Cover letter:

Flameless oxyfuel for highly visible results

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INTRODUCTION

Steel producers are continuously striving for shorter heating cycles with more uniform heating properties in an effort to achieve more production capacity and reduced consumption of fuel. Emissions is an issue under constant discussion, with various approaches on how to enforce and motivate industry to reduce. The paper will present results from flameless oxyfuel installations in 10 continuous and batch type furnaces, including both reheating and annealing applications. Flameless oxyfuel combines the positive aspects of conventional oxyfuel combustion, such as up to 50% more throughput with 50% less fuel in an existing furnace with even better heating results. In flameless oxyfuel, flue gases dilute the flame, which is effectively spread into the furnace volume. The dispersed flame contains the same amount of energy as conventional oxyfuel, which in combination with an effective stirring, results in more uniform heating of the steel. This promotes better results in rolling, forging and annealing operations. The dilution of the flame brings down the flame temperature thus avoiding the creation of NO_x, even with ingress air.

Flameless oxyfuel is the result of close cooperation with steel producers to fully understand processes, customer constraints and challenges, paired with Linde's proprietary combustion technology development. The development is based on accumulated know-how from over 90 all oxyfuel installations since the very first installation at Timken, USA, in 1990. "All oxyfuel" is defined as combustion in the whole furnace via a fuel, gaseous or liquid, and industrial grade oxygen, which completely replaces air.

RESULTS FROM FULL-SCALE FLAMELESS OXYFUEL INSTALLATIONS

Since the first flameless oxyfuel installation in 2003, this technology has proven to surpass the already, and earlier recognized important benefits of conventional oxyfuel combustion; high heat flux with high thermal efficiency for increased heating capacity, reduced specific fuel consumption, Fig. 1, and more uniform heating.

Results from pilot studies, and the most important findings from the 10 most current full-scale industrial applications of flameless oxyfuel in reheating and annealing furnaces can be summarized as follows:

- More uniform heating for improved downstream processing
- Shorter heating cycles have been reported
- Ultra low emissions of NO_x even with ingress air

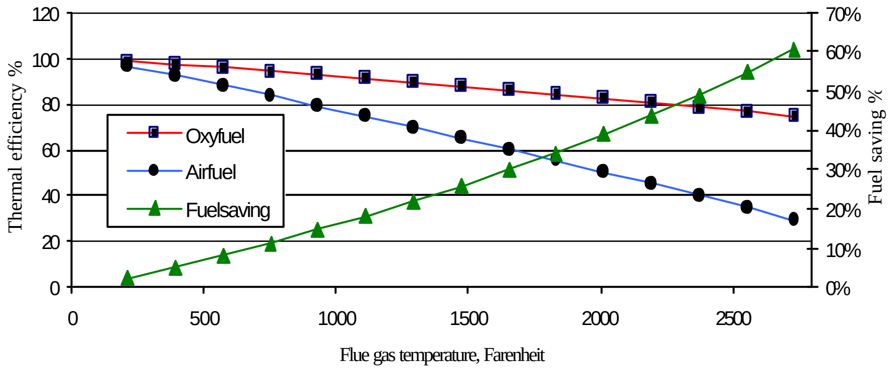

Figure 1, Thermal efficiency as function of flue gas temperature at lambda 1.02.
The thermal efficiency of oxyfuel is high with important fuel savings.

The following are examples of applying flameless oxyfuel in industrial scale operations.

Ascometal – Less fuel consumption with only 9 instead of 13 soaking pit furnaces.
Ascometal, Fos-sur-Mer, France is an important producer of bearing and engineering steels. They use soaking pit furnaces to reheat ingots prior to rolling. Since the first flameless oxyfuel installation in 2004, which replaced airfuel combustion, electrical blowers and recuperators, they now benefit from 33% shorter heating cycles, 40% reduced specific fuel consumption, 40% less emissions of NO_x, uniform heating and less scale formation. They have so far revamped 5 pit furnaces with the goal to use only 9 instead of today's total 13 furnaces for the same total production volume. The increased furnace utilization will count for savings in energy efficiency, reduced maintenance and improved logistics.

