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Application and Performance Analysis of Low-NOx Combustion Technology in Metallurgical Heating Furnaces

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Abstract

Nitrogen oxide emissions from gas-fired reheating furnaces remain a major barrier to cleaner steel rolling, yet retrofit decisions are often made without field data linking emission reduction to heating quality and fuel use. This study reports the retrofit of a 150 t/h walking-beam slab reheating furnace fired with natural gas. Its conventional nozzle-mixing burners were replaced by staged-air low-NOx burners, combined with external flue gas recirculation at 12% and an air–fuel ratio control system with oxygen trim. Two groups of 84 hourly records, collected before and after the retrofit at loads of 60% to 100%, were compared with Welch's t-tests and simple linear regression. The NOx concentration, referred to 8% oxygen, fell from 236 to 92 mg/m^3, a reduction of 61.0%, and the reduction stayed between 59% and 63% across the load range. Thermal efficiency rose from 71.6% to 74.9%, specific gas consumption fell from 38.6 to 36.9 m^3/t, and the transverse spread of slab discharge temperature decreased from 14.6 to 9.8 °C. Carbon monoxide increased from 28 to 41 mg/m^3, which is the main cost of lower excess air and diluted combustion. The results indicate that, in air-preheated gas-fired furnaces, staged combustion with moderate recirculation can lower NOx substantially without sacrificing heating quality, provided that flame stability and CO are monitored.

Keywords

Low-NOx Combustion; Reheating Furnace; Staged Combustion; Flue Gas Recirculation; Thermal Efficiency; Temperature Uniformity.

1. Introduction

Reheating furnaces bring slabs, blooms and billets to rolling temperature, typically between 1150 and 1250 °C. Their flue gas contains nitrogen oxides formed mainly through the thermal route (the extended Zeldovich mechanism) [11]; the rate of this route climbs steeply with local gas temperature with the local gas temperature and is further promoted when combustion air is preheated to recover waste heat. The preheating that saves fuel therefore pushes NOx upward, and reheating furnaces illustrate the conflict between energy efficiency and emission control particularly well[7,10].

Several technical routes have been tested to resolve this conflict. Air staging holds the primary flame fuel-rich and completes burnout downstream; in a real-scale reheating furnace, burner-level and furnace-level air staging lowered nitric oxide by about 23%. Flue gas recirculation dilutes the oxidiser with inert gas and lowers flame temperature. In a swirl burner, fuel-side and combined recirculation reduced NO by about 50%, and combined recirculation also stabilised the flame when the air was preheated[2]. In a coal-fired grate furnace, however, recirculation improved low-NOx performance only up to an optimum ratio of about 10% in the leading combustion stage, beyond which burnout deteriorated[4].Regenerative and flameless burners spread the reaction through a large volume of hot, dilute gas and can lower thermal NO substantially and even out the temperature field, but they need a furnace temperature above the autoignition point and more demanding valve and control

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hardware[8,9].Pulsed fuel-flow operation has also been examined; in a test furnace fitted with six 20 kW burners, pulsing all burners reduced NOx by up to about 77% and shortened the heating time[1].

The fuel base of the industry is changing as well. Recent simulations of slab heating with natural gas–ammonia blends[3],and of ammonia burners in regenerative heating furnaces, show that fuel-bound nitrogen and ammonia slip add new constraints. Surveys of the field stress that emission reduction and energy efficiency have to be pursued together[10].

Most of these studies rely on computational models, laboratory burners or pilot furnaces, and plant-level data that set emission reduction against temperature uniformity, stability and gas consumption are less common. This paper reports such a case. A walking-beam reheating furnace was converted to staged-air low-NOx burners with external flue gas recirculation and refined ratio control, and its performance was compared before and after the conversion.

2. Low-NOx Technology Routes and Retrofit Design

2.1 Principles and Selection

Thermal NO formation depends on local peak temperature, oxygen availability and residence time, so each practical route lowers the peak temperature, removes oxygen from the hottest region, or does both. Air staging achieves the second effect. Fuel burns first with a deficit of air, and the remaining air is injected after the flame has transferred heat to the load. It fits existing burner blocks, but a poorly sized secondary jet can lengthen the flame. Flue gas recirculation achieves the first effect by replacing part of the oxygen in the oxidiser with CO_2 and H_2O. Its limit is flame stability: too much diluent lifts the flame and raises CO. Regenerative and flameless systems combine both effects at a high degree, yet they require alternating air and flue paths and a furnace wall that stays above the autoignition temperature in every zone, which was not the case in the preheating zone of the furnace studied here.

