



## Know the Secret of Fired Heater Design and Operation with Ultra Low NOx Burner

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### *Introduction*

New burner technologies have been developed to meet the more stringent emission requirements. Most of these new technologies use internal flue gas recirculation and fuel staging to reduce NOx. These burners are often referred to as Ultra Low NOx Burners (ULNB). The techniques used in ULNB for reducing NOx emissions from process heaters affect key aspects of burner and heater performance.

The existing guidelines for burner specifications are generally based on conventional and Low NOx burners. These guidelines may not be sufficient as Ultra Low NOx burners behave differently.

### *NOx Basics*

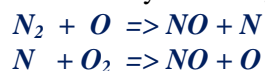
Nitrogen oxides formation is commonly grouped into three mechanisms or types: (a) Fuel NOx (b) Thermal NOx and (c) Prompt NOx.

#### (a) Fuel NOx

Fuel NOx is the result of reactions between fuel-bound Nitrogen and Oxygen in the combustion air. The conversion rates of the fixed nitrogen in the fuel can be as high as 50 to 60% percent of the nitrogen present. Most refinery fuel gases do not have fuel bound Nitrogen; therefore there is virtually no fuel NOx for fuel gas firing.

#### (b) Thermal NOx

Thermal NOx is refers to the oxidation of molecular nitrogen contained in the air or fuel by oxygen. The rate of Thermal NOx formation is very sensitive to local flame temperature. The formation of Thermal NOx is described by following reactions:



The first reaction has high activation energy and therefore requires high temperature for NOx formation. The formation of a NOx molecule from the first reaction results in a release of an N atom which rapidly forms another NOx molecule.

The formation rate of Thermal NOx increases exponentially with increasing flame temperature and is also directly proportional to residence time of reactant in the peak flame zone. The key parameters of Thermal NOx formation are temperature, Oxygen and Nitrogen concentrations, and residence time in the flame zone.

#### (c) Prompt NOx

Prompt NOx is a newly recognized mechanism of NOx formation. Although it only represents a small portion of the NOx formed, it becomes a significant emissions source with Ultra-Low NOx burners.

Under the fuel-rich conditions of the flame zone, particularly areas where the stoichiometry is less than 0.6, both HCN and NH<sub>3</sub> can be formed through an extremely rapid reaction of Hydrocarbon radicals with atmospheric Nitrogen. As these components enter areas of the combustion zone where additional oxygen is available, HCN and NH<sub>3</sub> are oxidized to form CO<sub>2</sub>, H<sub>2</sub>O and NOx.

The major source of NOx in a fuel gas fired heater is Thermal NOx emissions created through high-temperature reactions of Nitrogen and Oxygen present in the combustion air. Since the reaction is highly temperature-dependent, the best direct method of lowering NOx emissions is to lower the peak flame temperature. Various burner suppliers have developed specialized Ultra Low NOx burner to accomplish these goals.

### Ultra Low NOx Burners

Ultra Low NOx Burners have design features and operating philosophy, which are different from a conventional burner. An Ultra Low NOx burner uses fuel staging and flue gas inspiration (internal flue gas recirculation).

In fuel staging, combustion is carried out in stages, one fuel-rich and the other fuel-lean. Fuel gas is injected into the combustion zone in two stages which creates a fuel-lean zone and delays completion of the combustion process. This keeps combustion away from the stoichiometric mixture of fuel and air where flame temperature peaks.

These burners are designed to re-circulate relatively cooler flue gas from the firebox back into the combustion zone using the pressure energy of fuel gas. This re-circulation of largely inert flue gases into the combustion zone reduces the peak flame temperature and average O<sub>2</sub> concentration.

The fuel-air mixture gets diluted by re-circulated flue gas resulting in lower combustion rates. Lower burning rates increase the flame length which can often result in flame to flame interaction as well as flame impingement on tubes.

Flame to flame interaction can result in the merging of flames from individual burners. Merged flame is much longer than stand-alone flame. The prolonged flames can tilt towards the tubes and flame tails can impinge on tubes.

