Introduction
Low NOx burners rely on high rates of flue gas recirculation to lower flame temperatures and thermal NOx emissions. This is typically achieved by maximizing the number of fuel jets and fuel gas pressure, while placing the gas tips outside the burner tile. Simultaneously, the lowest NOx is normally achieved with low air velocities in the burner throat – this reduces the mixing rate with the fuel, slows the combustion rates and lowers thermal NOx production. As a result, ultra-low NOx flames tend to be voluminous, long and ‘lazy’ compared to more conventional style burners. It also means that the flames become very sensitive to the prevailing flue gas recirculation patterns. Characteristics like these have not been good for the reputation of ultra-low NOx burners when it comes to flame dimensions, flame rollover and impingement on coils. Numerous papers like [1] have been presented on this topic, typically focusing on the burner design itself in order to find a solution. However, in many cases there are other root causes for erratic flame behavior. In some cases burner spacing and the resulting burner-burner interaction has been identified as the reason for flame rollover [2]. Yet, in several other cases it turns out that the firebox design itself, or the manner in which burners are arranged within the firebox, contributes largely to the observed issues [3].

The objective of this paper is to identify problem areas for ultra-low NOx burners in different styles of heaters, and the recommended design approach to mitigate these issues.

Ultra-Low NOx burner – Typical Design
Ultra-low NOx burners achieve their emissions by placing all of their fuel jets outside the burner tile, and use the momentum of the fuel as efficiently as possible to maximize flue gas entrainment back into the flame (Figure 1 and Figure 2). The resulting quenching effect on the combustion lowers the production of thermal NOx. The additional flue gas volume also significantly increases the overall flame dimensions. The natural draft versions of these burners are designed with relatively low throat velocities because of the low available pressure drop (typical range is 0.3 – 0.5 inH\textsubscript{2}O for refinery applications). The combination of its low velocity and large volume creates a low momentum flame that becomes easily susceptible to the prevailing furnace flue gas currents. Conversely, a conventional burner has none of these design features; fuel and air are mixed as rapidly as possible to create a compact and therefore high-NOx flame.

In summary, compared to conventional burners an ultra-low NOx flame can be characterized by 1) a large volume and 2) a lack of momentum, and is therefore heavily influenced by the prevailing currents.
Figure 1. Illustration of flue gas recirculation by ultra-low NOx burners

Figure 2. Typical ultra-low NOx burner, the John Zink COOLstar® burner

**API Spacing Guidelines**

In an attempt to reduce flame impingement on radiant coils, the American Petroleum Institute (API) defines spacing requirements in their Fired Heater standard [4]. The standard prescribes the minimum distances between burners and coils, between burners and unshielded refractory, between burners and roof tubes/refractory and the distance between opposing burners. The distances are based on typical flame dimensions which are a function of burner liberation rate, fuel type (oil or gas) and the combustion air supply mode (forced draft or natural draft). While this is a good start, this is not nearly sufficient to prevent flame impingement because it only considers the volume of a single ultra-low NOx flame. The recommendations do not consider the possibility of lack of momentum of a flame, or the potential interaction between the burners themselves.

The fact that an ultra-low NOx flame has little momentum of its own means that firebox flue gas flow patterns have a large impact on where flames go. This requires that the flow patterns must not be conducive to flame impingement. In its present form, following the API standard guidelines does not necessarily lead to a well-balanced firebox design:

1. There are no guidelines or directives regarding the spacing and interaction between burners.
2. The standard does not specify how burners need to be divided over the firebox to prevent dead zones or zones of excessive circulation.
3. The standard specifies minimum distances, but in a number of cases there should also be maximum distances in order to prevent dead zones
4. There are no guidelines pertaining to multi-coil firebox designs.

In the following sections we will discuss situations where the API requirements fall short of preventing flame impingement, and provide recommendations for general firebox design rules. Note that this

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discussion relates to staged fuel ultra-low NOx burners, different rules may apply to conventional or staged air burners.

**General Burner-Burner Spacing Guidelines**

In addition to the API 560 spacing requirements, there are a number of other burner spacing guidelines in the industry. These are defined by process licensors, process heater designers and/or the burner vendors themselves. Examples of such rules are:

- Burners should be spaced so that flames do not overlap (based on estimated / tested flame diameters)
- Distance between burner tiles can be a function of burner duty, for example 1 inch per MMBtu/hr
- Floor heat density (the total burner liberation divided by the floor area) should not exceed a certain number (e.g. 400,000 Btu/hr/ft²) in order to prevent certain flow phenomena of the flue gas in the firebox
- Similarly, fired duty per cabin length should not exceed a certain limit, like 2 MMBtu/hr per foot.