For this reason the plant chose a combination of staged-air burners and external recirculation, retaining the existing recuperator and gas train. The decision rested on three points: the burner blocks and air ducts could be reused, the preheating zone ran well below the temperature needed for flameless operation, and the recirculation rate could be tuned during commissioning.

2.2 Case Furnace and Retrofit Scheme

The furnace is a four-zone walking-beam reheating furnace rated at 150 t/h, with preheating, first heating, second heating and soaking zones, rolling carbon and low-alloy steel slabs 230 mm thick. It burns pipeline natural gas with a net calorific value of 35.0 MJ/m³. Before the retrofit, 36 nozzle-mixing burners (18 on the upper and 18 on the lower side) were fed with air preheated to 460 °C in a metallic recuperator, and a fixed ratio setting gave a mean excess air ratio of 1.21. As Table 1 shows, the retrofit kept the capacity, fuel, slab size, discharge temperature and zone set points unchanged, and changed only the burners, the oxidiser and the ratio control.

Table 1. Main process and combustion parameters before and after the retrofit

Parameter	Before retrofit	After retrofit
Rated capacity (t/h)	150	150
Fuel and net calorific value	Natural gas, 35.0 MJ/m³	Natural gas, 35.0 MJ/m³
Slab thickness (mm)	230	230
Slab discharge temperature (°C)	1230	1230
Soaking-zone set point (°C)	1250	1250
Burners (upper/lower)	36 (18/18), nozzle-mixing	36 (18/18), staged-air low-NOx
Combustion air preheat (°C)	460	460
Secondary air share (%)	0	30
Flue gas recirculation rate (vol.% of oxidiser)	0	12
Air–fuel ratio control	Fixed ratio	Ratio with O_2/CO trim
Mean excess air ratio	1.21	1.11
Flue gas O_2, dry (vol.%)	3.6	2.1

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The new burners send 70% of the combustion air through the primary nozzle and 30% through secondary ports offset from the burner axis, so that the fuel burns first in an air-lean core. Flue gas is drawn at about 250 °C downstream of the recuperator by a variable-speed fan and mixed into the air main before the burner headers. At 12% recirculation by volume the mixed oxidiser contains about 18.6% oxygen. The control system, outlined in Figure 1, keeps the zone temperature controllers as the master loops. Their fuel demand sets the gas valve and, through the ratio station, the air and recirculation damper positions. Flue gas oxygen and CO analysers trim the ratio so that the excess air follows the load rather than a fixed value.

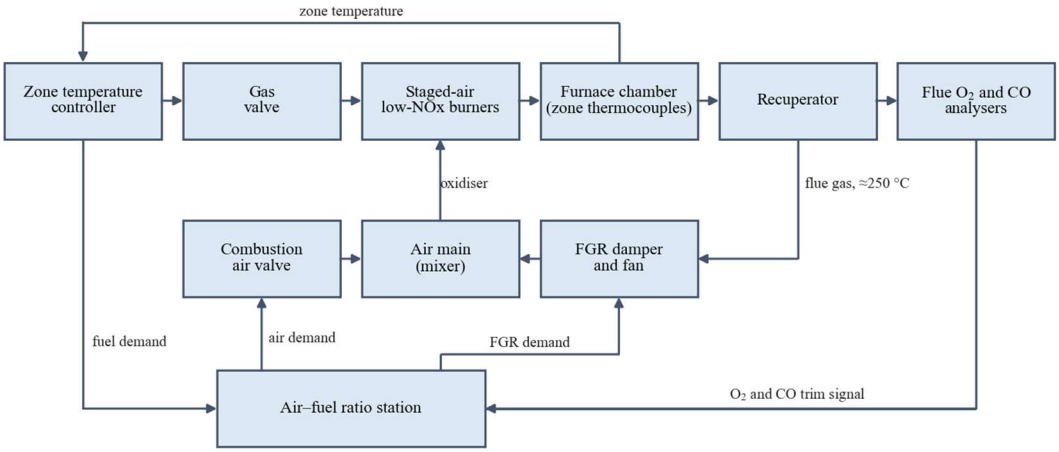


Figure 1. Control scheme of the retrofitted furnace, showing the temperature master loops, the ratio station with oxygen and CO trim, and the recirculation branch

