The development and application of direct fuel injection techniques for emissions reduction in high temperature furnaces.

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ABSTRACT

The direct fuel injection technique known at the authors' company as LNI (Low NO_X Injection) is described. The direct injection of oxidant and fuel into a furnace above autoignition temperature has been proven to reduce NO_X emissions in the laboratory and in numerous successful commercial applications. The progression in laboratory development and commercial installations is traced, and application of the technique to various types of commercial burners and processes is described.

The proven capability of this technique to significantly inhibit NO_X formation even in the presence of extremely high air preheat temperatures means that furnaces for high temperature processes can deliver extremely low NO_X emissions without penalties in fuel efficiency or heating capability, thereby minimizing greenhouse gas emissions such as CO and CO_2 as well.

Examples of successful applications of the technique in glass melting, steel reheating, aluminum melting and ladle preheating are cited.

INTRODUCTION

The control of pollutants from industrial combustion processes has become a requirement for many industries over the last decade. One of the most difficult tasks is that of controlling NO_X emissions in high temperature applications. High furnace temperatures create increased kinetic rates, strong re-radiation, and hotter gas exit temperatures. These factors in turn raise NO_X emissions and reduce the available heat and efficiency of the combustion process. Heat recovery devices have been added to many applications, boosting process efficiency, but further increasing NO_X emissions due to higher flame temperatures. A solution that can provide both high efficiency heating and low NO_X emissions simultaneously is essential to increasing the profitability of high temperature industries.

The Japanese government and industry were among the first to address these issues. With their shortage of fossil fuels and bulk materials, it was essential for them to operate in the most efficient manner possible. A dilute gas combustion scheme named “Fuel Direct Injection” (FDI) was developed by Tokyo Gas Company [Ref. 1, 2, and 3] in the late 1980’s to help fill this need. As the exclusive licensee of this technology, The North American Manufacturing Company has developed commercial products and extended their application to a range of industries as “Low NO_X Injection” or LNI.

LNI COMBUSTION SYSTEMS

An LNI burner operates as a nozzle mixing burner when the furnace temperature is below 1030 K. Above 1030 K, fuel is switched to one or more strategically positioned nozzles adjacent to the burner tile port. These injectors are displaced from the burner tile exit inside the furnace [Figure 1]. Fuel and oxidant streams mix thoroughly with furnace gases, becoming extremely dilute before combining in front of the burner tile. Oxygen concentrations can be reduced to below 5% in the oxidant stream. The dilute gas streams autoignite and achieve complete combustion within the furnace environment. In the flame envelope, entrained gases limit maximum in-flame combustion temperatures that generate high NO_X emissions.

All combustion takes place within the furnace, not inside the tile port, providing short high temperature residence times that further inhibit NO_X production. After combustion, the gases lose their heat through radiation and convective heat transfer to the work. These cooled gases travel throughout the furnace and are again entrained by the burner oxidant and fuel jets, sustaining the NO_X inhibiting process. Separated high velocity oxidant and gas jets can reduce the combustion system NO_X emissions by as much as 90%.

Schematic of LNI Burner

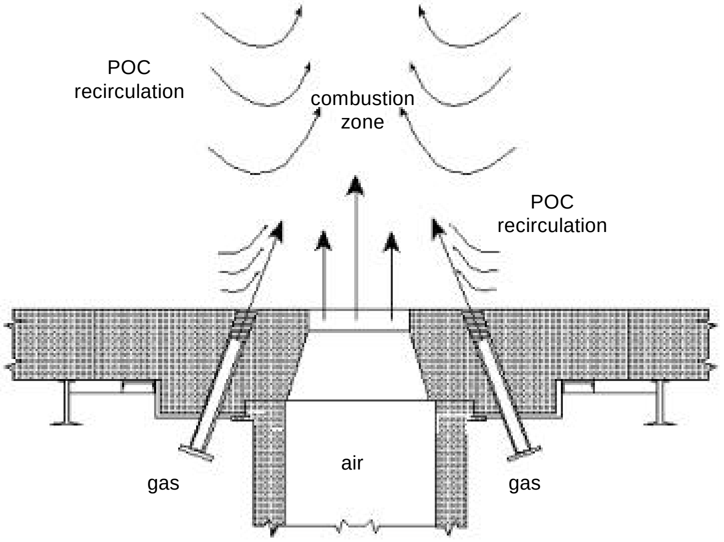

Figure 1

LNI BURNER DEVELOPMENT

Developing LNI for commercial applications requires selecting parameters of burner geometry that will provide the lowest possible NO_X and CO emissions, maintain or enhance the capability of the burner(s) to heat the furnace and load, provide safe and reliable operation of the furnace, all with minimum impact on capital and operating costs.

The parameters which affect the rate of NO_X formation and/or the combustion zone mixing and heat release patterns for LNI combustion are:

The orientation of fuel injector to oxidant injector (offset distance and angle)
Oxidant velocity leaving the oxidant injector (typically the burner tile)
Fuel stream velocity leaving the fuel injector
The number of injectors
Oxygen level in combustion products in furnace
Furnace temperature
Air preheat temperature
Furnace geometry

The first four of the above parameters are burner dependent, the last four parameters controlled by the application. Development effort focused on optimized combinations of the first four, and quantification of the effects of the last four parameters on emissions. As the parameters interact, application parameters can influence the selection of particular combinations of burner parameters.

An LNI burner is required to perform two functions. It must operate as a conventional burner, providing a flame holder and mixing of fuel and oxidant to raise the furnace temperature above autoignition to sustain LNI combustion. It generally serves as the oxidant nozzle for LNI combustion. High velocity burners are ideally suited to both functions. In conventional firing mode, high velocity burners are inherently low NO_X producers as they entrain significant amounts of “cool” furnace gases into the flame envelope prior to completing combustion of the fuel. The reduced port tile which is typical of high velocity burners provides an excellent oxidant nozzle for LNI combustion by entrainment of cool furnace gases with the oxidant stream prior to mixing with the fuel.

Our development programs to date have been devoted to commercial LNI products in the following categories:

- Forward Flame Burners
    - Regeneratively preheated combustion air, natural gas, #2 and #6 fuel oil
        - (air preheat temperatures typically from 800 to 1400 K).
    - Combustion air preheated by recuperator, natural gas fuel.
        - (air preheat temperatures typically from 360 to 920 K).
    - Ambient combustion air, natural gas fuel.
    - Oxygen enriched and pure oxygen combustion, natural gas fuel.
- Flat (swirled) Flame Burners
    - Combustion air preheated by recuperator, natural gas fuel.
        - (air preheat temperatures typically from 360 to 920 K).
    - Ambient combustion air, natural gas fuel.

