Tenova FlexyTech® regenerative flameless burners

*With more than 40 years’ experience in R&D on combustion systems, furnace design and installation of Tenova’s FlexyTech® regenerative flameless burners combine the advantages of minimising NOx emissions with high temperature combustion air preheating for important energy savings and efficient furnace heating.*

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*Tenova LOI-Italimpianti SpA*

Following the world economic crisis, the primary goals of the steel industry continue to be high quality products, saving energy, environmental care and production cost cutting. In recent years Tenova has started R&D projects based on the FlexyTech® Furnace concept in industrial reheating furnaces, with special focus on NOx emissions and reduction of fuel consumption. Environmental regulations, especially after April 2002, when the Kyoto protocol on climate change became effective, have made performance targets for fossil-fired reheating furnaces even stricter. By 2020, furnace technologists must find a further ~90% improvement in NOx emissions and a reduction in fuel consumption of 20-30%.

This article illustrates the development by Tenova in cooperation with CSM (Centro Sviluppo Materiali) of the latest generation of FlexyTech® flameless regenerative burners, which give the reheating furnaces both very low NOx emissions from flameless combustion technology and higher energy efficiency from regenerative technology. An overview is given on NOx emissions and CO₂ production at the latest reheating furnaces. CO₂ production is strictly related to energy efficiency or fuel consumption.

**TENOVA FLEXYTECH**

Tenova FlexyTech® is the framework that includes all the innovative activities applied to a reheating furnace (see Figure 1).

The principal fields of innovation are:
- FlexyTech® burners providing lowest NOx and highest efficiency
- Tenova combustion control techniques which are quicker and more accurate
- Computer model for offline simulation of different design solutions and online optimisation of furnace regulation (level 2).

The application of the FlexyTech® furnace concept to a standard reheating furnace offers top performance and high efficiency independently of the running conditions of the furnace itself.

The most widely used technique to enhance furnace efficiency is intensive air preheating as it significantly lowers fuel consumption, but it also increases NOx emissions. However, as flameless technology provides significantly lower NOx emissions and better thermal uniformity, this is the right platform to target energy savings and emission reduction via flameless regenerative burners (see Figure 2).
Tenova’s state-of-the-art steel reheating furnaces (production higher than 100t/h) are characterised by specific consumption values of 1,200-1,400kJ/kg (see Table 1).

NOx emissions are more complex than CO2 and depend strongly on the combustion technology adopted, fuel type and operating conditions of the furnace (ie, furnace pressure, zone temperatures, oxygen concentration, etc). For example, furnaces for slab reheating have higher NOx emissions than those for billet reheating due to the higher process temperatures used. Consequently, current reheating furnaces are characterised by NOx levels which vary quite significantly from case to case.

However, the most important factor that influences NOx emissions is the type of burner installed. The data in Table 1 give a clear indication that technology development for CO2 reduction, which is mainly concerned with the increase of efficiency of combustion systems, also has to take into account the problem of NOx emissions. In this regard flameless burners coupled with a regenerative system, as well as flameless burners using air enrichment up to 100% O2, may represent an effective solution for steel reheating furnaces.

Since the early 1960s, Tenova has been designing and building its own furnaces and burners, aided by a programme of continuous R&D activity (see Figure 3). Tenova burners are designed and installed to comply with customer local standards concerning air pollution and NOx emissions and, as a result of US market requirements for an ultra-low NOx burner, Tenova commenced its Flexy-Tech® research programme to significantly lower the NOx emissions of the then current generation burners through the following steps:

