# HEATING INGOTS WITH OXYFUEL AND HYDROGEN BEFORE ROLLING AND FORGING

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*Since 1990 Linde has converted 190 reheat furnaces to oxyfuel operations; 62 of them for heating of ingots before rolling or forging. Oxyfuel combustion can significantly increase energy efficiency and immediately reduce the carbon footprint, paving the way for the efficient future use of hydrogen as fuel. An overview of these installations and technology used, flameless oxyfuel, is presented. The transition to green steelmaking is a multi-decade journey involving diverse technologies and pathways, in most scenarios with the use of hydrogen − both as reductant and as fuel − as the endgame. While its broader integration will take time, hydrogen as a fuel has already been proven to perform effectively in reheating operations, without compromising the preferred energy-efficient oxyfuel combustion or negative impact the steel product. In early 2024, Ovako began the use of 100% hydrogen to fuel its existing flameless oxyfuel combustion systems in the soaking pit furnaces where steel is reheated before rolling at its plant at Hofors, Sweden. This was the successful conclusion of a five-year journey including laboratory scale tests and full-scale demonstrations in cooperation between Ovako and Linde. 48 furnaces, charged with about 25 tonnes of engineering or bearing steel grade ingots, are since then running permanently in this operation mode. The hydrogen is supplied by an onsite alkaline electrolyzer powered entirely by renewable electric power. The flameless oxyfuel combustion operates with 100% oxygen and 100% hydrogen. This technology, the challenges overcome, and the excellent results achieved are discussed along with the development of hydrogen-oxygen combustion. At Ovako Hofors using 100% hydrogen as fuel at reheating is now a tangible and fully practical solution – to date successfully reheated more than 500,000 tonnes of ingots. Operation with hydrogen in forge furnaces is the next step, also using Dual Momentum Lancing flameless oxyfuel burners.*

**KEYWORDS:** REHEATING – OXYFUEL – HYDROGEN – FUEL SAVINGS – DECARBONIZATION

## INTRODUCTION

The modernization of industrial heating systems is becoming a major focus area in the drive to address the global challenges of reducing both energy usage and pollution. One method that has been identified to address this challenge is to modify the combustion system by using oxygen instead of air as the primary oxidizer. This technology, called Oxyfuel combustion, has been extensively investigated and gradually employed in industry. Naturally, Oxyfuel combustion is an example of a near-term approach to decarbonization focused on minor alterations and improvements in parallel to mapping out longer term options to reduce the carbon footprint of the steel industry. In general, it has the potential to substantially decrease both energy use and emissions. If existing Oxyfuel technologies were implemented fully across the steel industry, the sector's total $CO_2$ emissions could be decreased by several hundreds of millions of tonnes annually. [1][2]

Linde's experience of converting reheating furnaces into complete oxyfuel operations has shown energy savings ranging from 20% to 60%. It should be noted that the total energy saving is much greater than the amount observed simply by reading a meter at the furnace. This is because the energy needed to transport the natural gas, for example, to be used in the furnace, is also saved. In the mid-1980s Linde began to equip the first furnaces with oxygen-enrichment systems that increased the oxygen content of the combustion air to 23-24%. The results were encouraging as fuel consumption was reduced and the output, in terms of tonnes per hour, increased. In 1990 Linde converted the first furnace to operation with 100% oxygen, that is full oxyfuel combustion, at Timken in the US. Today, the total number of installations exceeds 190.

Among the early adapters of oxyfuel combustion was Ovako, a leading European manufacturer of engineering steel for customers in the bearing, transportation and manufacturing industries, that belongs to the Nippon

Steel Group. Ovako's first installation of full oxyfuel combustion took place as far back as 1994, at a reheat furnace for a soaking pit. When Linde introduced flameless oxyfuel combustion in 2003, Ovako quickly became a user of the new technology. Previous conventional oxyfuel installations were converted into flameless oxyfuel and since then many additional installations using flameless oxyfuel have taken place at Ovako's steel mills. Today, in terms of number of installations, Ovako is the world's most prominent user of flameless oxyfuel, contributing to its globally leading position in energy-efficient and sustainable steel production. Further conversion to using hydrogen as a fuel, as discussed in this paper, was therefore a natural next step for Ovako.

## FLAMELESS OXYFUEL

The expression 'flameless combustion' explains the visual aspect of this type of combustion. This is because the flame is no longer seen or easily detectable by the human eye. Another description is that the combustion is extended in time and space – it is spread out in large volumes, that is why it is sometimes referred to as 'volume combustion'. This flame has a uniform and lower temperature, practically the same temperature as air-fuel combustion, yet it contains the same amount of energy as conventional oxyfuel.

