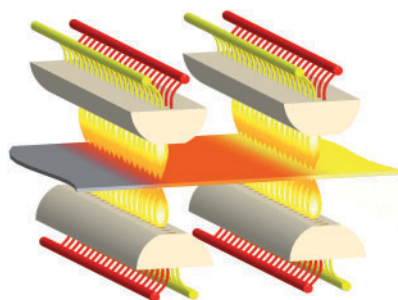
- reduction of CO₂ emissions by up to 50%
- reduction of NO_x emissions.

Big and diffuse, small and sharp

Linde has continued to develop the processes to meet new demands and challenges. As a result, some very interesting technologies have emerged in parallel with conventional oxyfuel, which is widely used to boost melting in electric arc furnaces. Among these, the most important ones are flameless combustion and direct flame impingement (DFI). These new technologies not only fulfil existing needs with astonishing results, also open up completely new areas of application. Flameless combustion, also known as 'volume combustion', creates a huge practically invisible



1 Comparison of heat transfer efficiencies



2 Schematic of direct flame impingement (DFI) Oxyfuel unit with thermal efficiency of around 80%

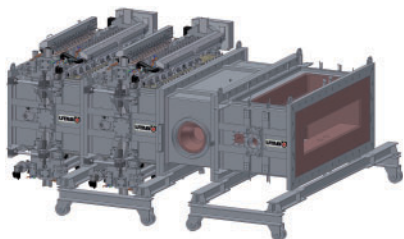
oxyfuel flame, whereas DFI technology uses small, well-defined sharp flames.

Compared with conventional oxyfuel, flameless oxyfuel provides even higher production rates, excellent temperature uniformity and very low NO_x emissions. The first installations of this innovative flameless oxyfuel technology were made by Linde in 2003. Linde now has over 30 installations of this technology at more than a dozen sites, some using a low calorific fuel.

DFI Oxyfuel is a fascinating, compact, high-heat transfer technology, which provides enhanced operation in strip processing lines such as galvanising. DFI Oxyfuel has been used to boost capacity of strip annealing and hot dip metal coating lines by 30% or more, while reducing the specific fuel consumption. Systems are in operation at Outokumpu's Nyby Works in Sweden (Fig. 3) and ThyssenKrupp's works at Finnerntrop and Bruckhausen in Germany (Figs. 4 and 5). In October 2009, a unit will be installed in a continuous annealing line at POSCO in Pohang, Korea.



3 DFI Oxyfuel installation at entry side of stainless strip annealing line at Outokumpu, Nyby Works, Sweden



4 View of DFI Oxyfuel unit at galvanising and aluminising line at TKS's Bruckhausen works



5 DFI Oxyfuel unit installed at Finntrop

DFI Oxyfuel technology

DFI Oxyfuel, where oxyfuel flames directly heat the moving metal, is a patented solution within Linde's portfolio of REBOX Oxyfuel solutions. The main benefits are:

- significantly higher heat transfer (10 times the process in use) resulting in increased production capacity
- low fuel consumption due to small flue gas volume
- ability to use high power input in limited furnace volume
- compact and powerful unit for easy retrofit
- heating and cleaning in one operation
- option to modify surface conditions.

Tests have verified the higher level of local heat flux for this technology. In general, the use of oxyfuel combustion substantially increases the thermal efficiency of a furnace, primarily due to the fact that radiant heat transfer of furnace gases produced by oxyfuel combustion is significantly more efficient than those of air-fuel. Owing to the absence of nitrogen in the combustion mixture, which does not need to be heated, the volume of

exhaust gas is also substantially reduced, thus lowering total heat loss through the exhaust gas. Thanks to improved thermal efficiency, the heating rate and productivity are increased and less fuel is required to heat the product to a given temperature, while at the same time economising on fuel and reducing CO₂ emissions.