2.3 Measurement and Data Analysis

NOx and CO were sampled with an extractive system in the flue duct downstream of the recuperator, using a chemiluminescence analyser for NOx and a non-dispersive infrared analyser for CO. The analysers were span-checked every shift. Measured concentrations C_{m} were converted to the reference oxygen content with

$$C_{\mathrm{ref}}=C_{\mathrm{m}}\,\frac{21-\varphi_{\mathrm{ref}}}{21-\varphi_{\mathrm{m}}} \tag{1}$$

where C_{ref} is the concentration at the reference oxygen content (mg/m³, dry gas at 0 °C and 101.325 kPa), φ_{m} is the measured dry-gas oxygen volume fraction (%), and φ_{ref} is the reference value, taken as 8%. The excess air ratio was obtained from the same oxygen reading by

$$\lambda=\frac{V_{\mathrm{a}}}{V_{\mathrm{a}}^{0}}\approx\frac{21}{21-\varphi_{\mathrm{m}}} \tag{2}$$

where V_{a} and V_{a}^{0} are the actual and stoichiometric air volumes. Gas flow was measured by an orifice meter and corrected to standard conditions, and the calorific value came from an on-line chromatograph. The thermal efficiency of each record was calculated on a one-tonne basis as

$$\eta=\frac{G\,\bar{c}\,(t_{\mathrm{d}}-t_{\mathrm{c}})}{V_{\mathrm{g}}\,Q_{\mathrm{net}}}\times 100\% \tag{3}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202611_12(11).0003

where G is the slab mass (1000 kg), $\bar{c}$ is the effective mean specific heat of the steel including the phase transformation (about 0.80 kJ/(kg·K)), t_d and t_c are the discharge and charging temperatures (°C), V_g is the specific gas consumption (m³/t) and Q_{net} is the net calorific value of the gas (kJ/m³). Temperature uniformity was judged from the transverse scan of slab discharge temperature at five points across the width, using

$$\sigma_T = \sqrt{\frac{1}{n_p - 1}\sum_{i=1}^{n_p}(T_i - \bar{T})^2} \tag{4}$$

where T_i is the temperature at point i, $\bar{T}$ is the mean of the n_p=5 readings, and σ_T is the spread of one scan.

The data set holds 84 hourly-averaged records from the 14 days before the shutdown and 84 from the 14 days after commissioning and tuning, giving 168 records. Records were taken during steady rolling, and they were stratified by furnace load: 12, 18, 24, 18 and 12 records at 60%, 70%, 80%, 90% and 100% of rated capacity, in both periods. Differences were tested with Welch's t-test, and NOx was regressed on load by ordinary least squares within each period.

3. Results and Analysis

3.1 Emissions and Energy Indicators

Table 2 summarises the main indicators. The retrofit lowered the NOx concentration referred to 8% oxygen from 236 to 92 mg/m³, a reduction of 61.0%. Welch's tests gave $p < 0.001$ for every indicator in the table. In commissioning at rated load, raising the recirculation rate from 6% to 12% reduced NOx by a further 24 mg/m³, whereas 16% recirculation lowered NOx by only another 7 mg/m³, while CO at the lower burners exceeded 110 mg/m³ and the flame began to pulsate. The rate of 12% was therefore adopted as the working value, in line with the observation that recirculation helps up to an optimum and then costs stability.

Table 2. Emission, energy and uniformity indicators before and after the retrofit (mean ± standard deviation, n = 84 records per period)

Indicator	Before retrofit	After retrofit	Change
NOx at 8% O_2 (mg/m³)	236 ± 31	92 ± 15	−61.0%
CO at 8% O_2 (mg/m³)	28 ± 9	41 ± 14	+46.4%
Flue gas temperature after recuperator (°C)	265 ± 8	248 ± 7	−17 °C
Thermal efficiency (%)	71.6 ± 1.4	74.9 ± 1.2	+3.3 points
Specific gas consumption (m³/t)	38.6 ± 1.1	36.9 ± 0.9	−4.4%
Spread of slab discharge temperature (°C)	14.6 ± 2.5	9.8 ± 1.6	−32.9%

The energy indicators move together. Lowering the mean excess air ratio from 1.21 to 1.11, as set out in Table 1, reduces the flue gas volume, and the flue gas temperature after the recuperator fell by 17 °C. The calculation by Eq. (3) shows thermal efficiency rising by 3.3 percentage points, which corresponds to the 4.4% fall in specific gas consumption for the same heat delivered to the steel.