Regenerative Burners

North American Mfg. Co. TwinBed™ II regenerative burners are characterized by air preheat temperatures approaching to within 100 K of furnace temperature. A typical pre-LNI regenerative installation firing natural gas into furnace temperatures in the 1480 to 1540 K range could result in NO_X emissions levels of well over 1000 ppm (corrected to 3% O_2 basis) as a result of the high air preheat level. The high potential for reductions in NO_X emissions due to these high emissions levels, combined with high furnace and combustion air temperatures made regenerative burners a natural first choice for implementation of the LNI technique.

Application of LNI to the TwinBed™ II burner results in NO_X emission levels of less than 80 ppm at the same conditions. (Where ppm is used for NO_X emissions in this paper, it is a volume concentration corrected to 3% O_2 in the products of combustion unless stated otherwise.)

The effect of the orientation of the fuel and air nozzles on NO_X emissions was investigated in extensive laboratory testing. Two parameters were determined to be significant. One is the angle between the axis of the fuel and oxidant injectors; the other is the displacement (or offset) between the centerlines of the air and fuel nozzles in the plane of the burner wall.

For the purpose of investigating the effect of varying the displacement of the fuel nozzle from the air nozzle, a dimensionless injector offset parameter l is defined as the ratio of the distance between fuel and air injector centers to the sum of the air and fuel injector radii:

$$\mathrm{l} = X \Bigg/ \left(\frac{D+d}{2}\right)$$

Where:

X = Distance between the air nozzle and fuel nozzle centers
D = Diameter of the air nozzle
d = Diameter of the fuel nozzles

Results of some those tests are illustrated by figures 2 and 3 below.

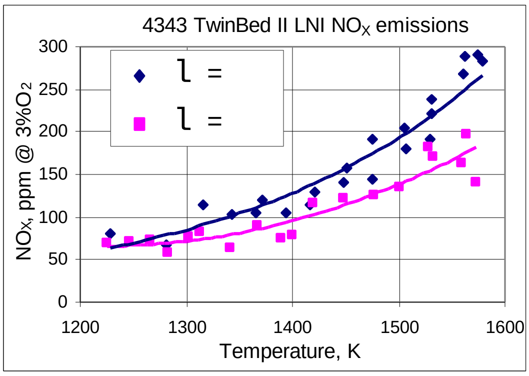

Figure 2

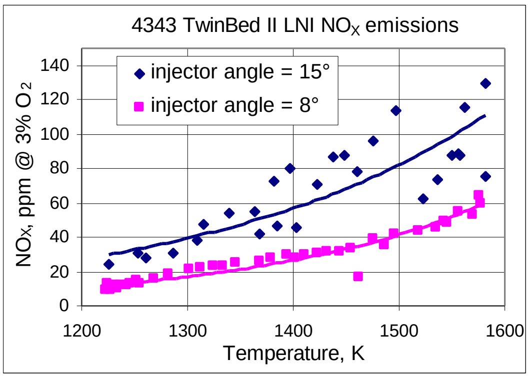

Figure 3

Recent regenerative burner development has focused on the application of the LNI technique to #2 and #6 fuel oils. A steam or compressed atomizer is used as a remotely located fuel injector for introduction of a stream of atomized fuel into the furnace.

Figure 4 shows the effectiveness of the LNI technique in reduction of NO_X emissions for oil firing, and the favorable comparison with the high reductions obtained on gas firing.

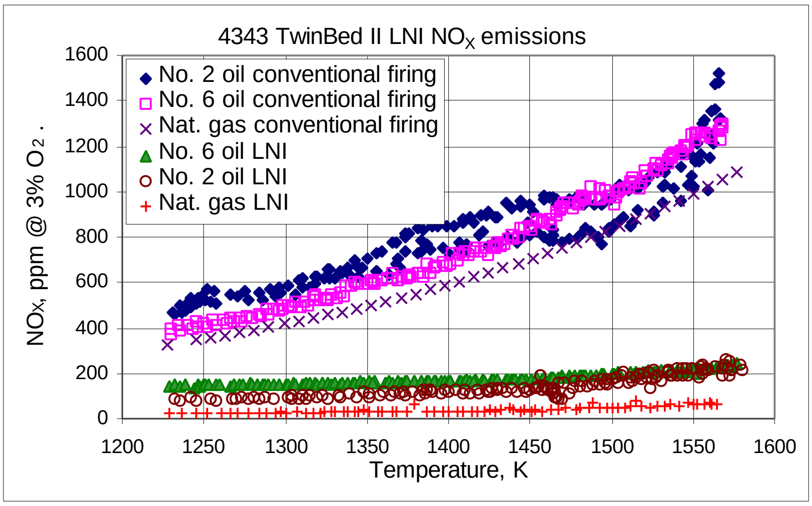

Figure 4

Recuperated Combustion Air

With the effectiveness of the LNI technique in reducing NO_X emissions from regenerative burners proven in both laboratory tests and commercial installations, the next step was to apply it to burners using recuperatively preheated combustion air.

The development platform for low to moderate air preheat burners was a high velocity version of a proven 920 K air capable burner with capacity range up to 12 MW. A similar philosophy to that used for regenerative burners was followed in the investigation process, with the addition of investigation of the effects of varying the air preheat on the LNI performance.

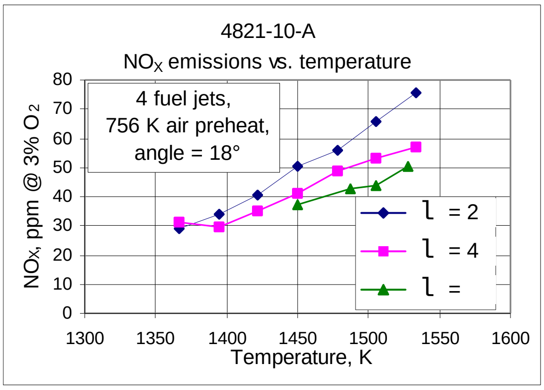

Figure 5

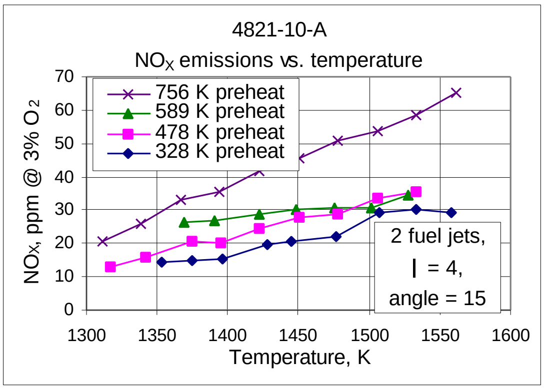

Figure 6

As can be seen from Figure 7, LNI results in a dramatic reduction in furnace NO_X emissions, from 290 ppm for a conventional burner firing into a 1530 K furnace with 760 K preheat temperature, to 66 ppm for the LNI burner firing at the same conditions.

