A step-by-step approach to managing emissions

A comprehensive review of combustion systems and controls underpins a strategy for emissions reduction

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Nitrogen oxides, or NO_x, result when the combustion of a mixture of air and fuel in a combustion engine or device produces temperatures high enough to drive endothermic reactions between atmospheric nitrogen and oxygen in the flame. In areas with large concentrations of industry or heavy traffic, the amount of NO_x in the atmosphere can reach significant levels and negatively affect the environment and human health.

In light of these environmental and health hazards, the hydrocarbon processing and petrochemical industries face ever-increasing environmental regulations. Over the past two decades, a variety of measures aimed at mitigating the negative impact of emissions such as NO_x have also emerged. These include a number of Federal NO_x emission reduction programmes and the Clean Air Act Amendments of 1990, which aim to address these health concerns and ultimately reduce common air pollutants, including overall NO_x.

To remain successful, companies must simultaneously meet the rising demands of these emissions regulations while keeping operating costs at a minimum. Striking this balance can be challenging. Various emissions requirements have made the need for timely and accurate emission data collection and reporting more important than ever. And companies must address ageing and inefficient technologies, which can become a drain on resources.

Still, it is possible for companies to address the balancing act of cutting emissions — specifically NO_x — across the board while managing the cost of compliance. Choosing a comprehensive, single-source solution for reducing NO_x emissions can help lower the total cost of ownership and achieve emission reduction goals. The ideal solution combines new and innovative process technologies that optimise the combustion process — from start to finish — while providing online control and monitoring in real time.

When applied to a process heater during the production of ammonia, for example, these types of solutions can effectively reduce NO_x emissions while maintaining an optimal level of system performance. To successfully implement a NO_x emissions-limiting solution, you must examine all points in the ammonia production process, including:

- Fuel composition and control of the gas train
- Burner design and management
- Flue gas recirculation
- Air and temperature control.

Beyond these points in the production process, a comprehensive emissions-reduction strategy can include post-combustion solutions, such as selective catalytic reduction (SCR), stack emissions monitoring, and regulatory compliance and reporting.

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Fuel gas control

The first step in reducing any process heater's NO_x emissions begins by focusing on the combustion of fuel. As hydrocarbon fuels combust, the high-temperature reaction forms pollutants when the combustion conditions achieve peak flame temperatures or when fuel and air mixtures stray from optimal stoichiometry in any flame zone of a specific burner design. Although the flames are contained inside the heater, controlling the formation of pollutants, such as NO_x, carbon monoxide (CO) and sulphur oxide (SO_x), actually begins by looking outside the heater at the fuel gas control skid and air control devices.

Most installations consolidate fuel gas instruments and controls to a single location in a fuel gas skid or fuel train. The heater and skid can be fed with a variety of fuels, ranging from commercial-quality natural gas to refinery gas, to process off-gases. The mix of constituents in the fuel gas can dramatically affect heater emissions. Heavier hydrocarbons tend to be more difficult to mix with air and burn more slowly, and this decreased rate of reaction can increase the impact of a NO_x formation pathway called prompt NO_x. The presence of hydrogen in fuel gases can counter this by accelerating combustion rates and, with the proper burner design and air-to-fuel ratio control, can mitigate reactions that increase NO_x.

