INNOVATIVE FLAMELESS REGENERATIVE BURNERS FOR DIRECT FIRED FURNACES OF HOT DIP GALVANIZING LINES

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UP TO 15% LINES PRODUCTIVITY INCREASE

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1. ABSTRACT

On some hot dip galvanizing lines, the heating furnace entry is equipped with direct fired burners managed with sub-stoechiometric gas combustion conditions. Indeed, the production of high added value steel grades and the respect of the high product coating quality requirements lead to continuously control the interaction between the furnace atmosphere and the strip surface: a key point consists on mastering the strip surface oxidation / heating kinetics to be able to reduce the oxides during the soaking time. The air deficiency into the preheating atmosphere is used to control the oxides nature and its thickness depending on the steel grade and the process conditions. A perfect wettability of the strip during the galvanizing process is thus ensured.

ArcelorMittal and GDF Suez worked together on an innovative technology dedicated to the pre-heating sections equipped with direct fired burners on Hot Dip Galvanizing (HDG) lines.

The innovative burning technology dedicated to non-oxidizing heating atmospheres consists on a combination of an integrated post-combustion, a regenerative system and a flameless combustion technology. The association of those three principles is an European innovation by itself. It had to allow to:

- guarantee a complete combustion at the furnace exit
- lead to high energy efficiency
- achieve a cleaner process (NOx & CO emissions)
- obtain a homogeneous heating temperature

The main issues to solve before implementing the innovation on one industrial line are:

- How to design the regenerative burners' technology to reach a healthy behaviour in flameless combustion? What optimization of the working parameters to achieve maximal performances?
- What feasibility to implement flameless regenerative burners into heating section firing under sub-stoechiometric combustion conditions? What impact on the steel surfaces?

We demonstrated the particular interest of the technology for continuous annealing lines through five work axes.

1- Specific design of prototype burners with integrated post-combustion

2- Experimental campaigns with specific measurements performed in semi-industrial facility (combustion efficiency, gas atmosphere, optimized working parameters).

3- Based on previous results, experimental campaigns in laboratory conditions to qualify and quantify the impact of the generated gas atmosphere to the steel surface.

4- Specific simulation tools dedicated to dimension preheating sections of Hot Dip Galvanizing lines with the innovative regenerative technology.

5- To support the first industrial implementation.

The collaborative Research and Development program led to evaluate the expected energy savings, pollutant emissions and productivity gains in the case of a line retrofit:

- A saving up to 15% on gas consumption and associated CO2 emission,
- A decrease of 10% on CO emission
- A low level of NOx emission: 200 mg/Nm3 @ 3% O2
- No impact on product quality

These encouraging results allowed predicting a productivity increase up to 15% on some bottlenecks encountered on HDG lines. Complementary measurements and tests will be conducted in real production conditions on the industrial line where the first implementation of developed flameless regenerative solution will be done to assess the performances measured in the semi-industrial conditions.

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2. INNOVATIVE REGENERATIVE BURNERS READY TO BE IMPLEMENTED IN DIRECT FIRED FURNACES OF CONTINUOUS ANNEALING LINES

2.1. Flameless regenerative burners answer to industrial needs

ArcelorMittal lines are especially interested in increasing the productivity of high added value steel grades like the hot stamping “Usibor” grade dedicated to automotive and industry applications. The markets perspectives show a high demand of those grades so that the identified lines require corresponding productivity increase.

The key processes of galvanising lines are the annealing treatment occurring into the annealing furnace, the galvanising section and the finishing section (Figure 1).

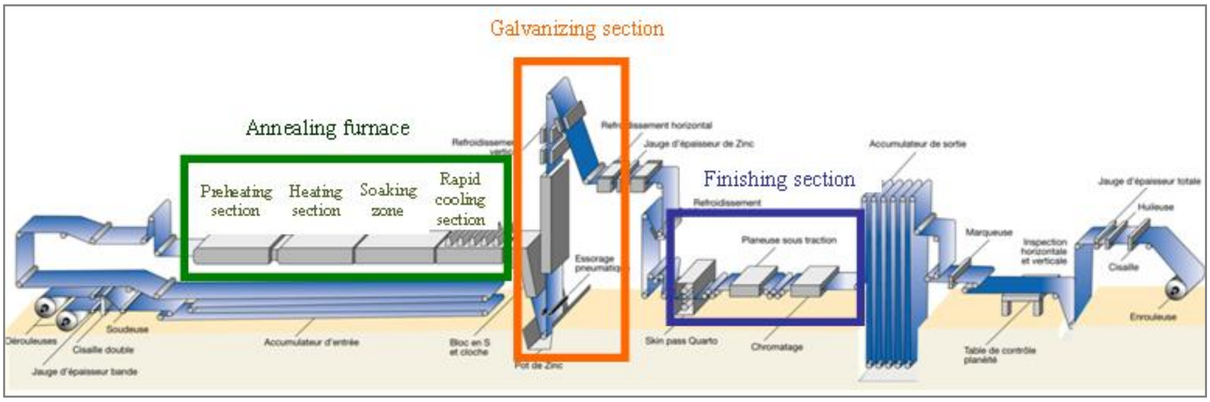

Figure 1: Diagram of a galvanizing line

The metallurgical characteristics and the mechanical properties are obtained during the heating treatment and by mastering the cooling profiles. The coating aspect and the corrosion properties of the galvanised strip are obtained during the coating deposition on the strip surfaces at the exit of the galvanizing bath (liquid metallic coating).

The preheating section, the heating section, the soaking zone and the rapid cooling section make up the annealing furnace. Most of the strip heating occurs into the preheating section.

Many hot dip galvanizing lines are equipped with a preheating section divided in 2 zones (figure 2): a post-combustion section and a heating zone equipped with direct flame burners managed with sub-stoechiometric gas combustion conditions.