Uddeholm Tooling – More uniform heating for improved forging and drastic drop of NO_x.
A 52% reduction in specific fuel consumption has been achieved since the installation of oxyfuel in 5 car bottom furnaces at Uddeholm Tooling, Hagfors works, Sweden. The first installation took place in 1993. These furnaces heat 8-77 ton (short) ingots prior to forging. The heating time was reduced by 25-50%, with improved surface quality and reduced scale formation. In 2005 they installed flameless oxyfuel to further improve the temperature uniformity of the steel and to comply with strict legislation on NO_x emissions.

Outokumpu Stainless – 40 to 50% capacity increase and 25% less fuel as a turnkey project.
The complete turnkey project, performed by Linde included the rebuilding and refurbishment of the existing walking beam furnace at Outokumpu Stainless, Degerfors, Sweden, Fig. 2. It entailed replacing the airfuel system (including the recuperator) with flameless oxyfuel, and installation of essential control systems [1]. Performance was guaranteed, with an increased slab heating capacity of 40-50%, reduced fuel consumption by 25%, NO_x below 0.16 lb./mmBtu and improved temperature uniformity.

Figure 2, Outokumpu Stainless in Sweden increased their heating capacity in the existing walking beam furnace by 40-50% when implementing flameless oxyfuel. With this investment in an existing furnace the plate mill could accumulate production volumes from another site.

Scana – Further improved uniform heating for improved forging and less NO_x.
Scana, a 350 year old company in Björnerborg, Sweden, is active in forging products for the energy sector; drilling platforms, windmills, power generators etc. To meet customer demand, oxyfuel has been implemented in 3 car bottom furnaces. This has boosted throughput by 40% and significant fuel savings without any investments in new recuperators. Conventional oxyfuel improved the uniform heating properties. But to further improve this and to reduce emissions of NO_x, flameless oxyfuel was implemented in one furnace in 2005, Fig. 3. Having optimal heating conditions reduces unnecessary overheating, cuts heating time and is important for a correct and fast forging.

Figure 3, Flameless oxyfuel employed in car bottom furnace for reheating prior to forging at Scana, Sweden. It has resulted in more uniform heating and reduced emissions of NO_x.

Outokumpu Stainless – Turnkey project with 50% more heating capacity and 40% less fuel.
Outokumpu Stainless, Nyby works, Sweden required increased production throughput in an existing furnace, while local authorities stipulated even lower levels of NO_x emissions. In this Linde turnkey project, the catenary furnace for annealing of stainless steel strip was converted to flameless oxyfuel[1]. It resulted in a 50% increase in heating capacity without any need to increase the pickling section length, since the effective and rapid heating forms less and easily removed scale. The replacement of the airfuel system, combustion blowers and recuperators resulted in a 40% reduction in specific fuel consumption. NO_x levels were below the guaranteed level of 0.16 lb./mmBtu.

Vessel preheating in steel shop.
Oxyfuel combustion was early recognized for its benefits to effectively heat different vessels such as converters, ladles and tundishes of the steel shop. Oxyfuel is easily installed since it is powerful, rugged and compact in comparison to large and bulky recuperator or regenerative airfuel systems. These installations today have also benefited from more uniform heat distribution and low NO_x emissions by the application of flameless oxyfuel.

OXYFUEL FOR THE NEW MILLENNIUM

Expansion, rationalization and re-structuring of production sometimes calls for more heating capacity, not necessarily always to produce more but to improve utilization of furnaces, preferably reduce the number of furnaces in use, create flexibility and cut lead-time. The dependency on fossil fuels, along with high and unstable fuel prices, cause already slim product margins to be further reduced. Any implemented solution to deal with the said issues must at least maintain the same product quality or if possibly improve it. After reheating, the steel must be properly soaked and ready to be rolled or forged with good results. In parallel to that, the effects of NO_x emissions are strongly negative to mankind and have 230 times more global-warming potential than CO_2, which is reflected in current legislation. The introduction of staged combustion, which has a better heat distribution and lower flame temperature, had shown good results in achieving said targets. Flameless combustion, a principle that has been known for many years but only recently been industrially exploited, offers possibilities for even better heat distribution and reduced flame temperatures. Selected steel customers and Linde embarked together, in the beginning of the 20th century, to find out if a suitable oxyfuel burner technology for flameless combustion could be implemented and what the results would be.