### Key Considerations for Process Fired Heaters with Ultra Low NOx Burners

Every design step in fired heater and burner design is critical for optimum performance. Oversight at any stage, from fuel gas supply to flue gas disposal system, will adversely affect burner performance and hence fired heater capacity, overall thermal efficiency, and run length. Proper burner selection, number of burners, fired duty per burner, and location of burners etc. are very important for optimum performance of a fired heater. Following are the most critical parameters that are need to be evaluated when designing a fired heater with Ultra Low NOx burners:

- (1) Burner Design Parameters
- (2) Heater design parameters
- (3) Fuel Gas Delivery System
- (4) Operating Parameters

A fired heater with well-designed burners with good engineering practice should be able to attain followings:

- Minimize flame-to-flame interaction
- Prevent leaning of flames
- Prevent flame impingement
- Prevent burner to re-circulate flue gas from its own flame
- Meet the emission requirements

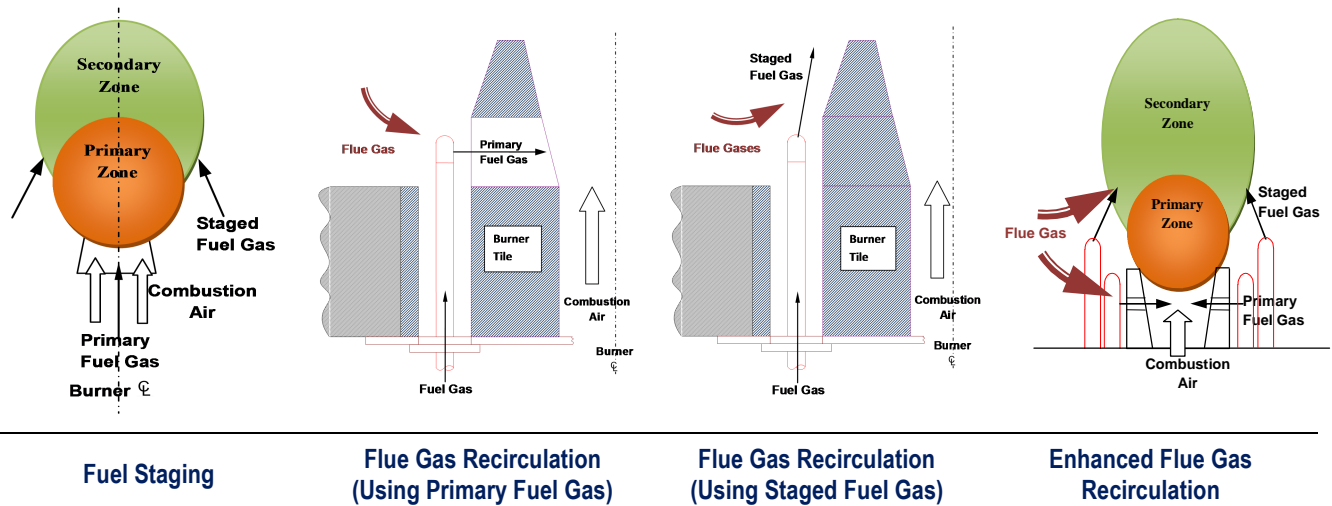


Figure-1 : Basic Concept of NOx Reduction Methods

## (1) Burner Design Parameters:

### 2.1 Selection of number of burners

Increasing the number of burners will reduce the heat liberation per burner. This will result in the shortest possible flame length and more uniform heat distribution.

Two separate CFD modeling were performed; one for a fired heater with three burners and one with four burners. A comparison of Peak Heat Flux Profile for the three and four burner arrangements was plotted for the tubes. CFD modeling (as shown in Figure-2) predicting a significant reduction in peak heat flux for the four burner arrangement.

The tube skin temperature was also reduced significantly with the four-burner arrangement. This resulted in significant improvements in overall fired heater run length.

