Annealing and pickling lines: benefits from advanced combustion systems

The performance of combustion equipment is a major issue in modern stainless steel strip annealing and pickling lines, not only for energy saving and abatement of nitric oxide emissions, but also for product quality and reliable operation. A compact regenerative burner for this purpose has been designed, extensively tested and successfully installed on industrial furnaces in several countries.

Volker Burkhardt, Werner Roth, Hans Tibbenham and Joachim Wuenning
WS Wärmeprozesstechnik GmbH and Engineered Thermal Systems

Continuous annealing and pickling lines (A&P) for stainless steel strip are large plants where the strip is annealed in free-flame furnaces at high temperature (1250 °C max) and where uniform heating and oxidation is important for surface quality. The coils are cold rolled, then annealed in a downstream A&P line where the quality requirements are very stringent. Energy saving, NOx emissions from combustion of natural gas and from pickling, productivity and good performance (uniformity, ease of operation and control) are major issues, as they directly affect product quality and costs. *Flameless* technology has been developed to make possible extremely high air preheating together with low NOx in high temperature process furnaces (*G. Capoferri, A. Mattarini and M. Ricci – Millennium Steel 2001, 269-273*).

Heat recovery and flameless combustion

Increasing preheat of the combustion air by heat recovery from hot flue gases is the best way of increasing the thermal efficiency of high temperature furnaces. With burner-integrated heat recovery there is also a significant productivity advantage when compared to the traditional design of counter-current furnaces, as air is preheated and flue gases are cooled inside each burner that extracts most of its own combustion products locally. Therefore, no centralised uptake of hot flue gases and no passive zone at the stock inlet are required in order to cool down flue gases and to recover energy from a central heat recuperator at the chimney. The temperature profile along the furnace can peak higher from the furnace inlet and, as a result, the maximum throughput for a fixed furnace length may be increased, typically by 25-30%.

Air preheating system	Temperature limits °C	Air preheat °C	Pre-heat efficiency %	Thermal efficiency %
Central	800	300-500	40	60
Burner integrated metal/ceramic	1000/1200	600-800	> 60	~ 70
Regenerative ceramic	1250	900-1050	> 80	> 80

Table 1 ***Comparison of air preheat systems***

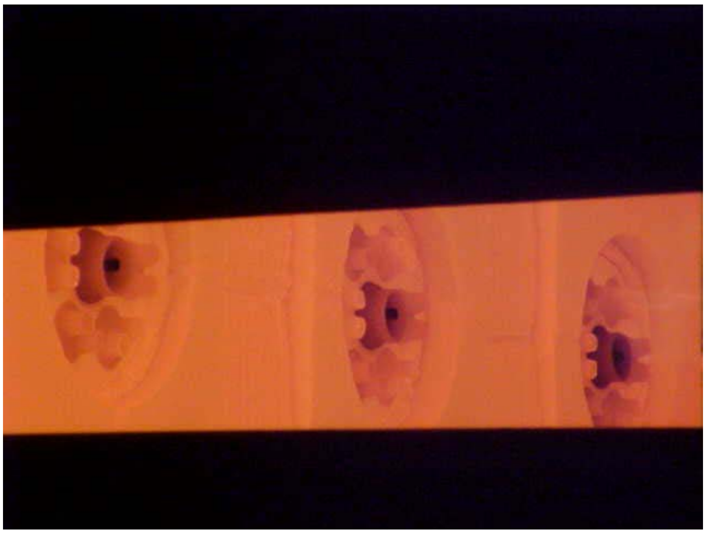

Figure 1 ***Flameless combustion mode***

The burner-integrated heat recovery design also promises a higher thermal efficiency with respect to the conventional, centralised heat exchanger at the furnace outlet, as shown in Table 1.

The regenerative burners have a large energy saving potential and thermal efficiencies above 85 % have been reported in industrial practice. The principle is based on two heat reclaiming beds alternatively heated by flue gases and cooled by combustion air - a long established method in large steelmaking plants. Advanced ceramic materials for the regenerative beds and for the burner nozzles (typically moulded silicon carbide), reliable heavy duty electro-valves and digital control are employed to implement the new technology.