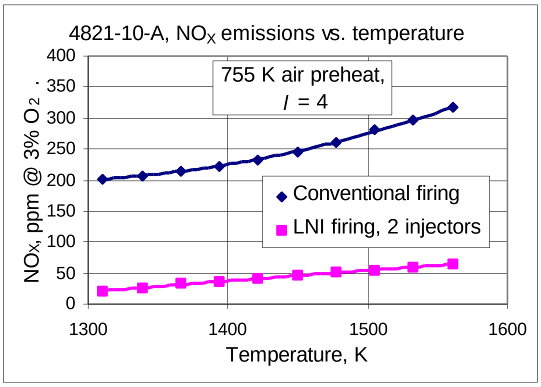

Figure 7

Ambient Combustion Air

NO_X emissions in high temperature furnaces fired with burners using ambient temperature combustion air are generally much lower than for preheated combustion air applications. However, successes achieved by manufacturers of combustion equipment in reducing NO_X emissions have been accompanied by a steady ratcheting downward of emissions levels required by regulators in many parts of the world. The result has been that even burners and processes that have been considered “Low NO_X” are not always capable of meeting the latest requirements. The success of LNI in meeting the requirements for preheated air applications led to its application on ambient air burners as well.

The 4575 HiRam™ burner is a proven conventional high velocity low NO_X burner with capacities up to 5.3 MW, making it an obvious choice as the development platform for an LNI ambient air burner. Since the NO_X emissions for this burner were already fairly low (50 ppm in a 1370 K furnace), an extensive development program was defined to achieve the maximum possible reductions in NO_X emissions. The variables of injector offset, angle between air and fuel injectors, air velocity, fuel velocity, and number of fuel injectors were evaluated with the following objectives:

Determine a configuration of burner and injector parameters to achieve the lowest NO_X emissions with suitable combustion characteristics.

Quantify the effect of the application-related parameters on NO_X emissions.

Quantify the effect of deviations from the optimum configuration to facilitate flexibility in application, particularly physically constrained retrofits.

Air and fuel injector orientation. The effects of offset distance and relative angle between fuel and air injectors are interdependent. Intuitively, either decreasing the angle between injector axis (i.e. approaching parallel) or increasing the injector offset distance will have the same effect: greater distance between the injector nozzles and the point that fuel and air streams begin to mix, providing increased dilution and hence lower NO_X emissions. Our results from testing of LNI with ambient combustion air support the intuitive conclusion to a degree.

With respect to the offset parameter l defined previously, offsets corresponding to l = 4 combined with angles of 5° produced unacceptable combustion results (stingers from furnace openings, swirling clouds of luminous combustion gases, and generally poor mixing) as did larger offsets with angles of 20° between air and fuel injectors. Comparison of NO_X vs. temperature curves for various combinations of l and injector angle are shown in Figures 8 and 9.

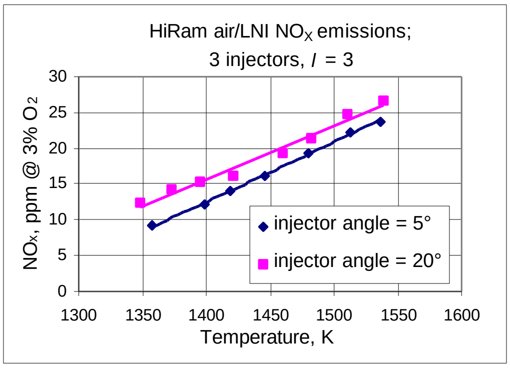

Figure 8

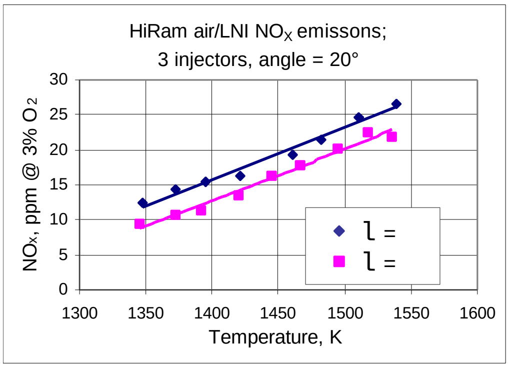

Figure 9

Air velocity. As Fig. 10 shows, it was found that air velocity had a significant effect on NO_X emissions at velocities from 12 to 40 m/s. Increasing from 40 to 85 m/s resulted in only a slight improvement in NO_X emissions.

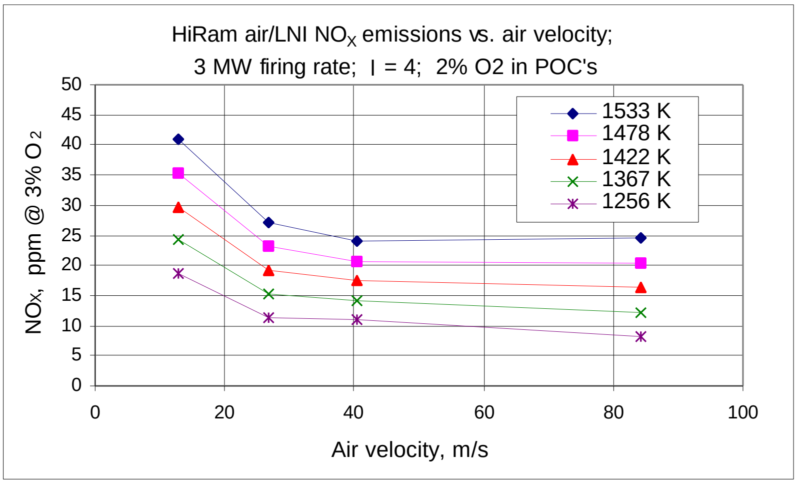

Figure 10

Fuel velocity. Fuel velocities were varied from 70 to 230 m/s. There appeared to be a small improvement in NO_X emissions as velocity increased. Velocities below 90 m/s often resulted in poor flame appearance and furnace pressure pulsation, and occasionally in higher CO emissions from the furnace. Fig. 11 shows a typical comparison of NO_X emissions for varying fuel velocity.