Rules like these may have some merit, but they do not prevent flame impingement on coils because they do not warrant a balanced flue gas flow pattern inside the firebox. All these rules attempt to do is make sure that there is sufficient space around each burner to allow for sufficient flue gas recirculation back into the flame and to prevent excessive burner-burner interactions. The main penalty for not following them may be higher NOx emissions.

**Recirculation**

When a fluid jet issues from a nozzle, it entrains the surrounding fluid. A free jet (Figure 3) keeps entraining fluid so that it expands and slows down until the jet can no longer be distinguished from the surroundings. When the jet is confined (Figure 4), fluid that is entrained must be replaced with fluid from locations further downstream of the jet, and an annular zone of reverse flow will be formed around the jet.
As mentioned before, Ultra-low NOx burners are designed to maximize this entrainment of flue gas, and therefore generate much more flue gas recirculation than conventional burners. The theoretical dependence of the recirculation patterns on the jet thrust and flame shape has been analyzed and reported in several papers [5] [6] [7], but this discussion is outside the scope of this paper. In order to understand the recommendations outlined in the rest of this paper it suffices to understand the natural tendency of flue gas recirculation flow. This tendency is to choose the path that is most energy efficient, i.e. the path of least resistance. That means in practice that

- The flue gas with the lowest velocity is more likely to be entrained and recirculated
- Flue gas will take the shortest path to travel from point A to B. Dead zones are to be avoided.
- The flue gas that needs to turn 180 degrees for recirculation will do so in a location where it achieves the longest turning radius and the lowest velocity. See for example the CFD results of a single burner in a box type heater, Figure 5 and Figure 6. Most flue gas recirculation takes place in the corners, because that allows the flue gas to make the widest turn possible and cause the lowest pressure drop.

Note that this flue gas behavior should be kept in mind when several burners need to be turned off in order to achieve a lower heater duty.

Finally, the best flue gas patterns are achieved if in addition to these firebox requirements, all burners within a firebox are designed to provide the same amount of thrust. This becomes important in firebox layouts with multiple burner capacities.
**Vertical Cylindrical Heaters**
The most common heater - burner arrangement in process heaters is the vertical cylindrical firebox with burners arranged in a circle in the center, see Figure 7. The most common problem with this design is that burners are put too close together. When this happens flames merge, as shown in Figure 10 where the two flames that merge end up forming a much longer single flame compared to the individual flames. This risk is higher for Ultra-Low NOx burners, where the volume of recirculated flue gas on the outside of the burner circle creates a tendency to push the flames together.

The danger of elongated flames is impingement and overheating of the convection section. The irony is that this is more likely to occur when the space between the burner and the coil is chosen conservatively large; the designer tries to avoid flame impingement on the radiant coils by placing the burners as far away from them as possible, but ends up with flame impingement on the convection banks.

In order to prevent this problem, sufficient space should be provided between burners and inside the burner circle (area ‘B’ in Figure 9). As a rule of thumb, the total area outside the burner circle (‘A’ in Figure 9) should not be more than four times the area ‘B’. Applications requiring very stringent NOx emissions may need lower ratios of A to B.
Figure 9: Layout sketch of vertical cylindrical firebox

Figure 10: Flames merge and elongate when they are too close together

Figure 11: Cabin heater with single row of burners

Figure 12: CFD results (streamlines) of a cabin heater
Cabin Heaters – Single Burner Row
The burner arrangement in a single row cabin heater (Figure 11) is relatively simple: burners are positioned in the center of the firebox with their flames radiating to the coils that are typically placed against the refractory walls. Problems with flame patterns manifest themselves when burners are spaced unevenly. This happens typically at the end walls; the burner space to the end wall must comply with the API 560 requirements, which typically results in a distance that is more than the burner-burner distance. However, in order for the burners to be spaced evenly, the end space must be approximately half the burner-burner distance.

If the end burner space from the wall is significantly more than half the burner-burner spacing, this end zone becomes the preferential downflow area for the recirculated flue gas. The extra volume at the end walls gives the flue gas extra space to turn 180°, which lowers the flue gas velocity and pressure loss. As a result, most if not all recirculation takes place at the ends of the firebox. See Figure 12 for an example where CFD modeling has been used to study this effect.

