

Advanced combustion system for cracking furnaces

A discussion of design considerations for burner technology used in cracking furnaces. Significant improvements include more uniform heat flux profile, wider turndown, stable flame, high combustion efficiency, and low CO and NO_x emissions

Roger Poe, Ashok Patel, Charles E Baukal and Daniel Wright

John Zink Company LLC

Cracking furnaces often present significant burner challenges compared to process heaters, because of higher temperatures and more specific heat flux profile requirements. Minimising pollution emissions is a general requirement for all industrial combustion applications. New generations of burner technology continue to reduce emissions, but often impose operational limitations. For example, low NO_x emissions may only be achievable over a relatively narrow range of operating conditions. New burner technology has been developed using some advanced fluid dynamic mixing and control techniques, which minimises both NO_x and CO emissions over a wide range of operating conditions. This new burner has a much wider turndown ratio and a more compact flame, which are both important advantages in cracking furnaces.

Burner design challenges

Some of the more important challenges for burners used in cracking furnaces include heat flux distribution along the furnace wall, burner turndown and draft variation, flame quality, ease of maintenance and emissions performance.¹

One of the most important design considerations for burners used in cracking furnaces is the heat flux distribution to the process tubes.² The total firing rate or capacity alone is not a sufficient parameter to determine throughput and run length. The heat must be properly distributed in the furnace to maximise the heat transfer to the tubes, without overheating the tubes, which causes accelerated coking, leading to reduced run length. Furnaces are designed around a target heat flux profile. The trend in cracking furnaces is toward fewer but larger burners. This makes it difficult to uniformly distribute the heat, as there are fewer burners to adjust along the height of the furnace to produce the desired flux profile.

Another important challenge with burners is achieving a wide turndown range. Changes in production, startup

and shutdown all require burners capable of operating at firing rates below the normal operating rates. A burner with a wider turndown range allows operators to reduce furnace temperatures for decoking without having to take burners offline, which is labour intensive. However, wide burner turndown has become increasingly difficult for many reasons. Some burners in cracking furnaces use at least some premixing of the fuel and combustion air, so the burner is referred to as a premixed burner. While there are some advantages to a premixed burner, one of the disadvantages is reduced turndown due to the possibility of flashback. Another related disadvantage of premixed burners is that significant hydrogen content in the fuel further limits turndown due to flashback concerns, because of the exceptionally high flame speed of hydrogen flames. Ultra-low NO_x burners use a variety of techniques to minimise NO_x emissions, such as fuel staging, furnace gas recirculation and ultra-lean premixing. These burners generally have lower turndown due to the more closely controlled mixing of the fuel and air, and the closer operation to the limits of flammability.

Burners must have acceptable performance over a wide range of operating conditions. The furnace draft can vary considerably and change quickly. During a cold startup, the draft is low compared to the draft during normal operation. In natural draft furnaces, the draft can fluctuate due to wind conditions blowing across the stack outlet. These changes in draft directly impact the flow of combustion air to the burners. This means the burner must be capable of safely operating at both low and high O₂ conditions.

Flame quality refers to the shape and stability of the flame. While it is important for any application, it is particularly important in cracking furnaces for several reasons. If the flames are too wide, they can interact with each other and adversely affect performance. Coalescing flames can increase the flame

length, causing flames to rollover into the tubes, changing the heat flux profile, and causing both NO_x and CO emissions to increase. When CO and unburned hydrocarbons mix with oxygen in the vicinity of the process tubes, localised combustion can create hot spots that lead to premature coking in the tubes. Controlled mixing is important to ensure burning occurs at the burner rather than downstream in the furnace.

Maintenance is important for any technology because new equipment will not be effective if it does not have adequate on-stream performance. Equipment that will be used in a continuous high production environment must have good reliability, require relatively little maintenance and be easy to maintain whenever service is required. There are several aspects of burners that need to be considered relative to maintenance. Cracking furnaces have relatively high temperatures (>1200°C or 2200°F), which means burners must be capable of withstanding the higher heat levels. Any metal parts must be made of the proper alloys and have minimal exposure to the heat. This is especially important if a burner needs to be shut down suddenly while the furnace is still hot. Bringing this same burner back online when the burner tips (fuel injectors) have had no convective cooling allows the gas to be subjected to temperatures that promote coking of the fuel gas if the burner is not designed to minimise this effect.

