Industrial Gases/Energy

High Velocity Burner Development For Low NOx Formation

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New furnace technologies utilizing high velocity/momentum flames are very popular instruments in industrial applications due to the intensive flue gas recirculation around the load created by using burners with high momentum flames. This leads to increased heat transfer, thermal efficiency, and improved temperature uniformity in the furnace chamber. This article describes a high velocity burner, developed by Eclipse Combustion, Inc., that employs the momentum flame technology to meet tough industry needs and environmental regulations.

Regulations recently proposed by the U.S. Environmental Protection Agency have caused the thermal processing industry to take a much closer look at emissions generated from a variety of thermal processes.[1] The emission of nitric oxide (NO) and nitrogen dioxide (NO_2), two of the gaseous oxides of nitrogen (known together as NOx), is being addressed by many industrial burner manufacturers.[2] NOx is produced in combustion from molecular atmospheric nitrogen (thermal and prompt NO), or from fuel nitrogen (fuel NO). Natural gas and other hydrocarbon based gaseous fuels contain negligible amounts of the fuel-bonded nitrogen to form fuel NO. Therefore, just thermal and prompt NO formation are inherent from combustion of these fuels.

Thermal NOx formation occurs based on the extended Zeldovich mechanism[3]

$$\begin{aligned} N_2 + O &\leftrightarrow NO + N \\ N + O_2 &\leftrightarrow NO + O \\ NO + 1/2O_2 &\leftrightarrow NO_2 \end{aligned}$$

with "rich" combustion (OH >> H and O):

$$N + OH \leftrightarrow NO + H.$$

Thermal NOx formation is directly related to peak flame temperature, residence time in the high temperature zone, and the local stoichiometric condition of the air/fuel mixing.

Prompt NO occurs from reactions of CH radicals with atmospheric N_2 in fuel "rich" zones with respectively low temperatures near the flame zone. The fuel molecules can be cracked easily into a number of forms as CH, CH_2, C_2, C_2H, C, etc., in these zones. The major contributor is CH and CH_2:[4,5]

$$\begin{aligned} CH + N_2 &\leftrightarrow HCN + N \\ CH_2 + N_2 &\leftrightarrow HCN + NH \\ HCN + O_2 &\leftrightarrow NO + \ldots \end{aligned}$$

Lean combustion (excess air condition) forms less prompt NO amount, and hence, the leaner the flame, the less prompt NO formation. There is also less prompt NO formation with faster mixing (rapid combustion) due to the reduced time available for cracking of the fuel molecules.

Intense fuel/air mixing creates intimate contact between oxygen and fuel molecules with fuel starved regions minimized. This increases the flame temperature which results in higher NOx emission. A reduction in peak flame temperature will result in lower NOx emission.

There are several approaches to reduce the peak flame temperature and NOx output level:

- **Rich combustion (under-stoichiometric condition):** the combustion air provided to the flame creates oxygen starved zones, which lower peak flame temperature and associated high NOx level. Additionally, NOx emission reduced due to the lack of oxygen in the chemical reaction zone.
- **Lean combustion (overstoichiometric condition):** the combustion air provided to the flame forms the flame which is ballast by excess oxygen and nitrogen. The more excess air, the more heat wasted to preheat that excess air; hence less flame temperature and NOx emission level.
- **Staged gas/air mixing (staged combustion):** the combination of two approaches mentioned above is the basis for the staged combustion method. If combustion air is staged, there are gradually decreasing rich combustion zones along the direction of staging. If the gas is staged, there are gradually decreasing lean combustion zones in the direction of staging. In this manner, gradually rich/lean combustion zones mean progressive transition from more rich/lean zone to less rich/lean zone and finally to the combustion zone of chemical reaction completion.
- **Flue gas recirculation in the furnace chamber:** the higher the initial momentum of the flame, the higher flue gas recirculation inside the chamber, and hence, a larger amount of flue gases return back into the flame envelope. Recirculating flue gases contain less oxygen than combustion air as well

as a lower temperature than the flame envelope. Hence, recirculating flue gases keep the flame temperature down, reducing NOx emission.