### 2.2 Burner Layout

#### 2.2.1 Burner to Burner Spacing

Ultra-Low NOx burners require maximum clearance between the tiles of neighboring burners. This space is required for internal flue gas recirculation. For example, in a vertical cylindrical heater with burners too close together, the inner portion of burner tips may not have internal flue gas recirculation. This can produce longer flames and produce higher NOx.

#### 2.2.2 Burner Circle Diameter

Traditionally, burner circle diameter in a vertical cylindrical heater is calculated using following formula:

$$BCD = \frac{D_b + C_b}{\sin\left(\frac{180}{n}\right)}$$

Where:

$BCD$  = Burner Circle Diameter

$D_b$  = Burner Controlling diameter (generally, front plate Outside Diameter)

$C_b$  = Clearance between burner controlling diameter

$n$  = Number of Burners

In a competitive market, just barely meeting API-560 minimum clearance requirement can be expected to minimize overall cost. Burner installed with minimum API clearance can cause flame impingement for slight change in fuel pressure or upset in fired heater operation.

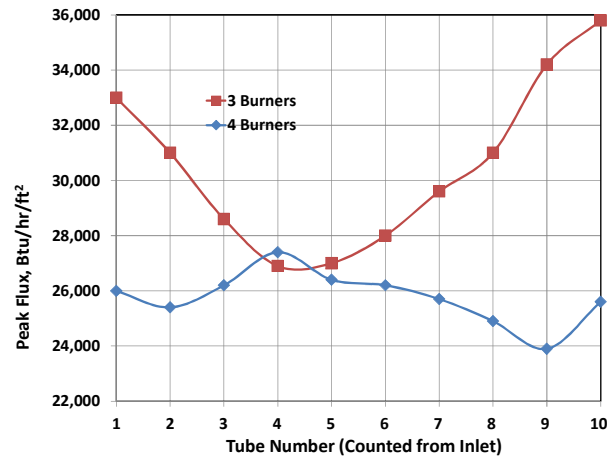


Figure-2 : Peak Radiant Heat Flux Profile with 3 and 4 Burners

This formula works well for conventional burner and still need to be checked for ULNB. The calculation considers actual size of burners to provide required burner circle diameter.

A new formula is required in addition to the above formula which considers spacing between tiles of neighboring burners. The following formula can be used to calculate the burner circle diameter in a vertical cylindrical heater with Ultra Low NOx Burners:

$$BCD = \frac{D_t + C_t}{\sin\left(\frac{180}{n}\right)}$$

Where:

$BCD$  = Burner Circle Diameter

$D_t$  = Burner tile Outside Diameter

$C_t$  = Clearance between burner tiles

$n$  = Number of Burners

A general clearance guideline is to use 1 Inch per MMBtu/hr of heat release. For example, if burner heat release is 10 MMBtu/hr, then clearance between tiles should be 10 Inch. Another suggested guideline is keeping burner center to center spacing as 2 times the burner tile outside diameter.

#### 2.2.3 Burner in Two Concentric Circles

It has been a common practice to install burners in two circles for conventional burners (see Figure-3).The two circle arrangement provides better clearance between tubes and burners. In most of the cases, an inner circle is added during fired heater revamp to provide additional firing rate.

This is not a preferred option with Ultra Low NOx Burners. The inner circle burners do not

get the cold flue gases for internal flue gas recirculation. This lack of internal flue gas recirculation increases the NOx emission from the inner circle burner. The overall NOx from the heater will go up and may not meet the emission requirement.

### 2.3 Heat Liberation and Overdesign

A good engineering practice for specifying the overdesign for a burner as per API-560 is as follows:

- 5 or fewer burners : 120%
- 6 or 7 burners : 115%
- 8 or more burners : 110%

It has been common practice in the industry to overdesign the burners. Additional margin on burner design is sometimes applied on top of margin on fired heater design. Overdesign shifts the burner design point away from the actual operating point.