With process temperatures up to ~ 1250 °C, very efficient air preheat implies combustion air over ~ 1000 °C at the burner nozzle. Air at that temperature requires special burner design and good control of the combustion process. Conventional direct injection of fuel into the air stream would produce exceedingly high flame temperatures which would damage the burner nozzle and produce intolerable NOx emissions of the order of thousands of ppm, whereas the admissible limits are below 250 ppm. It is well known that NOx increases exponentially with peak flame temperatures and therefore R&D effort of over many years has been concentrated on reducing these temperature peaks.

As a result of WS technology, a combustion system, FLOX, that reduces NOx even below values typical of burners fired with cold air has been developed (*Wünning J.A. and Wünning J.G. - 4th Int. Symposium - High Air Temperature Combustion & Gasification – Rome, November 2001*). FLOX is suitable for high temperature processes above a threshold of ~850 °C, when the combustion chamber is above the self-ignition temperature and safety regulations dispense with flame detectors. Under such circumstances, a burner-stabilised flame attached to the burner nozzle is no longer required. If the pure reactants (hot air and fuel, like natural gas) are allowed to mix with hot combustion products entrained from the combustion chamber before reaction, then firing is brought about in a diluted environment with chemically inert partners and the

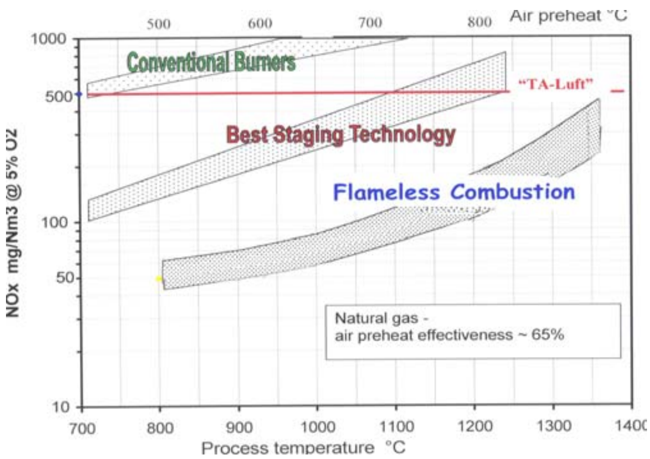

Figure 2 ***NOx from high temperature furnaces***

flame cannot be stabilised. Provided that sufficient kinetic energy is imparted to the air jet in order to fully mix with re-circulated combustion products, typical of high velocity burners, and a suitable nozzle design is provided, a stable and thorough firing pattern can be obtained for flameless combustion.

Detailed investigations have demonstrated that flameless reactions are distributed in a volume (rather than in a highly turbulent, two-dimensional flame front), without visible flame and without combustion roar. Figure 1 shows flameless combustion with natural gas fired, high velocity burners.

The different chemistry explains the different pollutant emissions. The most impressive difference concerns the low NOx emissions which can be expected because gas temperature peaks, conducive to high NOx formation, are effectively avoided as well as a flame front rich in active radicals. The abatement in NOx emissions can be clearly seen in Figure 2 referring to

High velocity regenerative burners

To implement flameless firing in practical burners, plant start-up from cold conditions must be taken into account, as burners cannot be fired in flameless mode until the flameless threshold is passed. This may be carried out by providing two separate gas injection nozzles. By radial injection into a primary combustion chamber, a stable flame is established (see Figure 3a) while central gas injection prevents a flame front and makes flameless firing possible under suitable conditions (see Figure 3b).

Regenerative burners consist of twin heat reclaimers or regenerators embedded in the burner which are capable of accumulating / yielding heat. Their great surface to volume ratio and the short inversion time (≈ 10 - 30 s) make it possible to significantly limit the volume of the regenerators. Ceramic beads or pebble beds are relatively bulky, but honeycombs allow very compact design, moderate pressure losses and high effectiveness of heat recovery (air preheat temperature >~ 85-90 % of the flue gas temperature).