- **Luminous flame and surface combustion:** both luminous flame and surface combustion create the regime when the combustion zone is quenched by the intense radiant flux which goes out from the flame envelope or radiant surface (for example, porous surface). As a result, the flame temperature is reduced and, hence, thermal NOx emission declines, as well.

Burner Concept and Design

A high velocity burner, known as *Thermjet*, has been developed utilizing the staged air mixing approach. Lack of oxygen in the combustion zones leads to a reduction of flame temperature and incomplete combustion products which together depress the NOx emission. Outside the burner, the high momentum flame jet entrains respectively cold combustion products in such a way that further reduces the flame temperature and NOx emission.

The burner consists of the metal housing, rear cover with openings for UV/flame rod and peepsight, combustor (alloy firing tube, ceramic block, or silicon carbide tube), nozzle for air/fuel mixing, air and fuel inlet blocks with measuring orifices (Fig. 1).

The visible flame structure is a highly turbulent and forms very focused jet. Combustion of heavier fuels results in a more saturated color of the flame. The total length of the high momentum jet is approximately three times longer than the visible flame envelope, which positively influences the movement of the furnace atmosphere around the load. Pulse combustion, as an option of the high velocity jet operation, forms in even higher degree of turbulence in the furnace atmosphere improving heat transfer to the load, hence increasing the thermal efficiency and potentially, raising the furnace capacity.

Burner Principles of Operation

Fig. 2 shows the zone of stable burner operation between two control regimes curves. The first curve represents fixed air control is a fixed air control, when the burner operates with 1:50 capacity turndown at fixed an air flow rate. This high degree of turndown (1:50) applies when the burner is operating at a rate of 15% excess ($\alpha = 1.15$) above the stoichiometric air level delivered for combustion at maximum burner capacity. The second curve represents "on-ratio" control, where a ratio regulator maintains the steady air-to-gas ratio within 1:10 turndown range.

With the burner operating at maximum input with an excess air ranging from 15% ($\alpha = 1.15$) to 100% ($\alpha = 2$), the flame stabilized front is formed on the nozzle outlet disk, where the last stage air stream is met with a rich mixture entering to the combustor from the nozzle. Keeping the air flow steady, fixed air control, and progressively reducing gas input leads to smooth flame movement back into the nozzle's inner volume. At 20 to 25% of maximum input (1:5/1:4 turndown), the combustion is practically completed inside the nozzle and firing tube, and there is no visible flame outside of the burner. At 2% of maximum input (1:50 turndown/minimum input), the combustion occurs just inside the rear cover's small volume.

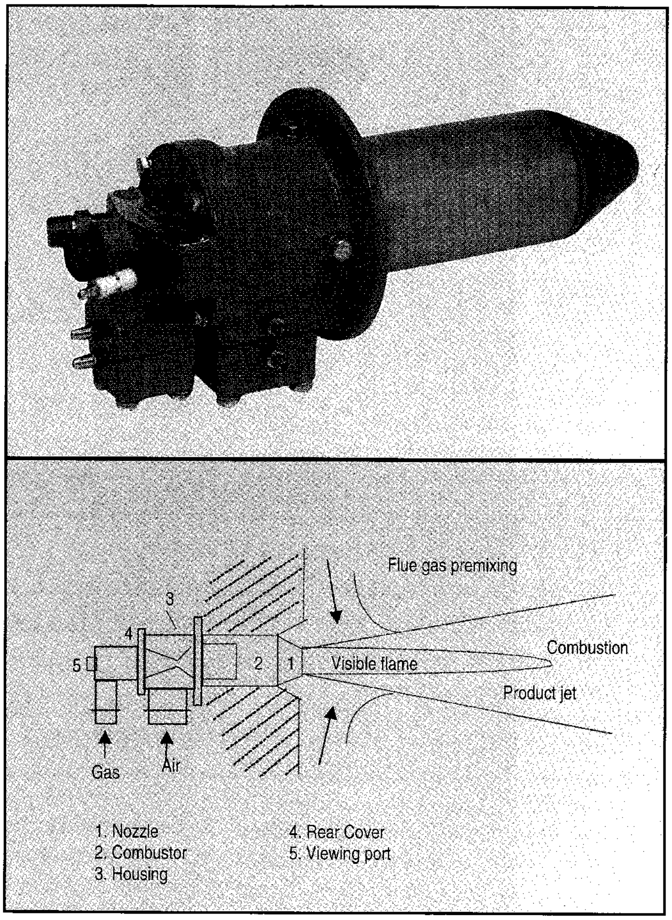

Fig. 1 ThermJet burner design concept and flame structure.

