Non-Catalytic NOx Reduction Options and Combustion Challenges for Coal-Fired Boilers

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ABSTRACT

In India, all coal power plants will have to comply with stringent NOx emission limits which were set by the government in 2015. NOx reduction and management experience in the US and Europe suggests that the most cost-effective approach is to first maximise NOx reduction through primary and secondary methods. Therefore, the need for any downstream post combustion NOx reduction technology such as Selective Catalytic Reduction (SCR) may be significantly reduced in terms of cost, or eliminated.

The paper provides an in-depth discussion of the principal primary and secondary NO_x control approaches, including the expected range of NO_x reduction that can be achieved, as well as typical capital and operating costs. Basic combustion optimization with existing plant equipment is the lowest-cost option, but typically only achieves 5%-15% NO_x reduction. Combustion optimization plus the installation of primary low NO_x combustion technologies such as LNBs, OFA, or advanced OFA systems can achieve 30% to 40% NOx reduction, depending on fuel diet, boiler design and combustion optimization & tuning. The associated capital costs of these systems are reasonable with relatively low operating costs. Integrating multiple primary NO_x reduction methods, when properly combined, can provide between 40% and 50% NO_x reduction at a relatively low cost. SNCR technology is best applied as an add-on to the primary NO_x reduction methods, which has been demonstrated to provide NO_x compliance at less than 200 mg/Nm^3.

While it is very likely that primary method alone may be able to achieve below 300 mg/Nm^3 for most of coals being used in India, it must be stressed that improper design and application of these technologies can also result in serious combustion issues and adversely affect normal boiler operations, such as reduced combustion efficiency, low load burner operation, potential furnace slagging, etc. In addition, the key to facilitating improved combustion performance is the balancing of fuel distribution across the burner zone, management of fuel quality and PF particle size distribution and minimising uncontrolled air ingress to ensure the combustion zone operates at the required air-to-fuel ratio. This is best achieved by obtaining a detailed understanding of the current combustion system through a customized detailed analysis.

It is essential that any NOx reduction programme is undertaken with appropriate rigour and attention to detail. This paper identifies and discusses some of the typical combustion challenges and issues that can be experienced during selection, installation and commissioning of the various primary and secondary NOx controls for coal-fired boiler technology. The paper offers key learnings from extensive and detailed experience gained over many decades on a wide range of coal-fired boilers. It is offered to help ensure lessons learned elsewhere can be applied to the Indian Power Industry.

INTRODUCTION

Utility boilers burning fossil fuels worldwide are increasingly challenged by ever tightening emissions limits and associated regulation. For example, in European Union countries, the NOx emission limit has dropped to below 200 mg/Nm^3 for most coal-fired boilers, in accordance with the Industrial Emissions Directive (IED). In China, the NOx limit for large coal-fired utility boilers has been set to below 100 or 200 mg/Nm^3, depending on the year that the boiler was installed [2]. In India, the new NOx emission limits set by government in 2015 are divided into three levels: 1) 600 mg/Nm^3 for utilities installed before 2002, 2) 300 mg/Nm^3 for utilities installed between 2003 and 2016; and 3) 100 mg/Nm^3 for utilities installed since 2017 [3].

To meet these NOx emission limits, utilities are faced with the option of either installing a costly SCR system or a combined primary low NOx combustion and secondary NOx systems. However, NOx reduction and management experience in the US and Europe in the past suggests that the most cost-effective approach is to first maximise NOx reduction through primary and secondary methods before any post combustion flue gas treatment technology, such as an SCR, is considered. Achieving the greatest NOx reduction through primary and secondary measures can result in either reducing the size of an SCR, or eliminating the need for an SCR.