The development of flameless oxyfuel was driven by increasingly stricter legislation on emissions. Flameless oxyfuel combustion occurs under diluted oxygen concentration as flue gases are mixed into the combustion zone. This slows down the oxyfuel combustion reactions and results in lower flame temperatures, below the point of thermal NOx creation. It reduces flue gas volumes by 75-80% due to lower fuel consumption and no nitrogen in combustion. Low flue gas volumes with very high $CO_2$ concentration are of course favorable for Carbon Capture Utilization and Sequestration (CCUS). The mixing of flue gases into the flame also disperses the energy throughout the entire vessel or furnace for faster and more uniform heating. Linde started applying flameless oxyfuel in 2003, with the first installations at the stainless steel producer Outokumpu in continuous furnaces for strip annealing and slab reheating. The capability to reduce NOx emission has been an important factor, but the large improvement in temperature uniformity has been key to its success. Use of flameless oxyfuel has demonstrated energy savings of up to 65%; most installations with an operation fully converted from air-fuel to flameless oxyfuel show fuel and $CO_2$ savings of 20% to 50%. Linde has made more than 500 installations of flameless oxyfuel in practically all kinds of steel reheating and annealing furnaces, aluminum and copper melting furnaces, and ladle and other vessel preheating systems.

In flameless oxyfuel the mixture of fuel and oxidant reacts uniformly through the reaction flame volume, with the rate controlled by partial pressures of reactants and their temperature, cf., Figure 1. In flameless oxyfuel, the combustion gases are effectively dispersed throughout the furnace, ensuring more effective and uniform heating of materials even with a limited number of burners installed. Although the first installations took place in reheating and annealing, flameless oxyfuel was quickly adopted for preheating of ladles and converters where it has also demonstrated good results. The next area to be exploited, with a substantial positive impact, could be blast furnace hot stoves. Another interesting area is the use of low calorific fuels, e.g., blast furnace top gas; use of oxyfuel strongly supports the successful use of low calorific gases. The lower flame temperature – same temperature as at traditional air-fuel combustion, together with temperature uniformity – substantially reduces NOx formation so it is lower than with air-fuel combustion. Moreover, the excellent temperature uniformity leads to reduced heating times and, in reheating applications, to reduced scale losses. [2][3][4]5]

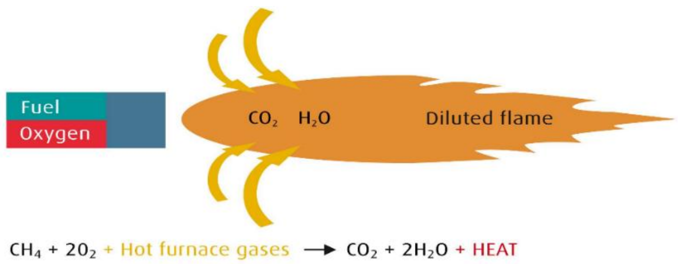


**Fig. 1.** The principle for obtaining Flameless Oxyfuel.

Reheat furnaces typically consume 1.2-1.6 GJ/t of steel, and flameless oxyfuel solutions can reduce fuel and $CO_2$ emissions from reheat furnaces by up to 60%. Linde is the world-leader in oxyfuel steel reheating; its flameless oxyfuel technology for reheating and annealing was introduced more than 20 years ago. It now has over 190 installations – in all types of furnaces and for all kinds of steel grades – and at almost 50 steel mills worldwide. Converting a reheat furnace completely into full flameless oxyfuel combustion is a major project, particularly if it is a large continuous furnace. Therefore, most such complete conversions have been for batch furnaces, e.g., heating ingots in soaking pit (as shown in Figure 2) and chamber furnaces, but there are also many examples of installations in continuous furnaces.

**Fig. 2.** Discharge of a heated stainless steel ingot from a soaking pit furnace fired with flameless oxyfuel at Alleima in Sweden.

## THROUGH ENERGY EFFICIENCY TO HYDROGEN

Reheating furnaces are a substantial source of emissions and generally the second or third largest GHG (greenhouse gas) emitter in integrated mills, and the top emitter in many mini mills. This is due to the furnace's fuel needs which are currently met with natural gas, LPG, coke oven gas, blast furnace gas, oil, or other carbon-bearing fuels. Using hydrogen as a fuel is one pathway to decarbonize the reheating furnace, with the potential to eliminate 100% of the Scope 1 emissions by directly replacing carbon-bearing fuels. Full or partial replacement is possible and may be done as a retrofit application with minimal impact on the overall furnace operation.