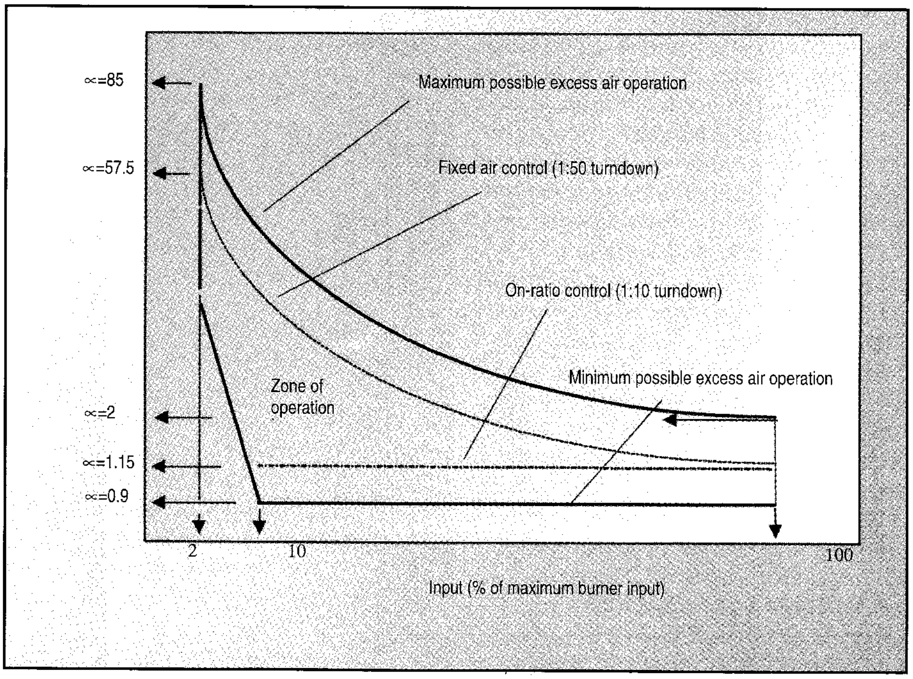

Fig. 2 Principles of burner operation.

The rest of combustion air serves as the diluting air, creating the very lean flame jet in the burner outlet. The burner is able to operate at fixed air control (Fig. 2, top curve) with maximum excess air changed from approximately 100% (α = 2) at maximum input up to approximately 8,600% (α = 87) at minimum input with turndown of 1:50. This wide turndown and extremely high air number is possible due to the unique nozzle and rear cover design.

With on-ratio control, the burner maintains a stable flame shape, while operating from maximum input down to 10% of maximum. The excess air can be set up in the range between 15% and –10% (α = 1.15 – 0.9) at maximum input and between 50% and –10% at minimum input. The bottom curve reflects the minimum excess air operation at a = 0.9 (rich combustion). In the middle of the on-ratio control range, the burner can operate with an even lower air number (down to α = 0.5).

The typical stable operational zone is shown in Fig. 2. The factors which limit the upper and lower limits of the operational zone are flame instability and UV or Flame Rod sensing. The operational zone has approximately the same shape for natural gas, propane, and butane combustion. Burner operation with preheated air up to 600°F (315°C) is possible without any burner design changes. Higher preheated air temperatures require the nozzle material to be changed from cast iron to stainless steel.

NOx Formation in ThermJet Burners

The process of NOx formation inside the nozzle, combustor, and flame jet envelope is dramatically different for each method of control, due to the different mixing and flame forming conditions along gas and air motion through the burner. The basic point for both methods of control (on-ratio and fixed air) is the high fire set-up point, when the conditions of mixing and reaction are similar to each other. Further, input reduction from high fire for each control method, leads to the different condition of NOx formation.