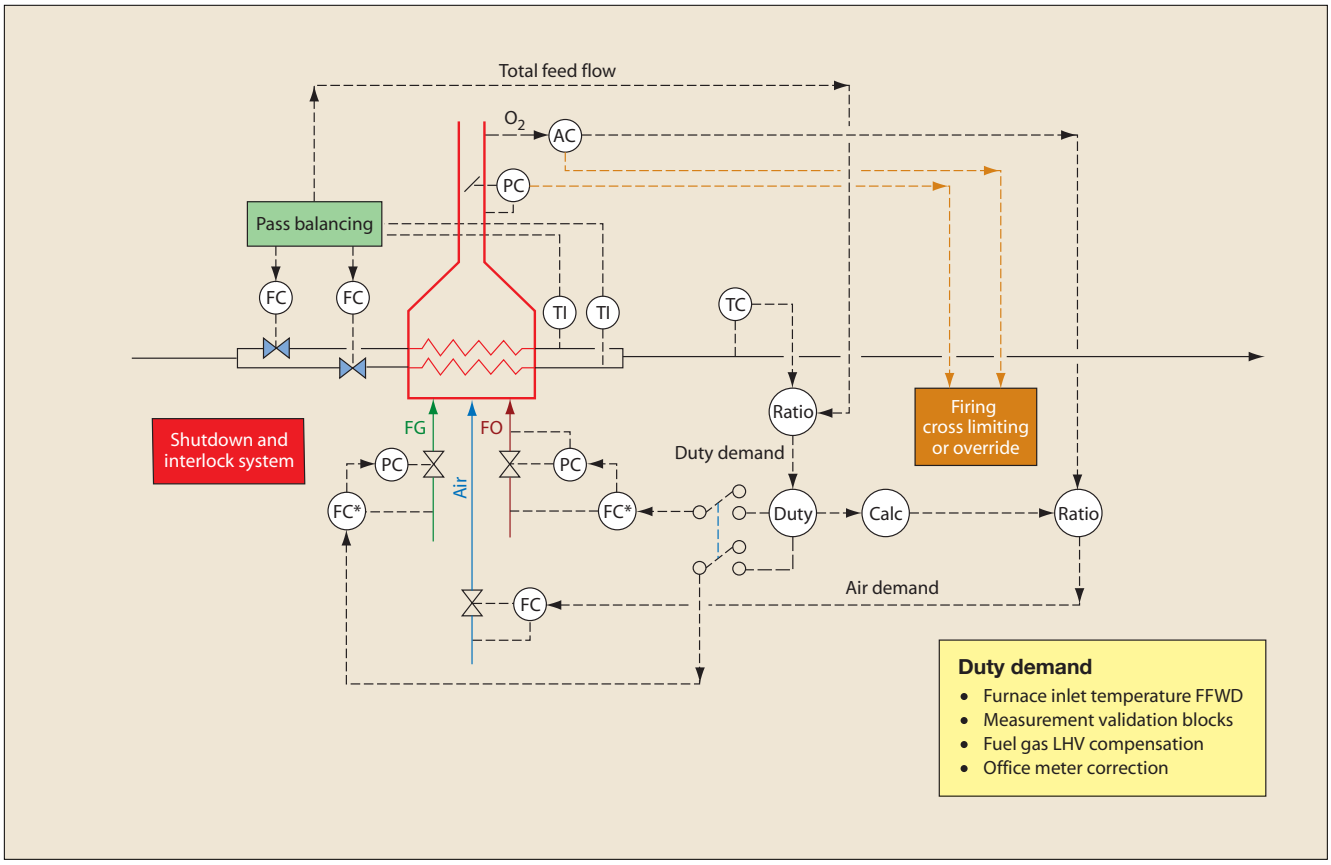


Figure 1 Fired heater advanced regulatory controls

To reduce emissions from hydrogen or heavier hydrocarbons, you must also understand how to detect the range of fuel composition changes. Active adjustment of fuel and air ratios can combat the formation of emissions by reducing variations in flame temperature and combustion conditions. A variety of methods can help measure fuel composition or quality, including complex gas calorimeters for widely varying fuels and tools to measure simple mixture density for slight changes in hydrocarbon content. Overall, diligent design and control system compensation can enable active air-to-fuel ratio adjustments to minimise peak flame temperatures and provide the correct feed to burners for pollutant control.

Once measured, changes in fuel gas can then lead to adjustments in air-to-fuel ratio with high-resolution control actuators in the fuel skid. Air registers located on the burner "windbox" assembly can enable combustion air control, while dampers in the stack or air piping can control available heater draught. By finely tuning air-to-fuel ratios, burners can operate at optimal conditions and reduce peak flame temperatures and burning speeds.