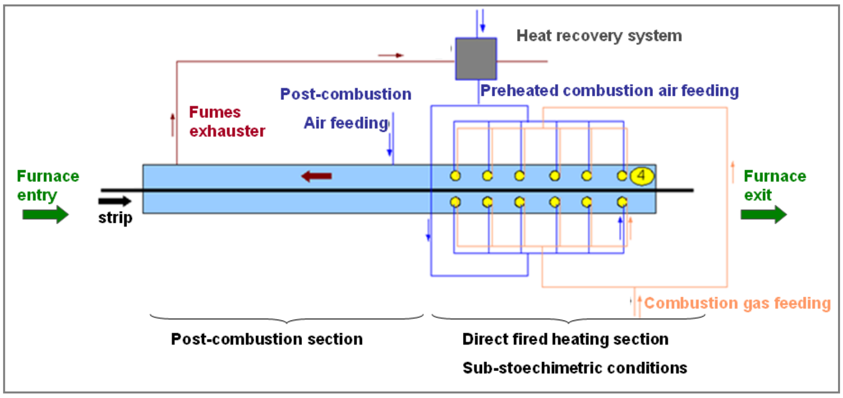

Figure 2: Diagram of a preheating section equipped with direct fired burners

The production of high added value steel grades and the respect of the high product coating quality requirements lead to continuously control the interactions between the strip surface and the gas furnace atmosphere, especially in the direct fired section: a key point to take care during the galvanizing process consists on mastering the strip surface oxidation/heating kinetics to be able to reduce the oxides during the soaking time. A perfect wettability of the steel strip during the galvanizing process is thus ensured. The air deficiency into the furnace is used to control the oxides nature and thickness on the steel surface depending on the strip chemical components and the process conditions

Many continuous annealing lines and more especially hot dip galvanizing lines equipped with direct fired furnace preheating section encountered bottlenecks issues to increase their productivity thanks classical heating power boosting.

The principle of regenerative burners with the fumes aspirations cycling particularly arouses the industrial lines interest. In addition, the reduction of energy consumption that allows the flameless regenerative technology is relevant to respect the European environmental standards and to reduce the production costs. For both productivity and energy savings objectives, an innovative technology based on flameless regenerative burners matches the industrial needs.

The principle of regenerative burner as a high efficient heat recovery system is well known for steel reheating furnaces since the seventies. But NO_x concentrations from first regenerative burners significantly exceeded most of national regulations. Japan, Germany, and USA investigated new types of burners operating with such high temperature combustion air facilities (over 1000°C) able to reduce NOx emissions. These new types of burners operate in a combustion mode named HiTAC combustion, flameless combustion or mild combustion. Its main characteristics are the global homogeneity of heat release, the non-visibility of the reaction zones, and the very low NOx emissions that can be divided by ten compared to a conventional regenerative burner [1-4].

In Europe, the first applications of flameless regenerative burners appeared in the metals industry some years ago. GDF Suez and ArcelorMittal have been particularly active on the subject in the framework of partnerships [5-6]. They promoted the diffusion of these new burners in Europe, through a better knowledge of the phenomena inherent to this new combustion mode, and by developing new design tools to ensure the installation efficiency, and the heating quality adapted to each process and industry needs.

2.2. GDF SUEZ and ArcelorMittal validated together the innovative technology

GDF-Suez and ArcelorMittal identified the potential interest to apply flameless regenerative burners to the specific conditions of preheating section on galvanizing lines. The innovative burning technology dedicated to non-oxidizing heating atmospheres consists on a combination of an integrated post-combustion system, a regenerative system and a flameless combustion technology. The association of those three principles should allow meeting the following requirements:

- to guarantee a complete combustion at the furnace exit
- to lead to high energy efficiency
- to achieve a cleaner process (NOx & CO emissions)
- to obtain an homogeneous heating temperature

GDF-Suez and ArcelorMittal decided to join their complementary competencies within collaboration (2007-2010) to test and to characterize in semi-industrial conditions the performances of this innovative solution, and to prepare the first industrial implementation.

The working principle of these industrial burner prototypes is presented on Figure 3:
During the exhausting mode, the fumes of the furnace (~1300°C), that still contains combustible (air deficiency combustion) are sucked through the burner chamber. Then the combustion of the not burnt elements occurs thanks a second air injection to reach a complete combustion (post-combustion in over stoechiometric conditions). Finally the clean fumes (~1400°C) go through the regenerator to transfer their heat to the ceramic spheres of the regenerative store so that the fumes are quite cold at the exit of the regenerator (< 300°C).

When the burner’s cycle switches from exhausting phase to combustion mode, the ambient air (~25°C) is injected through the regenerator store to be preheated (~1000°C) before entering into the burner’s chamber. The preheated air is then sent into the furnace chamber at high velocity and separately from combustion natural gas so that the combustion occurs into the furnace with the flameless principle.