FLAMELESS OXYFUEL FOR A VISIBLE DIFFERENCE

Conventional and staged oxyfuel can have flame temperatures above 3,600°F. A lower flame temperature would be possible by applying ‘flameless combustion’. In essence, ‘flameless combustion’ describes the visual aspect of the combustion type, i.e. the flame is no longer seen or is easily detected by the human eye, Fig. 4. A more accurate definition would be that combustion is highly diluted by different means, normally the hot furnace gases, and thus spread out in a large volume, Fig. 5, which some refer to as ‘volume combustion’, resulting in a lower flame temperature[2].

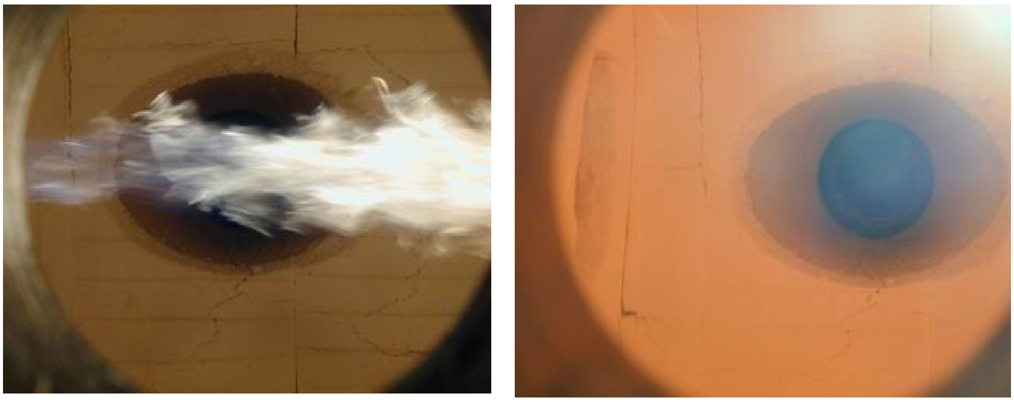

Figure 4, The photograph on the left shows a conventional oxyfuel flame where the flame has a bright and luminous hot flame. The right-hand photo shows the same burner in flameless mode; i.e. invisible volume combustion with an almost transparent flame.

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. The flameless combustion takes place spontaneously at furnace temperatures over 1,400°F.

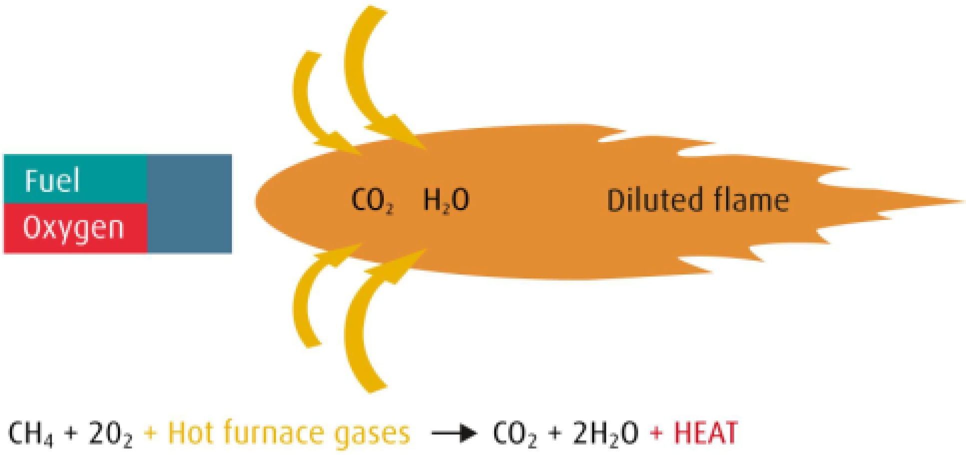

Figure 5, In flameless oxyfuel, the hot furnace gases dilute and disperse the flame. The flame contains the same energy, well distributed in the furnace and with a lower flame temperature.