In a case study, burners were designed with 120% margin on required firing rate. The draft available at heater design condition is 0.6 InchWC. However the draft utilized at heater design condition will be 0.41 InchWC instead of 0.6 InchWC actually available. This overdesign on the burner reduces the draft loss requirements for actual heater operating condition which results in a larger flame dimension. It is highly recommended to minimize the overdesign to avoid increasing the overall flame dimension.

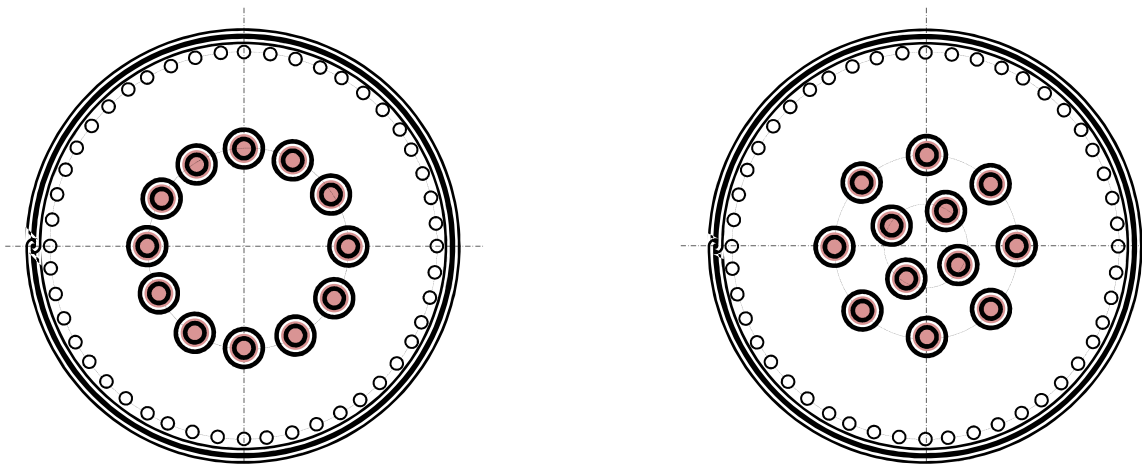
An adequate air pressure drop should be used for

Ultra Low NOx burners for forced draft application. In this type of application, higher air pressure drop across the burner (say 2 InchWC) can significantly improve burner performance. The higher air pressure drop results in better flame pattern, minimize tube impingement, and lower NOx. It becomes more critical in application with large number of burners in a single chamber such as in a Coker heater. The coupling of flames results in much higher NOx values than expected based on shop test of a single burner.

### 2.4 Burner Performance Shop Test

The burner test is critical for Ultra Low NOx Burners. With conventional and low NOx burners, the performance seen in the test is similar to multi-burner heaters. However this may not be always true with ultra-low NOx burners. If burners are not placed with sufficient spacing, the flames may merge, resulting in longer flame length. It may also result in flame impingement on furnace tubes. Ultra-low NOx burners are more prone to flame interaction in multi-burner heaters. Therefore, it is always recommended to carry out a burner test. Also, if a burner supplier has a sufficiently large heater, try to test two or more burners with the same spacing as the actual heater. The test furnace conditions (e.g. Bridge wall temperature, draft etc.) should replicate that of the actual heater.

It is critical to measure flame dimensions during test. Visually establish the flame dimensions may not be correct. It is recommended to use



**Desired layout: Burners in one circle**

**Non-desired layout: Burners in two circles**

**Figure-3 : Burner Layout Options**

CO probing to establish more reliable flame dimension. CO levels must be low in the firebox outside of the flame envelope. CO levels of more than 2000 ppm are generally considered as flame.

Many users do not specify a burner test if they have used a similar burner in the past. Even though operating conditions and heat liberation are similar performance test is still recommended. A small difference in tip drilling (which is very common) can have a big impact on NOx emissions and flame stability.