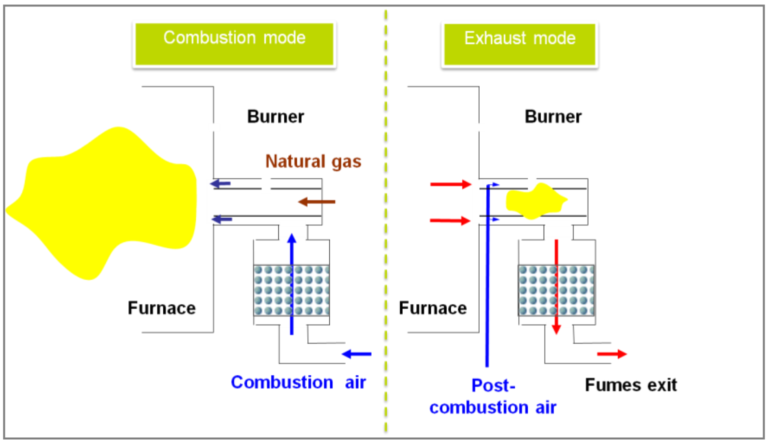

Figure 3: Working principle of innovative technology

The adaptation of the flameless regenerative burners to sub-stoechiometric conditions of the preheating section of galvanizing lines is a European innovation by itself and raises issues like:

- How to design the regenerative burners’ technology to reach a healthy behavior in flameless combustion? What optimization of the working parameters to achieve maximal performances?
- What feasibility to implement flameless regenerative burners into heating section under sub-stoechiometric conditions? What impact on the steel surfaces?

To answer these questions, the project was set-up following three work axes:

1. Experimental characterization of the combustion efficiency and the gas atmosphere generated within an semi-industrial scale furnace, optimization of operating conditions;
2. Based on previous results, impact of the generated gas atmosphere to the steel surface.
3. Evaluation of the energy savings, the environmental impact and costs savings for specific ArcelorMittal hot dip galvanizing lines with dedicated numerical tools.

Complementary and dedicated experimental means, complex measurements and numerical tools have been developed, based on GDF Suez and ArcelorMittal expertises.

2.3. Dedicated way and means to ensure the industrial transferability

2.3.1. Semi-industrial scaled pilot facility to optimize the combustion parameters

A 500 kW furnace has been designed and set up at GDF SUEZ research Centre. It allows making vary one specific parameter (as an example the furnace temperature) while keeping constant the other operating conditions (Figure 4 a).

Every relevant parameter such as combustive temperature, input power, air ratio can be separately controlled:

- The chamber dimensions are about 1m width; 0,95m height and 4,00 m length,
- The maximum temperature is about 1350°C,
- The furnace temperature is regulated by a motor driven water tube thermal load of 300 kW on the crown for temperature adjusting in the furnace.

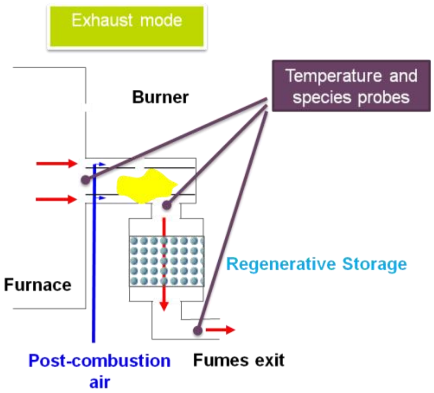

Figure 4: a) GDF SUEZ 500 kW furnace b) Burner monitoring

This furnace is designed to recreate industrial conditions and is exhaustively equipped by sensors delivering continuously following data:

- At the exhaust chimney and exhaust of the burners: flue gases temperature (in °C) and composition on volumic dry basis (CO_2, O_2, CO, CH_4, NOx),
- In the furnace:
  - Crown temperatures in °C,(eleven temperature measurement probes)
  - Pressure in mmCE,
- For energy balance calculation:
  - Water temperature (input, output) of the thermal load in °C, and flow rate in m3/h,
  - Wall outside temperature in °C,
  - Outside air temperature in °C.

The pair of burner prototypes is based on a commercial regenerative flameless burner design. The regenerative storage and the post-combustion chamber between the nozzle and the regenerative tank have been adapted to investigate several technical options (size, injection...).

To characterize the performances of the burner, one of the two burners is also exhaustively equipped by sensors (Figure 4b) to provide:

- The combustive temperature at the entrance and exhaust of the storage in °C,
- The combustive flow rate of the primary and secondary air injection in m3(n)/h,
- The combustive pressure in mbar,
- The natural gas temperature (in °C) and flow rate in m3(n)/h,
- The flow rate of the extracted combustion products in m3(n)/h,
- The temperature (in °C) and components contents ((CO, CO_2, O_2 in volume fraction dry basis) of the fumes, before and after the post-combustion, as well before and after the storage, in °C
- The temperature of the external walls of the system.

Additional precise in-flame measurements in stationary mode were carried out for four firing cases (figure 5) to provide:

- The temperature field cartography by fine-wire thermocouples,
- Stable species concentration fields cartographies (CH_4, H_2, H_2O, traces of O_2, CO, CO_2 and NOx) by sampling with a specific sonic nozzle probe.

These experimental data have been used for a better understanding of the physico-chemical characteristics of these flames by making vary process parameters. We made the most of the same experimental data to characterize the energy and environmental performances of the burner but also for the validation of its numerical simulation.

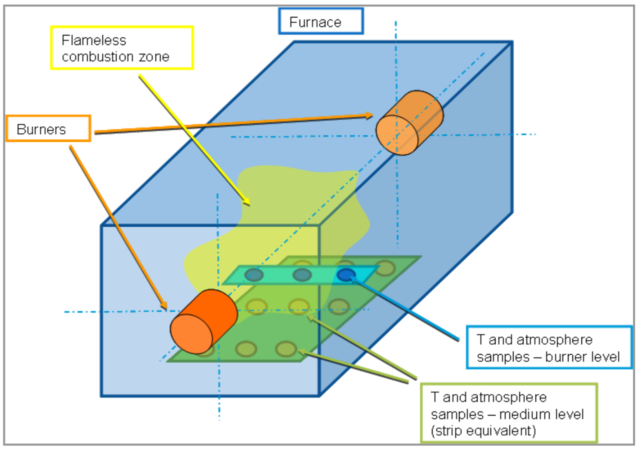

Figure 5: Schematic view of the in-flame measurements within the semi-industrial furnace equipped with the pair of innovative regenerative burners

2.3.2. Laboratory scale preheating pilot to investigate the impact on product quality

The effect of the gas atmosphere composition on oxidation and heating kinetics of typical steel grades of HDG lines equipped with classical burners and potentially with regenerative burners has been investigated at ArcelorMittal Maizières laboratory, especially on the preheating simulator presented on the figure 6.