The flame temperatures of different combustion types have been verified by the Royal Institute of Technology in Sweden in a pilot scale furnace[3]. The power input was 0.7 mmBtu/hr. The diagram in Fig. 6 shows the flame temperature measured at a distance from the burner tip, (the closest possible measurement point was 1-1.3 feet). It shows the flame temperature of the typical hot and luminous

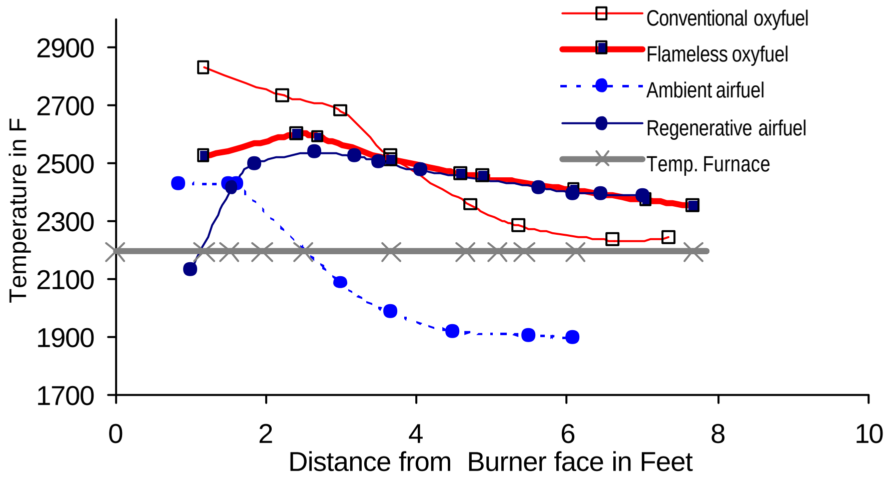

Figure 6, Flame temperatures for various combustion technologies as a function of the distance from the burner tip[3]. Flameless oxyfuel has a flat temperature profile with no peeks.

conventional oxyfuel flame. Flameless oxyfuel and regenerative airfuel technology have almost the same temperature profile, flat with no peeks. Ambient airfuel burner had difficulty maintaining the furnace set point of 2,190°F, and only reached a furnace temperature of around 1,830°F.

More heating capacity and improved downstream processing.
It is proven that the heat transfer property of oxyfuel, with elevated concentrations of highly radiating CO_2 and H_2O gases, provides optimal conditions for fast and uniform heating. This reduces for example large top-bottom temperature variations, resulting in a more uniform temperature for better rolling and forging results. Sampling of the heat flux, Fig. 7, which was done in the same tests as above by Royal Institute of Technology in a pilot scale test furnace, shows good heat flux distribution for flameless oxyfuel combustion.

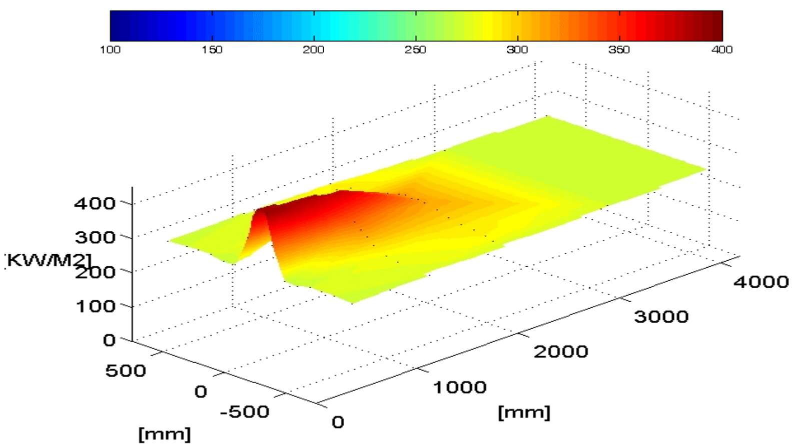

Figure 7, Measured heat flux[3]; in kW/m^2 shows that flameless oxyfuel has high values in a larger part of the furnace. This and the effective stirring of the flue gases promote uniform heating.

A lower flame temperature, with even distribution, results in a more even heat exposure of the object to be heated since the diluted flame temperature is only 390-570°F higher than a temperature of the surrounding furnace. Secondly, the flameless condition is a result of higher gas velocities, which cause a more effective dispersion, and stirring of the combustion gases[4].