The auto-regenerative burner Regemat from WS (see Figure 4) has been conceived for possible substitution of existing burners. Twin ceramic beds have been embedded into a single, very compact unit instead of two separate units, which is more normal with regenerative burners. For instance the Regemat for a nominal power 200 kW is not much bigger than an equivalent preheated air burner. The twin thermal capacities are each made of three ceramic cartridges connected in parallel by means of passageways in the burner body. Hot flue gases are extracted from three regenerators (coloured beige) while cold air is introduced into the other three (coloured blue), and every 10 seconds the four inversion valves switch to exchange flue and air flow. The body is an aluminium casting that also houses the four inversion valves, all

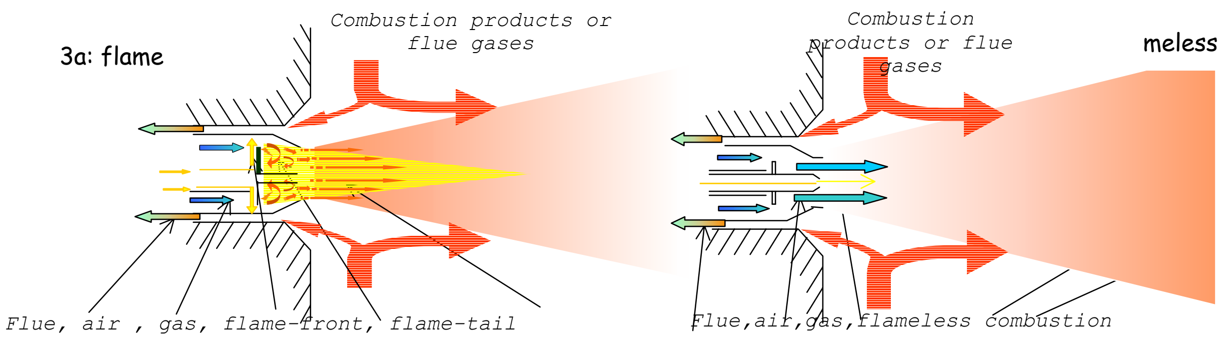

Figure 3 ***High velocity burner: flame and flameless mode***

accumulated data from industrial sites (air preheat ~ 60-75% of flue gas temperature). The NOx is reduced by one order of magnitude with respect to the best *staging* burner design. It should be remembered that development of flameless techniques was first driven by low NOx investigations and that practical application of high air temperatures for energy saving purposes has been hindered for a long time just because of high NOx emission levels.

the control solenoid valves (air, gas-flame and gas-flameless*)*, the safety switches (over-temperature, flow or pressure failure etc) and flow calibration devices (Figure 5).

All burners are connected in parallel to manifolds for air, natural gas and flue gases and suction of flue gases requires an extraction fan that collects combustion products at a typical temperature ~ 120-150 °C. In the Regemat burner, air is injected into the combustion chamber via 3+3 Si-SiC ceramic nozzles in an annulus, and gas is injected at the burner axis.

For start-up, a burner-attached flame is required and this is carried out by supplying cold air to a central, high velocity burner, independently supplied; non-preheated air is used for flame mode firing. In flame mode, each burner is monitored by its own flame detector, while flameless mode is only allowed over the flameless threshold, detected by a safety thermocouple.