This paper provides an in-depth discussion of the principal primary and secondary NOx control option approaches, including the expected range of NOx reduction level that can be achieved as well as the typical capital and operating cost. This paper also discusses the potential risks of causing serious combustion performance issues if primary and secondary NOx control measures are not managed appropriately. Such issues can seriously impact boiler operations, and can lead to reduced combustion efficiency, poor burner and combustion performance at reduced load, increases in furnace slagging, as well as increases in carbon-in-ash and particulate emissions, etc. Key learnings shared through this paper are based on extensive and detailed experience gained over many decades covering a wide range of coal-fired boiler applications. We want to ensure that lessons learned elsewhere can be applied to best advantage to the Indian Power Industry.

NON-CATALYTIC NO_X REDUCTION OPTIONS

This section provides an in-depth overview of the non-catalytic NOx reduction options that have been successfully applied to coal-fired boilers. These options are listed as follows:

- Combustion tuning and optimisation
- Burner modifications and combustion optimisation
- Burner replacement (i.e. Low-NOx Burners)
- Over-Fire Air (OFA)
- Advanced OFA (AOFA)
- SNCR

Combustion Optimisation Through Tuning

Combustion optimisation through the adjustment and tuning of existing combustion systems is the lowest-cost method of improving NOx emissions. This approach is more effective on those units already been equipped with OFA technology and have existing combustion air control systems. Through many years of tuning experience, we have witnessed the following effective adjustments and tuning with little or no mechanical retrofit required:

- Burner air flow control damper positions
- OFA port damper positions
- OFA flow setpoint
- Improved management of total combustion air flow / excess air levels (often involving the reduction of uncontrolled furnace air ingress, tramp air)
- Burner Out of Service (BOOS) – burner and combustion zone biasing.

The goal of such adjustments is to optimize combustion performance to allow operation at a lower excess air level (if possible), to ‘stage’ the burner combustion zone to drive some NOx reduction, typically in the range of 5%-10%. Further NOx reduction performance is often limited by low windbox pressure and a deterioration in combustion efficiency, often illustrated by increased and high CO as well as an increase in LOI, which will be discussed later.

Burner Modifications and Combustion Optimisation

Burner modifications usually take the form of reduced burner throat diameter (for wall-fired boilers), or reduced secondary area nozzle area (for tangential boilers), to maintain windbox pressure and secondary air velocity when a large amount of air is diverted from the windbox to OFA systems. Together with Combustion Optimisation as discussed earlier, this would allow a further reduction in total combustion air flow, an increase in staging with OFA for NOx reduction and improved uniformity of air flow among the burners. It is expected that burner modifications and combustion optimization can result in NOx reduction between 10% and 20%. Higher NOx reduction levels could be achieved, depending on the baseline boiler operation conditions and the capacity of OFA design being achieved prior to optimisation.

Burner Replacement with Low-NOx Burners

Prior to the requirements for NOx reduction, coal-fired burner was predominantly designed to achieve maximum combustion efficiency through rapid mixing of fuel and air in the combustion zone, resulting in low levels of CO and LOI. However, rapid mixing of fuel and air promoted high levels of NOx, typically in the order of 800-1000 mg/Nm^3. Later when NOx reduction was required, the low NOx burner was developed, based on the principle of staging the mixing of fuel and air through burner designs. So, in cases where low-staging based combustion technology is in use, the more cost-effective option is to replace and retrofit with low NOx burners.

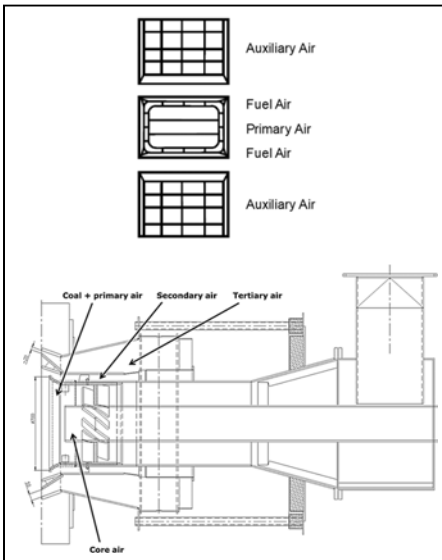

Figure 1. Typical Low-NOx Burner for (up) tangential-fired boilers and (low) wall-fired boilers