On-Ratio Control and NOx Emission

As shown in Fig. 3, NOx emissions gradually increase when the input is gradually decreased from 100% down to 10% of maximum. In theory, on-ratio control, the air-to-gas ratio remains steady along the burner axis. The accumulative air number increases along the gas path and becomes, for instance α = 1.15 in the combustor chamber. As a result, the total NOx formation rate would be approximately steady through the 1:10 operational range. But in reality, the NOx increases with decreasing input for all three fuels. This can be explained by the increase in the flame residency time inside the burner.

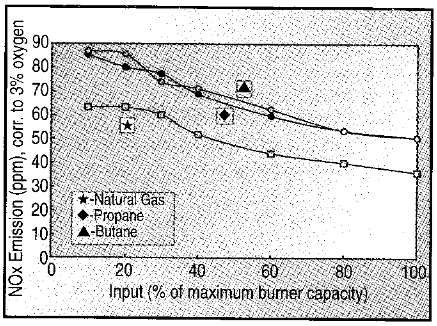

Fig. 3 NOx emission vs input on-ratio control.

Fixed Air Control and NOx Emission

The data of NOx emission for fixed air control is plotted in Fig. 4. The drift of the curves is different from those which represent NOx forming with on-ratio control. This is due to the differences in controls mechanism.

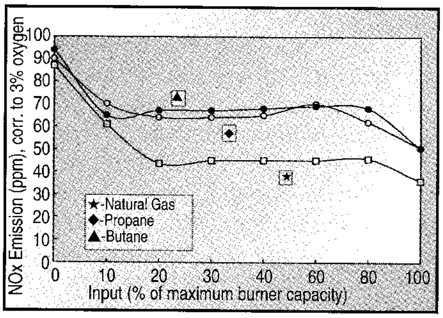

Fig. 4 NOx Emission vs Input at Fixed Air Control.

The initial NOx emission increase, when input diminishes from 100% down to 80% is caused by the movement of the flame envelope from the furnace chamber back to the combustor, and as a result, increased residency time and temperature inside the combustor. Further input reduction from 80% down to 20% gives a slight NOx reduction due to the predominance of flame quenching above the potential temperature increase expected due to the smaller combustion volume.

The excess air quenching process occurs when air flow surrounding the nozzle, in excess of stoichiometric, does not participate in combustion, which is mostly accomplished inside of the nozzle and in the center of the combustor near the nozzle's outlet. That air flow quenches the flame envelope in such a way that it depresses the NOx emission. With further input reduction from 20% down to 2%, the flame shifts into the rear cover. The combustion process is accomplished totally in this small volume. It promotes a rise in temperature of the chemical reaction due to the ineffective quenching of this zone. As a result, this temperature rise encourages NOx output. That phenomena is reflected in Fig. 4. The NOx emission is changed from 40 to 87 ppm (natural gas), and from 64 to 93 (propane/butane).

Rich/Lean Operation and NOx Emission

Fig. 5 compares NOx emission data taken for natural gas operation with data taken at propane/butane operation for the burners firing with changeable excess air. The NOx emission data is plotted in a relative manner, where the divisor is the NOx emission at 15% excess air (α = 1.15) for each fuel tested.

The curves reflect the main theoretically-proven tendency of NOx formation: NOx formation decreases with both increasing and decreasing excess air levels, from a local maximum. The local maximum is at an air number/excess air level of burner operation with a maximum NOx output. For the *ThermJet* burner family, the level of maximum NOx formation in the flame envelope is considered to be a = 1.15.

Propane/butane combustion show precise coincidence with this theory.

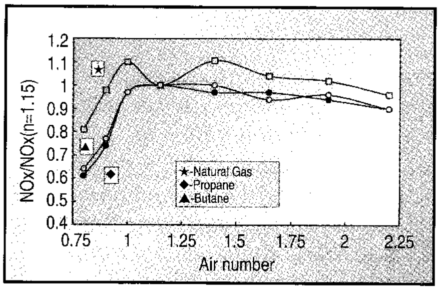

Fig. 5 Relative NOx emission vs Air Number (Excess Air)

Natural gas combustion has two obvious deviations from a theoretical curve. On both sides of the extreme point NOx emission rises approximately 10% at the beginning, and then diminishes gradually when input has been increased or decreased. Within the range of $\alpha = 1.0 - 1.15$ the prompt NOx formation predominates because cracking of methane molecules occurs, which leads to the fast reaction of CH/CH_2 radicals with free oxygen molecules. Further excess air reduction ($\alpha < 1.0$) leads to richer combustion, and hence, to NOx reduction.

