

# Ultra-low NO<sub>x</sub> Combustion in Industrial Water-steam Systems

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## Kurzfassung

### Ultra-low-NO<sub>x</sub>-Verbrennung in industriellen Wasser-Dampf-Kreisläufen

NO<sub>x</sub>-Verringerung ist ein Thema, das dauerhaft hoch auf den Prioritätenlisten steht. Das gilt auch angesichts der Tatsache, dass der aktuelle Focus sich mehr in Richtung CO<sub>2</sub>-Abscheidung bewegt.

Stork Thermeq, als Originalhersteller von Kessel-equipment, richtet sich im Segment NO<sub>x</sub>-Verringerung auf Neubauanlagen sowie bestehende industrielle Wasser-Dampf-Systeme. Im vorliegenden Beitrag wird die Verwendung von vorgemischter Verbrennung zur Anwendung in industriellen Kesselanlagen vorgestellt. Es werden die bestehenden Ursachen der NO<sub>x</sub>-Bildung in Industriekesseln besprochen. Möglichkeiten der NO<sub>x</sub>-Reduktion, inklusive Fuel- oder Air-Staging und Rauchgasrezirkulierung werden diskutiert. Weiterhin wird die vorgemischte Verbrennung in industriellen Kesselanlagen dargestellt. Die Realisierung dieses Prinzips in Kombination mit Fuel-Staging wird anhand des Beispiels des Stork Impulse-Gasbrenners vorgestellt. Experimente mit diesem neuartigen Brennersystem in Testanlagen ergaben NO<sub>x</sub>-Werte von 9 mg bei 3 % O<sub>2</sub> mit vernachlässigbar geringen CO-Emissionen und einer O<sub>2</sub>-Konzentration von weniger als 1 %. Allerdings ist dieses Ziel eine wirkliche Herausforderung bei größeren Multi-Brennern oder Systemen mit flüssigen Brennstoffen, wenn auf nachgeschaltete Filteranlagen verzichtet wird.

### Introduction

A significant portion of the world's energy demand is provided using utility boilers fired with fossil fuels. Energy is converted in various forms, the most significant of which is heated steam for use in the process industry or for expansion in a steam turbine to generate electricity. Recently, attention is drawn to this field because of two main developments: the ultra-high supercritical cycles (USC) for cycle efficiency improvement and the increasing attention to Carbon Capture and Storage (CCS) technologies. Both developments mean a radical departure from the current state of the art. Except in some variants of CCS technologies (most important oxyfuel firing), NO<sub>x</sub> emissions remain an important issue in both these fields. The high-intensity conditions that are present in the furnace of a USC cycle increase the potential for high NO<sub>x</sub> emissions, whereas in post-combustion (i.e. stack-) carbon capture technologies, NO<sub>x</sub> needs to be removed before the CO<sub>2</sub> capturing step to prevent degradation of the CO<sub>2</sub> separation step (e.g. poisoning of membranes, reduced CO<sub>2</sub> separating efficiency). Legislation tends to move to lower NO<sub>x</sub> emissions, usually with a time lag in demands for existing designs (which then need to be retrofitted to meet the new demands or be decommissioned) with respect to new designs. This means that the issues in connection with NO<sub>x</sub> mitigation are as alive as ever, both in existing as well as in novel plant designs.

The best way to tackle NO<sub>x</sub> emissions is at the root, i.e. through optimising the combustion process. This is best treated through burner optimisation, but also interaction between burners and furnace can be taken into consideration. In some situations, selective catalytic reduction processes can be employed to further reduce NO<sub>x</sub> emissions. Stack emissions of NO<sub>x</sub> which are still higher than legislation permits can be further reduced by post-combustion cleanup through a DENOX installation. These are however costly measures, both in equipment, operational complexity and in overall plant efficiency, and should only be considered as final measure. The first two items will be the topic of this paper. Further, the focus will be on gas- and oil-fired installations, although most of the mentioned topics are also applicable to pulverised coal combustion.

Stork Thermeq is an Original Equipment Manufacturer (OEM) of combustion systems industrial installations, for new built as well as for retrofit purposes. Further Stork Thermeq is a service provider for these installations. Therefore, our focus is on new technologies as well as on retrofitting existing technologies, and the consequences of these for operation and maintenance. For these businesses, a novel burner concept is being developed which employs premixed combustion as a means of further reducing NO<sub>x</sub> emissions. A proven technique in gas turbine combustion for several decades, it has not yet been translated to water-steam systems. This burner principle will be outlined in this paper.