A typical low-NOx burner for tangential boilers is shown in upper panel of Figure 1, which illustrates the staged combustion concept and is composed of a primary area nozzle surrounded by fuel air as part of secondary area from windbox. Above and below the coal nozzle are auxiliary air nozzles. While the nozzle size for primary air, and auxiliary air are determined by the design velocity, the distance between these nozzles could affect the ignition of the coal particles, as well as the ability of NOx reduction within the burner zone. The lower panel of Figure 1 illustrates a typical design of low NOx burners for wall-fired boilers, where the air is progressively mixed with primary air through secondary air and tertiary air nozzles. It is well known that burner replacement in combination with combustion tuning could provide up to 30% or more NOx reduction, resulting in NOx levels in the range of 500-700 mg/Nm^3 with no OFA, and 300-400 mg/Nm^3 with well-designed OFA systems, for most of bituminous coals.

Over-fire air (OFA) system

An OFA system diverts a portion of combustion air from the burner windbox to air ports located above the burner zone. Typical OFA air flow is designed to be 15%-20% of total combustion air, which results in 15%-30% NOx reduction alone or 25%-35% NOx reduction when combined with LNB, from baseline emissions. For a tangential-fired furnace, usually two levels of closed-coupled OFA (CCOFA) ports are assembled with burners through the same windbox at each corner. In addition, a separated OFA (SOFA) port may be installed at a higher furnace elevation and at each corner of the furnace. In this case a portion of combustion air is also diverted from the windbox to SOFA ports through air ductwork. For a wall-fired furnaces, OFA ports are installed above the burner zone on either the front wall only or on front and rear walls. Again, a proportion of combustion air is diverted from the windbox to OFA ports through air ductwork.

It is our experience that most OFA systems are installed without a proper evaluation of the existing burner combustion system or commensurate system modification therefore there is an increased risk of causing low windbox pressure and subsequent combustion and slagging issues, as discussed later.

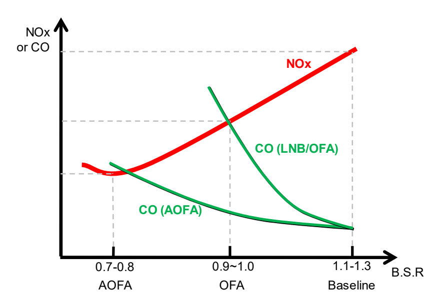

Figure 2. Correlation of NOx and CO versus Burner Stoichiometric Ratio (BSR)

Advanced OFA (AOFA)

Advanced OFA (AOFA) requires adding an additional level of air injection above the existing OFA system to create deeper furnace staging environment for increased NOx reduction. With AOFA, the total OFA air flow could be as high as 30% of total combustion air with the air injection nozzles installed at an elevation between the existing OFA ports and the furnace nose. The added air injection could be boosted or non-boosted, depending on boiler configuration.

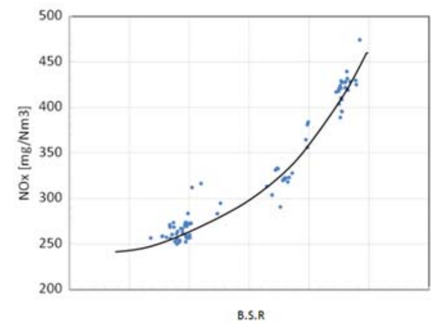

Figure 3. NOx emission as a function of BSR with Advanced OFA systems installed on a 500 MW coal-fired boiler

Figure 2 is a schematic diagram illustrating the trade-off relationship between NOx and CO, as a function of Burner Stoichiometric Ratio (BSR), which represents the degree of furnace staging. With conventional OFA, as BSR is reduced and furnace combustion staging is increased, additional NOx reduction is achieved, but there can be an associated detrimental impact on furnace combustion. If deemed necessary, Advanced OFA designs can involve high momentum air jets using a booster fan to facilitate both deeper staging and combustion performance improvement; as illustrated in Figure 2. Figure 3 shows NOx emissions as a function of BSR on a 500 MW unit when applying an advanced OFA in conjunction with existing an OFA system [4]. With the deeper staging capability from this integrated system, NOx emissions correlate very well with BSR, and can attain below 250 mg/Nm^3 when burning bituminous coal. CFD modeling in Figure 4 demonstrates that a well-designed boosted advanced OFA system located above the existing OFA system can result in simultaneous reduction of CO and NOx.

