New Pregenerative Burner for Flameless Oxidation in Radiant Tubes

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Summary
Effective combustion air preheating in high temperature furnaces makes considerable energy saving possible, but requires rigorous NOx abatement techniques. To this purpose, flameless oxidation has become increasingly popular in steel heat treatment furnaces. Advanced technologies with small capacity burners, in particular for radiant tubes, have incorporated effective air preheating coupled with low-NOx measures using both recuperative and regenerative heat recovery principles. Design criteria for radiant tubes are briefly reviewed and a new burner + radiant tube embodiment for large industrial furnaces is presented.

1. Introduction
Gas fired radiant tubes are commonly used devices for heat treating furnaces in metal industry processes operated with a protective atmosphere. Gas burners are firing into a tube which transfers the heat to the furnace predominantly by radiation. This form of heating is also referred to as indirect heating since the products of combustion are not in direct contact with the product. The furnace atmosphere can be composed of nitrogen, hydrogen, carbon monoxide or other gases to achieve desired surface effects on the product surface. The main goals for the development of radiant tube heating systems are efficiency and low NOx emissions next to usual demands regarding cost, safety and performance.

2. Flameless oxidation
Flameless oxidation (shortly FLOX®, a registered trademark of WS Wärme-,prozesstechnik GmbH) was developed to suppress thermal NO formation in high temperature processes even when highly preheated combustion air is used [1-3]. A definition of flameless oxidation can be provided as follows [4]: flameless oxidation is a stable combustion process without a flame and with defined recirculation of hot combustion products
in contrast to often expressed assumptions, flameless oxidation does not require:
- preheated combustion air
- low oxygen levels
- separate injection of air and fuel
- large combustion chamber volumes
but flameless oxidation does require:
- recirculation of hot combustion products above self-ignition
- suitable measures to avoid the formation of flames, attached or lifted.

Not every chemical reaction is considered to be combustion and not every combustion is accompanied by flames. A classification of different redox-reactions is given in Figure 1. Relatively slow redox-reactions with low intensity are going on almost everywhere. Examples are rusting of steel, browning of a fresh cut apple but also various reactions in the
earth's atmosphere. Combustion can happen naturally as forest fire which could be sparked by a lightning strike. Controlling combustion was one of the fundamental skills of mankind which allowed civilization. Most combustion processes involve flames, which enable controlling combustion by visual examination. But there are also combustion processes which are not accompanied by flames. Catalytic surfaces can lower the activation energy for reactions and therefore enable reactions at lower temperatures without formation of flames. A camp fire will first burn with blazing flames. Later on the flames will extinguish but reactions will still occur in the fire bed until all char is burnt to ash. Flameless oxidation is a case of flameless combustion, that is in absence of flames.

Flameless oxidation was first applied to heat treating furnaces but since then many other applications were examined and developed [4-5]. Typical *FLOX®* burners fire into a hot furnace steadily above self-ignition range (above 850 °C for safety). The burner near field is generally formed by a high velocity jet or by separate air and/or fuel jets issuing directly into the combustion chamber, that provides an undisturbed, infinite source of exhausted flue gases. Entrainment ensures stabilization by heating above ignition and a *volume distributed* or *diluted* reaction pattern is formed. Design is not very critical. Design becomes critical when flow is tightly confined and/or boundary conditions are particularly stringent: a good example is the ultra low-NOX, high pressure combustor for gas turbines studied in the *NGT* project [6]. The radiant tube is another example of closed confined flow, that requires ingenuity to be able to carry out low-NOx and uniform combustion and flameless oxidation firing whenever possible. The present paper reports examples of these applications.

3. Radiant tube designs

The commonly radiant tube designs encountered in industrial furnaces, are shown in Figure 2. The size of the burner (usually firing natural gas) is proportional to the radiant surface and the specific heat flux varies in a wide range: the power is in the order of 5-150 kW per unit and the size of the tube is 80-250 mm in diameter. Size and geometric confinement are far from usual free-flame burners and the combustion chamber is a long tubular conduit [7]. Since flameless oxidation requires the recirculation of hot combustion products, the recirculating tube designs on the right side of Figure 2 are preferable. These designs incorporate an internal recirculation of hot combustion products. Recirculation is anyway the key for low-NOX performance: then the tube designs on the left hand side of Figure 2 would require external recirculation of combustion products which are hot; it is not an easy task to carry out in an economical way.