This paper is set up into four main parts. First, NO<sub>x</sub> formation routes which arise in industrial boilers will be shortly reviewed. Then, some conventional NO<sub>x</sub> reduction measures will be presented. As one of the methods for further reduction of NO<sub>x</sub>, the application of premixed combustion to boilers will be introduced. Finally, some conclusions will be drawn with respect to the consequences and need for extreme reduction of NO<sub>x</sub> through the combustion process.

### NO<sub>x</sub> Formation Routes in Boiler Combustion

The formation of nitrogen oxides in combustion processes originates from two main sources: Molecular nitrogen (N<sub>2</sub>) and from nitrogen that is chemically bound in the fuel. For molecular nitrogen, two main formation routes of NO<sub>x</sub> are usually distinguished, namely the so-called thermal NO<sub>x</sub> and prompt NO<sub>x</sub>, yielding three main routes for the formation of nitrogen oxides. Most NO<sub>x</sub> is formed as NO in the flame, typically 90 % of the NO<sub>x</sub> of a natural gas – air flame is NO, however in low-NO<sub>x</sub>, low-temperature flames, the ratio can be shifted to NO<sub>2</sub>. For detailed information to the formation of NO<sub>x</sub> from combustion systems, the reader is referred to [1], a brief review will be given below.

#### Thermal NO<sub>x</sub>

Thermal NO<sub>x</sub> is formed in a process which is initiated due to the thermal dissociation of N<sub>2</sub> in the presence of oxygen. It is described by the well-known and generally accepted

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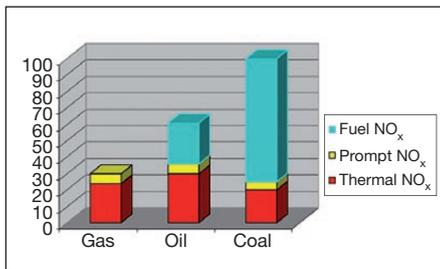
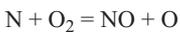
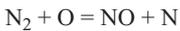


Figure 1. Contribution of different pathways in total NO<sub>x</sub> formation of different fuel types.

Zeldovich mechanism (hence the name Zeldovich NO<sub>x</sub> quoted in some literature references):

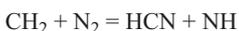
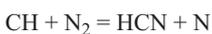


These reactions are highly dependent on temperature and the presence of atomic oxygen. A threshold of 1500 °C is widely used as the minimum temperature for which the thermal NO<sub>x</sub> route becomes significant, although there is some confusion since this value is sometimes mentioned in Kelvin. Studies involving chemical reaction kinetics show that the NO formation is significantly reduced at temperatures below 1400 to 1600 K. These reactions compete with the hydrocarbon oxidation process through the competition for the oxygen atom, O, especially the oxidation step of CO to CO<sub>2</sub>.

The Zeldovich mechanism is the major contributor to NO<sub>x</sub> formation in most gaseous and liquid fuel combustion. This, however, does not apply to pulverised coal flames, due to the lower overall temperatures and the local fuel-rich nature of these flames.

#### Prompt NO<sub>x</sub>

The formation of NO<sub>x</sub> through hydrocarbon radicals reacting with atmospheric nitrogen is called prompt NO<sub>x</sub>. In another popular definition, NO<sub>x</sub> formation that cannot be attributed to either the thermal or the fuel mechanism is lumped into prompt. It is arising in the early stages of the flame where the fuel is dissociated into intermediate species but not yet converted to final products. These intermediates attack N<sub>2</sub> to form intermediate species like HCN (hydrogen cyanide) which can subsequently oxidise to NO:



It is estimated that some 90 % of the prompt NO is due to the HCN intermediate pathway. Since it requires a hydrocarbon radical it is prevalent in fuel-rich regions of the flame. It has no temperature threshold attributed to it like in the thermal mechanism. Generally, it is the least significant mechanism for NO formation.

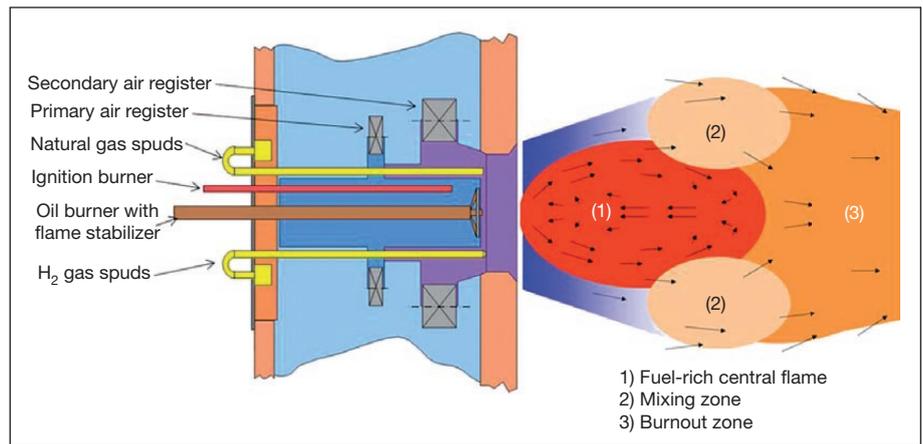


Figure 2. Air staging with the Stork Double Register Burner (DRB).