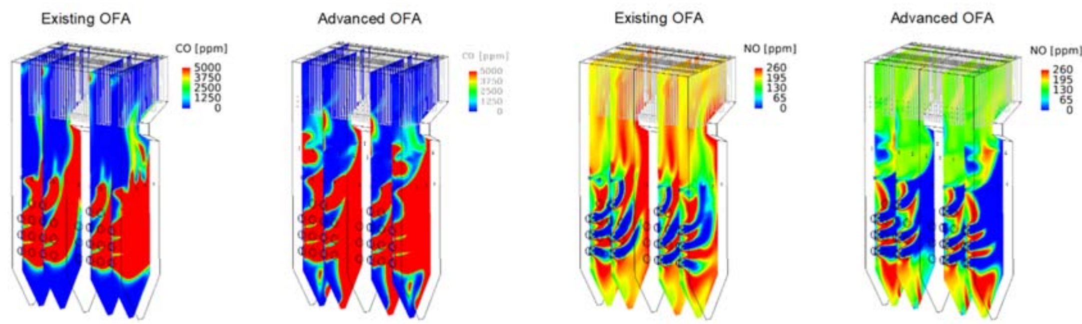

Figure 4. CFD predicted CO and NOx distribution of an Advanced OFA system installed on top of existing OFA for a 600 MW wall-fired boiler.

Selective Non-Catalytic Reduction (SNCR)

Selective Non-Catalytic Reduction (SNCR) is a proven technology for reducing NOx emissions through in-furnace reagent injection. SNCR is usually designed as an add-on to an OFA system, where diluted urea (or ammonia solution) is injected into the upper furnace region to reduce the outlet NOx concentration, typically in the range of 25% to 35% for large utility boilers. SNCR chemistry occurs effectively in a temperature window of 950-1100°C; below or above this window will result in low SNCR efficiency and/or high ammonia slip which may cause downstream fouling in the air preheaters. CFD combustion modeling with SNCR kinetics can be effectively used to assist the design of SNCR systems to help ensure optimum performance. The combination of advanced OFA and SNCR has been proven to be capable of achieving significant levels of NOx reduction [4], which may eliminate the need of SCR, with associated cost benefits, depending on the NOx emission targets.

CAPEX AND OPEX OF NO_X REDUCTION OPTIONS

The NOx reduction percentage and the estimated capital cost of the above discussed NOx reduction options are listed in Table 1. Note that the estimated cost range is from the US and European based experience and associated market environments, and applies to units greater than 200 MW only.

Achieving NOx reduction on Units smaller than 200 MW generally costs more on a per kw basis. Among these options, Advanced OFA and SNCR are the highest capital cost, yet provide the highest NOx reduction potential.

Table 1. Expected NOx Reduction and Capital Cost of Non-Catalytic NOx Options

Non-Catalytic NOx Options	Expected NOx Reduction (%)	Est. CAPEX cost ($/kw)
Combustion Optimisation	5-10	0.4-0.8
Burner Modification	10-20	4-6
Low NOx Burners	15-30	10-15
Over-Fire Air	15-30	10-15
Advanced OFA*	30-40	12-20
SNCR	25-35	15-20

*Note that this NOx reduction level is combined AOFA and OFA, whereas the cost is AOFA alone.