1. Investigation of innovative combustion techniques for reheating processes.

Table 1 Tenova reheating furnace characteristics

<table>
<thead>
<tr>
<th>Furnace type</th>
<th>Production [t/h]</th>
<th>Reference charge length [mm]</th>
<th>Steel type</th>
<th>Steel type</th>
<th>Charge type</th>
<th>Discharge temp. ['C]</th>
<th>Burner type</th>
<th>Fuel</th>
<th>Air/ O2 temp. ['C]</th>
<th>Energy cons. [kJ/kg]</th>
<th>CO2 prod. [kg/t]</th>
<th>NOx [mgNm3 @3% O2 in DFG]</th>
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<tbody>
<tr>
<td>WB 370</td>
<td>10,000</td>
<td>C, SS</td>
<td>Slab</td>
<td>Flame</td>
<td>1,290</td>
<td>Mix gas</td>
<td>450</td>
<td>1,400</td>
<td>63.3</td>
<td>215</td>
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<tr>
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<td>C</td>
<td>Billet</td>
<td>Flameless</td>
<td>1,170</td>
<td>NG</td>
<td>450</td>
<td>1,158</td>
<td>65.0</td>
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<tr>
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<td>Flame</td>
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<td>NG</td>
<td>500</td>
<td>1,250</td>
<td>70.2</td>
<td>200</td>
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<tr>
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<td>Billet</td>
<td>Flame</td>
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<td>NG-COG</td>
<td>450</td>
<td>1,150</td>
<td>52.0</td>
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<td>Flame</td>
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<td>Slab</td>
<td>Flame</td>
<td>1,250</td>
<td>NG</td>
<td>500</td>
<td>1,150</td>
<td>64.3</td>
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<tr>
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<td>1,250</td>
<td>NG</td>
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<td>WB 300</td>
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<td>Slab</td>
<td>Flame</td>
<td>1,270</td>
<td>NG</td>
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<tr>
<td>WB 240</td>
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<td>C</td>
<td>Slab</td>
<td>Flame</td>
<td>1,270</td>
<td>NG</td>
<td>450</td>
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<tr>
<td>WB 450</td>
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<td>1,285</td>
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<tr>
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<td>C, SS</td>
<td>Billet</td>
<td>Flame</td>
<td>1,260</td>
<td>Mix gas</td>
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<td>1,320</td>
<td>59.7</td>
<td>230</td>
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Fig 3 Timeline of the FlexyTech® burner family development

Fig 4 TSX burner simulation in flame and flameless mode operation
Development of new components and control strategies for reheating furnaces on R&D scale
Technology transfer from R&D scale to industrial application

Within this research programme Tenova and CSM set up a joint design process based on synergy between mathematical modelling, industrial scale testing and industrial applications mainly using DOE (design of experiment) techniques to lower drastically the number of field tests and the time to market the new products, with a consequent reduction of costs.

This approach was used for the development of the flameless burners from the TSX, TRX and TLX families into a new flameless regenerative family (TRGX) starting from the traditional flame configuration (TRG).

FLAMELESS BURNERS
The development of Tenova FlexyTech® flameless burners was carried out through computational fluid dynamics (CFD) simulations and laboratory furnace tests. In the first phase the diluted-flame TSN burner was developed, reaching the target value of 65ppm for NOx emissions (calculated at 3% O2 in dry flue gases (DFG)), on a reheating furnace operating with zone temperature set point between 1,150°C and 1,250°C and preheated air temperature of 450°C.

TSN is a burner capable of both start-up function and low NOx operation (high impulse jet). Burner geometry was studied to delay fuel and air mixing so that products of combustion could dilute O2 available in the combustion air so reducing the temperature peak generated in traditional burners. The experience made on the TSN development allowed Tenova to start a new and more ambitious project: the TSX.

This project started in 2004 with the aim of developing a natural gas side burner with the following characteristics:
- NOx emissions below 40ppm @ 3% O2 in DFG
- Ultra low CO emissions (below 5ppm)
- No valves on hot air for air staging
- Least excess air operations for maximum fuel efficiency
- NOx emissions not affected by air temperature
- NOx emissions not dependent on turn-down
- Air preheating up to 550°C

Flameless combustion was the technological platform for TSX burner development and it has been successfully employed in association with highly preheated combustion air, maintaining considerably low NOx values, adding unbeatable heat transfer uniformity as well as improvements in charge temperature uniformity. All of the TSX project goals were reached through extensive CFD modelling (see Figure 4) and industrial tests. Currently, thousands of Tenova FlexyTech® flameless burners are installed on reheating and heat treatment furnaces all over the world.

REGENERATIVE BURNERS
The development of the TRG regenerative burner (see Figure 5) commenced in 1999 in co-operation with CSM as the first step of the regenerative flameless solution. It is equipped with an internal honeycomb regenerator of high thermal capacity and specific surface which allows preheating of the combustion air up to 1,000°C.