#### Fuel NO<sub>x</sub>

When the fuel contains chemically bound nitrogen, which is often the case in liquid or solid fossil fuels, it can be converted to nitrogen oxides in the combustion process. It is released from the fuel as a radical, which can either convert to NO<sub>x</sub> or to N<sub>2</sub>. That ratio is, amongst others, dependent on the presence of atomic oxygen at the time of N-radical formation. When it is not present, N<sub>2</sub> is formed; otherwise the reaction path tends to the formation of NO. Practically this means for fuel oil- or coal-fired installations that the devolatilisation (coal) and evaporation (oil) process need to take place under oxygen-deficient conditions.

Intermediate species in the fuel-N conversion are HCN and NH<sub>3</sub>. Consequently, the NO formation processes of the fuel NO<sub>x</sub> and prompt NO<sub>x</sub> pathways are closely linked. The conversion of fuel-nitrogen into NO<sub>x</sub> is increasing with fuel-N content of the fuel. In fuel oil-fired installations, some 50 % of the total NO<sub>x</sub> emissions can be attributed to fuel-NO<sub>x</sub>, to up to 80 % in coal-fired installations.

The contribution of each mechanism to practical combustion systems is illustrated in Figure 1. It illustrates the relatively small contribution of the prompt mechanism. Also, the large contribution of the fuel mechanism in liquid and solid fuel combustion is apparent.

Consequently, if one wishes to reduce the total NO<sub>x</sub> emissions of a flame, the primary route is to minimise thermal NO<sub>x</sub> emissions of a gas flame and the fuel NO<sub>x</sub> of liquid and solid fuel flames. As can be seen in Figure 1, the thermal NO<sub>x</sub> mechanism is also important for liquid fuels, especially so for fuel oils with a low or negligible fuel nitrogen content. For ultra-low NO<sub>x</sub> combustion, all sources of NO<sub>x</sub> need to be tackled, leaving the combustion system designer with some difficult choices and trade-offs. This will be further explained in the following section about methods for NO<sub>x</sub> reduction using the burners and furnace of a boiler installation.

### Conventional In-furnace NO<sub>x</sub> Reducing Measures

Practical techniques for reduction of NO<sub>x</sub> emissions use roughly two main methods: Minimisation of high-temperature regions and realising an oxygen-depleted primary combustion zone. As described in the previous section, the first method mainly aims at minimising the thermal NO<sub>x</sub> route, the second method the fuel NO<sub>x</sub> path. Consequently, the first is most effective for gaseous fuels, while the second method is chosen almost without exception for liquid and solid fuels. Several methods exist in practice for boiler combustion which implement one or both of these measures. The ones that will be discussed here are:

- air staging,
- using over-fire air,
- fuel staging and
- flue gas recirculation.

Other methods also exist. These are usually combinations of several methods; most notable is the reburning technique. This technique is complicated to realise, it is most often carried out for pulverised coal-fired units. Most of the instances other, less complex, measures suffice in yielding the same reduction in nitrogen oxides. It will not be further discussed here. Another example is selective catalytic reduction where additives are used in combination with specific conditions to reduce the emissions. This too will not be further discussed here, focus is on methods through smart guiding of fuel and air flows.

#### Air Staging

One of the techniques of minimising high-temperature regions is to separate part of the air flow from the main combustion zone. Practically this means that in the primary combustion zone, near the burner mouth, is sub-stoichiometric or oxygen deficient. Temperatures in a combustion zone are highest

when the fuel-air ratio is ideal, such that no oxygen or fuel exists after combustion. An oxygen deficiency causes incomplete combustion which decreases the temperature in the combustion zone, reducing thermal NO<sub>x</sub>. Moreover, as described in the previous section, this causes chemically bound nitrogen to be converted into atmospheric nitrogen rather than into NO. The prompt mechanism does not become prevalent since the nitrogen release from the fuel in the fuel NO<sub>x</sub> path is dominant over the N<sub>2</sub> conversion of the prompt path. However, prompt NO<sub>x</sub> increases and can become a factor when deep staging (highly oxygen-deficient combustion in the primary zone) is applied. It can be an issue in coal-fired installations where up to 50 % oxygen deficiency is applied with respect to the VOC (Volatile Organic Compounds, or that portion of the fuel that is in the gas phase and can hence take part in combustion), as investigations suggest [2].