The preheating simulator is made of a furnace equipped with SiC resistances. The gas atmosphere circulating within the furnace match the combustion's products contents at the air/natural gas equilibrium. The dried gas dew point can be adjusted at the furnace entry by making circulate the gas (N_2-CO_2-CO-H_2) within a humidifier. The temperature within the humidifier is adjusted as desired.

After cleaning, the steel sample (20 mm x 20 mm) is transported with a translation rod into the heated furnace (~ 1200-1300°C, i.e. the roof temperature on the industrial line). When the sample reached the desired temperature, we translate the sample to the nitrogen quenching box (U type).

The samples temperature is continuously measured by welded thermocouples on its surface. As the thermocouple ensured directly the fixation between the sample and the rod, the temperature measurement does not take into account potential thermal losses due to conduction with the translation rod. The oxidation kinetic at the sample's surface is stopped by the quenching with nitrogen so that we can easily characterize the effect of the furnace atmosphere and temperature on the product quality thanks traditional surfaces observations tools (Glow Discharge Optical Emission Spectroscopy or GDOES) [7].

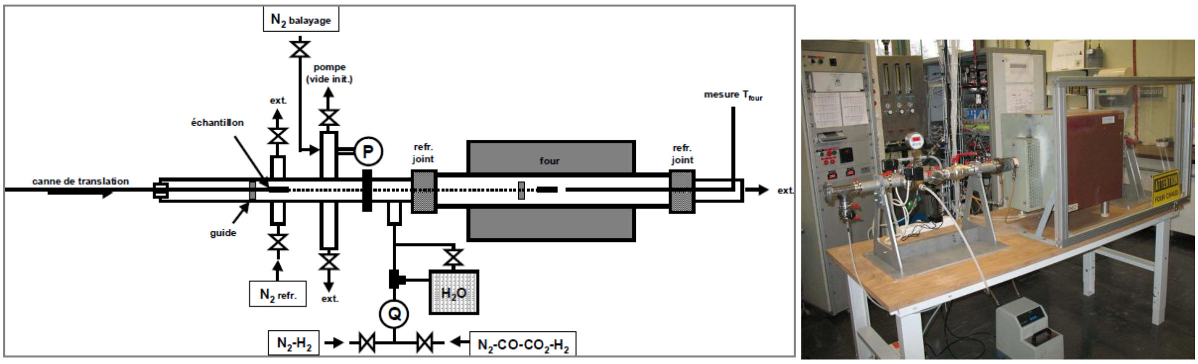

Figure 6: ArcelorMittal laboratory scaled preheating pilot

2.3.3. Representative numerical tool to dimension industrial furnaces

The industrial lines are interested to implement regenerative burners within their preheating sections equipped with direct fired section. It requires pre-dimensioning investigations to evaluate the new furnace design (burner's location, power…) and to estimate the expected energy savings and productivity stakes.

To support investigation, we build simulation tool dedicated to direct fired section and able to take into account the furnace geometry (including current burners positioning), the product format, the heating profiles required by the metallurgy, the line velocity, the strip transportation, the combustion parameters (air-gas ratio per zone, post-combustion section, etc.).

We validated the direct fired preheating section model with the data set of two conventional ArcelorMittal industrial lines. Six months process data have been collected on the two lines A and B. During this stable production time, the effect of strip thickness, width and line speed could be investigated.

The figure 7 compares the strip temperature at the exit of the preheating section measured on the industrial configurations (Line A) and the ones computed with the developed model. Global thermal imbalances, walls and fumes temperatures have been also checked. The green tendency curve shows very good accuracy between predicted and on line measured strip temperatures whatever the strip format is.

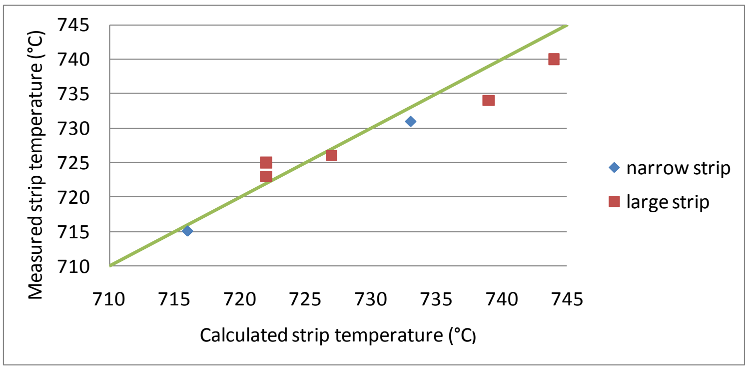

Figure 7: Validation of the line A modeling – comparison between the calculated and the measured strip temperature at the end of the direct fired preheating section

To model the innovative technology, we developed specific subroutines for regenerative system (including post combustion within the burner). These subroutines have been carefully qualified, based on experimental data measured within these particular burners in the frame of the project on GDF SUEZ semi-industrial scale furnace

We validated the dimensioning tool for 2 lines conditions, for a large range of product formats and various process conditions. So, the model is representative of annealing furnaces with air deficient combustion conditions and is able to integrate the studied technology.

2.4. Innovative burner's design and optimization of high efficient regenerative solution

Tests have been performed on GDF SUEZ semi-industrial scale furnace, to evaluate the performances of this innovative technology regarding safety, energy efficiency, pollutant emission and heat transfer.