The ideal actuators combine high-resolution control architecture capable of 0.1-degree positioning accuracy with intelligent positioning feedback. This enables the integration of high-performance valves with advanced control algorithms. You can then apply actuators to fuel control valves, pressure-reducing valves, stack dampers, air control valves and process control valves. Today, many available valves operate on a 24 VDC power supply and a digital communication network. This architecture provides the advantage of distributed intelligence for increased reliability and improved safety through error reporting.

In addition, high-accuracy fuel flow meters applied to fuel skids can provide real-time adjustment capabilities to air-to-fuel ratios or fuel blending control. Such meters offer precision flow reading and are corrosion resistant, making them ideal for most hazardous environments where NO_x emissions frequently originate.

Multiple air-to-fuel ratio control

Many industrial process heaters may use multiple fuels to provide heat to the furnace. Refineries, for example, often use a combination of fuel oil and fuel gas, and the pulp and paper industry often taps a combination of gas, coal or biomass such as wood chips to provide thermal energy.

In cases that involve multiple fuels, the control strategy may employ an overall duty control that takes contributions of duty from each fuel source. Ideally, each source has its own air flow so you can determine and provide individual air-to-fuel ratios. This is not always possible in practice, however. As a result, it becomes necessary to estimate the overall air-to-fuel ratio and the overall excess air required.

Typically, furnaces will operate with one fuel as a base load and another type of fuel that you can adjust to achieve the desired outlet temperature. In process heaters with both oil and gas fuel flows, the oil flow often serves as a base load but, as it is likely to be a heavy oil residue from the bottom of one of

the cracking units, it can be very viscous and difficult to control.

Pressure control maintains the fuel gas flow into the process heater. As with the single-fuel conditions, measuring the lower heating value (LHV) or calorific value of each fuel is beneficial, as you can apply these values as a disturbance or feed-forward effect in the control strategy.

Figure 1 demonstrates this type of process heater control strategy from a functional perspective, which can help set the air-to-fuel ratio and control the process heater outlet temperature. In addition to implementing this in traditional regulatory control strategies, you can also implement this strategy using a multivariable controller.

In this specific strategy, the temperature of the process fluid leaving the heater is normally either the master controller or the primary controlled variable. This controlled variable cascades onto the duty controller, which in turn sets the required fuel flow of each of the fuels fired in the furnace.

Also in this control strategy are feed-forward or disturbance variables that include the LHV of each fuel and the pre-furnace inlet temperature of the process fluid, as well as the impact of changing the process feed flow rate into the furnace. In Figure 1, the desired air-to-fuel ratio sets the air flow into the furnace heater, while adjustments to the stack damper position maintain the draught pressure. In a natural draught furnace, directly adjusting the stack damper position helps control excess air.

Other control strategies commonly seen on process heaters include cross-limiting controls, which ensure that as the process outlet temperature calls for more duty, the air will be increased ahead of the fuel, thus making sure sufficient air is always present. Conversely, when the process calls for less duty, the dynamic response ensures, cutting the fuel flow before reducing the airflow.

Heater burners

After establishing optimal control and metering of fuel, the next step in reducing NO_x emissions involves examining a process heater's burner design and integration with heater parameters. Every process heater design provides different conditions that can affect the operation of burners and variables, such as burner spacing, distance between burners and process tubes, radiant heat flux, downstream flow field development, and even the location of stacks and sight windows can all impact the formation of pollutants. Taken as a whole, successful emissions control requires designing burners for each specific application and modelling them into the process conditions for optimal emissions performance.

An ideal burner design emits the lowest level of NO_x emissions over a wide range of operating conditions by featuring a smaller visible flame profile and burner size when compared to conventional raw gas burners. In addition, an ideal burner design also enables lean pre-mixing and deep fuel staging, which can fit with both retrofits and new heaters and reformers.