Combustion in the primary zone is incomplete due to the lack of oxygen. The remaining fuel and intermediate combustion products are combusted in a burnout zone where the remaining combustion air is introduced. Although the final overall fuel to air ratio approaches stoichiometry, the temperatures at this zone are suppressed by the presence of combustion products of zone 1 and the introduction of still relatively cold fresh air. This minimises NO<sub>x</sub> production through the thermal pathway in this zone.

An example of a burner which employs air staging is given in Figure 2, where Stork's Double Register Burner, or DRB, is outlined. At the left hand side the burner cross section can be seen in the windbox, the flame is situated on the right hand side, inside the furnace. The combustion air is split using two registers, which can add swirl to the air flow. The primary register provides air mainly to the primary combustion zone (1), the secondary air register, larger than the primary one, provides largely the remaining air necessary for complete combustion. The fuel is injected in such a way that a central combustion zone (1) arises which is fuel-rich. Combustion products and the remaining fresh air are mixing in zone (2), while complete burnout follows in zone (3). This particular example shows two different gaseous fuels on top of the liquid fuel, namely hydrogen and natural gas, which are injected through separate gas spuds around the impeller flame stabiliser. The swirling action of the registers causes the existence of a large central recirculation zone which stabilises the flame through recirculation of hot flue gases back to the ignition zone. A flow pattern is indicated by the arrows in Figure 2.

Air staging is mostly used for firing liquid fuels because of the oxygen-deficient primary zone attacking fuel-NO<sub>x</sub>. However, due to its very stable and highly robust flame, the DRB-

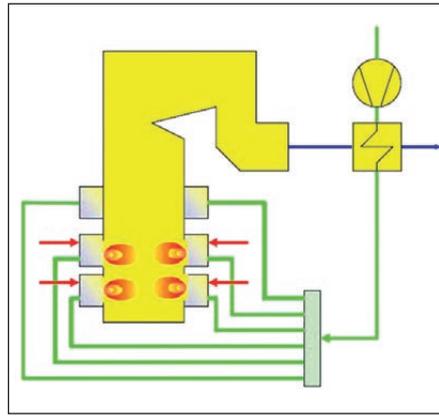


Figure 3. Air staging using over-fire air ports.

design is often used to fire a wide range of fuels, liquid as well as gaseous, with good low-NO<sub>x</sub> performance. It has become the "workhorse" for application to difficult circumstances, where flexibility, flame stability and unit availability are essential. One example is an installation firing seven different components on one firing system, of which two are liquids which are supplied through separate atomisers and where the components include waste streams of different origin.

#### Over-fire Air

Whereas air staging is a technique that is applied with the burner, an even better separation of air flows to the flame can be realised with over-fire air ports. A schematic drawing (also including air preheat) is given in Figure 3. This method is usually applied on top of burner air staging, to enhance its effect. As can be seen in Figure 3, not all the air is supplied directly to the burners, some of the air is directed to a location in the region of the burnout zone of the flames. As a consequence, the overall fuel-air ratio of all the burners is sub-stoichiometric. This creates a large combustion zone for fuel-nitrogen conversion to N<sub>2</sub> and, due to the (air staging) burner design, low overall temperatures. The burnout zone is realised by the injection of the over-fire air.

Due to the physical rather than aerodynamic separation of primary and secondary combustion air, this method is very effective in minimising fuel-NO<sub>x</sub> as well as thermal NO<sub>x</sub>. However, care needs to be taken to ensure proper burnout of the fuel in the over-fire zone; as soon as the combustion products enter the convection zone of the boiler, reactions are effectively frozen and any remaining CO leaves through the stack. The method is very effective for both liquid and gaseous fuel firing, due to the lowering of peak temperatures in the main combustion zone and the minimisation of the fuel-NO<sub>x</sub> path.