The higher propensity for coking in cracking furnace service mandates that fuel injectors be designed to minimise the potential for coking leading to plugging. Fuel-gas injectors must be easy to clean or to replace while the burner is in service, ensuring the furnace does not need to be shut down for maintenance. The burners also need to be capable of handling some degree of thermal cycling as furnaces are ramped up and down at various times for the decoking cycle, for example. Maintenance should be simple, without the need for specialised tools or

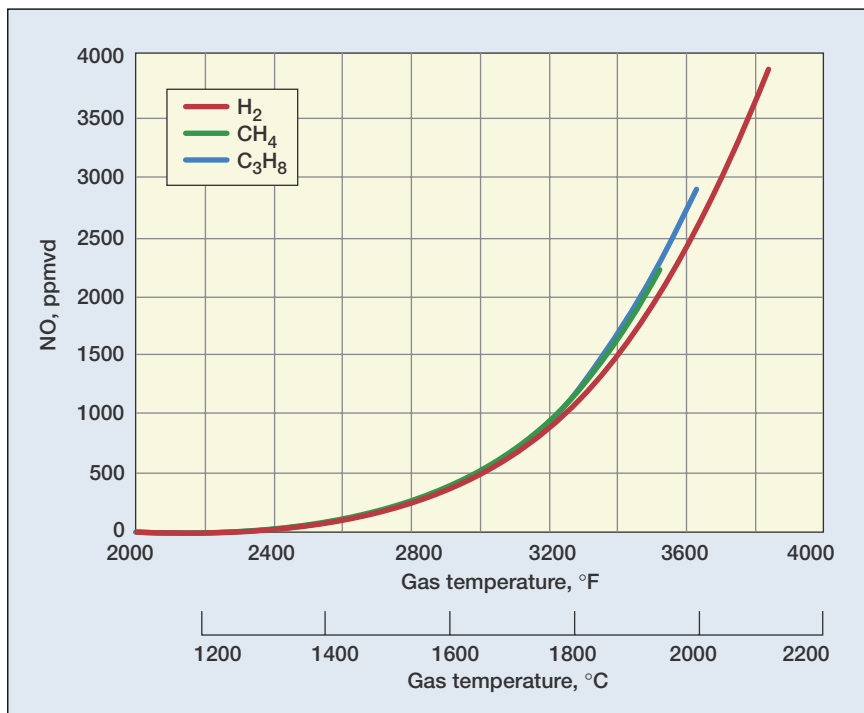


Figure 1 Equilibrium NO_x predictions for stoichiometric combustion of a fuel with air

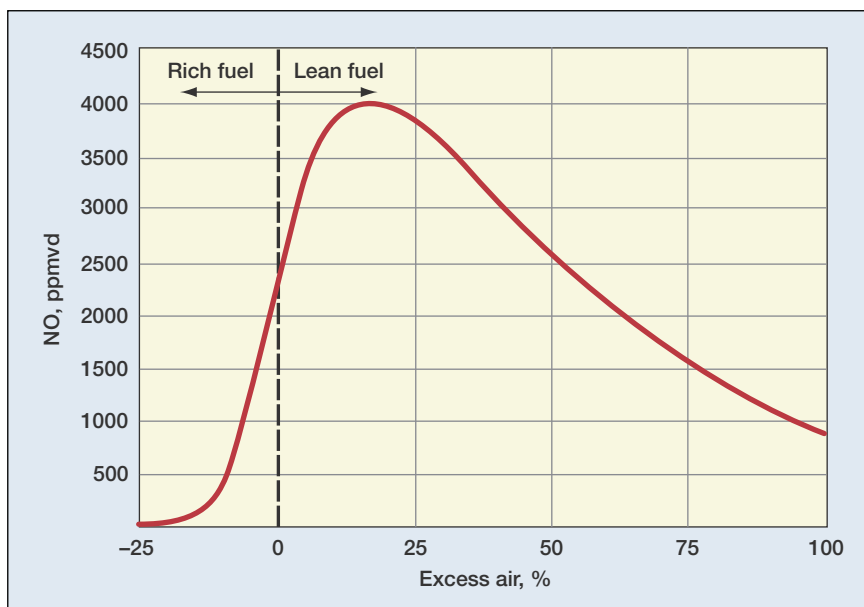


Figure 2 Equilibrium NO_x predictions for combustion of CH_4 as function of excess air level

numerous replacement parts. Ideally, maintenance can be performed quickly and easily by site maintenance personnel or furnace operators.