Oxyfuel combustion can significantly increase energy efficiency and immediately reduce the carbon footprint, paving the way for the efficient future use of hydrogen as fuel. Moreover, oxyfuel combustion produces a much lower flue gas volume with a high concentration of $CO_2$, and this also supports CCUS. For the foreseeable future, the cost of hydrogen is expected to be relatively high, and not below \$2/kg. Currently the cost is much higher in many parts of the world. This makes it essential to minimize the use of hydrogen by making the combustion process as energy efficient as possible. Accordingly, applying flameless oxyfuel that immediately reduces the fuel consumption is an important first step. However, the conversion must be done using a hydrogen-ready technology to ensure a swift changeover when a viable supply of hydrogen is in place. Figures 3 and 4 illustrate the transition from air-fuel via oxyfuel with a fossil fuel and then to use of hydrogen.

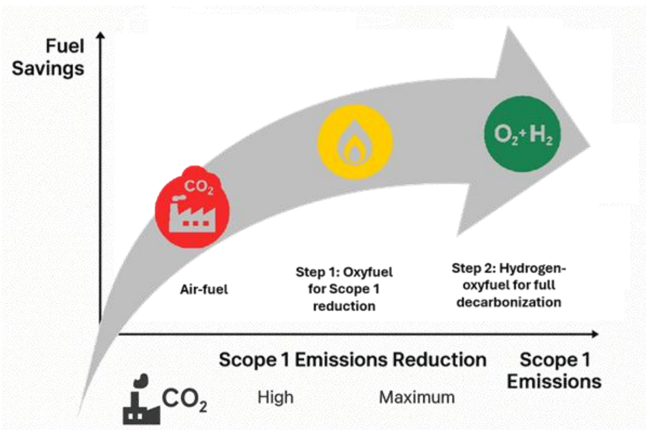


**Fig. 3.** The pathway to Flameless Oxyfuel with 100% hydrogen.

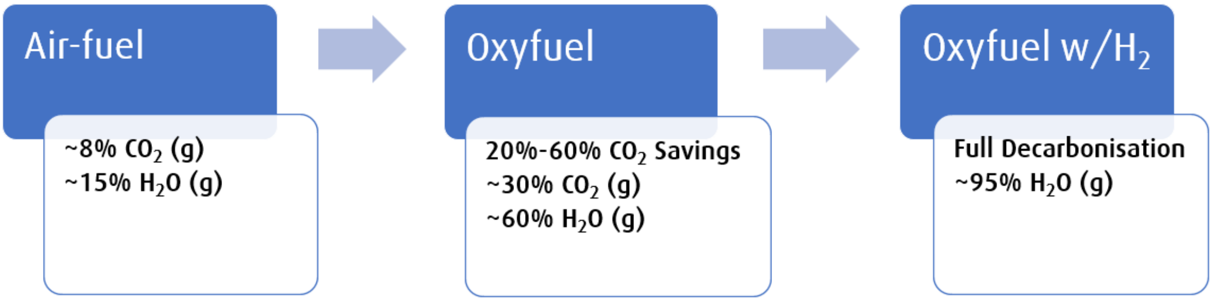


**Fig. 4.** Flue-gas composition when transitioning to Flameless Oxyfuel with 100% hydrogen.

Ovako was one of the first steel producers to use oxyfuel in its reheat furnaces. From 1994 onwards, and with flameless oxyfuel since 2003, installations have been made in soaking pit, rotary hearth, and walking beam furnaces at multiple Ovako sites in Sweden and Finland. The benefits are summarized (see also Figure 5) as:

- Reduced heating time, up to 50% less
- Reduced fuel consumption, up to 45% less
- More uniform heating
- Reduced scale losses

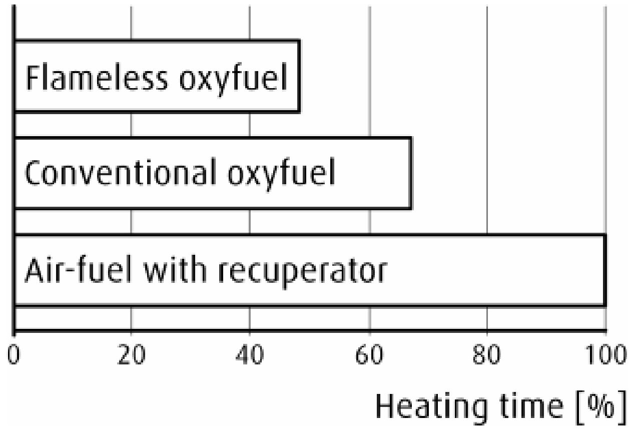


**Fig. 5**. The diagram shows heating times in same furnaces at Ovako, but with different combustion technologies and unchanged or reduced power inputs.