An ideal burner design enables lean pre-mixing and deep fuel staging, which can fit with both retrofits and new heaters and reformers

At work, the ideal lean pre-mix burner design achieves lower emissions through several steps. First, these types of burners maintain a larger portion of the available momentum of combustion reactants along the burner's centre line, which allows for better resistance to furnace currents. A steep velocity gradient along the burner axis also provides more rapid mixing for the remainder of the fuel and air. Increased fuel along the central axis of the burner removes duty from the secondary nozzle-mix fuel stage, which is influenced more easily by furnace currents.

An ideal lean pre-mix burner design also provides increased application flexibility to allow for high hydrogen content in the fuel gas, wide turndown ranges and stable flame shapes. When successfully implemented, such burners provide increased heat release without producing increased flame length, non-compliant NO_x levels or excessive draught requirements common with other burners.

Finally, in addition to adequate burner design, furnace modelling services and advanced computational fluid dynamic tools can help ensure successful integration with all furnace parameters. Such services and tools enable the modelling of burner installations in specific conditions so that burners can provide optimal emissions and heat transfer performance. Modelling combustion inside the furnace also prevents excessive heat flux to process tubes and reduces the likelihood of any unexpected furnace currents that cause flame drift.

Burner management systems

The next step in reducing a process heater's emissions is to examine the operation of a burner management system (BMS), which is responsible for the safe startup, operation and shutdown of a boiler or fired heater. The proper operation of a BMS is crucial to the safety of any industrial boiler. Such systems monitor and control igniters and main burners, among other tasks, and can apply flame scanners to detect and discriminate between the igniter and main flames. A BMS also employs safety shut-off valves and pressure, temperature, flow and valve position limit switches.

A BMS is required to meet the applicable codes for large furnaces and boilers (such as NFPA 8502 in the US). Historically, a BMS has been a standalone relay or PLC system integrated into a plant automation strategy using a communications gateway. Many control platform suppliers do not offer certified BMS solutions, while most BMS suppliers do not provide systems that exhibit the capabilities of a modern control system.