TRG burners work in pairs (see Figure 6) with typical cycles of 30-40s, and are controlled by automatic valves installed on the combustion air and the flue gas ducts:
- The first burner takes in hot flue gases (T=1,300°C) from the combustion chamber through a cold ceramic honeycomb whose temperature is raised to 1,200°C. Flue gases are exhausted at 150-200°C. Gas valve and combustion air valve are shut
- The second burner is fed with cold combustion air through the hot regenerator. Air temperature is raised to 1,000°C. Air valve and combustion air valve are shut

TRG burners are characterised by relatively high NOx emissions due to the high combustion air preheating temperature. Some reference data on this burner are...
The cartridge consists of a dense structure of parallel channels that produces a low pressure drop. The high value of the specific surface (about 800-1,000 m²/m³) and the low packing density (about 800 kg/m³) allows concentrating high energy exchanges in a very small regenerative mass. For example, a 6 kg, 50 x 50 channel honeycomb can exchange up to 250 kW. From the thermal point of view, honeycombs are the best solution to obtain local air preheating inside a burner. A potential drawback, however, is clogging, which depends on several factors, including: furnace atmosphere, furnace refractory and regenerator material. Unfortunately, honeycombs cannot be applied in all types of furnaces because of the presence of dust in the flue gases. Dust can attack and even damage the honeycomb structure by means of two main mechanisms:

- **Physical:** dust in the flue gas occludes the channels which act as a filter. In this case, the obstruction prevents the correct flow of combustion air and flue gas. This problem can be limited through a correct choice of the honeycomb type, size, and material.
- **Chemical:** the ceramic honeycomb can be damaged by acids, alkalis, or silicates. Acid attack occurs when the dew point of acid vapours in flue gases is exceeded. In the case of natural gas-fired furnaces, the only expected acid compound is SO₂, and so it is necessary to prevent the flue gases temperature dropping below 120°C. On the other hand, the presence of alkalis at temperatures above 700°C causes an interaction with the ceramic material forming a ceramic phase (alkali-alumino-silicates). This can cause deformation of honeycombs and sometimes even the partial melting of the structure. The presence of Si or SiO₂ creates deposits on the channel surfaces, thus increasing the pressure drop.

Whether the interaction be acid or alkaline, in the case of a dirty furnace atmosphere, the use of honeycombs is not recommended. In this case, a regenerator bed of ceramic balls is used.

Ceramic ball regenerators (see Figure 8) contain corundum balls, (TiO₂ + Al₂O₃ >99%), which are characterised by a very high compression strength (>15 kN), but they have a low specific surface (from 144 m²/m³ for 25 mm spheres to 720 m²/m³ for 3 mm spheres) with high packing density (2,300 kg/m³) compared to honeycomb regenerators. This causes a dramatic increase (from 48 kg/MW to about 350 kg/MW) of the regenerator weight and of the consequent pressure drop.

The thermal behaviour of ceramic ball regenerators has been analysed from experimental trials and mathematical modelling, following the same approach used for the characterisation of the honeycomb regenerators.

### Table 2: Tenova FlexyTech® TRG regenerative burner reference data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn down range</td>
<td>50-100%</td>
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<tr>
<td>NOx emissions @ 3% O₂</td>
<td>80 ppm</td>
</tr>
<tr>
<td>furnace temp. 1,250°C and air temp. 1,000°C</td>
<td></td>
</tr>
<tr>
<td>Recirculation ratio</td>
<td>0.8</td>
</tr>
</tbody>
</table>

![Fig 7 Honeycomb ceramic regenerator](image)

![Fig 8 Ceramic ball regenerator](image)
In principle there is no optimum choice between honeycomb and ceramic ball regenerators for all applications and it is necessary to select the regenerator bed according to furnace type, fuel, atmosphere, etc. For this reason Tenova is able to apply both the configurations to its regenerative burners.

**REGENERATIVE FLAMELESS BURNERS**

The TRGX burner was realised in 2006 when we decided to integrate flameless technology with regenerative combustion in order to obtain a burner that could guarantee pollutant and energy consumption reduction. TRGX FlexyTech® regenerative flameless burners (see Figure 9) represent the latest generation of regenerative burners and can work both in flame mode (for cold ignition) and flameless mode (to reach the best performance in term of NOx emissions). Thanks to coupled gas and air staging, working in flameless mode NOx emissions are reduced to 35-40ppm.