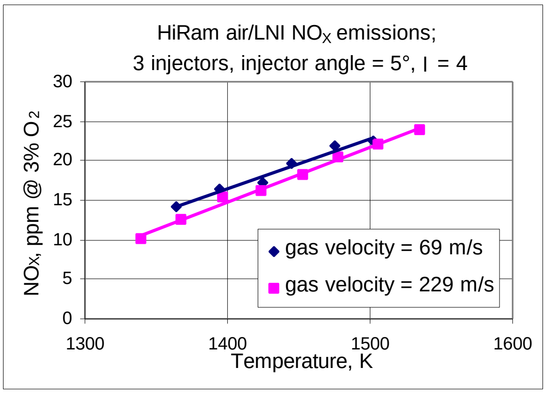

Figure 11

Number of injectors. Work to date regarding optimum number of fuel injectors is inconclusive. Some configurations performed as well or better with one injector as with three. Others appeared to be slightly better with three injectors.

Results of our laboratory testing of LNI with the HiRam™ burner conclusively demonstrate that NO_X emissions can be dramatically reduced by application of LNI method to burners fired with natural gas and ambient air. Fig. 12 shows a comparison of NO_X emissions for an LNI burner compared with a conventional low NO_X burner firing into the same furnace. The NO_X emissions at 1367 K were 14 ppm for the LNI burner, compared with 50 ppm for the same burner fired in conventional mode. The LNI technique reduced NO_X emissions from the HiRam™ burner (which already met requirements for a "Low NO_X Burner" in many areas) by a factor of three.

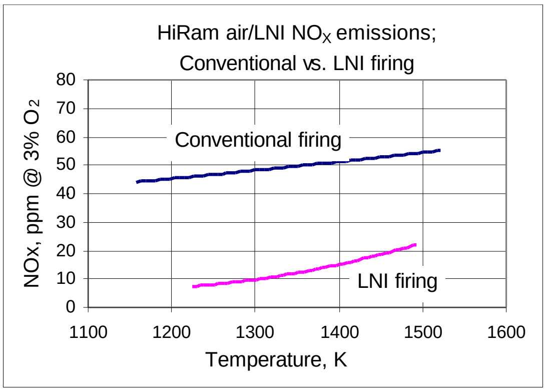

Figure 12

Oxy-fuel burners

The LNI burner resulting from the ambient air work previously described has been augmented with the addition of oxygen capability to allow either mixed air/oxygen or 100% oxygen firing capability. Several configurations have been developed:

oxygen nozzle concentric with air nozzle and external fuel injectors,
both oxygen injector(s) and fuel injector(s) external to the central air nozzle,
fuel nozzle concentric with air nozzle and external oxygen injectors.

The magnitude of NO_X emissions reductions achieved with the various configurations is similar enough that the selection of one configuration over another is more likely to be based on application requirements than on NO_X emissions.

Results of parameter evaluations similar to those described for the previous investigations are shown for the first configuration in Figures 13 and 14, in which can be seen the effects of injector offset (*l*), and number of injectors. Significant differences in NO_X emissions levels are attributable to variation in both the number of injectors and in the injector offset.

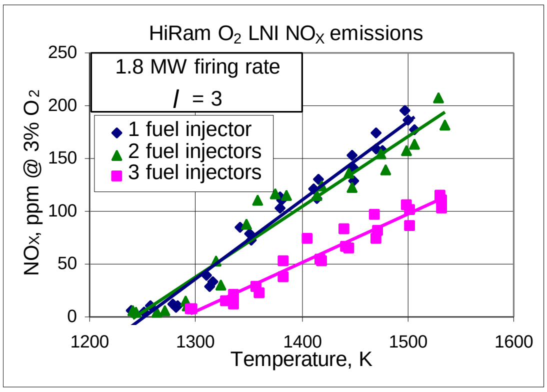

Figure 13

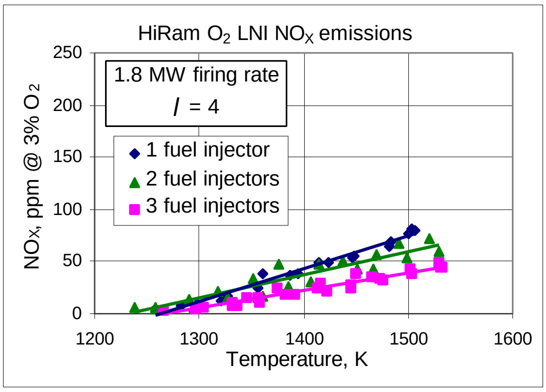

Figure 14

Figure 15 shows the dramatic difference in NO_X emissions for the HiRam Oxy-LNI burner firing in conventional mode vs. LNI mode, both with 100% of the oxidant from oxygen.

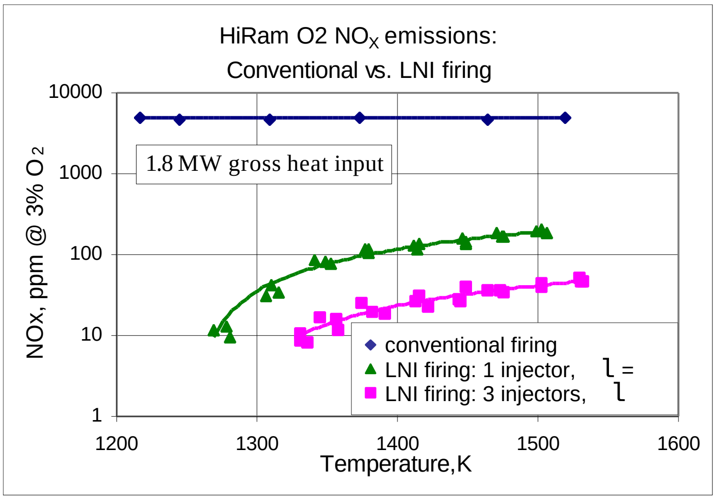

Figure 15

Flat Flame Burners

All the of the burners discussed previously were either developed directly from high velocity burner platforms, or were characterized by high forward momentum, and the LNI versions of the burners generally had heat release characteristics similar to the burner platforms that they were developed from. However, there are a great many applications which require an entirely different type of flame, characterized by a highly swirled flat profile, with resultant rotational, as opposed to forward, momentum. For such burners, the primary recirculation zone is located centered on the burner axis, close to the center of the air nozzle exit, rather than surrounding the nozzle perimeter. Application of

LNI to such burners must be done differently than for high velocity burners whose recirculation mode is one of jet entrainment.