**PATHWAY TO USING 100% HYDROGEN IN FLAMELESS OXYFUEL COMBUSTION**

The combustion of hydrogen produces only water ($H_2O$), so there are no $CO_2$ emissions. Linde's technology designed to utilize oxygen in reheat furnaces has been further developed to use hydrogen as a fuel while maintaining similar performance to fossil fuel, with the same NOx emissions and heat transfer profile. The flameless oxyfuel burners utilize high momentum oxygen and hydrogen jets, which quickly entrain furnace gases, and reduce the overall concentration of the fuel and the oxidant prior to combustion – it is extremely important that these features are maintained when switching to hydrogen.

For some years Linde has performed tests at its technology centers to develop hydrogen burners and to assess the impact of hydrogen combustion. Starting in 2018, Linde has evaluated combustion with flameless oxyfuel up to 1.0 MW in scale using hydrogen as fuel, both partly and fully. The results clearly showed the benefits of flameless oxyfuel, and that temperature uniformity and low NOx emissions could be maintained. The next step was then to evaluate the effect on materials, and pilot reheating tests were carried out on 10 kg samples from four steel producers that contributed their various steel grades, cf., Figure 6. The results of these pilot tests were encouraging, displaying no negative impact on the heated materials.

**Fig. 6**. Laboratory tests with 100% hydrogen as a fuel using 10 kg samples of various steel grades at Linde's Technology Center in Stockholm, Sweden.

Based on the positive outcome from the pilot tests, Ovako then decided to carry out a full-scale demonstration of hydrogen reheating in a soaking pit furnace at its Hofors mill in Sweden. The test in March 2020 was the world's first time that heating of steel with 100% hydrogen as the fuel was carried out; this historical moment is shown in Figure 7. The test material was 25 tonnes of bearing steel ingots. The pit furnace was fired with 100% hydrogen in flameless oxyfuel burners. After heating and soaking, the ingots were successfully rolled to bars in the rolling mill. Rolling forces, dimensions, scale losses and temperature uniformity were at the same high level of quality achieved with conventional heating. A thorough inspection and analysis of the final bars showed that heating using hydrogen as fuel does not impact the quality. The Ovako project team concluded that they were confident hydrogen can be used simply and flexibly, with no impact on steel quality, which would mean a very large reduction in the carbon footprint. Based on this, Ovako decided to embark on the journey towards permanent full-scale implementation.

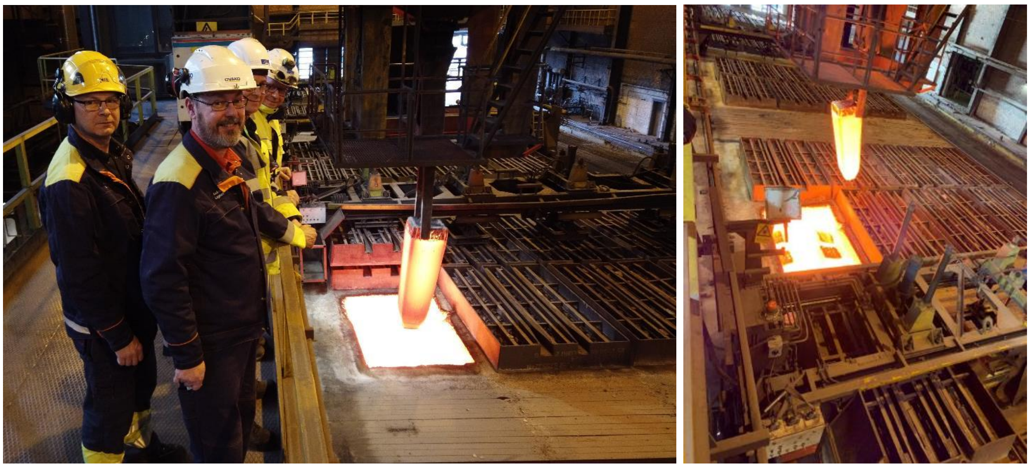

**Fig. 7.** The world's first full-scale reheating of steel with 100% hydrogen as fuel, using Flameless Oxyfuel, at Ovako's Hofors mill in Sweden in March 2020.