The honeycomb regenerator provides a very high preheating efficiency due to both high thermal capacity and specific surface in a really compact geometry. On the other hand the ceramic ball regenerator is much more bulky and heavier but allows better access and easier maintenance of the regenerative media and hence is more suitable when the furnace atmosphere is very dirty.

Basically, the TRGX burners work in pairs: when one is firing and heating the combustion air the other is recovering and storing the heat from the waste gases. The typical reversion time is around 20-30s for the honeycomb type whereas it is around 50-60s for the ball type due to its greater thermal inertia.

As a consequence, the sum of the burner thermal power must be twice the necessary thermal power to be installed. In general, regenerative burners can be usefully used to increase the production in existing furnaces and or to reduce the dimensions for new furnaces.

The development of the TRGX burner in collaboration with CSM was by means of an iterative design methodology consisting of prototypes based on TSX and TRG experiences, extensive CFD modelling for optimisation of the burner design, laboratory furnace tests and industrial furnace tests.

**CFD simulations** The CFD simulations have been performed by commercial CFD code FLUENT™ and the selection of the physical models was based on previous extensive validation work to evaluate the performance of the different turbulence models for simulating high velocity round jets and combustion scheme for natural gas.

The first goal of the simulation work was to understand the effects of combustion air temperature on the fluid dynamics and the flameless combustion process inside a representative furnace (see Figure 10a). Then CFD simulation was used during the conceptual development of the new TGRX burners in order to design the air baffle, thus allowing proper dilution level of combustion air and natural gas with combustion products inside the furnace (ie, maximisation of the recirculation factor KV – see Figure 10b – in the zone near the air baffle, where natural gas is injected) and, at the same time, minimisation of air pressure losses.

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**Fig 9** TRGX regenerative flameless burners (honeycomb and ceramic ball regenerators)

**Fig 10** Example of TRGX burner simulation results
Pressure drop on the air side and uniformity of velocity field at the regenerator inlet are also crucial aspects in burner design and result in engineering constraints so CFD has been also used for optimising the design of the burner plenum, thus defining the proper position of ceramic regenerator (see Figure 11).

To check the effect of the installation of a pair of burners on a furnace wall at 1.3m distance on the same furnace wall, both single and pairs of burners have been simulated (see Figure 12). The deviation from the ideal working conditions due to the presence of the furnace wall (Coanda effect) does not significantly affect flue gas entrainment and the recirculation factor $KV$ close to the burner tip, allowing maintenance of the flameless combustion regime. The results of the simulations, in terms of the temperature field, confirms that for both installations the maximum value of the temperature (temperature peak) is significantly lower that the adiabatic flame temperature of air/CH$_4$ mixture with preheated air at 1,100°C.

The effect of the temperature increase due to the installation mode (single vs pair) on NOx emissions was evaluated using the correlation between the CFD temperature peak and experimental NOx measurements that was developed during the RFCS NOx-RF project. The NOx emissions evaluated for the two conditions (Table 3) indicate that the installation of a burner pair on the same furnace wall is a conservative condition for running characterisation tests.

**Laboratory tests** The laboratory tests on the TRGX burner were carried out on a modular furnace at the CSM combustion laboratory in Dalmine, Italy (see Figure 13). The structure is representative of a section of an industrial furnace and is a steel structure thermally insulated to resist at temperatures as high as 1,350°C. Its main characteristics are:

- Square cross section: 2 x 2m
- Adjustable length: 4 x 1.5m modules (variable total length 3, 4.5, 6, 7.5m)
- Thermal input (based on gas flow rate) up to 2.5MW
- Water cooled lances to control process temperature
- Furnace pressure control: -10mm H$_2$O to +10mm H$_2$O
- Automatic flow balancing and data storage on dedicated control system

<table>
<thead>
<tr>
<th>Burner configuration</th>
<th>ppm @ 3% O$_2$, DFG</th>
<th>mg/ Nm$^2$ @ 5% O$_2$, DFG</th>
<th>mg/ MJ</th>
<th>lbs/ MMBTU @ 3% O$_2$, DFG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>38</td>
<td>69</td>
<td>21.5</td>
<td>0.0456</td>
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<tr>
<td>Pair</td>
<td>46</td>
<td>83</td>
<td>26</td>
<td>0.0552</td>
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</table>