The reference case of this parametric study was based on the line A furnace operating conditions.

Following parameters varied to evaluate the optimised operating conditions:

- Burner power input (from 100 to 400 kW),
- Furnace temperature (up to 1300°C),

- Air gas ratio in the furnace (from 0.85 to 0.95),
- Oxygen content in fumes after regenerator (from 0.5% to few %),
- Regenerative burner cycling time (from 1 to 2 min),
- Extraction rate of fumes inside the regenerator (from 50 to 90%).

Main conclusions regarding efficiency of flameless burner, post combustion and regenerative system under air deficient combustion condition are presented below.

2.4.1. Efficient flameless system

The first important result is that no problem has been noticed to operate a flameless burner nozzle under air deficient conditions: ignition and combustion stability have been easily managed. The classical flameless appearance of the combustion has also been noticed.

In terms of pollutant emissions, NO_x measured inside the furnace are around 200 mg/Nm^3 @3%O_2. This level is similar to those observed for low NOx technologies such as flameless regenerative burners for over stoechiometric combustion conditions.

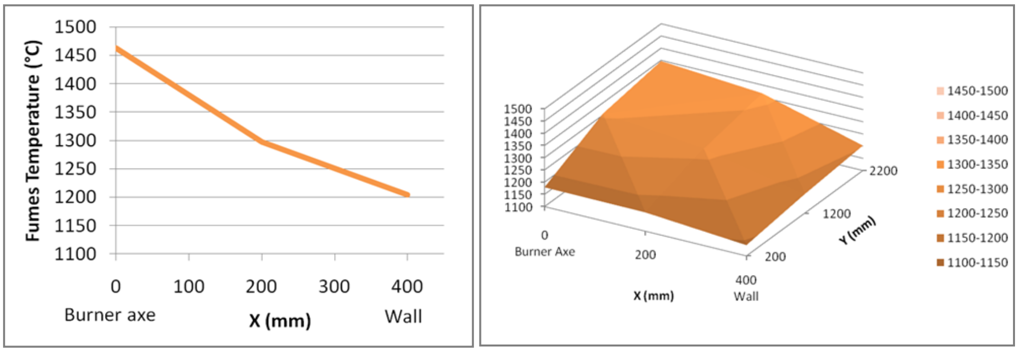

Figure 8: Temperature (in °C) measured inside the furnace - radial temperature profile from the burner axe (left side) and temperature field close to the strip (right side)

In terms of temperature fields, we can observe weak temperature gradients and maximal temperature under 1500°C (figure 8). Near the strip, the temperature field is homogeneous: no hot point has been observed on different configurations.

As a consequence better heat transfer to the strip is expected compared to classical burners and a more homogeneous heating repartition across the strip width, what should conduct to a better control of the strip quality and more specifically to the strip flatness.

2.4.2. Efficient integrated post-combustion

The containment was the main issue raised concerning the integrated post-combustion system: is the space between the burner and regenerative tank sufficient?

- to achieve a complete combustion (minimum CO level) and to burn all sucked non burnt elements (CO, H_2)
- to comply with NOx environmental regulations (350 mg/Nm^3 @ 3% O_2)

It appears that, with the tested prototype, it is possible to reach such expected performances.

However, a right set of parameters has to be set to optimize the post combustion performances (figure 9). Concerning the influence of the post combustion air/gas ratio on CO levels, a reference value has been observed below which the CO content in the fumes exponentially increases, even if there is theoretically enough air to achieve a complete combustion. Besides injecting higher air flow rates can help decreasing CO emissions but leads to damage the global energy efficiency of the system.

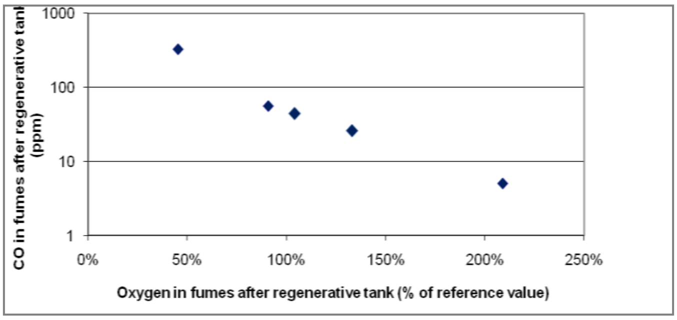

Figure 9: Influence of the post-combustion air/gas ratio on CO emissions at the exhaust of the regenerative storage

The NOx contents measured after the post-combustion (i.e. at the exit of the regenerative tank) show light higher values than the NOx contents measured into the furnace. If the NOx contents measured are all under the today's regulation requirements with an appropriate set of operating parameter, we noticed the potential and future improvements to achieve lower NOx emission especially within the post-combustion chamber. These optimisation perspectives do not prevent any immediate industrial operation.

2.4.3. Efficient regenerative storage

The regenerator performances and its ability to preheat air with the extracted fumes have been evaluated during the tests on GDF SUEZ semi-industrial scale furnace. .

In most of studied cases, the technology is able to preheat the combustion air at a temperature level of 1000°C, while keeping exhaust fumes temperature at around 250°C, as shown figure 10. It means that the combustion efficiency of such a system is very high. The effect of the post-combustion on the fumes temperature can also be noticed: the superposed red and yellow curves on the Figure 10 show that fumes temperature increase by more than 150°C because of the post-combustion heat.