The DFI unit has a thermal efficiency of around 80%. This reduces the specific fuel consumption while delivering a powerful 30% capacity increase in an existing strip processing line. In galvanising, zinc adhesion and surface appearance are also improved due to DFI's effective pre-cleaning properties, leaving both strip and furnace rolls cleaner than before.

It is important to note that applying a DFI Oxyfuel system for pre-heating strip does not create an oxidation problem, for example, experience with pre-heating up to 300°C shows no problems. In metal coating lines, the thin oxide layer formed is reduced in the subsequent reduction zone. It is also possible to influence the oxidation level to a certain extent by adjusting the stoichiometry of the flames.

First installation at stainless annealing

Since the beginning of the 1990s, Linde has pioneered the use of 100% oxyfuel applications in reheat furnaces in close cooperation with customers such as Outokumpu, which was one of the first customers to which Linde provided turnkey solutions. At Outokumpu's Nyby site in Sweden, the company wanted to increase the production capacity of a stainless strip annealing line, but the furnace already contained an oxyfuel combustion system and had extremely limited physical space available. In 2002, Linde installed the first compact DFI Oxyfuel unit, making it possible to increase the production by 50% (from 23 to 35 t h⁻¹) without extending the furnace length.

This installation consisted of:

- 2 m long DFI unit at the entry side
- four burner row units
- 4 MW installed power
- 120 oxyfuel flames.

Metal coating lines at ThyssenKrupp

In 2007, the REBOX DFI system was installed at ThyssenKrupp Steel's (TKS) galvanising and aluminising line in Bruckhausen, Germany. Earlier, Linde

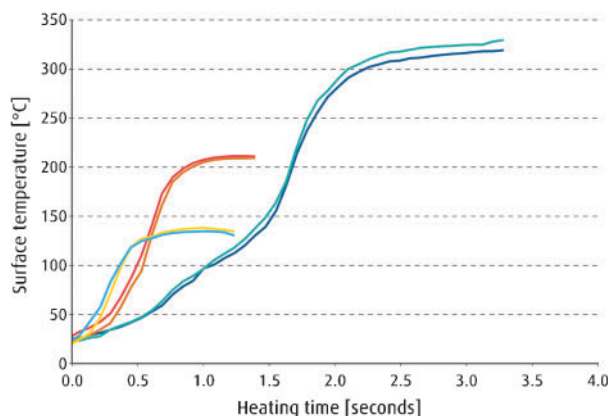
had installed a DFI unit at the TKS galvanising line at Finntrop, and increased production from 82 to 105 t h⁻¹, or over 30%. The results at the Bruckhausen installation matched those in Finntrop: increasing capacity from 70 to 90 t h⁻¹. Oxyfuel not only effectively heats, contributing to a reduction of fuel consumption, but also cleans, thus eliminating the need for the pre-cleaning section. In addition, the process made it possible for ThyssenKrupp to pre-oxidise steel strips in a precise and controlled manner.

The Finntrop plant carries out zinc coating of hot and cold strip of 650–1550 mm width and 0.3–3.25 mm thickness. Before the DFI installation, it had a 25 m long pre-cleaning section with electrolytic cleaning and brushes. The total furnace length is 130 m, with 48 m pre-heating section. The total installed power was 22 MW, 17.5 MW for preheating with air-fuel (pre-heated air temperature at 450°C) and 4 MW in radiant tubes in the reduction zone. Natural gas is used as fuel. The maximum line speed was 180 m min⁻¹, and the maximum production capacity was 82 t h⁻¹.

TKS's brief to Linde was based on having identified that, by increased strip heating, the production capacity of the line could reach 105 t h⁻¹. It also required that the appropriate heating solution should free strip surface from unwanted contaminants, such as emulsions, oils, grease and particles, which originate from the upstream production process. TKS had earlier tried to get the same results from electrical strip pre-heaters, but soon realised that these pre-heaters typically have poor thermal efficiency and low reliability and require too much maintenance. The boosting unit needed to allow strict control of the required surface properties essential for successful galvanising of the strip, which electrical strip pre-heaters could not provide.