**(2) Heater design parameters:**

**3.1 Burner to Tube Spacing and Flue Gas Recirculation**

It is suggested to maximize burner to tube clearance not only to avoid flame impingement on tubes but also for better internal flue gas recirculation. This spacing becomes even more critical for a vertical cylindrical heater. In a well-designed furnace, the hot flue gases should flow upward through the center of the heater. The cold flue gas should flow downward behind and along the tubes. A smaller clearance between the burner and tubes may not allow cold flue gases to flow downward. The small space will be filled with hot gases. Refer to Figure-4 for a typical flue gas flow profile in heaters with a normal firebox and a tight firebox.

API recommends a clearance between tubes and burners. For natural draft, fuel gas fired burners; this can be translated into the following equations:

$$C_{B-T} = \frac{Q_B}{4} + 1.5$$

Where:

$C_{B-T}$  = Burner to Tube Clearance, ft

$Q_B$  = Burner Liberation, MMBtu/hr

For Ultra Low NOx application, adding 6 inch to API recommended spacing seems to provide needed clearance for proper flue gas recirculation. The modified equation shall be:

$$C_{B-T-ULNB} = \frac{Q_B}{4} + 2$$

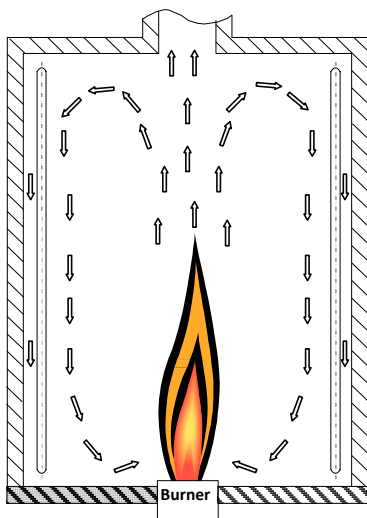
Table-1 provides suggested clearances for Ultra Low NOx Burners.

Table-2 provides summary of results form a case study comparing the required minimum Tube Circle Diameter (TCD) for a fired heater with conventional burners and Ultra Low NOx Burners.

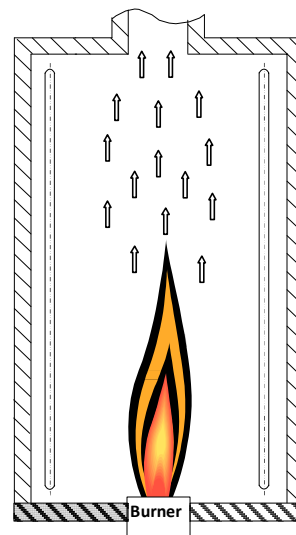
**3.2 Bridge Wall (Firebox) Temperature**

Ultra Low-NOx burner performance is much more dependent on firebox temperature compared to conventional burners. Burner NOx and other emissions are a function of firebox temperature. Higher firebox temperature leads to higher NOx formation.

The firebox temperature calculation methods



**Normal firebox : With flue gas re-circulation**



**Tight firebox: With no or low flue gas re-circulation**

**Figure-4 : Firebox flue gas flow profile**



generally used are empirical correlations based on experimental data. The heat transfer in the radiant section is calculated with widely used Lobo-Evans method. This method assumes complete flue gas mixing in the firebox such that there are no longitudinal or transverse temperature gradients. The equation for radiant heat transfer is as follows:

$$\frac{q_r}{\alpha A_{cp} F} = 0.173 \left[ \left( \frac{T_g}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right] + 7(T_g - T_s)$$

Where:

- $q_r$  = Total heat absorbed in Radiant Section, Btu/hr
- $T_g$  = Average Radiating flue gas temperature in radiant section, °R
- $T_s$  = Temperature of cold surface (Tube Metal Temperature), °R
- $\alpha A_{cp}$  = Equivalent Cold Plane area, ft<sup>2</sup>
- $F$  = Overall exchange factor

This correlation was developed based on operating data from heaters using conventional burners. Ultra Low NOx burner flames are significantly different than a conventional burner flame. An Ultra Low NOx burner flame is cooler than conventional burner flame. A lower flame temperature will result in lower heat transfer in the radiant section. Therefore, the flue gas temperature leaving the radiant section will be higher than that of a heater with conventional burners. One must account for this when designing fired heater. An Ultra Low NOx burner installed in an existing fired heater (burner retrofit) may result in loss of capacity or overall thermal efficiency.