Laboratory testing has demonstrated that similar reductions in NO_X emissions can be obtained from application of LNI to flat flame (highly swirled) burners as are achieved for forward momentum high velocity burners, provided that the geometry of the fuel injectors is designed to be compatible with the natural burner recirculation pattern. This has been achieved by locating the fuel injector on the burner axis, near the air nozzle exit, and injecting the fuel radially into the swirling air stream [Ref. 4].

Figure 16 below shows a typical burner cross-section, including the fuel injector. Figure 17 shows the NO_X emissions compared for LNI and conventional firing, for both ambient and preheated combustion air. The reduction in NO_X emissions with LNI is very similar to that described above for the high velocity burner platforms.

Beta testing has confirmed that laboratory NO_X emissions are achievable in field installations, and allowed evaluation of different injector materials and constructions, to ensure that injectors can survive in real world operating conditions. Start-up of the first commercial installation is scheduled for early in the year 2000.

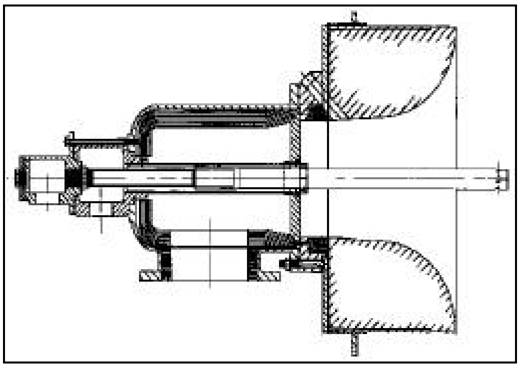

Figure 16

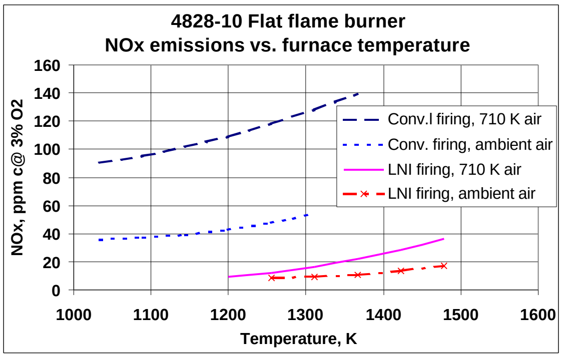

Figure 17

EXPERIENCE WITH PRACTICAL APPLICATIONS OF THE LNI TECHNIQUE

To date there are more than 60 commercial installations in operation in the US and Europe with more than 300 burners in total. Regenerative burner fired furnaces dominate the installed base in aluminum melting and steel reheating. Two regenerative LNI aluminum melting installations will be reported here. Also covered are a conventional recuperative hot air fired steel reheat furnace where the existing burners were converted to the LNI technique, a ladle preheat installation where burners using oxygen enrichment were replaced with Oxy—LNI burners, and a fiberglass melting furnace where conventional hot air burners were replaced with LNI burners.

Fiberglass Furnace, Bakersfield, California

The subject furnace is a 30 t/day E glass melter, 2.4 m wide, 7.9 m long, 1.02 m glass line to crown, with 10 burners per side, firing directly opposed into a nominal 1800 K chamber. With combustion air at an average 830 K, the burners are fed with natural gas at an individual maximum rate of 202 kW, for a maximum input of 4.0 MW.

The burners used in this installation are conventional refractory-lined nozzle mix burners fitted with reduced port tiles to provide the appropriate hot air velocity as previously described. One water-cooled injector is mounted directly below each burner. Figure 18 shows this arrangement.

The furnace was started in June 1996, and was emissions-compliance tested in the following September after a debugging period. During that time various gas nozzle exit sizes were tested as the velocity provided by the initial choice entrained sufficient tank atmosphere to cause condensation of volatiles on the cool nozzle surface and led to blocking of the nozzle. Reduction of the gas velocity by a factor of 4 from the original design eliminated this problem without significant effect on the NO_X emissions.

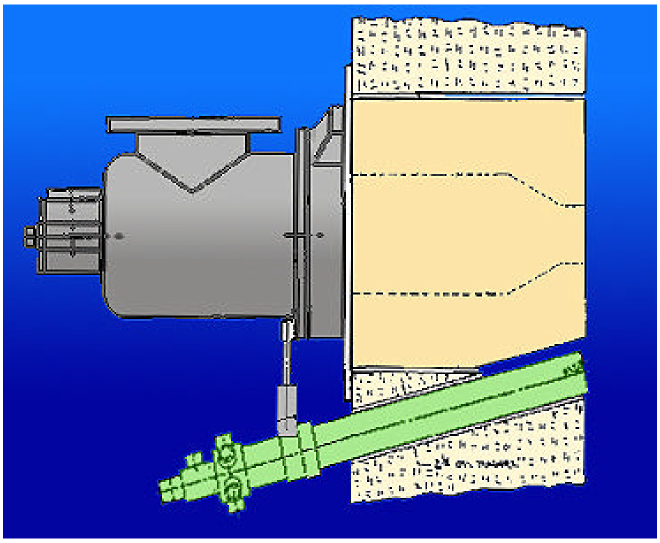

Figure 18

Our testing during this process yielded the following typical figures:

Furnace Temperature	Air Preheat Temperature	O2	NOx corrected to 3% O2	CO corrected to 3% O2
K	K	%	ppmv	ppmv
1756	917	3.3	145	25

Table 1

NO_X recorded in the State emissions compliance test was lower - 91 ppm.

Steel Reheat Furnace, New York State

This three zone, natural gas fired pusher furnace was converted to LNI firing using the original hot air burners. Conventional parallel tiles were replaced with converging to increase the air velocity, and one external gas injector was added to each burner.

The furnace is a 4.6 m wide longitudinally fired configuration with 14.6 m long, 2.3 m high under and over-fired heat zones and a 8.5 m long overfired soak zone.

Zone	Burner Quantity	Nominal Capacity with 672 K air at 1.5 kPa
Top Heat	4	3.9 MW each
Bottom Heat	3	5.3 MW each
Soak	5	0.77 MW each

Table 2

With a maximum heat input capacity of 35 MW and zone set points of 1533 K, the furnace has a nominal production output of 80 t/h of 0.140 m square billets to 1480 K.