Within a = 1.15 – 1.35, the NOx increase is defined by the predominance of thermal NOx, when the mixing condition at $\alpha = 1.35$ creates the maximum temperature inside the flame envelope. Further increase of excess air $\alpha > 1.35$ leads to lean combustion with a gradual diminishing of NOx. The lack of oxygen in a rich mixture and quenching of the flame in a lean mixture are the major contributors in the diminishing of total NOx output.

Combustion Air Preheating and NOx Formation

The higher the combustion air preheat, the higher NOx formation (Fig. 6). The NOx curves are plotted in relative manner, where the divisor is the NOx emission at maximum input with 15% excess air ($\alpha = 1.15$) and 110°F preheat air temperature.

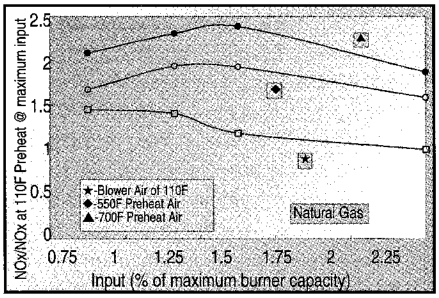

Fig. 6 Air preheat influence on relative NOx emission

Having the burner operate with on-ratio control within 1:10 turndown, the air preheat from 110°F to 700°F promotes an increase in NOx emission of approximately 80% at maximum input, 100% at 50% of maximum input, and 50% at 10% of maximum input. The smaller increase in NOx emission as function of preheat air temperature at the low end of the firing range can be explained by the respectively low mixing intensity and, hence, respectively low temperature in the combustion zone.

The Combustor Type and NOx Emission

The combustor type (high velocity-HV/medium velocity-MV) influences on relative NOx emission is shown in Fig. 7. All points on the curves are relative to NOx level measured at maximum input with a HV combustor.

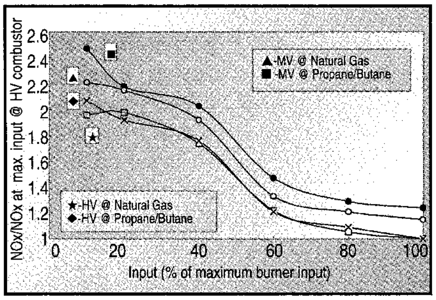

Fig. 7 Combustor type influence on relative NOx emission.

The comparison of combustors for each fuel tested shows that the medium velocity outlet creates higher NOx emission than the high velocity outlet. This is because the medium velocity flame has a bigger envelope outside combustor, and hence, longer residence time, less flame recirculation inside the combustor, and less flame quenching due to less recirculation intensity in the furnace chamber. High velocity combustor operation on natural gas and propane/butane (curves 1 and 2) demonstrates no difference in NOx formation through the turndown range. Contrarily, the medium velocity combustor forms a flame with approximately 10% higher NOx output on propane/butane operation than on natural gas (curves 3 and 4). The dissonance is caused by the respectively slow mixing between propane/butane fuel and combustion air, and hence, longer residency time of the chemical reaction.

Relative Combustor Length and NOx Emission

Fig. 8 compares NOx data taken at L/D = 1.2 with data taken at L/D =2.0 on both natural gas and propane/butane operation, where L is a distance between nozzle and the combustor outlet and D is the diameter of the combustor. NOx data is presented as a ratio of NOx measured in the testing to NOx measured at maximum input of natural gas operation with an L/D = 1.2 combustor.

As follows from Fig. 8, at 45 to 55% of maximum and higher burner capacities the longer combustor forms higher NOx emission because of higher flame residency time inside the combustor together with more complete mixing and higher combustion temperature. At low end of burner capacity, with respectively slow mixing, higher flame residency time inside the longer combustor coupled with respectively low temperature of reaction promotes CO emission rising, and due to this, NOx reduction.