The yellow and blue curves on the graph represent the ability of the regenerative storage to absorb the fumes heat. The Figure 10 b shows the locations of the 3 species and temperature measurements used to characterize the regenerative system

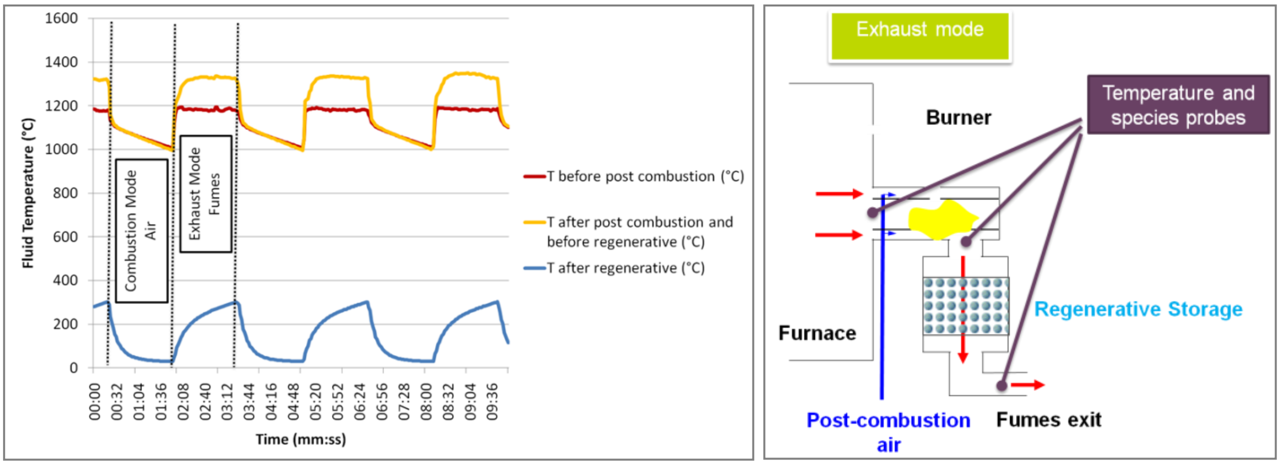

Figure 10: a) Fluid temperature at three different monitoring points of the regenerative system
b) Schematic view of the regenerative system and location of the species and temperature measuring points

The global combustion efficiency of the system also depends on several parameters such as the fumes extraction rate: the higher it is, the better the combustion efficiency is. Thus, an optimised value has also to be found to obtain the best compromise between efficiency of the regenerative system, exhaust fumes temperature (a too high value could damage electro-valves) and post-combustion efficiency. Nevertheless, for the studied configurations, combustion efficiency can easily reach values above 75 % until 85 % obtained for optimized parameters.

In term of performances, the regenerator can be modelled as an exchanger that is characterized by two values: the efficiency and the yield. These values have been determined thanks the experimental data obtained during the campaign tests and have been implemented in the dedicated subroutine in order to model direct firing preheating furnaces equipped with this technology.

2.4.4. Global efficiency of the innovative technology

Resulting from the trials campaign at semi-industrial scale, the results of the tested burners are already encouraging and already suitable for industrial use:

- No operating problem has been detected. The burners and its associated post combustion systems run under safe conditions, during ignition and operation phases.
- Performances in terms of NO_x and CO emissions need a set of optimised values of the operating parameters, but have already satisfying levels for an industrial use.
- Combustion efficiency of this innovative technology is very high and promises to reach a more energy efficient furnace compared to actual technology.
- Temperature field within the furnace, and particularly near the strip, seems to be quite homogeneous, leading to a better heating quality.

2.5. No impact on surface quality of high added value steel grades

As described in paragraph 2.3.1, the main species contents (CO, CO_2, H_2, H_2O, O_2, CH_4) have been measured in the semi-industrial furnace during the experimental campaign, so that exhaustive species cartography could be built for each tested setting point. Those fine measurements allow us to reproduce artificially the atmosphere generated by the innovative technology on the semi-industrial facility, on the laboratory scale preheating pilot.

The effect of gas atmosphere composition on oxidation and heating kinetics of the typical steel grades of HDG lines equipped with classical or regenerative burners has been investigated at ArcelorMittal Maizières laboratory, especially on the preheating simulator described previously (paragraph 2.3.2). If the results presented hereafter are focused on the line A only, the analysis of Line B conditions show similar conclusion.

Based on the line A order book, two sensitive steel grades (AlK and IF) and their critical formats have been selected to conduct the tests. The strip temperature at the exit of the line A preheating section is around 700°C. We simulated on the preheating pilot three sample temperature: 600, 700 and 800°C. Based on the trials on the semi-industrial cell equipped with the regenerative burners, two cell vault temperature have been tested: 1200 and 1300°C. The industrial reference of line A is 1200°C whereas the vault temperature measured on the experimental cell equipped with the regenerative burners is 1300°c due to the high efficiency of the burners.

We conducted two kinds of trials:

- “Long time” trials. The sample is maintained into the furnace until the sample temperature reaches the furnace temperature. The sample is then quenched.
- “Interrupted” trials. The sample is removed from the furnace as soon as the sample temperature reached the desired temperature. The sample is then quenched.

2.5.1. Surface oxidation kinetic and product heating kinetics

The trials confirmed that both surface oxidation and sample heating phenomena are coupled into a direct fired preheating section. It means that the sample heating kinetic is accelerated from a critical temperature. This effect is due to the oxidation of the extreme sample surface, what leads to make vary the sample emissivity. For both tested steel grades, the critical temperature is around 700 °C (Figure 11).