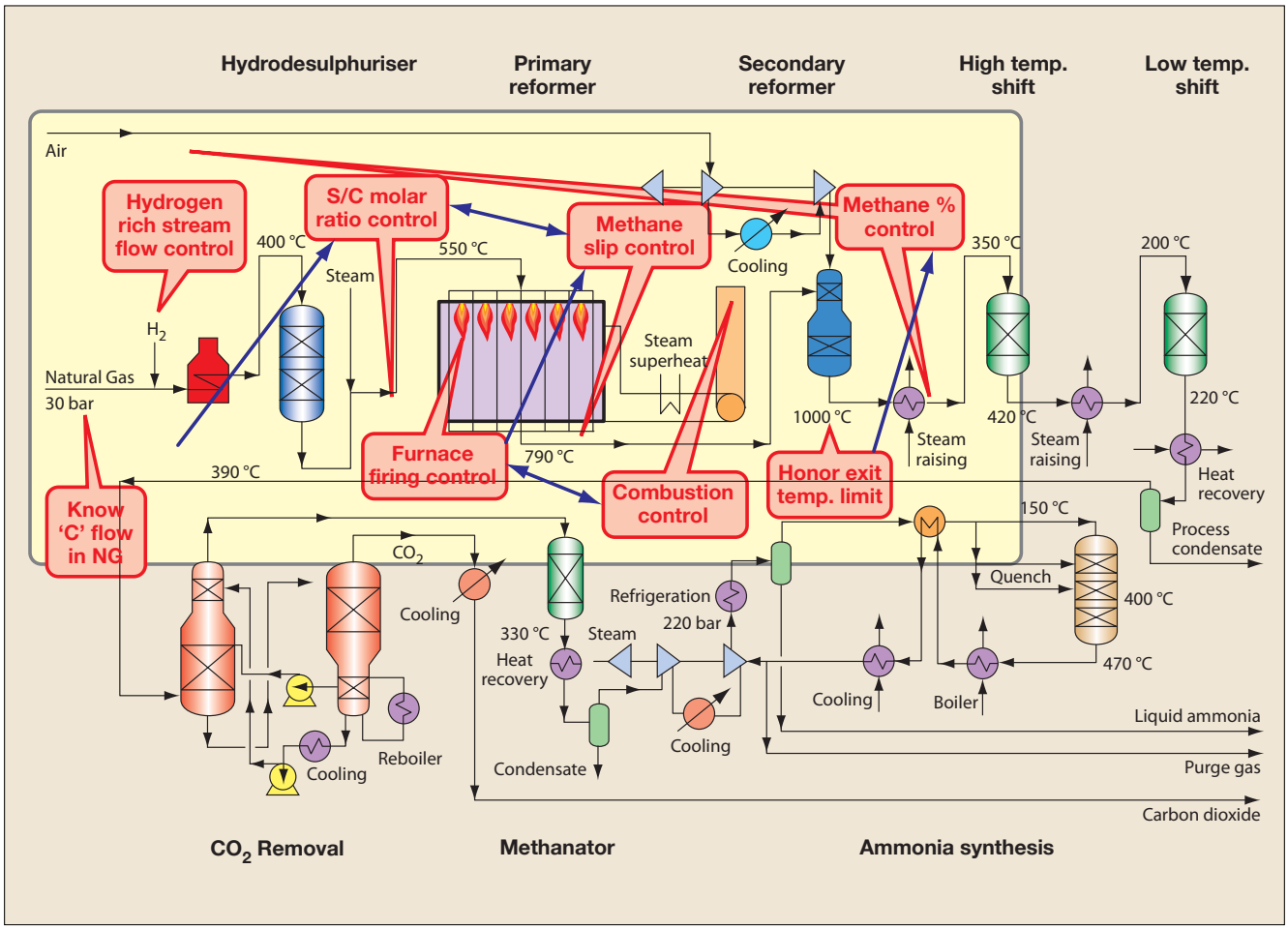


Figure 2 Example of a typical controller for an ammonia primary reformer

Engineering a gateway to support automation and a human-machine interface (HMI) with acceptable response times can also be challenging. However, solutions have recently been developed that provide tight integration of a BMS into a modern control platform. This can provide many functions, including: peer-to-peer communication between the BMS and the control system; use of a common fault-tolerant Ethernet; integration of alarms and events; and use of a common HMI. This type of solution addresses the challenge of providing improved integration while maintaining a dedicated separate safety management system and enables improved control.

This approach results in:

- **Improved profitability** Increased up-time due to the improved availability of the burner management system; elimination of unreliable relay-based systems that tend to fail, causing spurious trips of the process; and reduced maintenance costs inherent in self-checking and diagnostic capabilities readily available to control systems, information systems and plant personnel
- **Improved safety** Risk reduction for people, plant and environment; and personnel safety improved by not having to access the old relay boxes, which may be located in hazardous and high-temperature areas of the boiler
- **Regulatory compliance** Meeting required regulatory codes associated with the safe operation of large process heaters and boilers.

Process heater outlet temperature control in a steam methane reformer

Improving a boiler or process heater's overall efficiency of service is an indirect yet effective way to reduce NO_x emissions. Improving process efficiency results in less fuel consumption per tonne of process feed, which means more product can be made in accordance with the same NO_x emissions limits that may exist at the plant.

For example, with a steam methane reformer, the first step of the steam reforming process takes place in the primary reformer, where the hydrocarbon and steam mixture that is preheated to 505–520°C is passed downwards through vertical tubes containing a catalyst (typically nickel). The primary reformer is a fired heater, where the sensible heat and the heat of reaction are transferred by radiation from a number of wall burners to the catalyst tubes.

To ensure complete combustion of the fuel gas used in the burners, the burners operate with 10% excess air, which corresponds to 1.8% oxygen in the flue gas. The hydrocarbon in the gas, which leaves the primary reformer, then converts to methane. The exit temperature of the primary reformer is about 800°C, which is also the inlet temperature to the second step of reforming.