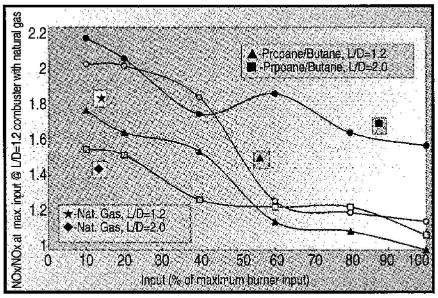

Fig. 8 Combustor length influence on relative NOx emission.

Recirculation Inside the Furnace Chamber and NOx Emission

The intensity of flue gas recirculation inside the furnace chamber is an important factor in the total NOx output. High momentum burners installed in a furnace with the same total capacity as low momentum burners would yield overall lower NOx formation. This is due to the high intensity recirculation inside the furnace and, hence, higher degree of flame quenching. Fig. 9 reflects the above mentioned tendency. NOx data is placed in a relative manner as a ratio of NOx measured to the NOx at maximum input of the higher momentum burner. Tests have been conducted on the same pilot scale furnace with two high velocity burners of different capacity. So, in each test conducted it was a different momentum in the burner outlet, determined as $M = m \cdot u^2$, where m is mass flow or capacity, and u is outlet velocity. A momentum ratio between high and low momentum burners has been determined as 1.67.

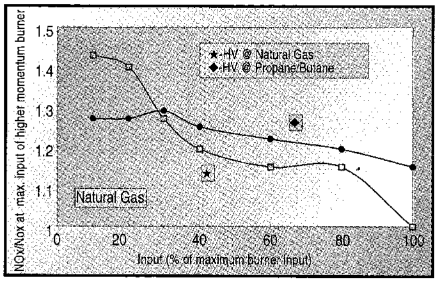

Fig. 9 Influence of the flue gas recirculation inside the furnace chamber on relative NOx emission.

The higher momentum burner (curve 1) creates more intensive recirculation in the furnace chamber, and therefore, less emission than the lower momentum burner (curve 2). This is true for inputs of 30 to 100% of maximum. At the low end of the firing range, NOx formation is higher for the high momentum burner. This is due to the lack of the furnace recirculation influence on flame quenching because of respectively low outlet velocity. The higher NOx is only caused by the condition of mixing inside the burner.

CONCLUSIONS

The main results of NOx formation by the high velocity Thermjet burners can be summarized as follows:

(1) The burner produces less than 40 ppm NOx at high fire under furnace operating conditions with chamber temperatures up to 1950°F (1065°C) because of unique nozzle and rear cover design.

(2) At both on-ratio and fixed air controls, the lower input, the higher NOx emission. On-ratio control within 1:10 turndown, NOx increases about 50% at the low end for all three fuels tested (natural gas, propane, butane). At fixed air control, the NOx rises approximately 80 to 100% at the low end of turndown in comparison with high fire operation.

(3) Preheated air temperatures up to 700°F (370°C) promote elevated NOx formation of approximately 80% within the operational range of the burner.

(4) The higher or lower excess air from optimum combustion air flow, the lower NOx formation in the flame envelope. The optimum from a thermal efficiency point of view, is a air flow relative to the fuel flow with air number of $\alpha = 1.15$.

(5) The longer the combustor length, the higher NOx emission due to the longer residency time within the high temperature zone inside the combustor.

REFERENCES

[1] "Summary of NOx Control Technologies and Their Availability and Extent of Application," U.S. Environmental Protection Agency Report EPA-450/3-92-004, February, 1992.

[2] "Reduction and Control of NOx Emissions from High Temperature Industrial Processes," A Market Research Report prepared for the American Gas Association by T.A. Engineering, Inc., Baltimore, MD, July 1997. (See Industrial Heating, March, 1998, p 77.

[3] Bowman, C.T., Prog. Energy Combust. Sci., v.1, p.33 (1975).

[4] Fenimore, C.P., Thirteenth Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, p.1093 (1971).

[5] Hayhurst, A.N. and Vince, I.M., Prog. Energy Combust. Sci., v.6, p. 35 (1980). IH