![Figure 1 – Redox reactions](image-url)
Another key development goal besides low NOx, is providing maximized thermal efficiency. For radiant tubes, decentralized heat recovery is the only available alternative. Central heat exchangers, which are common for large direct fired furnaces are not practical for radiant tube fired systems because there is no central exhaust outlet of the furnace.

Figure 2 – Industrial radiant tube designs
The hot exhaust gases would have to be transported to the heat exchanger in expensive, insulated ducts and then the hot air would be distributed back to the individual radiant tubes. For radiant tube heating, a good heat recovery system is essential since the exhaust temperatures are inherently higher than the furnace temperature. This is because the heat transfer process includes an additional intermediate step with respect to direct firing, that is flame-to-tube and then tube-to-stock. This implies a higher $\Delta t$, that increases in proportion of the specific heat flux.

The different radiant tube designs (see Figure 2) require different strategies for heat recovery. In straight through tubes, heat recovery is very rare. For U- or W-tubes, the most common way to preheat the combustion air is to use plug-in recuperators, that is air / flue gases heat exchangers (Figure 3). To enhance the air preheat, external recuperators are also possible. The limitation for air preheat is coming from the necessity to guide the hot air from the exhaust leg to the burner and also from the co-flow heat exchanger design.

Figure 3 – W-shaped radiant tube with plug-in recuperator
Higher air preheat temperatures, and thereby higher efficiencies, can be achieved with regenerative burner systems in U-, W- and A-shaped radiant tubes. Two burners per tube are firing alternating (see Figure 4). The regenerative systems allow air preheat temperatures close to the furnace temperature. Energy savings of more than 30% compared with plug in recuperators are typical.

Besides energy savings, the temperature uniformity of the tubes are much better due to the alternating flow direction in the tube. However, attention has to be paid to high NOx-formation due to the high air preheat and also to the complexity of the system due to two burner heads per tube.

Single end, A-, P- and Double-P-shaped tubes, that is recirculating geometries (Figure 2), are fired with self recuperative burners. A scheme of this burner integrated heat recovery system is reported in Figure 5. The counter-flow heat exchanger, which is placed inside the furnace wall, allows high air preheat temperatures and there is no hot air piping required outside the furnace. For high temperatures, also recuperative burners with ceramic heat exchangers in silicon carbide (SiSiC) are available. Air preheat temperatures in the range of 500 to 650°C are typical which corresponds to thermal efficiencies of about 75% for typical processes.
Figure 6 shows a double-P tube with a self recuperative burner. High velocity combustion results in good temperature uniformity and internal recirculation allows the application of flameless oxidation, as an effective method to reduce thermal NOx formation. Self recuperative burners are widely used since they combine good performance with a high efficiency.

4. Self regenerative burner

In order to combine the advantages of regenerative systems and of recuperative burners, a self regenerative burner for radiant tubes has been developed. Figures 7-8 show the new regenerative burner which can be used for direct firing and for heating re-circulating radiant tubes. The self regenerative burner is used in combination with a pulse firing system, that means, the burner is on/off controlled. All the logic for regenerative switching, flame safety, ignition and valve operation is handled by a local burner control unit. This makes the installation, start up and maintenance as easy as with self recuperative burners. The tube temperature uniformity is excellent because of the internal recirculation and NOx emissions are low (<50ppm) thanks to flameless oxidation.

The energy saving of the regenerative design is definitely 10-20% higher than the recuperative system.

To keep the number of radiant tubes and burners, and thereby the costs, at a minimum, radiant tubes with a large tube diameter should be used. With double P-shaped tubes, it is possible to heat a furnace with a fraction of burners only, compared to a system with small diameter straight tubes.
5. Conclusions

There are many options for increasing the energy efficiency and still achieving extremely low-NOx emissions. Preheating the combustion air is the most effective way to increase efficiency in most furnaces. To fight the challenges of rising energy cost and environmental regulations, a close cooperation of the end user, the furnace builder and the burner manufacturer is necessary to choose the best possible configuration with respect to:
- performance
- energy efficiency
- low emissions
- low maintenance
and of course not higher than needed investment costs.

6. References

2. Woelk G., Wünning J., Controlled Combustion by Flameless Oxidation, Joint Meeting of the British and German Sections of the Combustion Institute, Cambridge, 1993
6. Flamme M., Al-Halbouni, Wünning J.et al., Low Emission Gas Turbine Combustor Based on Flameless Oxidation, 14th IFRF Member Conference, Noordwijkerhout, Netherlands 2004

Figure 8 – Regemat ® 250 firing in double-P tube (photo WS)