Pre- and post-conversion furnace temperatures and emissions were recorded for this installation and are shown in Tables 3 and 4. Of note are (a) the reduction in the soak zone temperature for higher average billet discharge temperature, (b) the sensitivity of NO_X and CO to the furnace O2 content.

Target NO_X emissions for this conversion were 116 ppm - actual result for the State compliance test was 41 ppm.

Furnace Temperature Profile						
	Soak Zone	Soak Zone	Top Heat Zone	Top Heat Zone	Bottom Heat Zone	Bottom Heat Zone
	Pre-LNI	Post-LNI	Pre-LNI	Post-LNI	Pre-LNI	Post-LNI
Temp. Set Point, K	1533	1519	1533	1533	1533	1533
Firing Rate %	40	40		36	95	73
Zone Temp K	1543	1527	1541	1532	1544	1538
Air Preheat K	561-589	550-572	561-567	550-572	561-589	550-572
Av. Billet Temp K	1456	1474				
Refractory Temp K						
Burner Wall	1494-1517	1489-1517	1511-1522	1522-1533		
Side Wall					1539-1544	1556-1561

Table 3

Emissions corrected to 3% O2			
	O2	NOx	CO
Pre-LNI	3.80%	224 ppmv	1 ppmv
Post-LNI	1.20%	46 ppmv	728 ppmv
Post-LNI	1.50%	73 ppmv	4 ppmv
Post-LNI	1.80%	90 ppmv	3 ppmv

Table 4

The significant increase in billet temperature accompanied by a slight reduction in soak zone temperature noted above is noteworthy because it provides quantitative evidence in a commercial installation that LNI combustion may indeed enhance furnace efficiency and productivity. Prior to the earliest commercial applications of LNI technology, there was some question whether a reduction in flame luminosity, which often accompanies LNI combustion, would result in loss of production due to reduced heat transfer from flame to load. Qualitative experience from those early installations suggested that in fact the opposite was true. Comparison of temperature profiles between conventional and LNI burner flames in our laboratory furnaces also suggested that LNI flames transferred their heat to the furnace walls more efficiently, but in the absence of direct measurement of the heat fluxes, did not conclusively prove it. Most recently, in addition to the measurements noted above for this commercial installation, laboratory studies have been done in which furnace heat flux measurements were made for combustion using direct fuel injection techniques. One such is reported by R. Weber et. al., in the September, '99 issue of the Journal of the Institute of Energy [Ref. 5]. The high values of heat fluxes recorded in that study caused the authors to suggest that direct fuel injection increases furnace heat transfer and efficiency, even though measured furnace temperatures seem to be lower than for comparable conventionally fired furnaces.

Ladle Preheat Station, Midwestern U. S. A.

Each of two horizontally fired preheat stations for 70 ton ladles at a steel mini mill originally had been heated to setpoint temperature (1340 or 1395 K) by a single natural gas burner designed to use air enriched with pure oxygen, with a maximum rate of 2.1 MW. The combined oxygen-air stream was 45% oxygen. The oxygen enrichment allowed the ladles to reach setpoint more quickly and at a lower firing rate than would be possible with conventional burners. The NO_X emissions were very high, peaking at almost 5 kg/h from a single station.

Such high NO_X emissions levels are common with most commercial burners using oxygen or oxygen-enriched air, because the high flame temperatures resulting from oxygen enriched combustion promote the formation of thermal NO_X. Even when air can be completely eliminated from the furnace (never the case with ladle preheating), sufficient nitrogen exists in most natural gas to cause very high NO_X emissions; of course the problem is even worse when using oxygen-enriched air.

The original oxygen--air burners were replaced with HiRam Oxy--LNI high velocity burners. Each burner is fitted with a single outboard fuel injector and a single outboard oxygen injector. The arrangement of the ladle cover with burners, injectors, and fuel and oxygen trains may be seen in Figure 19. As configured for this application, the burner fires on 100% oxygen up to a maximum rate of 2.1 MW with oxygen and fuel through the respective injectors, or with 100% ambient air and fuel through the burner gas connection up to a capacity of 1 MW.

The new burners were commissioned in January, 1998. Emissions tests were performed in February, 1998; the results from tests on one of the units are shown in Figure 20. Note that emissions are reported in g/MJ input (based on HHV), and in kg/h, rather than in ppm corrected to 3% O_2 in the products of combustion as is done elsewhere in this paper[1].

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[1] Our experience testing these units demonstrates some of the idiosyncrasies associated with testing and reporting NO_X emissions for oxygen or air and oxygen combustion systems. Care must especially be taken when comparing emissions for systems or tests where the amount of oxygen enrichment varies from one system or test to another. For example consider two systems, both firing at 1 MW; the first uses ambient air as the only oxidant, the second uses pure oxygen as the oxidant. If the NO_X emissions measured for each unit are 500 ppm, corrected to 3% O_2, the unit firing on air will release about 1 kg/h of NO_X into the atmosphere. The second unit will release about 0.1 kg/h of NO_X into the air. This is because the concentration of NO_X measured in the exhaust is heavily diluted by the nitrogen in the combustion air of the first unit.

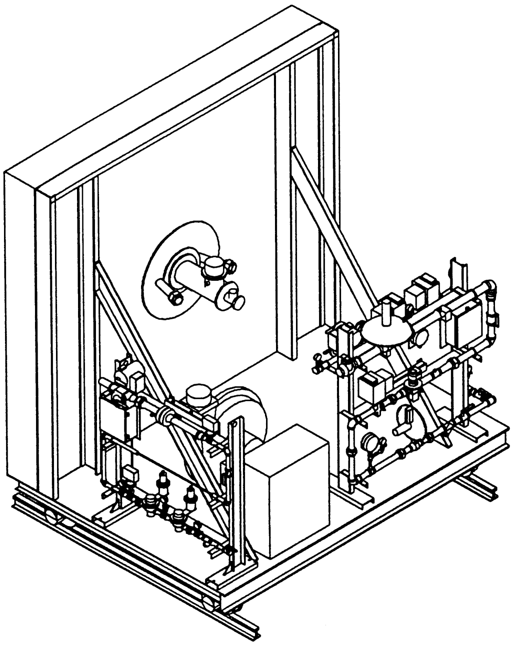

Figure 19

As can be seen from Figure 20, the NO_X emissions for the LNI system were much lower than for the combination oxygen air system which was replaced. All of the columns except the first represent operation on cryogenic oxygen of very high purity. Test # 1 was done using oxygen from an atmospheric generator, which was only about 94% pure (balance nitrogen). Test # 2 was performed on the burner without adjusting the fuel / oxygen ratio for the pure oxygen; the excess of oxygen in the combustion products resulted in higher NO_X. Test # 3 shows that reducing the fuel / oxygen ratio to compensate for the higher oxygen purity resulted in a corresponding reduction in NO_X emissions. Tests # 5 and # 6 were conducted with the gap between the ladle lip and cover loosely plugged with mineral wool insulation over the bottom half of the ladle circumference. They demonstrate the low emissions levels achievable when infiltrated air can be eliminated from the base of the combustion region.