Most petrochemical plants have regulations limiting their pollutant emissions. Of particular interest with burners are NO_x and CO emissions. Thermal NO_x is exponentially dependent on temperature, as shown in Figure 1. NO_x is also dependent on the fuel/air mixture composition, as shown in Figure 2 and the volume of combustion products recirculated back through the flame, as shown in Figure 3. These three figures are based on adiabatic equilibrium conditions where there is no heat loss from the flame. The temperatures are higher and therefore the NO_x levels are

much higher than for actual conditions where there is significant heat loss from the flame. The higher temperatures associated with cracking furnaces naturally generate high NO_x levels compared to lower-temperature process heaters. The higher levels of hydrogen in the fuels used for cracking furnaces also tend to increase NO_x emissions, because of the higher flame temperatures associated with hydrogen. These factors make minimising NO_x emissions especially challenging in cracking furnaces. CO emissions are typically low at normal operating conditions where the furnace is hot. However, CO emissions can be fairly high during startup conditions when the furnace is relatively cold.³ While CO rapidly

decreases once the furnace is heated, the transient CO spike during startup can cause emissions to significantly exceed permitted levels. Some burner designs have added operational complexity to minimise problems associated with high CO emissions during startup. This needs to be considered in the control of pollutant emissions from the process.

Burner development

A new burner (patent pending) has been developed that incorporates the Coanda principle for controlling fluid flow, mixing and stability. This aerodynamic effect is sometimes referred to as boundary layer attachment. Figure 4 shows a diagram of the Coanda principle. A fluid is supplied to a chamber with a small opening. A curved surface with a radius "R" within a specified range causes the fluid to be drawn against the surface instead of being injected straight out of the nozzle. The fluid outlet velocity must be within a certain range and the surface must have the appropriate characteristics for this principle to apply. If the fluid velocity is too low or too high, the fluid will not attach to the surface.

A drawing of the new burner is shown in Figure 5a, which is a natural draft version of the burner. The new burner is also available in a forced draft version. One of the key design features is the shape of the tile, which has inner and outer Coanda surfaces integrated into the overall design to augment both mixing and stability within the burner. Figure 5b shows a process schematic for the operation of the Coanda burner. Ambient air is entrained into the burner by the draft in the furnace. A damper is used to control the airflow into the burner. Depending on performance requirements, there may be up to three flame zones.

In the primary flame zone, a distribution ring is used inside the burner, where a small portion of the fuel is premixed with combustion air to produce a small flame around the inside circumference of the burner tile (quarl). All of the combustion air, but only a fraction of the fuel goes through this zone. This zone provides a constant and uniform flame front that greatly enhances the turndown range for the burner. The fuel lean mixture (high excess air) minimises NO_x formation. It also minimises the potential for flashback, because the flame speed is much lower at fuel lean conditions compared to stoichiometric conditions. The products from this primary zone serve to coat the inner surface of the staged flame envelope, which further reduces NO_x in the downstream flame zones.

In the secondary flame zone, a relatively small amount of fuel is injected into the core of the burner through the rectangular openings on the side of the burner tile. These openings are much

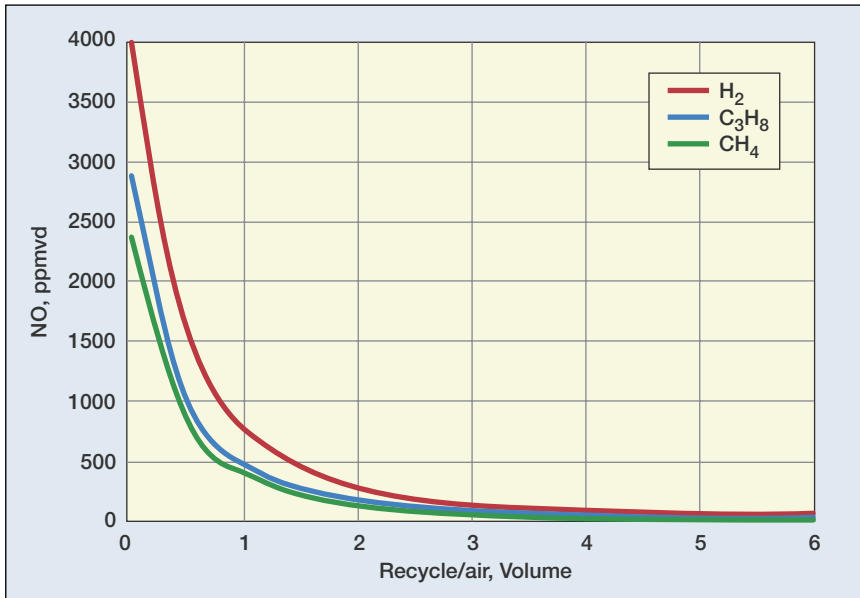


Figure 3 Adiabatic equilibrium NO_x predictions for stoichiometric combustion of fuel combusted with air as function of volume of combustion products (2000°F or 1100°C) recycled back into the flame