3.2 Dependence on Load

NOx varied with load as Figure 2 shows. Before the retrofit, NOx rose from 198 mg/m³ at 60% load to 281 mg/m³ at 100% load. After the retrofit the values were 74 and 115 mg/m³. The percentage reduction was 62.6%, 61.9%, 61.4%, 60.5% and 59.1% at 60%, 70%, 80%, 90% and 100% load, so

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the benefit shrank slightly at high load. The fitted slope of NOx against load was 2.1 mg/m³ per percentage point before and 1.0 after (R^2 = 0.76 and 0.70).

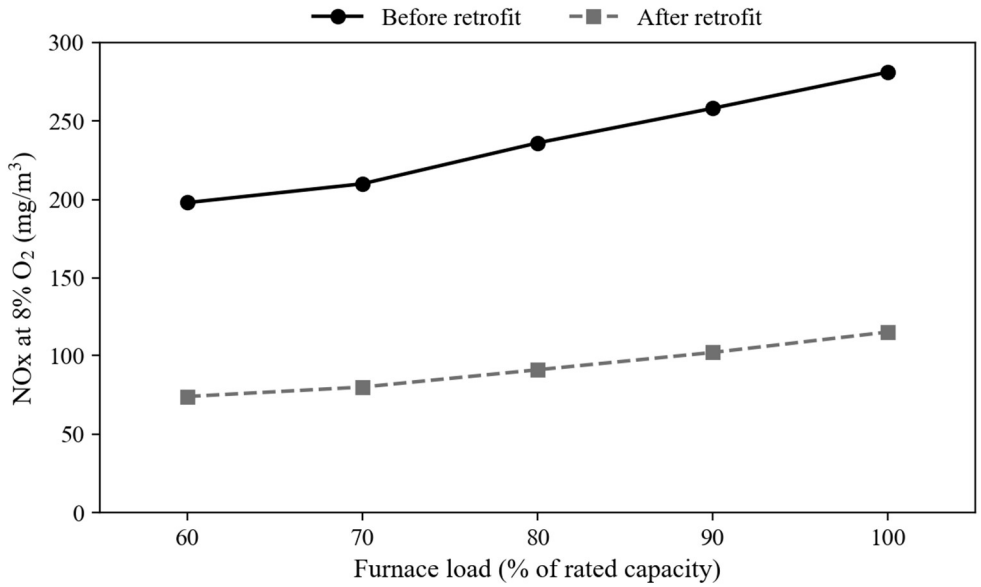


Figure 2. NOx concentration at 8% O_2 as a function of furnace load before and after the retrofit (means of 12 to 24 records per load level; standard deviations are 12–16 mg/m³ before and 6–9 mg/m³ after)

3.3 Temperature Uniformity

As Figure 3 shows, the mean transverse spread of slab discharge temperature fell from 14.6 to 9.8 °C, and the improvement held at every load level, from 12.1 to 8.4 °C at 60% load and from 17.6 to 11.7 °C at 100% load. The nozzle-mixing burners produced short, intense flames that left cooler zones between burners, whereas the staged flames are longer and cooler and spread heat release over a larger volume.