The following primary reactions occur in this process:

$$CH_4 + H_2O \rightarrow CO + 3\,H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$

To achieve the right level of conversion of feed gas to CO_2 and H_2 (syngas), it is necessary to tightly control the ratio of natural gas and steam added to the reformer. Usually producers aim to control steam to carbon content in the natural gas feed. You must not operate the reformer with a low steam-to-carbon ratio, as this could thermodynamically lead to carbon formation, especially inside catalyst particles. It is also important to avoid poisoning the catalyst with sulphur compounds, as this can also promote carbon formation. At the same time, a steam-to-carbon ratio that is too high affects the activity of the catalyst and also means wasted energy and fuel.

To tackle these challenges, the following control strategies can be implemented with a multivariable predictive controller application:

- Minimise steam consumption by optimising the steam-to-carbon ratio in the primary reformer in tandem with the overall carbon number predicted from gas composition or molecular weight or specific gravity or manually entered lab analysis
- Reformer exit temperature control along with furnace firing and combustion control in tandem with the off-gas flow from the purge gas recovery unit
- Minimise CH_4 slip from secondary reformer subject to maximum exit temperature constraint. This ensures that the primary reformer is running at a reasonable efficiency. Methane slip is the amount of unreacted methane that passes through the reformers and typically occurs at a level below 1%.

Although controllers do not directly maintain NO_x emissions, they can be included as a constraint to prevent violating overall NO_x emissions restrictions. This may limit the amount of feed processed.

Overfiring air for staged combustion

In some large industrial boilers or waste gas incinerators, NO_x emissions can become a limiting factor to operation. In these instances, you can lower the peak combustion temperature by performing a staged combustion. The peak temperature of combustion significantly affects the amount of NO_x a boiler or heater produces. Higher temperatures lead to more oxidised nitrogen.

Consider the following staged scenario: primary air — typically 70–90% of the total air required — is fed in a sub-stoichiometric ratio with the fuel, which results in a lower peak temperature. As a result, the combustion products contain more nitrogen than NO_x. This process will also result in incomplete combustion and high levels of CO. The second-stage area, just above the primary combustion zone, completes conversion of the CO in the flue through the addition of more secondary air into the boiler by overfiring the air ports.

This converts all of the CO to CO_2, and lowering the overall peak temperature results in the production of lower amounts of NO_x for the equivalent amount of energy supplied or steam generated in the boiler. The relatively low temperature in the secondary stage helps prevent the formation of NO_x, and the location of the secondary air ports, along with the mixing of overfire air, are all critical to maintaining efficient combustion.

This modified process allows for more degrees of freedom within the overall control strategy because it adds two areas of air to the process. Control of this process is enhanced when measurements of flue gas conditions exist in more than one area.

The control strategy is well suited to multivariable controllers, but it should also include CO levels as a constraint. Poor operation of staged combustion will result in significant levels of CO in the flue gas. Thus, the CO constraint must be handled as a non-linear input, as it will move very quickly to high levels if the air-to-fuel ratio becomes sub-stoichiometric, or if channelling in the heater occurs. This can result from poorly adjusted burners, which can lead to sub-stoichiometric conditions in a boiler, even if the stack analyser indicates an overall excess of air.

Flue gas recirculation

Flue gas recirculation (FGR) involves recycling and redirecting 15–30% of the flue gas to the burners, which dilutes combustion gases. Doing so also reduces the peak flame temperature.

FGR is not universally applicable. Since FGR limits thermal NO_x formation but has little effect on fuel NO, it is more effective in natural gas-fired heaters than in oil-fired heaters. Only mechanical draught heaters with burners that can accommodate increased gas flows are amenable to this technique. However, conversion of natural draught heaters to mechanical draught operations as part of a FGR retrofit is possible. Required FGR retrofit components include ductwork, recirculation fans and controls to vary damper settings on variable-load heaters. The difficulty of retrofit in crowded plants may be greater.