#### Fuel Staging

Whereas in air staging part of the air is by-passing the primary combustion zone, with

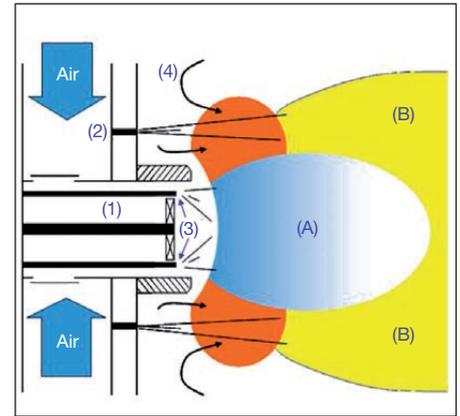


Figure 4. Stork Impulse burner schematic, fuel staging principle. (1) Combustion air; (2) Secondary gas; (3) primary gas; (4) Internal flue gas recirculation. (A) Primary combustion zone; (B) Burnout zone.

fuel staging all of the air is entering through the primary combustion zone and the fuel is staged, reversing the air staging principle. A schematic drawing of a burner according to the fuel staging principle is given in Figure 4, showing a schematic of the Stork Impulse burner. Some 10 to 20 % of the fuel is injected in the primary zone (A) with all the air, creating a very fuel-lean primary combustion zone. The presence of large amounts of excess air suppresses flame temperatures in the primary zone, minimising thermal NO<sub>x</sub>. The remainder of the fuel is injected in the burnout zone (B), where the temperatures are reduced by the presence of combustion products of the primary zone (A) and recirculated flue gases (4) (discussed in "Flue Gas Recirculation").

One of the most striking differences between fuel and air staging is the lack of swirl in the flow field of the former. In air staging, the central recirculation zone is large and swirl is used to have part of the air circumvent the primary combustion zone. However, in fuel staging, to maximise the distance between the primary and secondary combustion zones, swirl is absent. Fast mixing and intense combustion is taking place in the primary combustion zone, which does not yield high overall flame temperatures due to the air excess. However, slow mixing is enhancing low-temperature combustion in the secondary combustion zone (B in Figure 4). Adding swirl would only reduce the separation between primary and secondary combustion zone and hence make the staging less effective. Due to this slow mixing, fuel intermediates can even reduce NO<sub>x</sub> emissions from the primary zone in the secondary combustion zone due to a local reversal of the prompt NO<sub>x</sub> mechanism which can best be compared to selective catalytic reduction [1]. Maximum advantage of these phenomena is incorporated into the design of the Impulse burner.

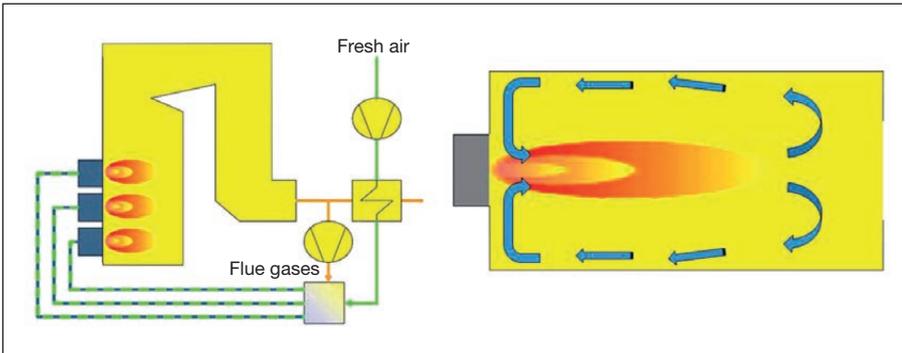


Figure 5. External flue gas recirculation (left) versus internal flue gas recirculation (right).

Fuel staging specifically attacks thermal NO<sub>x</sub>. Due to the fuel-lean centre, it is not very suitable for ultra-low NO<sub>x</sub> firing of fuel oil or other nitrogen containing fuels through the centre (item 3 in Figure 4). However, since it is a very effective measure in minimising thermal NO<sub>x</sub> and more effective at it than air staging, it is very often applied to gaseous fuels.

Flue Gas Recirculation

Minimising peak temperatures can also be realised by introducing excess gases into the combustion process that do not take part in it. In air, such an example is nitrogen which, apart from some very small portion, does not take part in the chemical reactions (after all, NO<sub>x</sub> emissions are measured in parts per million which is hardly significant in terms of bulk combustion products). Another such excess gas is the combustion flue gas. By recirculating the flue gases in such a way that they pass through the flame front, they effectively reduce peak temperatures and hence help to minimise thermal NO<sub>x</sub>. The advantage of flue gas over excess air is that it does not bring extra oxygen into the flame, making it a relatively more suitable measure for liquid fuel combustion.

There are two main variants of flue gas recirculation (FGR), as shown in Figure 5. These are external and internal FGR. Due to the physical separation of flue gases in external FGR, it is much more effective than internal FGR where burner aerodynamics and burner-furnace interaction are mainly responsible for its effectiveness. Also, with external FGR high recirculation rates are possible; up to 25 % of the flue gases can be recirculated without negatively affecting the combustion process. The main limiting factor for external FGR is the resulting oxygen content when mixing air with the recirculated flue gases, before entering the combustion process. Below roughly 18 % O<sub>2</sub> the resulting mixture is no longer flammable.