The overall heat transfer may not be affected in applications where the heater has a convection-section preheat coil followed by a radiant-section in which further heating occurs. In this case, the total heat absorption for both the radiant and convection coils will be about the same, regardless of the Bridge Wall Temperature.

However, it is very important to correctly estimate Bridge Wall Temperature where there are two or more separate services, one in the radiant section and one or more in the convection section. If the Bridge Wall Temperature is higher than expected, the radiant-section absorption will be relatively low and the convection-section absorption relatively high. In this case, such as when the radiant section consists of a process coil and the convection section consist of a steam-generating coil. An error in the predicted bridgewall temperature would result in an error in one or both of the predicted duties as well as in the guaranteed heater efficiency.

An accurate prediction of bridgewall temperature is required, not only for emission prediction, but also to correctly predict heat absorptions and other heater performance parameters.

In a case study, an estimated performance of a fired heater with conventional burner and Ultra Low NOx burners were analyzed. The case study was for a vertical cylindrical heater with

**Table-1 : Suggested clearance for Ultra Low NOx Burner**

Heat release, MMBtu/hr	Vertical clearance to centerline roof tubes / refractory (vertical firing), ft-inch	Horizontal clearance between tubes and burner centerline, ft-inch	Horizontal clearance from centerline of burner to unshielded refractory, ft-inch	Clearance between opposing burner (horizontal firing), ft-inch
2	10'-11"	2'-5"	1'-6"	14'-5"
4	15'-7"	3'-0"	2'-0"	21'-7"
6	20'-4"	3'-6"	2'-6"	28'-10"
8	24'-11"	4'-0"	3'-0"	36'-0"
10	29'-7"	4'-6"	3'-6"	43'-3"
12	34'-4"	5'-0"	4'-0"	46'-10"
14	39'-0"	5'-6"	4'-6"	50'-5"
16	43'-9"	6'-0"	5'-0"	54'-0"
18	48'-5"	6'-5"	5'-6"	60'-0"



process coil in radiant section only. Convection section is used for waste heat recovery (steam coil). The Bridge wall temperature with conventional burners is estimated as 1,560°F as compared to 1,620°F with Ultra Low NOx burners. This increase in bridge wall temperature do not only affect the firing rate & NOx emission but also affect the mechanical integrity of heater components like tube supports, structural steel, refractory etc.

### 3.3 Heat Density per unit area

Heat density is not used for conventional burners. However, it is a very significant parameter for Ultra Low NOx Burners. The reason for this is the importance of flue gas internal circulation in ULNB.

The following formula can be used to determine area heat density:

$$\text{Heat Density} = \frac{Q_b * n}{A}$$

Where:

- $Q_b$  = Burner Heat Release
- $n$  = Number of Burners
- $A$  = Floor Area (inside the tube circle or between tube rows)
- $A = \pi d^2/4$  (for Vertical Cylindrical Heaters)
- $d$  = Tube Circle diameter
- $A = LxW$  (for Cabin / Box Heaters)
- $L$  = Heater Length
- $W$  = Heater width (tube center to center)

Flue gas flow patterns in the radiant section of properly designed process fired heaters are usually similar irrespective of heater geometry / type. In most fired heaters, tubes are placed along the walls, and the burners reside in the middle. As heat is transferred from the flue gas, it cools and flows downward close to tubes. This results in a region of hot upward gas flow in the middle of the heater and cool downward flow adjacent to the tubes. However, this recirculation decreases as over-firing increases. An over-fired heater may have very little flue gas recirculation. The extreme case is plug flow case with no flue gas downward flow.

This over-firing characteristic can easily be correlated with heat density. It is recommended to limit area heat density to a maximum of 250,000 Btu/hr.ft<sup>2</sup>.