## FULL-SCALE IMPLEMENTATION

A permanent full-scale installation of Flameless Oxyfuel reheating with hydrogen went into operation at Hofors in early 2024. The site now operates a 20 MW electrolyzer, one of Europe's largest. Powered by renewable energy [6] it can produce 3,880 cubic meters of hydrogen per hour, along with oxygen. By using fossil-free hydrogen, the plant has the potential to reduce the site's carbon footprint by 20,000 tonnes a year. To date, the installation has successfully reheated more than 500,000 tonnes of steel. The current operation is shown in Figure 8.

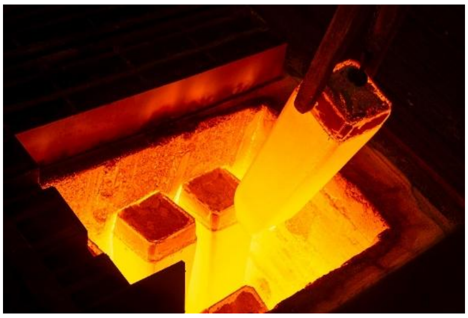

**Fig. 8.** Photograph from current full-scale operation at Ovako reheating with 100% hydrogen as a fuel.

The electrolyzer is located near the furnaces at Hofors, allowing the hydrogen production process to be seen as ‘borrowing’ water for a short time. The plant takes water from the local supply and splits it into hydrogen and oxygen. And when burned, the oxyfuel returns to water. This approach requires only a few minutes of storage as a buffer for fluctuations in production and demand. [6] A smart control system has also been developed for a smooth switch between hydrogen and propane (LPG) oxyfuels. Before the plant became operational, Ovako experts conducted extensive tests to ensure all parts of the system worked correctly. [7]

**Fig. 9.** The 20 MW alkaline electrolyzer plant, which provides hydrogen to the operations at Ovako Hofors.

## FLAMELESS OXYFUEL IN FORGE FURNACES

Over the years, flameless oxyfuel has been installed in various types of furnaces at forges shops, e.g., chamber furnaces and car-bottom furnaces, for heating and reheating of ingots from a few tonnes up to almost a hundred tonnes.

A Linde technology that has become of interest in reheating, particularly in chamber furnaces, is Dual Momentum Lancing (DML), which supports providing the heat where it is needed most in the furnaces. DML has been succesfully in operation at Ovako for a couple of years, and is now also considered for operation with 100% hydrogen as a fuel. The principle of DML operation and a photograph of a hydrogen-ready installation in a chamber furnace are shown in Figure 8.

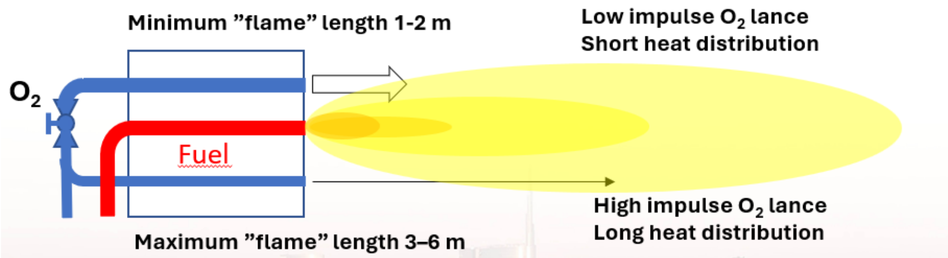


**Fig. 10.** The principles of Dual Momentum Lancing flameless oxyfuel, and a photograph from an installation of this technology in a forge furnace at ovako in Sweden.

## CONCLUSIONS

Fuel savings ranging from 20% to 60% have been demonstrated when using flameless oxyfuel at reheating of ingots before rolling and forging. These installations are the first important step in decarbonization of those operations, nowadays also made ready for using hydrogen as a fuel when a viable supply is available.

The second step of this pathway to full decarbonization, using 100% hydrogen from an electrolyzer powered with all renewal energy, is since 2024 already a reality. At the the steel producer Ovako in Sweden, where furnaces were first converted to flameless oxyfuel – resulting in large fuel savings – and then to using hydrogen, we find the world's first permanent full-scale installation of oxyfuel using 100% hydrogen. Since it went into operation in early 2024, it has successfully heated more than 500,000 tonnes of ingots in its soaking pit furnaces. A similar installation using hydrogen also in its chamber furnaces at the forge shop, is been considered.

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