External FGR is more complex than internal FGR. It requires extra equipment such as an extra induced draft fan, or a larger combustion air fan in case the flue gases are recirculated to upstream of that fan, which reduces cycle effi-

ciency. Also extra monitoring and control equipment is necessary. Further, it increases the flow through the burner which needs to be taken into account in its design. Usually this means a larger throat diameter, which might necessitate pressure part modifications of the furnace membrane wall to accommodate it in case of a retrofit situation. Internal FGR on the other hand, has none of these disadvantages. With smart design and a keen eye for burner – furnace interactions, internal FGR can yield promising results. However, care needs to be taken in the resulting flame length, since optimising for FGR usually means a more slender and thus longer flame.

Consequences of In-furnace NO<sub>x</sub> Reduction Measures

For significant NO<sub>x</sub> emissions reduction using in-furnace measures, first and foremost the burner and boiler furnace have to be assessed with an integrated approach. The burner flow field should be further optimised by incorporating the furnace geometrical design as well. Of course this approach is best suited for new build installations; it could be costly in retrofits where pressure part modifications are expensive, let alone applying geometrical changes to the furnace. Second, the route to lower NO<sub>x</sub> has potential consequences for boiler operation which need to be assessed.

As outlined in the paper at hand, the staging principles and flue gas recirculation strive for a reduction of peak temperatures and a broadening of the flame envelope with a proper burnout zone. Further, low-NO<sub>x</sub> combustion

should ideally progress with slow mixing processes which also result in a larger flame envelope. These measures generally increase flame length and reduce flame intensity. Consequences for complete burnout and proper flame monitoring need to be addressed properly. Moreover, these measures might also shift the heat transfer balance in the boiler. In the furnace, radiation is responsible for some 70 % of the total heat transfer. Since radiation is well known to scale to the 4th power of temperature, lowering the peak temperatures or having broader ranges of intermediate temperatures (roughly 1100 to 1400 °C) will have significant effects on the radiative heat transfer balance. This will shift the heat load balance more downstream of the flue gas path. The water-steam system heat transfer balance will then tend to shift towards the convection (i.e. superheater) parts of the cycle and away from the radiation section (i.e. the evaporator which is the furnace membrane wall). This will lead to less steam which is more superheated.

Summary

A summary of the various NO<sub>x</sub> reducing measures that are discussed here is given in Table 1. It follows from this Table that external FGR is the most effective measure in reducing NO<sub>x</sub> emissions, however, it is also expensive. It has the advantage that it can generally be considered on top of other NO<sub>x</sub> reducing measures. For fuel oil firing, air staging is the best option when using the burner to reduce NO<sub>x</sub>, for gaseous fuels, fuel staging is preferred. Over-fire air ports are best considered on top of, or as alternative of, air staging.

Application of Premix in Furnace Combustion

When firing gaseous fuels in fuel-staging mode, the application of premix is an attractive measure to further reduce the NO<sub>x</sub> emissions. Premixing means mixing of fuel and oxidiser prior to combustion. This is in contrast to the standard, or diffusion mode, where the flame front separates fuel and oxidiser. Premixed combustion is applied since the 1980s in gas turbines and has some limited application in

Table 1. NO<sub>x</sub> reducing measures, summary.

Measure	Effectivity at Oil combustion	Effectivity at Gas combustion	Risk of CO	Consequences for Boiler
Low-NO <sub>x</sub> burners Fuel staging	Good	Very good	Negligible	Longer, slender flames. Larger furnace depth preferential
Low-NO <sub>x</sub> burners Air staging	Very good	Good	Negligible	Shorter, wider flames; higher pressure drop over burners than with fuel staging due to swirling air
External FGR	Moderate	Good	Negligible	Effective measure, also attractive with H <sub>2</sub> combustion
Over-fire air	Very good	Very good	Take care for appropriate fuel burnout	More space necessary for complete fuel burnout

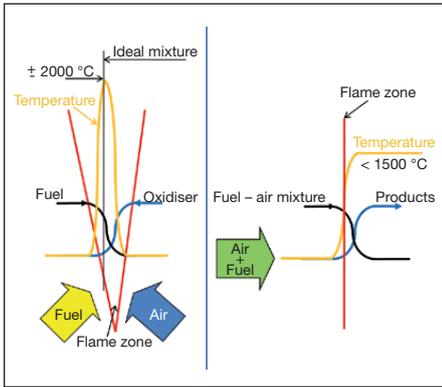


Figure 6. Stoichiometry of diffusion flame (left) versus premixed flame (right). Fuel- or fuel/air (black), oxidizer- (blue) and products (purple) concentrations through the flame front and resulting temperature profile (orange). Red lines indicate flame zone location.

industrial furnaces but has not yet been applied to industrial boilers. The diffusion mode is present when gas is injected via gas spuds or other holes, directly into the furnace. This is prevalent in almost all present-day burner designs for industrial boiler application.