Two heaters with different area heat density but

Table-2 : Case Study: Required Minimum Tube Circle Diameter for Conventional vs ULNB

	Conventional Burner	ULNB
Burner design liberation, MMBtu/hr	10.0	10.0
Number of burners	8	8
Burner spacing, Inch	30"	40"
Burner circle diameter, ft-inch	6'-6"	8'-9"
Burner to tube clearance, ft-inch	4'-0"	4'-6"
Min. tube circle diameter, ft-inch	14'-6"	17'-9"

with similar firing rate, bridgewall temperature and excess, will have different NOx. The one with lower heat density will likely to have lower NOx.

### 3.4 Common Air Plenum Design

Common combustion air plenums are sometimes provided to better control the combustion air. These need to be designed to provide equal air to all the burners. It is possible to achieve relatively uniform combustion air flow to each individual burner for a well-designed burner plenum. It is always recommended to carry out a Computational Fluid Dynamic (CFD) analysis to ensure proper air distribution to each burner.

The example in Table-3 demonstrates how air mal-distribution can starve some burners of combustion air.

It is very common to target 2% or even lower excess O<sub>2</sub> (2% O<sub>2</sub> is equivalent to 10% excess air). Most new fired heaters are able to operate at lower excess air because of lower tramp air (lower air leakage) due to better sealing of casing.

As noted in the table, a heater operating with 10% excess air will have a few burners starving for air at 10% air mal-distribution. A lower combustion air supply would result in sub-stoichiometric operation for that burner. This will increase CO emissions.

### (3) Fuel Gas Delivery System

The Ultra Low NOx Burner tip orifices are very small compared to conventional burners. Burner ignition ports in most of Ultra Low NOx burners are 1/16 inch. These small ports can and will get plugged if the fuel gas delivery system is not design to reliably supply clean, dry fuel.

The fuel delivery system for Ultra-Low NO<sub>x</sub> burner applications must have a filter /coalescer located downstream of the knockout drum. Use of stainless steel fuel piping downstream of the filter/coalescer is also recommended. Fuel piping downstream of the filter/coalescer may require insulation and heat tracing depending on local site conditions.

**(4) Operating Parameters:**

**4.1 Carbon Monoxide (CO) emission:**

Most fired heater emission requirements also limit CO emission. The factors influencing NO<sub>x</sub> emission (firebox temperature, excess air & residence time) also influence CO emission, although unfortunately in opposite direction.

NO<sub>x</sub> emission is reduced as firebox temperature decreases but CO emission increase.

CO emission is generally not an issue at heater design conditions where firebox temperature is relatively high. However, at low heater throughput CO emission will increase.

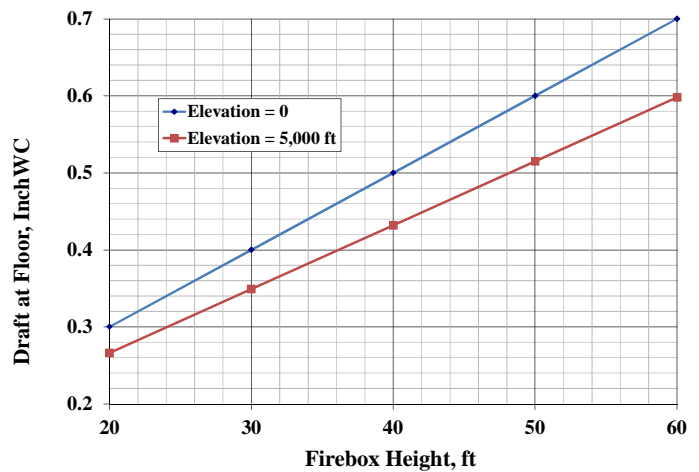
Carbon Monoxide is produced by incomplete combustion of fuel gases. The basic combustion process includes formation of CO as an intermediate product before it is converted to CO<sub>2</sub>. CO is easy to convert into CO<sub>2</sub> if sufficient Oxygen, temperature and mixing is available. The minimum ignition temperature of CO in air is 1,128°F. A firebox temperature higher than the ignition temperature is required to limit CO emission. Burner supplier must be consulted for minimum firebox temperature below which CO emission is not guaranteed. Generally, CO emission from a burner is guaranteed at a firebox temperature above 1300°F.