For FGR to be successful, process needs must be compatible with the lower flame temperatures it generates. Achievable emissions reductions are a function of the amount of flue gas recirculated, and they are thus limited by efficiency losses and flame instability at higher recirculation rates. Limited performance data and experience of industrial boilers suggest that reductions of 50–60% may be expected with natural gas-fired heaters, and somewhat less with oil-fired heaters.

Selective catalytic reduction

For very large energy-consuming processes, the total tonnage of NO_x emissions may require a more aggressive treatment than process, burner and control optimisation can offer. In these circumstances, post-treatment devices such as selective catalytic reduction (SCR) units can provide immediate solutions. In a SCR unit, pollutants undergo further reaction in the presence of a catalyst to greatly reduce the concentration of pollutants in the stack gases. Each unit is custom-designed for handling specific stack inputs, including pollutants, concentrations and flow rates for optimal conversion to harmless stack gases.

SCR systems have mostly been limited to large industrial installations. Over time, however, the technology and cost of SCR systems have evolved, making the device applicable to a wider range of processes and devices. As emissions regulations become more aggressive, a SCR system provides a positive assurance of compliance.

SCR systems are applicable to heaters that have both a flue gas temperature appropriate for the catalytic reduction reaction, as well as enough space for a catalyst bed to provide sufficient residence time for the reaction to occur. Specifically, several different available catalyst formulations make the temperature window fairly wide, ranging from approximately 250°C to more than 550°C. The installation of a SCR system on natural draught heaters requires conversion to mechanical draught in order to overcome the pressure drop that occurs across the catalyst. Finally, sufficient space must be available for ammonia storage.

The control system modifies the amount of ammonia that is added to the SCR system and used to convert NO_x to N_2 — all while maintaining NO_x emissions levels below their limits. The flow of flue gas acts as a disturbance variable within the control application.

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Excess air control

Maintaining low excess air minimises the air level above what is needed for complete combustion and lowers operating conditions. As a result, it also limits thermal and fuel NO_x formation and is a critical component in reducing overall emissions from process heaters.

Today, many process heater operators already minimise excess air levels in order to increase heater efficiency and decrease fuel requirements. You can reduce excess air levels on all process heaters, but this approach is most effective on mechanical draught heaters. Achieving better control of air flow — coupled with the higher pressure drop across the burners caused by the higher air flow — results in improved air-to-fuel mixing and allows for greater reductions in excess oxygen concentrations before they reach levels that negatively affect flame stability.

Lowering excess air levels normally requires minimal capital investment, although retrofit controls may be necessary for some older heaters. Achieving emissions reductions using low excess air depends on the initial excess air level, the fuel used and other heater-specific factors, with a

probable reduction range of 5–20%.

Also, very low excess air levels can lead to flame instability, as well as the formation of soot and increased emissions. A reducing atmosphere in the heater may also result in corrosion.

In addition to excess air control, a typical control strategy may include minimising pressure in the firebox to prevent over-pressuring. The same strategy may also monitor CO levels to ensure there are no pockets of incomplete combustion control in the heater.

A typical solution involves the use of a multivariable controller that aims to control 2–3% of O_2 in the flue gas by primarily manipulating the air damper in a natural draught furnace. In a forced draught furnace, the controller can be more precise by directly controlling the air-to-fuel ratio, which in turn adjusts the air flow to the heater.

Operating constraints are included in the multivariable controller and may act either to prevent further movement in an undesirable direction, or to directly adjust the operation to alleviate the constraint.

Examples of common operating constraints found in the multivariable control strategy include stack temperature, which impacts heater efficiency, as well as CO levels, draught pressure and any valve or positioner limits.

Monitoring

For an ammonia plant, emissions monitoring is typically required on steam methane reformer units. Natural gas and steam react in the steam reformer to produce hydrogen and CO_2. The reformer also introduces air to supply nitrogen. The process train then converts CO to CO_2 and removes the CO_2 while converting any remaining CO and CO_2 to methane. This yields a gas stream that is three parts hydrogen and one part nitrogen. The reformer then synthesises the process gas under high pressure to form ammonia.