Premixed combustion has some significant advantages over the standard diffusion combustion mode. Most importantly, it can be employed to minimise or even eliminate thermal NO<sub>x</sub> emissions. Due to the nature of a diffusion flame, combustion occurs at the stoichiometric interface, resulting in high peak temperatures. This occurs regardless of the overall stoichiometry. In a premixed flame, in contrast, the flame stoichiometry is a function of the fuel-air ratio that is determined by the burner design. This is further explained in Figure 6. In this Figure, the concentrations of fuel, oxidiser and products around the flame front are outlined, as well as the resulting temperature profile through the flame. The flame itself is indicated with red lines. It can clearly be seen that the peak temperature in a diffusion flame is roughly the temperature of a stoichiometric flame, which is around 2000 °C for methane – air combustion. In the

premixed flame, if one chooses the stoichiometry to be fuel lean (with, say 80 % excess air), the peak temperature is roughly 1500 °C, which is enough to yield a stable and well-burning flame but below the threshold for significant thermal NO<sub>x</sub> production.

The effectiveness of applying lean premix in minimising thermal NO<sub>x</sub> was the main driving force for its application to gas turbine combustion with great success, with single-digit NO<sub>x</sub> emissions currently well within range (at 15 % O<sub>2</sub> however; 9 ppmv NO<sub>x</sub> at 15 % O<sub>2</sub> corresponds to 55 mg/m<sup>3</sup> at 3 % O<sub>2</sub>). However, lean premix cannot be directly translated to boiler combustion since the demand there usually is to minimise the overall excess air amount, due to cycle efficiency considerations. Typically, in a gas-fired boiler the stack O<sub>2</sub> emission is less than 2 % which corresponds to roughly 10 % air excess. This means that the measure cannot be applied single-handedly; using premixed combustion at near-stoichiometric conditions would yield a flame which is extremely high-NO<sub>x</sub>. The best option is to combine it with fuel staging where the centre flame is lean premix and the staged fuel is employed to bring the O<sub>2</sub> concentration down to the desired level. This is the option that is realised using a further development of the existing Impulse burner concept of Stork Thermeq.

#### Application of Premix to the Impulse Burner

In the fuel staging principle as it is applied in Stork's Impulse burner, both the centre and main flames are diffusion flames (see the discussion in "Fuel Staging"). However, in the centre flame, intensive mixing is applied to ensure a stable flame on which the main flame anchors. The main flame is a diffusion flame with an optimized mixing process which produces relatively little NO<sub>x</sub> and can even convert NO<sub>x</sub> produced by the centre flame back to N<sub>2</sub>, as is discussed in section "Fuel Staging". Therefore, the optimal candidate for conversion to premix is the centre flame. This is schematically outlined in Figure 7, which

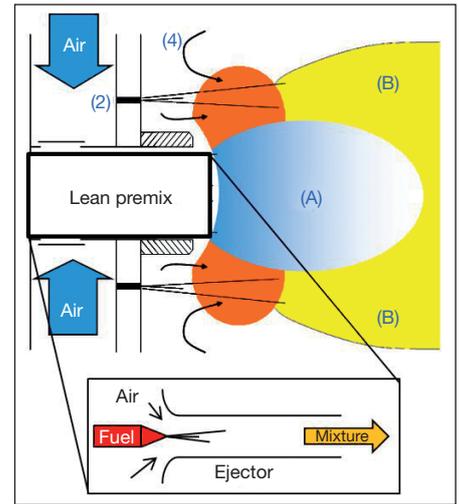


Figure 7. Fuel staging with premix using the Stork Thermeq Impulse burner principle. Insert shows means of premixing using ejectors. (A) Primary combustion zone, (B) Burn out zone, (2) Secondary gas; (4) Internal flue gas recirculation.

is a repeat of Figure 4, with the differences in approach shown.