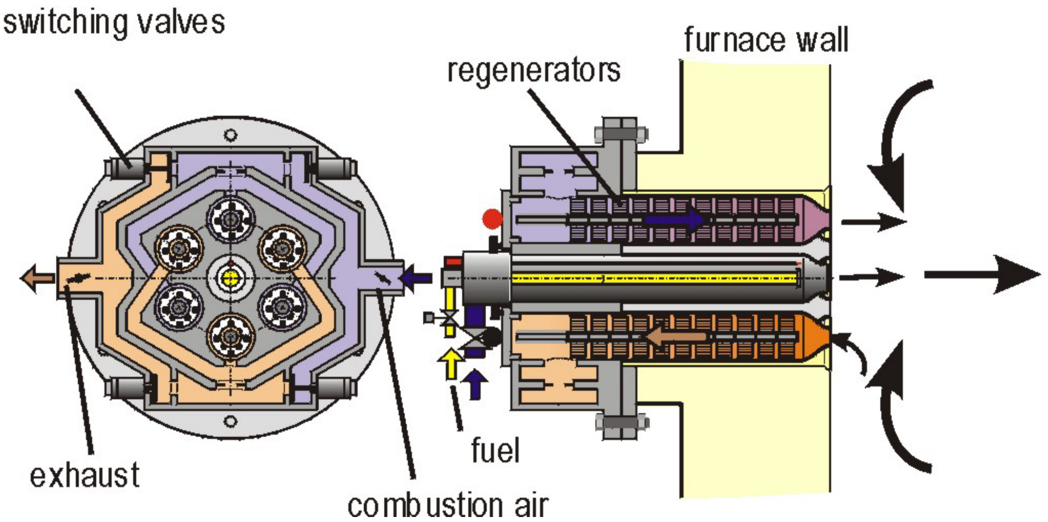

Figure 4 ***Schematic of the auto-regenerative burner***

Power control of the furnace zones is straightforward; burners are controlled on-off or in sequential firing and keep firing for a time span proportional to the difference set-point minus actual value. The flow-rates through burners are either 100% or zero, and drawbacks of `turned-down firing` are avoided. All the above requires a control system, both at burners and in the control room, but developments of digital devices and components make this more economic and reliable than in the past.

Figure 5 ***Compact auto-regenerative burner***

Demonstration applications and developments

The first industrial application of Regemat burners was in 1996 (*A.Milani, Salamone G. J.G. Wünning – Gas Wärme Int., No.46,H12, 606-12 – Dec 1997*): 50 units have been installed on the revamped furnace of an annealing and pickling line for stainless steel strip in Terni, Italy in 1996, and have been working since then. NOx emissions are close to 80 mg/Nm^3 or 40-50 ppm, natural gas consumption is ~ 30 Nm^3/t or ~ 40% of the original (cold air) plant, productivity has increased and product quality has improved. The Regemat units are still working with only a limited number being damaged and replaced after 7 years operation.

Following the success of the European Union-funded Thermie demonstration project in Terni, Regemat burners have been installed on several laboratory furnaces in academic and R&D centres in Europe for characterisation and testing. A number of possibilities were investigated for adapting the technology to many industrial processes and quite significant developments are now being designed and tested with respect to the first series (*J. G. Wünning – Thermprocess Symposium, May 2003, Düsseldorf*).

An additional development allowes the central start-up burner to fire while in flameless mode. By firing in parallel, the power input is boosted, which is useful for emergency peak demand, in spite of the overall penalty in efficiency due to the central cold air burner.

Annealing and pickling lines

Heat transfer occurs mainly by radiation : it be shown that the heating rate in °C/s is inversely proportional to strip thickness and proportional to the difference in absolute temperature at fourth power along the furnace (local zone temperature minus strip temperature). The productivity per unit of strip width can be characterised with a specific time τ_{sp}, expressed as residence time in seconds per mm strip thickness. The heated furnace length L (m) is related to residence time τ (s), strip thickness s (mm) and line speed V (m/s) as follows:

$$\tau = s * \tau_{sp} \qquad L = \tau * V = s * \tau_{sp} * V$$

With the same material and process temperature, the specific time τ_{sp} depends on:

- a profile of temperature set-point along the furnace zones which provides the maximum zone temperature at the inlet allows a reduction of τ_{sp}, and therefore of the furnace length. Conversely, a `cold` passive zone, typical of central heat recovery, necessarily implies a longer furnace.
- the surface emissivity: annealing a hot rolled and oxidised `black` strip, implies a high emissivity, while processing cold-rolled, `white` strip involves bright surfaces that reflect radiation. Here the process time tends to be inversely proportional to surface emissivity.

As an example for hot annealing of hot rolled coils, the specific time τ_{sp} is ~ 30-40 s/mm in old plants and may be typically reduced below ~ 22 s/mm in new furnaces. These values must be suitably increased for annealing bright strips (cold annealing) depending on surface property requirements.

Reducing τ_{sp}, and therefore furnace length and investment costs, or alternately, increasing production with the same available length, are clearly attractive. However, this is only possible with burner-integrated heat recovery and with a very accurate control of the heating process, as has been demonstrated with operating practice in several plants.