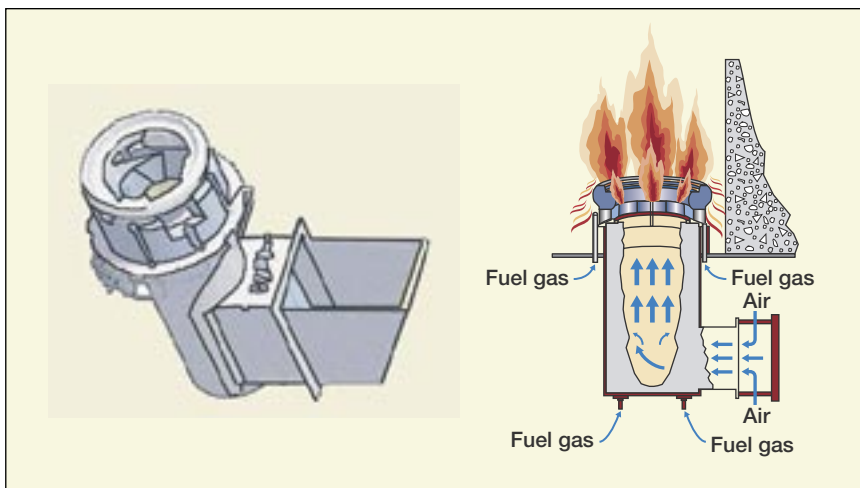


Figure 5 COOLstar Halo burner: Drawing (left) and process schematic (right)

larger than the conventional openings used in typical low-NO_x burners. A large volume of furnace gases is entrained into the primary flame zone by the high velocity fuel gas flowing through the openings. The fuel injected into the tile is transformed into a thin film of appreciable surface area by the inner Coanda surface. The outer portion of this fuel gas film mixes with both entrained furnace gas and air as it moves through the tile to form a secondary flame along a ledge just above the inner Coanda surface. Although this zone is heavily diluted by furnace gases, the flame is stable because of the heterogeneous mixing and because of the stability of the primary flame zone.

In the tertiary flame zone, the majority of the fuel is injected along the outside of the tile along an outer Coanda surface designed to improve the stability of the staged flame, while also increasing the mixing of the fuel gas and combustion products. The fluid dynamics in this zone

provide flame shaping to reduce the size of the flame envelope compared to conventional burner technology. The enhanced surface area created by the Coanda effect allows the staged fuel to entrain a large volume of furnace gases while maintaining a stable staged flame. The staged flame front remains anchored by a fuel rich inner boundary layer also created by the Coanda surface. The combustion air for the outer flame zone comes from the remaining air flowing through the centre of the burner.

This burner has some properties that give it enhanced performance.⁴ It can entrain more furnace gases than previous designs, where furnace gas entrainment has been limited by the lower flammability limit for the mixture of the fuel, air and inerts. In many burner designs, if too much furnace gas is blended into the fuel and air, the mixture can go below the flammability limit and the flame will go out, because the mixture is fairly homogeneous. This is

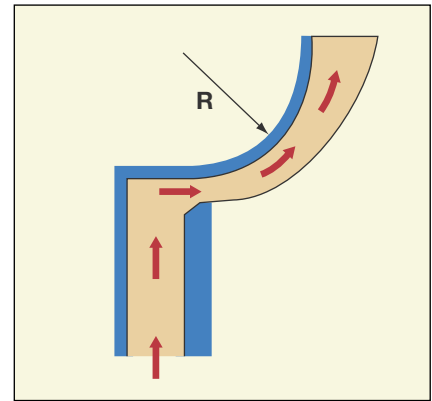


Figure 4 Coanda principle

problematic if the furnace is operated at low excess air levels in which case the furnace flue gas contains little available oxygen to compensate for swings in draft and O₂. The new burner can entrain many times the volume of furnace gases compared to other burners, because the mixture at the inner boundary layer of the Coanda surface is heterogeneous and is not well blended. There is a distinct region close to the Coanda surface that has a higher concentration of fuel, which creates a stable flame. A benefit of this high furnace gas entrainment into the flame is more uniform heat distribution and shorter flames due to the film. The effective flame length can therefore be designed to be shorter or longer to more uniformly distribute the heat along the furnace wall.

Another important benefit of the proprietary Coolstar Halo burner design is a wider turndown range. The premix distribution ring inside the burner helps to anchor the flame over a wide range of firing rates. Although only a small portion of the fuel is used in the premix distribution ring to minimise NO_x, a stable ring of flame is produced to provide a constant flame front. This permits stable burner operation over a wider range of firing rates. It also allows high hydrogen fuels to be utilised with expanded turndown ratios when the premix primary zone is designed to operate at a fixed pressure. This combination of high hydrogen fuels and wide turndown ratios is difficult to achieve in many other advanced burner designs.