Fuel gas and air are premixed by using ejector-type mixers. These provide excellent mixing over a short length. They have the additional advantage that, since air is drawn in by the high-pressure fuel gas jet, they augment the combustion air fan. For that reason ejector-type burners are sometimes used in the process industry for the smaller power ranges, since this omits the use of a combustion air fan. However, care should be applied in such an application. When there is no air fan to force a draft through the burner (or burner part), shutting down the fuel gas supply immediately shuts down the air supply too. This results in a quiescent explosive mixture of fuel and air, with only a spark needed to create a flashback explosion. This often occurs in these types of burners in practice when they are shut down, although flame arresters ensure flashback prevention during normal operation. Therefore, for safe




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Figure 8. Premixed center flame of the Stork Impulse test burner

and reliable premix burner operation, a forced draft should always be ensured to evacuate an explosive mixture by a fresh air draft as soon as the burner is shut down, making flashback due to this particular event virtually impossible.

Risks of applying lean premixed combustion are flame flash back and flame blow off. Both these issues can be tackled with the burner design. In case of flash back, the flame is able to stabilise in a region which is unintended in the burner design, usually this is referred to locations upstream of the burner throat. Prevention lies in designing a flame arresting zone at the burner throat through which the flame cannot penetrate and in ensuring in the design there are no possibilities for the flame to stabilise once it might get through the flame arrester for some reason. In this way, once a flame might penetrate through the flame arrester due to an unlikely event such as a furnace pressure wave, it is immediately blown back to the originally intended stabilization zone. This method is applied in all gas turbine premixed combustors and also on the present development of the Impulse burner.

Blow off occurs when a mixture can no longer be stabilised on its intended location and blows off, after which flame extinction occurs. Usually, some recirculation zone (created using swirling flows and/or baffle-type restrictions in the flow) is used to recirculate hot flue gases which continuously ignite the flame. When a premixed flame is too lean or the recirculation zone too weak – both of which result in a poor recirculation of hot

gases to the ignition zone – it is no longer capable of its main function, after which the flame becomes unstable and will at some point literally blow off that location. It is clear that prevention of blow off can be realised in a proper burner design, ensuring that there is ample opportunity for recirculation of hot gases. Also it can be prevented with proper burner operation, not allowing premixed fuel-air ratios beyond some lean limit. The latter is simply carried out in a ramp-limiter which is usually already present in most boiler control systems, limiting the lag between fuel-ramps and air ramps at boiler load changes (therefore limiting the range of fuel-air ratios that arise). Finally, proper flame monitoring should (as always) ensure burner shut down in case the flame is blown off, which is also a normal procedure in boiler safety and control systems.

#### Experiences in the Stork Test Facility

The premix burner principle, implemented in the Stork Impulse burner design, was extensively tested in our 9 MW test facility. Amongst others, extensive tests to analyse the blow off limits of the flame as well as investigations into the risk of flash back were carried out. The burner proved to be operating very reliably, with NO<sub>x</sub> emissions as low as 4 ppmv (9 mg/m<sub>0</sub><sup>3</sup> at 3 % O<sub>2</sub>) NO<sub>x</sub>. It is estimated that this translates to NO<sub>x</sub> emission values at multiple burner industrial installations of well below 50 mg/m<sub>0</sub><sup>3</sup>. During the tests, CO emissions were minimal and at most times at the level of the measurement uncertainty (less than 10 mg/m<sub>0</sub><sup>3</sup>), even at operation with

0.5 % O<sub>2</sub> at the stack. An image of the premixed centre flame from one of the view ports of the installation is shown in Figure 8. The flame inner and outer recirculation stabilisation zones can be very well observed near the burner throat.

### Conclusion

In this paper, the prevalent NO<sub>x</sub> formation routes appearing in boiler combustion have been briefly reviewed. Some conventional methods for NO<sub>x</sub> abatement have been discussed. The premix combustion concept for application to boiler combustion has been introduced, as well as experiences with this technique in the Stork test installation. With this technique, NO<sub>x</sub> emissions down to 9 mg/m<sup>3</sup> (at 3 % O<sub>2</sub>) were measured in the test installation. Practically, the limit value achieved in the Stork test furnace needs to be translated to expected values in practical industrial installations. This means taking into account multiple burner installations, fuel type, air preheat, furnace heat load, et cetera.

Concluding, very low NO<sub>x</sub> emissions are shown to be achieved in the test installation, however realising those figures in large industrial installations poses a real challenge. An integrated approach is necessary of burners and furnace. Further, operating conditions and installation geometry limitations also dictate what can ultimately be achieved with in-furnace NO<sub>x</sub> reducing measures. Nevertheless, with a keen eye to its consequences and side-effects, in-furnace NO<sub>x</sub> reduction measures can indeed be pursued to achieve ever decreasing NO<sub>x</sub> emissions, as is proven in the Stork Impulse burner concept of fuel staging with premixed combustion.

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