**4.2 Draft**

Draft is defined as negative pressure at any point inside a fired heater. Draft loss across the burner is the pressure drop of combustion air in the burner. Higher available airside pressure drop to the burner almost invariably improves flame pattern and the ability to effectively use internal flue gas recirculation in burners. It is very important to provide the actual calculated draft available to the burner supplier.

Design Excess Air (%)	% Mal-distribution	Maximum Excess Air (%)	Minimum Excess Air (%)
15	5	20.75	9.25
	10	26.5	3.5
	15	32.25	(-)2.25
10	5	15.5	4.5
	10	21.0	(-)1.0
	15	26.5	(-)6.5

	High draft operation	After draft change
Draft at Arch, InchWC	0.20	0
Draft at Floor, InchWC	0.6	0.4
Excess Air, %	15	(-) 6



**Figure-5 : Effect of Site Elevation on Draft Available at Heater Floor**

Site elevation (altitude above sea level) is one of the most often overlooked parameters while calculating draft. Stack effect reduces with increase in altitude. If draft is not calculated based on actual site elevation, the burner as well as the heater will have capacity limited due to insufficient draft.

Following correlation can be used to calculate the draft (Inch WC) generated in a heater.

$$Draft = 0.52 * H * P_{atm} \left\{ \frac{1}{T_{amb}} - \frac{1}{T_{fg}} \right\}$$

Where:

H =Height, ft

P<sub>atm</sub> = Atmospheric Pressure, psia

T<sub>amb</sub> =Ambient Air Temperature, °R

T<sub>fg</sub> =Flue Gas Temperature, °R



Atmospheric pressure ( $P_{atm}$ ) reduces with increase in site elevation resulting in reduction in available draft. Figure-5 provides a comparison of draft at site elevation of 0 ft and 5,000 ft.

Fired heater operators tend to operate the heater at higher draft to be on safer side. However, when there is a large change in draft, it can adversely affect the excess air. Example in table-4 indicates that air flow rate becomes substoichiometric for a draft change from 0.2 Inch WC to 0 InchWC. This change may not even trigger the low draft alarm (depending on setting of instrument).

#### 4.3 Air Leakage

Process fired heaters operate under negative pressure. Even small openings can allow significant quantities of air to leak into the heater. Air leaking into the furnace increases the O<sub>2</sub> measured at arch or stack, independent of the air actually coming through the burners. The actual air coming through burner shall be lower than measure by Oxygen analyzer. This may increase the NO<sub>x</sub> emissions. When furnace air leakage is high, the air coming through the burner may not be enough for complete combustion of the fuel, causing the flames to grow larger and possibly impinge on the furnace tubes. In such a situation, the heater may have to be operated at a higher excess O<sub>2</sub>, sacrificing heater efficiency in order to prevent flame impingement.

There are many sources of air leakage in a process heater. It can be tube penetrations, sight ports, joints between heater walls, out of service burners etc. It is very important to seal any and all noticeable openings in order to prevent air leakage for proper burner operation.

#### Conclusion

With the introduction of next generation Ultra-low NO<sub>x</sub> burners, there have been major reductions in NO<sub>x</sub> emissions. These burners are operating closer to their limits of flame stability and complete combustion. Ultra-low NO<sub>x</sub> burners are very prone to flame interaction in multi-burner heaters.

Ultra-Low NO<sub>x</sub> burners along with fired heater need to be specified correctly to get an optimal heater

operation. Proper selection of fuel gas supply system, number of burners, fired duty per burner, location of burners, fired heater design and operating parameter are very important for optimum performance of a fired heater. Every design step in fired heater and burner design is critical. An oversight at any stage, from fuel gas supply to flue gas disposal, will adversely affect burner as well as fired heater performance.

Many fired heater design and operating parameters may not be of significance with conventional burner but become important for Ultra Low NO<sub>x</sub> burners.

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