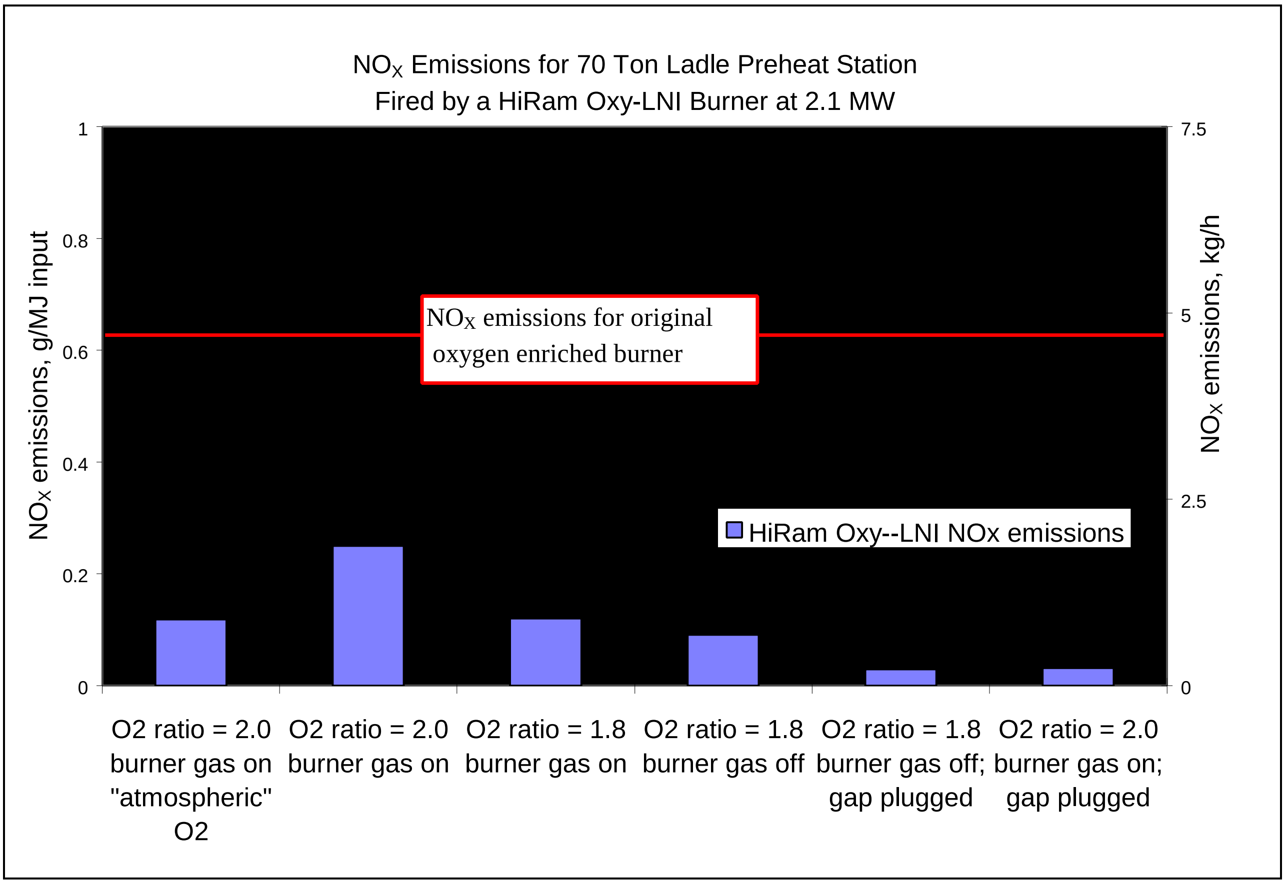

Figure 20

Well Charged Aluminum Melter, Los Angeles Area, California

This furnace was converted from conventional cold air burners to TwinBed™ II regenerative burners with LNI technology with the aim of reducing the specific fuel consumption and providing the low emissions mandated by the SCAQMD for the Los Angeles area.

Originally fired with 12 MW through 3 high velocity burners, the new installation comprised one pair of TwinBed™ II regenerative burners, each with 2 LNI gas injectors, with an input capacity of 8.8 cold, 7.3 MW hot. The as-installed arrangement is shown in Figure 21.

Operating roof temperature set point is 1408 K, bath set point 1006 K.

Target melt rate is 5670 kg/h with a charge of 70% continuously fed used beverage cans, 30% sow and coil.

Target specific fuel consumption was 2.44 kJ/g aluminum, and NO_X emissions of 58 ppm. The required average air preheat level for the regenerative burners in this installation would be above 1140 K in order to attain the desired melt rate and commensurate fuel input rate.

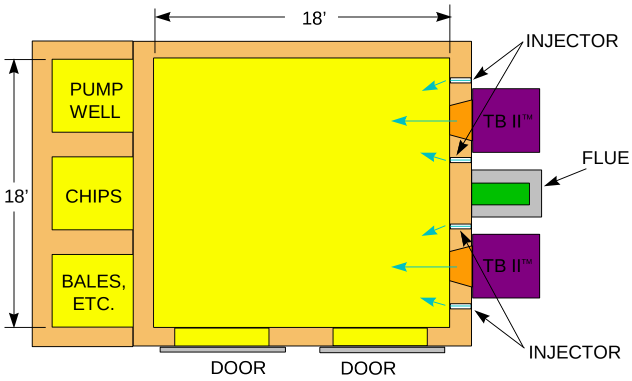

Figure 21

During commissioning it was determined that combustion product flows within the furnace were substantially disturbed by the influence of the two deep side door vestibules - disturbed to the point that air/gas mixing on the door side was poor, giving rise to formation of unacceptable CO levels. It was thus necessary to experiment with injector nozzle locations and jet configurations to effect a cure. The final configuration is shown in Figure 22 - one injector only for each burner, each with a bifurcated jet nozzle. Our experience with this installation demonstrated the flexibility of the LNI technique.