Table 2 illustrates suggested solutions for various NOx reduction targets, and their associated capital and operating costs. Combustion Optimization alone or Modification to non-low NOx burners will likely not achieve NOx levels less than 600 mg/Nm^3 especially when burning India coals. To achieve such performance the installation of Low NOx Burners (LNB) or OFA along with combustion system optimization is required. A combined LNB and OFA system would very likely to achieve NOx levels below 400 mg/Nm3, but with Advanced OFA, the combined system may achieve below 300 mg/Nm^3 without negatively impacting overall combustion efficiency IF commensurate optimization of the combustion system is also addressed (PF fineness, PF distribution, air flow management, tramp air etc). The capital cost for these solutions ranges from <$1/kw with combustion optimization to $25-35/kw with LNB and Advanced OFA system. The costs are estimated for units greater than 200 MW, whereas the cost on per kw base may be higher for units smaller than 200 MW. There is essentially no additional operating cost for any of these low NOx combustion technologies, individually or combined. Adding an SNCR to combined low NOx combustion technologies would be able to achieve less than 200 mg/Nm^3. The estimated capital cost would be $40-50/kw, and the estimated operating cost for SNCR reagent would be about $3.5-4.5/kw/year.

Table 2. Suggested NOx Reduction Solutions and Capital and Operating Costs for Different NOx Targets

NOx Target (mg/Nm^3)	Suggested Solutions	Est. CAPEX Cost ($/kw)	Est. OPEX Cost ($/kw/yr)
700-800	Combustion Optimisation	0.4-0.8	-
600-700	Burner Modification	4-6	-
500-600	Low NOx burners (LNB)	10-15	
400-500	Burner Modification + OFA	15-20	-
300-400	LNB + OFA	20-30	-
250-300	LNB + Advanced OFA	25-35	-
160-200	LNB + AOFA + SNCR	40-50	3.5-4.5

Note: the NOx targets are estimated based on baseline NOx of 900-1200 mg/Nm^3 without any NOx control methods.

All above costs are based on projects in the US and Europe. It is expected that the costs for these technologies will be significantly reduced for the Indian market when materials, fabrication, and installation are supplied locally.

COMBUSTION CHALLENGES OF NO$_X$ REDUCTION OPTIONS

As discussed above, low NOx combustion technologies can be extremely sensitive to the various parameters necessary for delivering satisfactory combustion performance, NOx reduction and overall boiler operation. If the retrofitting of low NOx combustion technology is not addressed correctly, subsequent combustion and boiler performance can be impacted significantly. This section describes the typical combustion issues that can be encountered as a result of inadequate and poor implementation low NOx combustion technologies and SNCR.

Boiler Operation & Efficiency

When the furnace combustion air is staged for NOx reduction, the combustion process is delayed so that it can inevitably increase CO and particulate emissions as well as increase in carbon-in-ash (or loss-of-ignition, LOI). Experience has demonstrated that CO and particulate emissions can dramatically increase for both wall-fired and tangential boilers, but the increase in tangential boilers tends not to be quite as dramatic compared with wall fired boilers. LOI levels are typically be in the range of 8-20%, depending on fuel type, PF fineness, PF distribution, excessive air ingress and overall combustion optimization status.

Such elevated CO and particulate emissions along with increased levels of LOI reflect poor combustion efficiency, poor heat rate with associated impact on boiler efficiency. As an example, in the case of a coal with a high heating value (HHV) of 24.1 MJ/Kg, and 14% ash content, when CO emissions increase from 200 to 500 ppm, and LOI from 8% to 12% as a result of poor low NOx combustion performance, the boiler efficiency is reduced by approximately 0.9% with commensurate wider impact on operational cost etc.

The use of an Advanced OFA system could help address any loss of combustion efficiency associated increase in CO and LOI emissions. The general concept of AOFA includes enhancing the mixing between well-designed OFA jets with flue gas, before the combustion flue gas leaves the furnace. CFD combustion modeling has proven to be an invaluable tool in helping to determine the optimum locations for OFA ports and the pressure needed for OFA jets (if boosted system is needed) to promote the required mixing.