Improved Regemat burners have been recently used to equip two large A&P lines for stainless steel strip (mainly austenitic, AISI 300 series), basically to confirm the following performance proven by the Thermie demonstration project :

- NOx emissions ~ 50 - 75 ppm
- fuel consumption ~ < 300 kWh/t
- installed power ~ 350 kWh/t
- thermal and oxidation uniformity very good

Productivity can be measured in terms of τ_{sp} (~ 22 s/mm for hot rolled coils) and is at least 25 % higher than the best conventional design with central heat recovery. If the advantage in productivity is taken into account (more tonnage from the same available furnace length), then the investment cost per t/h of treated steel is competitive with state of the art design, even without taking into account the energy saving.

A `green field` A&P cold-line (*Stahl Eisen, 123, 9, Sept. 2003*) has been built in Krefeld, Germany and includes a 60 m long furnace fired with more than 90 Regemat burners. The new plant processes mainly austenitic with ~ 20% ferritic grades, in a gauge range 0.2-2 mm, and with a maximum speed of 100 m/min. The plant has been fully operational since 2002 and performances are excellent for product quality, efficiency and care of the environment. Thanks to automation and in spite of the big size, a team of five operators per shift can manage production.

Figure 6 shows a recently commissioned application; the revamping of the continuous catenary type furnace in an A&P line in South Africa, also for austenitic stainless steel strip. The pre-existing large `concentrated` burners in the preheat zone did not perform satisfactorily due to maintenance problems and because they were not able to exploit the decentralised burner-integrated heat recovery mentioned above.

In this case the productivity increase obtained with the new technology has been a decisive factor and the first stock of Regemat burners has been used to equip the preheat zone followed by retrofitting of other zones. The characteristic process time τ_{sp} could be progressively reduced from >~ 40 s/mm down to the best value of ~ 22 s/mm. Field results are satisfactory and performances are well within the range quoted above. Revamping will be completed shortly. The overall furnace length will be increased by ~ 25%, but productivity will increase by ~ 150 %. The revamping plan could be conveniently broken down in successive packages without too much inconvenience to normal production.

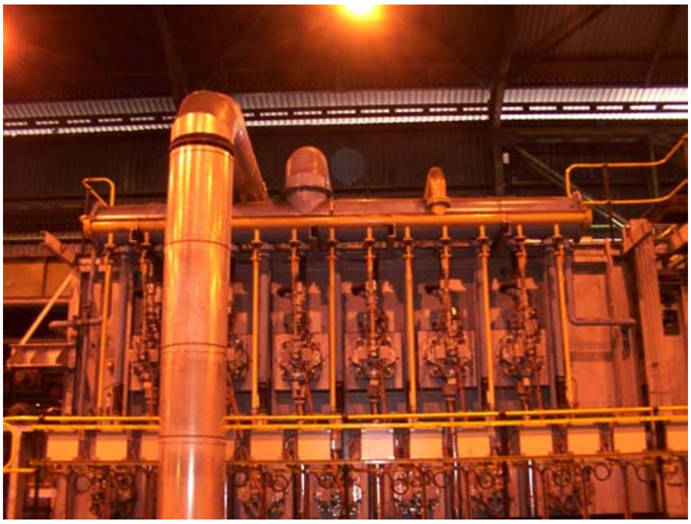

Figure 6 ***A&P line in South Africa***

Conclusions

Thanks to proven industrial applications, advanced, high-temperature firing equipment can now be used at no risk in continuous A&P lines for stainless steel strip. The burner integrated heat recovery FLOX fired burners allow an effective plant downsizing (at least 25%) with superior NOx emission performance, in spite of high combustion air preheat, and with effective energy saving.

The new technology is convenient because costs for retrofits can be compensated with a short pay-back time, not only by energy saving and reduced emissions, but also by improved product quality and more reliable and safe operation of the whole plant. Introduction of compact, regenerative burners, specifically developed for the purpose, has introduced a significant step forward in the furnace/process concept, bringing about significant advancements in the technology of continuous new and retrofitted annealing furnaces.

Joachim Wünning is General Manager, Volker Burkhardt is Technical Manager and Werner Roth is Manager in the Ruhr Area, all at WS Wärmeprozesstechnik GmbH, Renningen, Germany
Hans Tibbenham is General Manager of Engineered Thermal Systems, South Africa