These two effects result in more uniform heating conditions throughout the whole furnace volume. Pilot test and full-scale implementation results of flameless oxyfuel have lead to a review of the calculation and simulation tools that are employed when dimensioning and engineering a furnace installation.
Trials involving conventional and flameless oxyfuel combustion have recently been performed at one rolling mill. Rolling force, heating times, soaking times, NO_x emissions, scale formation and steel temperature out of rolling mill have been investigated. Historical data for airfuel and conventional oxyfuel reveals oxyfuel's ability to cut heating time and reduced specific fuel consumption. It was noticed that the flameless oxyfuel technology offered a further reduction in heating time and lower NO_x emissions. Given the lower flame temperature, which is typical of flameless oxyfuel, and the more effective stirring of flue gases, a more uniform temperature distribution within the heated steel was noticed during the rolling operation.

Ultra low NO_x and insensitive to ingress air.
The formation of NO_x originates from the presence of free nitrogen in the atmosphere together with available oxygen. In airfuel combustion, big volumes of flue gases are produced which make post-treatment processes of emissions bulky and costly as compared to oxyfuel. In oxyfuel the flue gas volumes are around 70-80% less due to no presence of nitrogen ballast in the combustion process and reduced fuel consumption. In oxyfuel combustion, levels of NO_x can be higher in situations when there is air present from poor furnace pressure control or extensive leakage of air into the furnace.

With the low flame temperatures of flameless oxyfuel, as indicated in Fig. 6, there is an improved way to control and reduce the generation of NO_x. Below a temperature of 2,600°F, NO_x formation is limited. Tests showed all combustion technologies to be fairly low in emission of NO_x, at 3% oxygen in flue gases. The tests however wanted to simulate realistic and industrial conditions for continuous types furnaces where air leakage is frequent. The oxygen content was measured in the flue. Flameless oxyfuel combustion proved to be insensitive to the air ingress. NO_x formation remained low even at high levels of oxygen in the flue gases, and conventional oxyfuel had NO_x levels similar to that of regenerative technology, see Fig. 8. For conventional oxyfuel, it is a known fact that furnaces must be kept tight and the pressure well regulated, however, this is the case for regenerative airfuel technology as well.

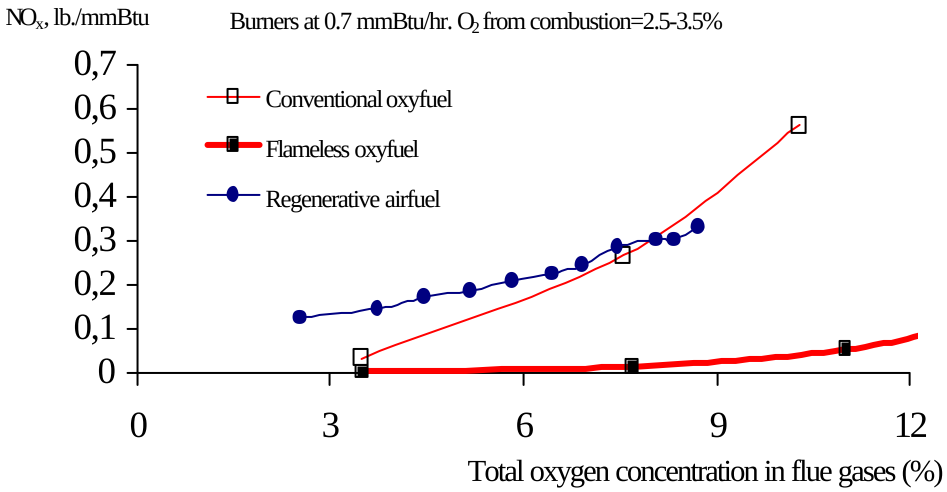

Figure 8, The diagram[3] shows how conventional oxyfuel results in NO_x levels similar to regenerative airfuel burners and how flameless oxyfuel is almost insensitive to any ingress of air into the furnace.

Recorded data from industrial installations, in large batch and continuous reheating and annealing furnaces, verifies that flameless oxyfuel results in lower emissions levels of NO_x. In all installations Linde has reached NO_x levels below what is stipulated in legislation, contracts and performance guarantees. Sweden has some of the toughest regulations on emissions of NO_x in Europe. Legislated levels are at 0.23 or 0.35 lb./mmBtu for gaseous and liquid fuels. Customers however require suppliers to fulfil the level of 0.16 lb./mmBtu.