No furnace length extension

Before the installation of the DFI Oxyfuel boosting unit at Finntrop, TKS and Linde had conducted several tests at Linde's laboratory facilities in Sweden. These studies were aimed at determining the exact levels of pre-heating that could be achieved with DFI Oxyfuel for the particular steel grades and thickness conditions at Finntrop, while assessing the surface property impact.



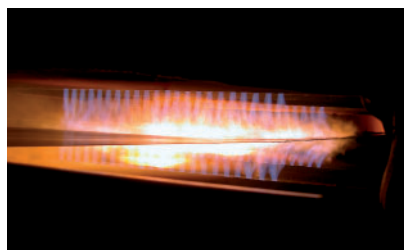
6 Surface temperatures when heating with DFI Oxyfuel: results from laboratory tests using different strip thicknesses, line speeds and firing powers

To minimise line downtime, TKS wanted a solution that would be easily integrated with the existing furnace. The design resulted in a 3 m long DFI unit equipped with four burner row units, with a total of 120 oxyfuel flames and 5 MW installed power, with an option of two more row sets for an additional 2.5 MW. The number of burner row units and burners employed depend on set pre-heating temperatures and the actual strip width and tonnage. At 105 t h⁻¹, DFI Oxyfuel results in an immediate steel strip surface temperature increase of more than 200°C (Figs. 6 and 7). This would equal a 10 m extension of the direct fired furnace, a length which is not normally available in existing galvanising or other strip processing lines and which would not have provided decreased fuel consumption and elimination of the cleaning section.

For the installation, 3 m of the existing recuperative entry section was removed to fit the DFI Oxyfuel unit. After a 12 day line stop (of which 4 days were used for installing the unit), production was resumed.

Increased galvanising capacity

With initial tuning and subsequent optimisation of the DFI unit and the



7 Internal view of unit in Finntrop: oxyfuel flames are heating directly onto moving strip, increasing temperature more than 200°C

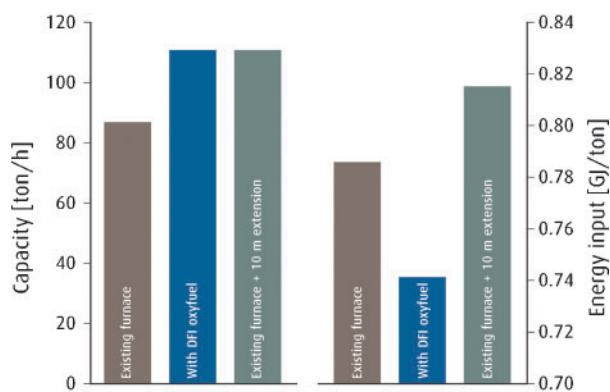
total line, capacity increased from 82 to 109 t h⁻¹. The DFI Oxyfuel unit also manages to burn off residue, particles, grease and oil from the strip rolling process, providing a cleaner strip than the 25 m long electrolytic and brush strip pre-cleaning section, which has now been removed.

The results are shown in Fig. 8. It includes a calculated alternative using a 10 m extension of the furnace in order to reach the higher capacity, which should be used as the reference when comparing with DFI Oxyfuel results.

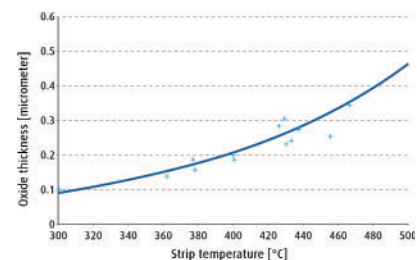
The Finntrop results show the impact of the DFI Oxyfuel installation on fuel and emissions. At a production level of 36 000 t per month, the solution including DFI Oxyfuel leads to an over 5% reduction in natural gas consumption, almost 20% less NO_x emissions, and a reduction of 1200 t per year in CO₂ emissions.