Windbox Pressure

When the furnace is retrofitted with OFA technology, a large amount of combustion air is diverted to OFA ports, resulting in less secondary air for the burners. This leads to a reduction in windbox pressure. This becomes more pronounced during low load operation and even more so when burning poorer grade coals. If there is excessive levels of uncontrolled air ingress in the furnace, across the air heater or in flue gas ductwork, this will have an adverse impact on FD and ID fan control because associated excess air and O_2 levels will be influenced by air ingress. The FD fan will be required to deliver less combustion air (due to in-leakage) resulting in reduced windbox air pressure with detrimental impacts on burner performance. As a consequence, the reduced windbox pressure could further cause the following issues:

- Primary air and secondary air velocity deviating from design, which could affect the near-burner ignition and combustion zone and therefore flame stability.
- Overheating of burner nozzle metals due to reduced secondary air velocity, leading to burn back at the burner tips.
- Increased potential for furnace slagging due to inadequate air/fuel ratio management further exacerbated by poor mill-grind performance and poor PF management.

(a) Burner nozzle deformation (b) Air nozzle slagging

Figure 5. Photos of burner nozzle deformation and air nozzle slagging as a result of low windbox pressure

Figure 5 illustrates some typical burner nozzle deformation and slagging due to overheating and poor combustion as result of low windbox pressure, especially at low load operation. This issue, however, can be addressed by modifying burner secondary air nozzles (for tangential furnace) or burner throats (for wall-fired furnace) to maintain the required windbox pressure when a portion of secondary air is taken out from windbox for OFA purposes. It is important that a comprehensive burner and windbox evaluation is done in conjunction with any OFA system design.

Fuel Distribution and Mill Performance

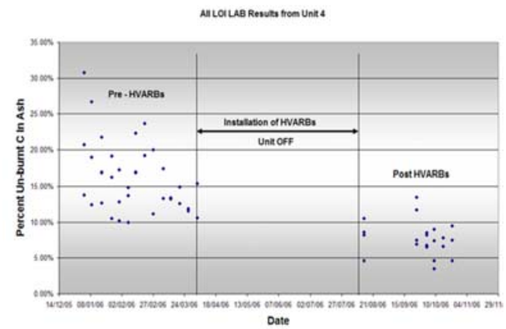

Figure 6. Reduction of carbon-in-ash from HVARB fuel distribution system for a 500 MW wall-fired boiler.

Balanced fuel distribution and associated burner-to-burner balance of air-to-fuel ratio (AFR) is fundamental to achieving satisfactory low NOx combustion performance and emissions such as NOx, CO, particulates, etc. It is also fundamental to addressing other combustion performance-related challenges associated with fireside corrosion and carbon-in-ash as well as slagging and fouling within the furnace. Figure 6 illustrates the reduction of carbon-in-ash by using HVARB fuel distribution technology for a 500 MW coal-fired boiler.

In addition, PF particle size distribution can have a significant impact on burner combustion performance. Good management of PF particle size distribution through appropriate management of the milling system is essential. Inadequate mill performance and poor primary air flow management can result in significant combustion performance deterioration. Therefore, the routine measurement of PF particle size distribution and the maintenance of PA flow measurement technology, such as venturi, is essential. An effective way of monitoring milling plant performance in terms of PF quality and Primary Air flow is through the use of on-line measurement and monitoring technology.

Key to facilitating improved combustion performance is the balancing of fuel distribution across the burner zone, management of fuel quality and PF particle size distribution and minimising uncontrolled air ingress to ensure the combustion zone operates at the required AFR.

Uncontrolled Air ingress (Tramp Air)

Another key factor that must be addressed is management of combustion zone stoichiometry (theoretical plus excess air necessary for complete combustion). Combustion zone stoichiometry is managed by controlling the appropriate amount of primary and secondary air flow to the furnace. Getting the balance right is extremely important but is often undermined by excessive 'uncontrolled' furnace air ingress (tramp air) or in-leakage at other locations such as mills out of service, leaking dampers, expansion joints and air-heater and duct seals. These pre-existing uncontrolled air ingress issues, if not addressed, will significantly undermine low NOx combustion technology performance.