The flame quality is improved because of the increased gas velocities that help minimise interactions between adjacent flames. The flames are less easily disturbed because of the increased momentum. This is especially apparent during startup, as the burner tile becomes highly radiant within moments of startup. The flames also tend to be significantly shorter than comparable low-NO_x burners. Shorter flames reduce the chances for flame impingement on process tubes in the convection section and minimise the chances for flame-to-flame interaction between adjacent burners. These

interactions can significantly increase flame lengths, possibly even causing flames to coalesce into larger flames, which can lead to flame impingement and increased NO_x emissions.

It is well known that entraining furnace gases into the flame is a proven technique for reducing NO_x emissions.⁵ While these gases are hot, they are nearly inert and still relatively cool compared to the flame. The entrained flue gases reduce the gas temperatures in the flame and minimise hot spots, which both help minimise NO_x formation. The entrained furnace gases absorb heat released by the burner to help reduce the furnace temperature and minimise NO_x formation. The additional capability to entrain large amounts of furnace flue gas has not only further reduced NO_x, but has also reduced CO in cold furnace conditions by allowing the capacity to reburn the CO as it is recycled through the burner tile.

Burner development

The capability of lighting off at a low rate means the furnace can be ramped to the desired rate without requiring some burners to be shut off to achieve a low overall firing rate. This can now be done with all burners on at a low rate instead of having some burners on at a higher rate and some burners off, which helps to maintain a more uniform draft across the furnace. It also helps minimise coking in the fuel injectors, which can be accelerated in a furnace at an elevated temperature where the burners are off and then turned on. Current testing indicates that turndown ratios of 10:1 should be possible. For decoke cycles, minimum rates as low as 0.1 MW (0.3 MMBtu/hr) can be achieved.

The heat flux profile in a cracking furnace is important to maximise the process fluid throughput. If there are hot spots in the profile, either the firing rate may need to be reduced or the furnace shut down sooner because of increased coking. NO_x emissions are typically less than 25 ppmvd at 3% O₂ at furnace temperatures of 1200°C (2200°F), depending on the fuel composition and operating conditions.

As previously discussed, one of the challenges for burners in cracking furnaces is high CO emissions during cold furnace startup conditions. In many cases, operating permits limit CO emissions under all conditions including startup. CO emissions for the new burner are typically less than 50 ppmvd even during cold furnace startup, where most burners normally produce high CO emissions unless they have been specifically designed to minimise CO. One technique that is used in some burner designs is to have a set of startup fuel injectors to increase fuel-air mixing and minimise CO. Unfortunately, these

injectors usually produce much higher NO_x emissions. However, because the furnace is colder during startup, NO_x emissions are naturally minimised. When the furnace temperature has increased to a certain level, at least above 540°C (1000°F), the fuel injection is switched over to the normal operating injectors. At the higher temperatures, the CO emissions are dramatically reduced, but NO_x emissions are beginning to increase. The normal operating tips for those burner designs have been designed to minimise NO_x. It can be shown that CO emissions for the HALO burner are low even during startup when the furnace is cold, without the need for startup fuel injectors or complicated startup procedures. This greatly simplifies operation, while minimising both NO_x and CO emissions compared to other burner designs.

Conclusions

Improvements to the newest burner developed for use in cracking furnaces include:

- More uniform heat flux profile
- Wider turndown
- Flame is stable over a wide range of operating conditions
- High combustion efficiency from startup to shutdown
- Easy maintenance
- Low CO and NO_x emissions.

Depending on the performance requirements, the burner may have up to three combustion zones: a lean premix primary zone, a heterogeneous secondary zone with fuel-rich and highly diluted regions, and a tertiary flame zone with enhanced fuel staging and furnace gas entrainment. This burner has been extensively tested under a wide range of operating conditions and fuels with no adverse operational issues.

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Roger Poe is research associate with John Zink Company LLC in Tulsa, Oklahoma, USA. Email: roger.poe@johnzink.com

Ashok Patel is with John Zink Company LLC in Tulsa, Oklahoma, USA. Email: ashokpatel@johnzink.com

Charles E Baukal is director of the John Zink Institute in Tulsa, Oklahoma, USA. Email: charlesbaukal@johnzink.com

Daniel Wright is with John Zink Company LLC in Tulsa, Oklahoma, USA. Email: danielwright@johnzink.com