Oxidation control

The oxidation is lower than normal at a specific strip temperature since the dwell time is very limited. The simplified Wagner model for parabolic scale formation can be used to explain



8 Comparison of results of DFI Oxyfuel at TKS Finntrop versus extending furnace



9 Relationship between oxide layer thickness and strip temperature

growth at a specific time and temperature.

It is important to note that applying DFI Oxyfuel for pre-heating a strip up to 300°C does not create oxidation problems. In metal coating lines, the thin oxide layer formed is reduced in the subsequent reduction zone. It is also possible to influence the oxidation by adjusting the stoichiometry of the flames, for example, by changing the lambda value from 1.0 to 0.9.

The oxide layer thicknesses have been measured to be in the range of 50–100 nm, even at high strip temperatures (Fig. 9). A well-performing reduction zone should be able to reduce the scaling further. For high strength steel, a small formed oxide layer, e.g. 200 nm, may be beneficial, since after reduction in the radiant tube furnace section, pure iron will form on the surface for improve zinc adhesion.

New design of continuous galvanising lines

In a project together with Drever International and SMS Siemag, Linde is looking into how the benefits of DFI Oxyfuel can be utilised in the design of new continuous galvanising lines. All radiant tube furnaces demand an excessive cleaning section consisting of spray cleaning section, two brush machines, electrolytic cleaning section

and final rinsing section to guarantee the quality of the final product. These operations are not only costly and requiring considerable maintenance, they also involve environmental issues.

Cleaning tests show that the carbon and iron fines contamination can be drastically reduced by the use of DFI. With this technology, the cleaning section can be shortened to a spray cleaning section, one brush machine and a final rinsing section. The final cleaning operation is transferred to the DFI Oxyfuel inside the thermal section. The elimination of one brush machine and the electrolytic cleaning section brings considerable cost savings in maintenance and operation due to energy savings and less wear parts. Furthermore, DFI gives potential to reduce investment and operating costs in the furnace section since the furnace length can be reduced; the preheating and one heating zone can be saved.

Boosting continuous annealing

In the beginning of 2010, REBOX DFI will, for the first time, be employed in a continuous annealing line for carbon steel. This will take place at POSCO's

integrated steel mill at Pohang, Korea. The unit provides a guaranteed level of preheating which will be capable of achieving ~15% higher capacity in the annealing furnace. The natural gas fired DFI unit consists of four oxyfuel burner row units with a combined capacity of close to 6 MW.

Conclusions and outlook

In 120 reheating and annealing installations, REBOX oxyfuel solutions provide more capacity and flexibility, as well as a reduction in fuel consumption and substantially lower emissions. Since 2003, most new installations employ flameless oxyfuel, which provides excellent temperature uniformity and reduced NO_x emissions.

Also, DFI Oxyfuel is an important part of the successful solutions portfolio, clearly demonstrated by the 30% or more capacity increases at ThyssenKrupp Steel in Bruckhausen and Finntrop and Outokumpu in Nyby. Additionally, an installation is under way at POSCO in Korea.

DFI Oxyfuel has a heat transfer that is 10 times better than system in

use. In a galvanising line, additional benefits include improved zinc adhesion and surface appearance; this is due to DFI's effective pre-cleaning properties, leaving both strip and furnace rolls cleaner than before. Currently, the DFI Oxyfuel system is being evaluated at many strip processing mills around the world, most of which work with metal coating such as galvanising and others and others which anneal and process silicon steel.

The use of DFI oxyfuel has just started. However, it does not require much imagination to see that it will be become largely used, not only for strip heating relating to annealing and coating of different kinds. There seem to be several opportunities to apply DFI technology also in agglomeration and ironmaking. Some of them are currently being evaluated, for example, ignition of sinter beds and agglomeration of briquettes. For heating, some of the ideas being evaluated relate its use for change of material properties, in press hardening, for edge-heating, to remove skid-marks, and many, many other things.