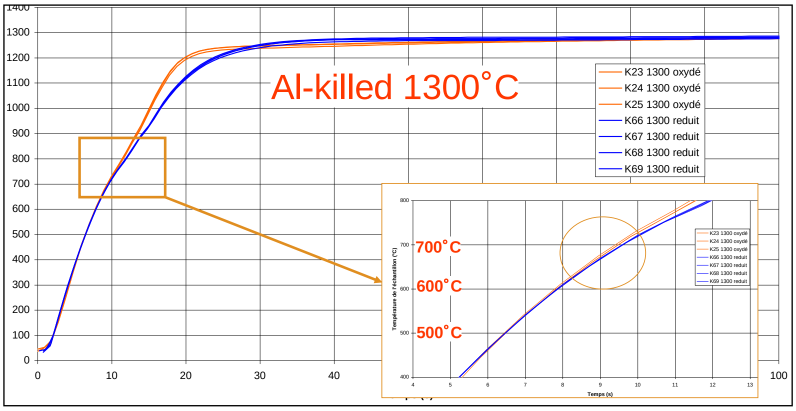

Figure 11: Effect of the surface oxidation on the heating kinetic from a critical temperature around 700°C: strip temperature (°C) versus time (s).

We observed the thickness effect: the thin samples heating kinetic is quicker than the heating kinetic of the thick samples so that the oxidation occurred earlier.

We observed the effect of the furnace temperature: the increase of the vault temperature from 1200°C to 1300°C resulting from the high efficiency of the regenerative burners leads to a reduction of the required time to heat the sample at the desired final temperature. The potential gain on the heating kinetic observed on laboratory conditions and for this sample can reach 20% as shown on Figure 12.

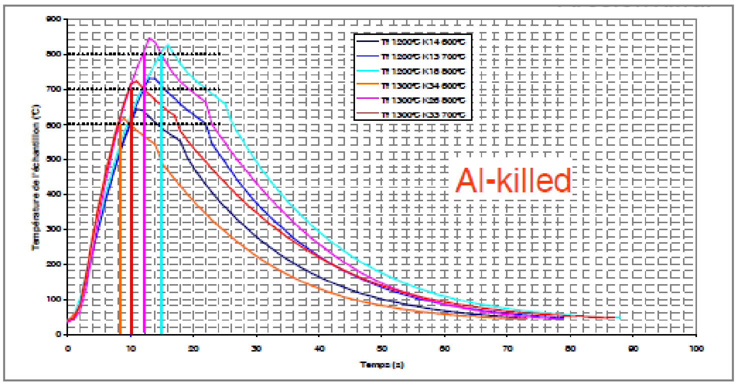

Figure 12: Effect of the furnace temperature (1200°C compared to 1300°C) on the sample heating kinetics

2.5.2. Surface observations confirmed the good product quality

The species cartographies realized in the preheating section of the industrial line A equipped with classical burners and into the trials cell equipped with the regenerative burners have been compared. The contents of H_2, CO_2, CO, H_2O is quite equivalent in both experimental and industrial conditions. The main difference is the O_2 content detected into the trials cell and especially the O_2 peaks (depending on trial, maximum observed 800 ppm) observed during the switch time of the regenerative burners (period of time between the exhaust and combustion modes). As a reference, the usual O_2 content is around 100 ppm.

The effect of the O_2 presence has been investigated on the preheating simulator on the AlK and IF grades. Thanks GDOS observations, we identified the metal-gas reactions occurring at 800 ppm O_2: the recarburisation phenomenon occurs but at lower proportion than the expected and usual ones. The manganese and silicon content within the oxide surface thickness show lower contents than expected usually for the AlK grades. It means that the classical reaction between the steel and the gas is lightly modified but does not induce significant damages on the sample surface.

However, the O_2 presence within the simulator atmosphere does not influence the heating kinetic if the furnace temperature is classically 1200°C, whereas the heating kinetic is higher for a furnace temperature of 1300°C.

A key improvement consists on technological solutions (specific electro valves) to limit the O_2 peaks to be able to ensure that the furnace atmosphere will content the minimum residual O_2 content required for the high surface quality of current and future steel grades (classically 55-155 ppm).

2.6. Investigations to implement the innovative technology on two ArcelorMittal HDG lines

We investigated two different industrial configurations:

- Case of Line A: the industrial stakes are focused on energy savings (gas consumption). A full conversion from standard burners to the innovative burners has been analysed.
- Case of Line B: The industrial stakes are focused on productivity increase of high added value grades (bottleneck issue). For that case, a retrofit of one combustion zone has been studied.

The gains estimation for the two industrial lines as well the preheating sections pre-dimensioning result from the developed numerical tool described in the paragraph 2.3.3.

2.6.1. Line A – case of energy savings

The line A preheating furnace is equipped with standard burners and with a classical heat recovery system. Calculations have been performed for a full regenerative case of the line and for 2 strips characteristics (various thickness and width).

For both strips, a reference computation has been carried out in order to determine:

- the whole thermal behaviour of the industrial furnace (current configuration and classical burners)
- the strip thermal behaviour

Two configurations have been investigated to implement the innovative regenerative technology (figure 13):

- Case 1: The innovative regenerative burners are implemented at the existing standard burner's location (full replacement).

- Case 2: case 1 configuration and innovative burners are also implemented into an additional heating section.

The computations show high potential energy savings in the case of an implementation into an additional zone (Case 2). Indeed, the additional regenerative burners allow managing on an optimal way the heating power of the classical zone. This configuration could lead to energy savings until 14% for thick products.

As shown on figure 13, in the case of a full replacement of the classical burners by the regenerative ones but restricted to the existing classical burner aera (case 1), the computation clearly highlights the risks that the roof temperature exceeds the acceptable one (industrial constraints due the existing refractory roof) even if energy savings are higher than the target required by the site (at identical production rate).