The remaining process emissions from the reformer typically move to a stack, where the outflow is continuously monitored by gas analysers for NO_x and CO, by-products of the process. Oxygen is also typically monitored to adjust emissions concentrations to nominal conditions. In cases where emissions are combined from multiple emission sources, stack flow monitors can help measure overall stack volume. To satisfy other criteria air pollutant requirements, periodic stack test measurements are often required for particulate matter, including SO_2, NO_x, CO and/or visible emissions.

A monitoring system may include some or all of the following components:

- Sample probe
- Heated sample line (to prevent condensation)
- Sample transport lines

Proper quality assurance is critical to accurately calculating emission rates, which are typically capped at hourly concentration levels or mass emissions limits

- Calibration assembly (including calibration gas bottles)
- Moisture removal system
- Particulate filter
- Sample pump
- Sample flow rate control
- Gas analysers.

The probe and sample line are typically heated, and the sample transport lines are made of non-reactive tubing such as Teflon, stainless steel or glass to transport the sample from the moisture removal system to the sample pump, sample flow rate control and electrochemical cells. The moisture removal system is typically a chilled condenser or similar device that removes the moisture while maintaining minimal contact between the condensate and the gas sample.

The gas analysers can be assembled in a rack and installed within a cabinet, or they can be enclosed in an air-conditioned weatherproof enclosure known as a shelter, depending on available space and environmental concerns. While calibration of the gas analysers can be initiated manually by operators or technicians, most calibration control is done through an automated, optimised sequence that is initiated through either a distributed control system or programmable controller designed to minimise the downtime associated with the calibration checks.

These calibration checks, which are essentially real-time data and quality assurance checks, are typically analysed and collected by a dedicated data collection system that is designed to analyse and store emissions data and related quality assurance data. Proper quality assurance is critical to accurately calculating emission rates, which are typically capped at hourly concentration levels or mass emissions limits.

For most situations, implementing an ammonia plant emissions monitoring system that includes built-in calibration control can minimise costs by eliminating the need for a separate programmable controller. This is ideal for situations where the shelter or cabinet is isolated from the primary control network.

Compliance reporting

In the US, requirements for emissions data collection, record keeping and reporting for ammonia plants are typically detailed in Title V operating permits issued by individual states. These permits specify the monitoring frequency requirements around quality assurance and testing, as well as applicable state and federal regulations.

An integrated data collection and reporting system can help meet such requirements. The actual configuration of the data collection system depends on the permit specifics, but there are some common themes that exist for specific emission units. For a steam methane reformer unit, if a stack monitor is not installed on the stack to measure the overall volume of

gas out of the stack, the individual fuels consumed in the reforming process (or other combustion processes) must be monitored.

All fuels that contribute to stack emissions must also be monitored, including combustion fuels if combustion sources such as auxiliary boilers or heaters are routed to the stack. These fuel measurements are used to derive the overall stack flow rate, which is in turn used to calculate mass emissions of NO_x and CO in pounds per hour.

In many cases, the fuel measurements, if properly corrected for temperature and pressure, can also be used for calculation of the greenhouse gas emissions required under 40 CFR Part 98 based on emission factors, heating values or fuel sampling. If the combustion sources, such as auxiliary boilers, are large enough, stack flow monitors along with CO_2 and moisture analysers may be required on the stack for proper reporting of greenhouse gas emissions.

Combining combustion sources with reformer emissions can also require the NO_x and CO monitors provided to be capable of multiple ranges, depending on which units are operating. Range filters and appropriate scaling must be applied at the initial point of data collection, and daily calibration data from each range must be captured as well, in aggregate 15-minute or hourly segment averages. These averages are then converted to mass emission values using the stack flow calculation or measurement. Emission limits can also be placed on annual or rolling 365-day averages, which are put in place to effectively limit overall fuel consumption or unit operating times.

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