**Table 3 Estimated NOx emission**
Standard equipment of the furnace includes several thermocouples on the roof and walls in order to monitor temperature profiles. To directly verify the thermal load received by a steel charge on a real furnace, a cooled and insulated pipe, monitored by recorded thermocouples, is also installed. Heat density in the modular furnace can be adjusted through the initial choice of furnace length and, during the tests, by controlling fuel input and air preheat. Heat extraction is also monitored through the measurement of temperature variation and mass flow rate of cooling water. A pressure transducer is used to monitor the furnace pressure, which is controlled via an air-cooled butterfly valve at the end of the flue gas duct. Flue gases composition (O₂, CO, NOx) is measured, through a suction probe installed at the exit of the furnace (before the butterfly valve) and an analyser fed through a heated line. Two different prototypes of the TGRX burner family have been tested: 1.0MW and 1.5MW size (gas-based) with honeycomb and ball regenerator, respectively (see Figure 14).

The installation of the TRGX burners on the CSM furnace required adaption of the air and gas piping. Moreover, since a high percentage of combustion products (60-80%) are taken in directly by the burners, the furnace has been modified by closing the original connection to the stack and opening a new flue gas extraction point on the top. Thermocouples (S type) are used to measure furnace walls temperature at different locations: 5 on top walls, 2 on side walls. A honeycomb regenerator has also been equipped with 10 thermocouples (K type).

Figure 15 shows a 1.5MW TRGX burner during two different combustion operating modes: traditional flame (left) and flameless (right) with furnace temperatures of 1,150°C. The TRGX burner operates in flameless mode when the furnace temperature is over the self-ignition temperature of the fuel (about 800°C for natural gas). NOx measurements indicate that flameless combustion allows a decrease of about 60% in NOx emissions compared to traditional flame mode over the whole range of tested O₂ concentration in the furnace. CO concentration in flue gases has been found negligible in all the test conditions, confirming a very good combustion inside the furnace. Figure 16 shows NOx emissions of a 1.5MW TRGX at two operating furnace temperatures 1,150°C and 1,250°C in flameless mode.

Average NOx emissions are not affected by the burner turn-down and the effect of furnace temperature is limited (the combustion air temperature is not so different from the temperature of the recirculated gases). Results of the tests confirm that flameless combustion coupled with high temperature air preheating, typical of the regenerative burners, is one of the best technologies for a very strong reduction of both NOx and CO₂ emissions, thus matching the incoming environmental requirements of the steel industry.

**Industrial scale tests** The last step of the development cycle of the TRGX burners consisted of verifying on industrial reheating furnaces for thousands of hours the performance and the reliability of the burners working in flame and flameless modes. The tests were carried out in co-operation with Tenova customers or in the framework of European R&D projects (see Figure 17). Particular attention was paid to the monitoring of the burner components working in alternative cycles such as...
During the tests at different sites no particular problems (such as leakages or malfunctions) were reported on valves and fans. Pressure losses through the regenerators and the waste gas exit temperature were monitored, and temperature measurements were performed inside the regenerators in order to evaluate their thermal efficiency. Different values of the recirculation ratio were tested and data were collected in all the operating conditions of the burners.

After several months of working the pressure drop through the regenerator, it was stabilised around a value of 200mm H₂O and the replacement of the honeycombs allowed an inspection for structural integrity. The behaviour of the regenerator is affected by the amount of dust in flue gases. In general, no significant clogging was detected on the honeycombs. Different types of honeycomb cartridges (cold side and hot side), burners engineered with different solutions for simplifying honeycomb regenerator replacement, and different materials of the pipes (air and gas) were tested.

CONCLUSIONS

There are many well-known potential drawbacks (cost, complexity, control, impact on the product quality, emissions) which have limited widespread use of regenerative technology in reheating furnaces. The key issues are the proper choice of materials and burner internal design (air baffle and gas lances) and the control strategy and furnace design.

Tenova has obtained the relevant know-how through more than 40 years of furnace design and installation and from continuous R&D into combustion systems. Tenova FlexyTech® regenerative flameless burners combine the advantages of flameless combustion of minimising NOx emissions with high temperature combustion air preheating for important energy savings and efficient furnace heating.

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