Uniform heating promotes further reduced scale formation.
Scale formation, which typically accounts for a 1-2% material loss, is a function of the steel properties, the oxygen content in the furnace atmosphere, furnace temperature and the heating time required. Furnace temperature and oxygen content are both controllable parameters, and here oxyfuel facilitates a significant reduction in the steel's exposure time to high temperatures. Experience from over 90 installations indicates that scale formation is less or the same. Flameless oxyfuel shows the same results, with slightly reduced scale formation where it has been possible to reduce the heating cycle. Furthermore, the scale has better properties for easier removal, which improves product quality, and reduces pickling time. Reduced scale formation not only reduces cost for lost material, but also results in lower scale removal costs.

POWER IN A SMALL PACKAGE

Oxyfuel burner technology has always been compact and powerful due to the absence of nitrogen ballast in the combustion, thus sizing of all required equipment is reduced accordingly. This facilitates positioning of the burner, installation, inspection and maintenance. A self-cooled flameless oxyfuel burner, with a power rating of up to 6.8 mmBtu/hr, integrated UV and pilot burner, is shown in Fig. 9.

Figure 9, The picture shows a 6.8 mmBtu/hr, self-cooled ceramic flameless oxyfuel burner, REBOX®-S.

Linde has designed and integrated a conventional oxyfuel burner into all types of flameless burners to be used to raise the furnace temperature above 1,400°F, at which point flameless combustion takes place. The burners are regulated, in order to achieve their optimal operating conditions, for most fuel-efficient combustion, best heating properties and absolute lowest possible emissions of NO_x.

Linde has conventional and flameless type oxyfuel burners for various applications, water-cooled and self-cooling ceramic burner types. Both natural gas and liquid fuels are applicable, as well as low-grade fuels. The later is normally available at integrated steel plants and here the higher high flame temperatures of oxyfuel makes it possible to reach the higher setpoint temperatures for reheating and certain annealing operations.

THE DOUBLE TO HEAT

Oxyfuel, and now lately the flameless technology, brings interesting results to the domain of reheating and annealing. They are processes often neglected, but to put it in perspective, 1.1 Bton/year (short) is now estimated to be produced in steel shops, and approximately double that figure passes through some kind of reheating and annealing processes. So, an estimated 2.2 Bton (short) steel is heated every year to elevated temperatures for a long period[5]. This has an impact on any steelmakers' profit, now lately actualized by raising fuel prices and sometimes an uncertain supply. The existing and probable new legislation on emissions will have to be met and there is a steady effort to improve product quality, reduce losses and maximize utilization of staff and equipment.

This scenario calls for powerful solutions to deliver fast, reliable and critical results. Through cooperation with our customers, Linde's development and implementation of oxyfuel combustion, such as the flameless technology, shows that such results are real, reachable and economically viable.

SUMMARY

There are today several oxyfuel combustion technologies that can be applied in reheating and annealing applications: oxygen enrichment or lancing, partial boosting and several all oxyfuel technologies. All of them have their particular application possibilities depending on what results and concerns are necessary to be fulfilled. Since 1990, Linde has proven in over 90 all oxyfuel installations the viability of this technology in creating effective solutions for reheat and annealing furnaces. The absence of nitrogen allows for a high thermal efficiency that results in reduced heating time, lower fuel consumption and less emission of CO_2 and NO_x. The addition of the flameless oxyfuel technology to the portfolio of possible solutions brings important results in terms of further improved temperature uniformity, even shorter heating time and lower NO_x emissions. To date flameless oxyfuel technology has been installed in 10 full-scale applications, the latest being at ASCOMETAL, France, Fig. 10.

Figure 10, ASCOMETAL has employed flameless oxyfuel to reduce the number of soaking pit furnaces from 13 to 9 for the same production volume. This is paired with fuel savings, more uniform heating of the ingots and less emissions of CO_2 and NO_x.

Flameless oxyfuel technology entails diluting the flame, spreading the flame into a larger volume for good heat distribution, and lower flame temperatures that minimizes the creation of thermal NO_x. The flame contains the same amount of energy, which is now spread out more homogenously throughout the furnace. This shows positive effects in terms of more uniform heating of the steel, which improves the quality in downstream processing such as rolling or forging. If temperature uniformity targets are already being achieved, then flameless oxyfuel technology can be utilized to further reduce the necessary heating time. Scale formation has been reported to be less or equal, but with more advantageous properties for easy and complete removal. Flameless oxyfuel has shown to be insensitive to ingress air, normally occurring in continuous type of furnaces, which limits NO_x emissions.

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NOTES

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