SNCR Issues

SNCR technology involves injecting diluted urea or ammonia solutions into flue gas to remove NOx. For large utility boilers, urea has been proven to be more effective than ammonia in terms of NOx reduction efficiency, and chemical utilization. Industrial urea of 19% or 20% concentration by weight is delivered to site, but is diluted to less than 10% before injected into the furnace. Large amount of water injection ultimately results in a reduction of boiler efficiency, typically between 0.5% - 0.8%. However, this reduced efficiency may be minimised or even completely offset by involving the following design approaches:

- Maximizing NOx reduction from low NOx combustion before considering SNCR, so that the design capacity of SNCR (CAPEX) and the amount of chemical and water injected (OPEX) can be minimized.
- Considering Advanced OFA design which could result in an efficiency gains, which could offset the efficiency reduction by water from SNCR system.

It should be noted that SNCR chemistry is only effective across a narrow temperature window of 950-1100°C. When load changes or furnace combustion changes, the location of SNCR temperature shifts up and down. This requires the SNCR system to be designed to respond to these changes, in order to obtain effective SNCR performance across the entire load range. Specifically, the detailed design to provide such flexibility may involve the following considerations:

- Multiple elevations of SNCR injectors. Usually at least two to three elevations are required for load range between 100% to minimum load of 30% or 40%.

- Dynamic variation of urea concentration. High load with hotter temperature usually requires urea concentration as low as 5%.
- Dynamic variation of urea flow through each elevation of injectors.
- Control system for automatic switch between different elevations of SNCR injectors when load changes.

Urea droplets are very corrosive to waterwall tube metal. Improper design of the urea lance and nozzle may lead to urea dripping from the injection nozzle to near-injector water-wall tubes, causing corrosion and subsequently tube leaks which can be severe. Such an operational problem can be prevented by:

- Selecting the correct atomizing nozzle
- Surrounding the injector with a protective air stream
- Implementing and adhering a procedure to ensure the urea lance is put in and out of service correctly and properly

Ammonia slip is created from unreacted ammonia of an SNCR system, and is very problematic when above 2-5 ppm at the air-heater inlet. Ammonia could potentially react with SO_3 to form ammonium bisulfate (ABS), which can deposit on air-heater surfaces, subsequently causing the adherence of coal ash on airheater surface thereby causing fouling and increasing the pressure drop across air-heater. This issue can be addressed and managed via the proper design and operation of the SNCR system, which includes proper selection of the urea spray nozzle, increasing mixing between the SNCR reagent and flue gas, and installing an ammonia slip meter.

CONCLUSIONS

A review of the Indian coal-fired power generation industry and associated air pollution regulation suggests that there will be increasing demand for NOx reduction technology, similar to that applied on power plants in North America & Europe. Initial activity to address NOx reduction may involve some combustion optimization exercise with associated plant modification, however, to deliver more substantial NOx reduction, bespoke technology will be required. Such technology will likely include low NOx burners, OFA and advanced OFA. To achieve greater reductions, further technology will be required which focuses on post combustion NOx control such as the use of SNCR or SCR. Each of these NOx reduction options provides a certain range of NOx reduction capability (ranging from 10%-50%) with a commensurate capital cost. Before making any decision on which technology to adopt for a given power plant it is recommended a comprehensive low NOx options review and feasibility study be undertaken to ensure the most appropriate and cost-effective compliance approach is adopted.

While it is very likely that low NOx combustion technology alone may be able to achieve below 300 mg/Nm^3 for most the coals currently being burned in India, it must be stressed that improper design, installation and commissioning of these technologies can result in serious combustion performance issues with associated adverse effect on normal boiler operations.

Based on vast experience gained in North America and Europe, such combustion performance challenges and issues can be prevented or significantly reduced through the proper design, installation, commissioning and tuning of the various primary and secondary NOx controls. Significant lessons have been learned based on the extensive and detailed experience gained over many decades on a wide range of coal-fired boiler technology which can be leveraged for considerable benefit to the Indian Power Industry.

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