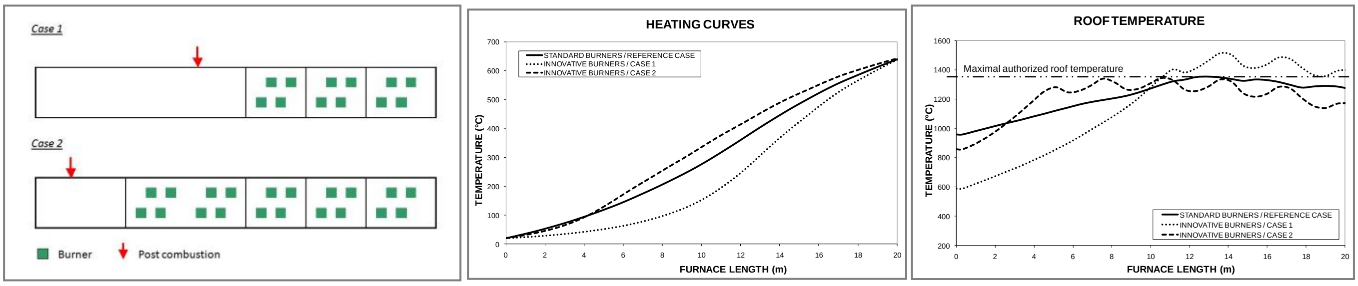

Figure 13: Simulation of preheating furnace of the line A

a) Case 1: full replacement of classical burners by regenerative burners

Case 2: case 1 + implementation of an additional innovative regenerative burners section

b) Computed vault temperature along the furnace length for reference case 1 and for case 2

c) Computed strip temperature along the furnace length for reference case 1 and for case 2

This first study points out the great interest of the provided innovative technology that requires an optimised configuration in order to respect all the constraints of the furnace.

The interest of the modelling tool that can deal with several design criteria such as the temperature of the roof and the required strip temperature profile is reinforced.

2.6.2. Line B - case of productivity increase

The preheating section of the line B is equipped with a classical recovery system and 3 burning zones. At current maximal production rate, the first burning zone is not be used because of extraction flow rate and temperature limitations into the recovery system. This power limitation implies a bottleneck in terms of production increase. No existing technology meets the issue except the full retrofit of the recovery system.

The computations performed to dimension the heating power repartition and the burners location show that the implementation of regenerative burners into the first burning zone coupled with the extension of this zone (Figure 14), can lead to a maximum productivity increase of 15 % for the considered product order book whereas additional energy savings can reach 5% (specific gas consumption).

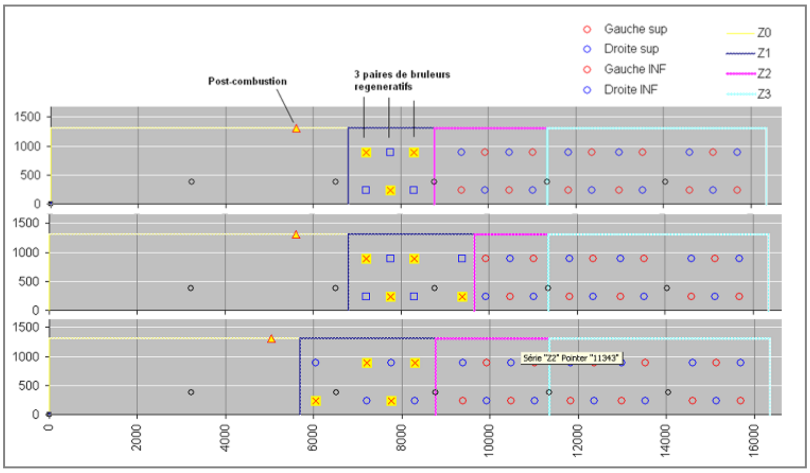

Figure 14: Example of simulation cases of preheating furnace of the line B (side view)

The strip thermal profile and target temperature at the exit of the preheating furnace are respected as well the acceptable roof temperature.

In that second industrial case, this technology is the optimal candidate to solve the furnace bottleneck in order to increase productivity at lower investment's costs.

2.7. Conclusion and perspectives

GDF-Suez and ArcelorMittal identified the potential interest to apply flameless regenerative burners to the specific conditions of preheating section on galvanizing lines. The innovative burning technology dedicated to non-oxidizing heating atmospheres consists on a combination of an integrated post-combustion system, a regenerative system and a flameless combustion technology.

We decided to join our complementary competencies within a collaboration (2007-2010) to test and to characterize in semi-industrial conditions the performances of this innovative solution, and finally to prepare the first industrialisation. Dedicated experimental means, complex measurements and numerical tools have been developed based on our expertise.

Resulting from characterization campaigns, the performances of the tested burners are very encouraging and already suitable for industrial use:

- No operating problem has been detected. The burners and its associated post combustion systems run under safe conditions, during ignition and operation phases.
- Performances in terms of NO_x and CO emissions need a set of optimised values of the operating parameters, but have already satisfactory levels for an industrial use.
- Combustion efficiency of this innovative technology is very high and promises to reach a more energy efficient furnace compared to current technology.
- Temperature field within the furnace, and particularly in the strip neighbourhood, is quite homogeneous, leading to a better heating quality.
- There is no impact of the generated atmosphere on the quality of the surface of the strip

Thanks to the experimental campaigns and the computations conducted with dedicated numerical tool, the collaborative Research and Development program led to characterize the expected energy savings, pollutant emissions and productivity gains in the case of an industrial implementation:

- A saving up to 15% on gas consumption and associated CO2 emission,
- A decrease of 10% on CO emission
- A low level of NOx emission: 200 mg/Nm3 @ 3% O2
- No impact on product quality

These encouraging results allow us to predict a productivity increase up to 15% on the studied bottlenecks of HDG lines, especially dedicated to high added value steel grades.

Complementary measurements and tests will be conducted in real production conditions on the industrial line where the first implementation of developed flameless regenerative solution will be done to assess the performances measured in the semi-industrial conditions and the estimated associated gains.

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4. LEGENDS FIGURES / TABLES