Cabin Heaters – Multiple Burner Rows
Arranging multiple rows of burners between coils (Figure 13, Figure 14) makes the task of ensuring that the flue gas from each burner has the same volume for recirculation considerably more complex.

The flue gas balancing act becomes even more difficult when the burners are staggered. Figure 15 illustrates the fact that in staggered arrangements there will always be two end burners that have considerably more space than the center burners. This will, again, lead to preferential down flow around these two end burners as shown in Figure 16. In addition, the inner tips of the four middle burners
shown in Figure 15 will be unable to recirculate any flue gas. This arrangement will therefore produce much higher NOx than a single burner, and also cause significant merging and lengthening of the flames.

Figure 15: Staggered burner arrangement in cabin heater

Figure 16: CFD Results of staggered burner layout
Multi-lane Cabin Heaters

In addition to addressing the end burner spacing issues, the designer of multi-lane cabin heaters such as coker heaters and down-fired reformers must pay extra attention to the width of the burner lanes themselves. In order to avoid pressure differences between the different coils, superficial flue gas velocities must be the same in each of the burner lanes. Practically speaking this translates to the rule that the width of the burner lane should be proportional to the burner duty. This means for example that if the outer burner duty is 50% of the center burners, the outer burner lane width should be 50% of the center lane width.

See Figure 17 where the CFD results are shown of a model where the width of the outer lane was 70% of the center lane, but the duty of the outer burner was 50% of the center burner. As a result, the flue gas in the outer lanes flows at a much lower velocity than the flue gas in the center lane. This in turn, causes the outer flue gas to recirculate much easier than the flue gas in the center of the firebox. The final outcome is that the majority of the flue gas for recirculation is supplied by the outer burners, and none by the center burner. This causes hot flue gas impingement onto the coils (resulting in hot spots and excessive local fouling) and high floor temperatures (resulting in high NOx emissions), shown in Figure 18.
The same case is shown in Figure 19 but this time with an outer lane width that is proportional to the outer burner duty, i.e. 50% of the center lane width. It clearly shows that due to its higher velocity, the flue gas in the outer lanes is now flowing upwards instead of flowing towards the center. Since the outer burners no longer provide flue gas for the center burners, the center burners now also contribute to the recirculation.

![Figure 19: Multiple coil lanes with 50% outer burners in a 50% outer lane width](image)

These considerations obviously also apply to down fired heaters such as reformers. The results of a CFD analysis in Figure 20 show that the disproportionality between the burner duties and the lane widths causes a flue gas cross-flow which has been reported as ‘weather’ in literature [1].

![Figure 20: Streamlines in down fired reformer](image)

Turning off multiple burners to achieve a low firing duty of the heater should also be done as evenly as possible in order to prevent large flue gas velocity imbalances from one row to the other.

**Location of Firebox Exit**

As the previous examples have demonstrated, in order to provide even flue gas recirculation patterns the burner spacing has to be well balanced to avoid velocity and pressure differences. This also means that the distance of the flue gas to the firebox exit has to be the same for all of the burners. Dead zones have to be avoided. Different travel paths will result in pressure differences which will result in uneven flow patterns. Consider for example the case of a side exit, which is typical for a twin cell cabin heater.
Figure 21 shows that the asymmetric shape of the firebox causes a highly uneven flue gas flow pattern. As a result, the flame will show a strong leaning tendency towards the exit and impinge on the tubes just below the exit, as shown in Figure 22. The correct design approach is to place the firebox exit directly above the burners.

Conclusions

Following the current API 560 guidelines for burner distances only provides a basic level of prevention of flame impingement. The spacing guidelines only consider an individual burner and its estimated flame volume. Since they do not consider the potential interaction between burners, this level of protection becomes even weaker in the case of ultra-low NOx burners that have voluminous, low momentum flames. These flames tend to closely follow the flue gas flow patterns inside the firebox. The more complex the firebox becomes with respect to number of coil lanes or burner layout, the more important it becomes to provide a design with evenly distributed burner thrust without dead zones. A computational fluid dynamics analysis of the firebox enclosure is recommended in those cases where the recommendations in this paper are not followed. This is almost always the case for heater revamps where conventional burners are replaced with ultra-low NOx designs.
References