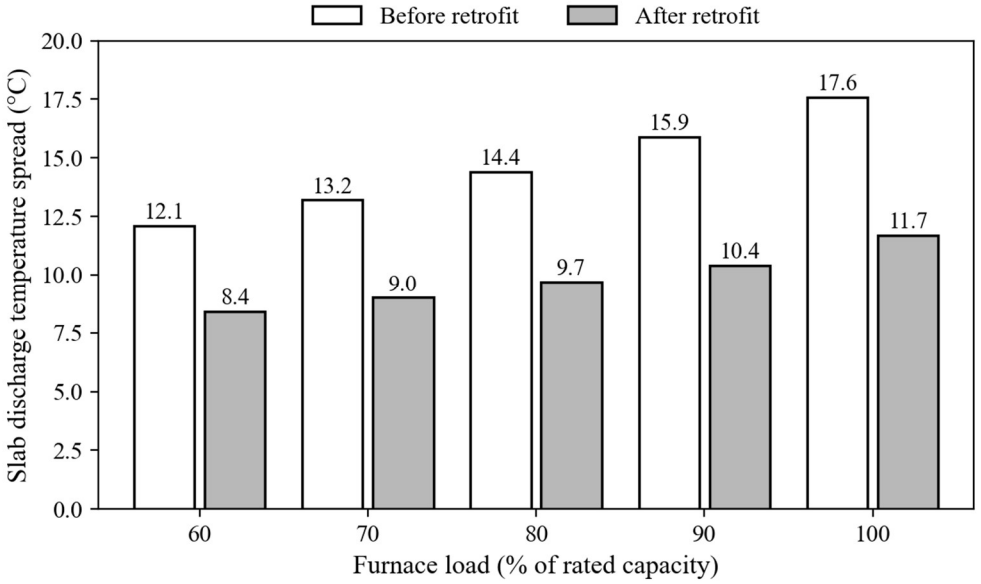


Figure 3. Spread of slab discharge temperature, σ_T from Eq. (4), at each load level before and after the retrofit (standard deviations are 1.6–2.0 °C before and 1.1–1.5 °C after)

ISSN: 2414-1895 DOI: 10.6919/ICJE.202611_12(11).0003

3.4 Combustion Stability and CO

CO was the only indicator that worsened. The mean rose from 28 to 41 mg/m³ at 8% oxygen, an increase of 46.4%, and individual hourly values reached 74 mg/m³ at 100% load. Lower excess air and an oxidiser diluted to 18.6% oxygen slow CO oxidation. No flame loss or ignition failure occurred in the 84 post-retrofit records.

4. Discussion

The case shows that the tradeoffs among NOx, uniformity, stability and energy are not equally severe. The expected conflict between low NOx and furnace performance did not appear: the cooler flame did not impair the discharge temperature and the spread narrowed. The costs showed up instead in CO and in the narrow window for recirculation. The result matches the pattern reported elsewhere: recirculation lowers NO at the price of stability, and an optimum exists beyond which gains vanish.The 12% rate found here lies above the 10% best value reported for a coal grate furnace, which may be reasonable, because a gas burner could plausibly tolerate more diluent than a fuel bed. The 61% reduction is also larger than the 23% obtained with air staging alone in a comparable reheating furnace[7], so recirculation and the better ratio control contribute substantially. It is smaller than the 77% reported for pulsed firing in a test furnace,1 but that figure comes from a small facility and a different firing pattern.

Several conditions bound the applicability of these results. First, the furnace burns clean natural gas with air preheated to 460 °C. With much hotter air from regenerative burners, the thermal route accelerates, and flameless operation, which dilutes the reaction more strongly, becomes the better choice. With ammonia blends, fuel-bound nitrogen and ammonia slip enter the picture, and the staging rules would need to be re-derived[5].Second, the benefit depends on the oxygen-trim control. Without it, the leaner operation would risk CO excursions at low load. This sensitivity to the air ratio is consistent with simulations of a radiant gas burner, where excess air governed NO formation[6]. Third, staged-air burners need enough furnace depth for the secondary air to burn out before the gas reaches the slab surface; in a shallow preheating zone the same design could cause flame impingement.

The study has limits. It covers one furnace, one fuel and 28 days of observation, so seasonal gas composition, refractory ageing and burner fouling are not represented. In addition, 92 mg/m³ at 8% oxygen is not the lowest possible value; plants facing stricter limits would have to add flameless operation or downstream denitrification.

5. Conclusion

A walking-beam reheating furnace rated at 150 t/h was retrofitted with staged-air low-NOx burners, external flue gas recirculation at 12% and an air–fuel ratio control with oxygen and CO trim, and its performance was compared over 168 hourly records before and after the change. NOx at 8% oxygen fell from 236 to 92 mg/m³ (−61.0%), with reductions of 59% to 63% at every load from 60% to 100%. At the same time, thermal efficiency rose from 71.6% to 74.9%, specific gas consumption dropped from 38.6 to 36.9 m³/t, and the spread of slab discharge temperature narrowed from 14.6 to 9.8 °C.

The price was a rise in CO from 28 to 41 mg/m³, and a narrow recirculation window: beyond about 12%, the lower burners lost stability and CO rose sharply. For gas-fired furnaces with moderately preheated air, a staged and diluted flame backed by closed-loop ratio control offers a practical retrofit that cuts emissions and fuel use together. Transfer to hotter-air or ammonia-blended operation calls for further field trials.

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