NO_X and specific fuel consumption targets were both met with this arrangement, and a successful compliance test completed.

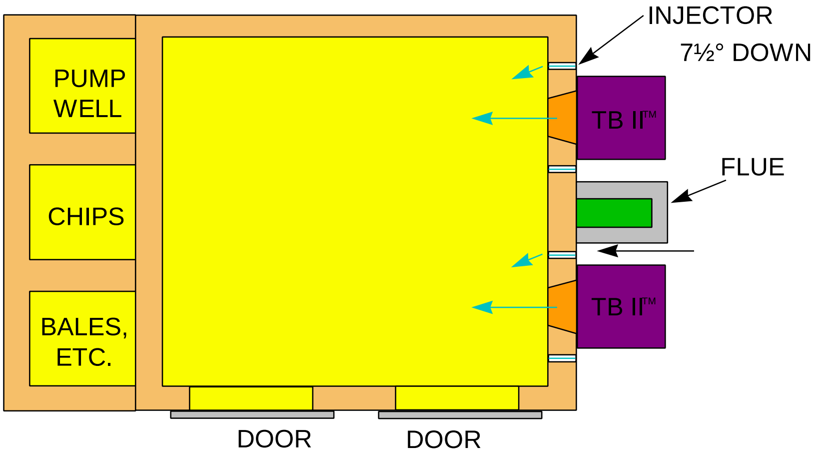

Figure 22

Direct Charged Aluminum Melter, Norway

The furnace is a rectangular, tilting, 30 ton capacity, 10 ton/h melt rate, unit charged with 70% extrusion scrap, 30 % ingot, having dimensions of 7.6 m wide, 5.2 m deep, and 2.4 m high, and is shown in Figure 23.

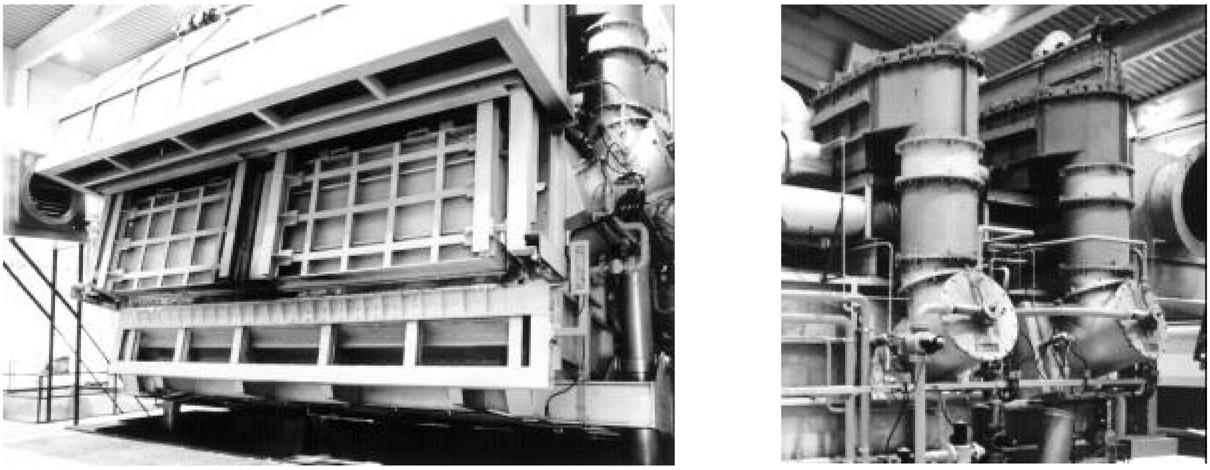

Figure 23

It is fired with 2 pairs of regenerative burners, one pair mounted on each 5.2 m' wall, with burners angled downwards to the bath surface at 15°. Each burner is fitted with two propane injectors for a capacity of 3.8 MW per burner pair hot.

The nominal furnace operating temperature is 1200 K and the specified NO_X target was a generous 225 ppm. Actually achieved NO_X is 55 ppm, with 51 ppm CO.

Our furnace OEM customer provided us with some interesting comparative data from 3 similar furnaces, one cold air, one low-NO_X recuperative (with 670 K preheated combustion air), and the subject LNI regenerative furnace (average. 1030 K preheated combustion air), which is quoted below (units converted) [Ref. 6]:

> *"A summary of average values measured under about the same conditions, is stated below:*

Combustion	T flue gas K	NOx (ppmv @ 3%O2)	CO (ppmv @ 3%O2)
Ambient	1183	66	401
Recuperative	1172	143	401
Regenerative	1189	55	51

> *From this table it can be concluded that furnaces equipped with regenerative air burners produce the lowest levels of NO_X and that ambient air burners produce about the same level.*

However, the energy efficiency of the ambient air burners is low. To compensate for this, the NO_X emission is related to the energy necessary to melt one ton of aluminum. The results can be seen in the table below:

Combustion	Energy consumption, MJ/kg aluminum	NOx emissions ppmv @ 3% O2 (g/MJ)	NOx, g NOx/kg Al melted
Ambient	3.04	66 (0.034)	0.1
Recuperative	2.43	143 (0.074)	0.18
Regenerative	1.94	55 (0.029)	0.055

The regenerative burner system produces the least amount of NO_X per ton of molten aluminum".

SUMMARY

Development work and application successes have demonstrated the power and versatility of the dilute gas combustion LNI technique in reduction of NO_X emissions in high performance combustion systems without sacrifice of efficiency or heating capability of the furnace.

Optimization of LNI burner parameters has been aggressively followed in conjunction with development of a substantial understanding of the application parameters required to match LNI in-furnace combustion with the fired process.

The LNI technique has been evaluated for several combinations of fuels and oxidant-supply conditions.

It has shown to be a powerful NO_X inhibitor with all commonly used practical industrial choices.

For regenerative burners, where high air preheat capability offers low fuel consumption, LNI offers striking NO_X emission reduction - to the point that such burners are most likely to offer the lowest mass emissions per unit of production of any combustion system type - ambient air, recuperative, or regenerative - in many high production processes.

Application of the technique to liquid fuels significantly broadens the available high-performance system options for their users.

Extension of LNI to oxygen and air/oxygen burners also provides high levels of emissions reduction.

Further evidence of the LNI's versatility is provided by its adaptation for highly swirled flat flame burners.

We believe LNI to be the most powerful NO_X-inhibiting technology available today for high-temperature process furnaces.

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