

REVIEW OF EMISSIONS CONTROL AND NO_x REDUCTION TECHNIQUES IN COAL FIRED THERMAL STEAM GENERATORS

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Abstract—Coal based thermal power plants account for more than 60% of India's total installed capacity while also playing a dominant role in meeting the rapidly expanding power sector in the future. However, expansion of modern thermal power sector has been beset with environmental concerns, with modern government policies directed towards higher emissions control in newer steam generator designs. This paper presents a review of some of the recent developments in emissions control technologies specifically towards development of NO_x reduction mechanisms in contemporary Boiler designs.

I. INTRODUCTION

Coal based power plants are a ubiquitous source of power generation in India. With over 60% of total installed capacity [16], and very high growth rates projected for the future, [15] thermal power plants have remained as the backbone of electricity generation in India. However, growth of thermal power plants has been hampered to some extent due to major concerns over emissions and environmental effects that are a consequence of current and legacy systems. Compared to the average emissions from coal-fired, oil-fired and natural gas-fired thermal power plants in European Union (EU-27) countries, India's thermal power plants emit 50% to 120% more CO₂ per kWh produced #. This principally has been a result of the poor quality that is characteristic of coal mined in India. The carbon content is low, and toxic trace element concentrations are negligible. Also, the natural fuel value of Indian coal is poor. On average, the Indian power plants using India's coal supply consume about 0.7 kg of coal to generate a kWh, whereas United States thermal power plants consume about 0.45 kg of coal per kWh. [14] The high ash content in India's coal also affects the thermal power plant's potential emissions. In order to mitigate this, the Government of India has mandated several policy changes in regards to emissions. The Ministry of Environment and Forests also publishes a technical guidance manual to help project proposers and to prevent environmental pollution. [13] The Government has enforced strict emissions norms for thermal power plants, with the most recent update to emissions standards taking place in December 2015.

From an engineering point of view, boiler design has to be modified and implemented in accordance with the emission standards that are in place. Several new technologies and methods have been designed and implemented in order to reduce and control emissions from the steam generators to a permissible limit. This

paper intends to present a review of some of those technologies which are in common use in the current Industry.

II. COAL COMBUSTION PROCESS

Coal is the principal fuel used in steam generating systems in India. In order to design a thermal powerplant, knowledge of coal composition is of paramount importance. The composition of coal is essential to determine the amount of emissions (both SPM and gaseous) that can be expected in the combustion process. Coal is analysed through two methods of analysis – Proximate analysis and Universal Analysis. Proximate analysis is used for determining physical characteristics such as Volatile matter and fixed carbon content and ash content. Ultimate analysis is done in order to determine the chemical composition of carbon, which include Carbon, Nitrogen, Oxygen and Sulphur percentages, along with multiple other dissolved minerals. In order to understand how emissions are produced, a review of combustion process of coal in a power plant has to be firstly undertaken. As a coal particle enters the furnace, its surface temperature increases due to radiative and convective heat transfer from furnace gases and other burning particles. As particle temperature increases, the remaining moisture is vaporized and volatile matter is released. This volatile matter, which ignites and burns almost immediately, further raises the temperature of the char particle, which is primarily composed of carbon and mineral matter. The char particle is then consumed at high temperature, leaving the ash content and a small amount of unburned carbon.[7]

The most prevalent method in use today internationally is Pulverized coal (PC) firing, i.e. burning coal as a fine powder suspension in an open furnace.[8] PC firing has made possible the large, efficient utility boilers used as the foundation for power generation in many utilities worldwide. Pulverized coal firing differs from the other coal combustion technologies primarily through the much smaller particle size used and the resulting high combustion rates. Most PC-fired systems have the burners located in the lower portion of the furnace. Wall-fired systems usually have the burners positioned on either one wall or on two walls in an opposed arrangement. The other common arrangement positions the burners in the corners of the lower furnace, and is referred to as corner or tangentially-fired. Primary air typically at 54 to 93C conveys pulverized coal directly to the burners. Secondary air is supplied by the forced draft

fans and is typically preheated to about 316C. All or most of the secondary air is supplied to the windboxes enclosing the burners. A portion of the secondary air may be diverted from the burners to overfire air (OFA) ports in order to control the formation of NO_x. [9]

The combustion process continues as the gases and unburned fuel move away from the burner and up the furnace shaft. Final burnout of the char depends on the coal properties, particle fineness, excess air, airfuel mixing, and thermal environment. The products of combustion proceed out of the furnace after being cooled sufficiently and enter the convection pass.

II. NO_x FORMATION

Nitrogen oxides (NO_x) are an unintended byproduct from the combustion of fossil fuels and are one of the primary pollutants emitted during combustion processes. Along with sulfur oxides (SO_x) and particulate matter, NO_x emissions contribute to acid rain and ozone formation, visibility degradation, and human health concerns. As a result, NO_x emissions from most combustion sources are regulated, monitored, and require some level of control.[6] This control is closely tied to the combustion process and to various boiler system components. The effectiveness of the pulverized coal NO_x control technology depends primarily upon the fuel characteristics and the combustion system design. There are two principal mechanisms of NO_x formation in steam generation: thermal NO_x and fuel NO_x.

A. Thermal NO_x

Thermal NO_x refers to the NO_x formed through high temperature oxidation of the nitrogen found in the combustion air. At these high temperatures, molecular nitrogen (N₂) and oxygen (O₂) dissociate into their atomic states and participate in a series of reactions. One product of these reactions is NO. Since the traditional factors leading to complete combustion (high temperatures, long residence time, and high turbulence or mixing) all tend to increase the rate of thermal NO_x formation, some compromise between effective combustion and controlled NO_x formation is needed. Thermal NO_x formation is typically controlled by reducing peak and average flame temperatures.[9] Controlled mixing burners can be used to slow the combustion process. A second approach is staged combustion, where only part of the combustion air is initially added to burn the fuel; the remaining air is added separately to complete the combustion process. A third method is to mix some of the flue gas with the combustion air at the burner, referred to as flue gas recirculation (FGR). This increases the gas weight which must be heated by the chemical energy in the fuel, thereby reducing the flame temperature.[10]

B. Fuel NO_x

The major source of NO_x emissions from nitrogen bearing fuels such as coal and oil is the conversion of

fuel-bound nitrogen to NO_x during combustion.[9] The majority of NO_x formation from fuel-bound nitrogen occurs by two separate paths. The first path involves the oxidation of volatile nitrogen species during the initial phase of combustion. During the release and prior to the oxidation of the volatile compounds, nitrogen reacts to form several intermediate compounds in the fuel-rich flame regions. These intermediate compounds are then oxidized to NO or reduced to N₂ in the post-combustion zone. The second path involves the release of nitrogen radicals during combustion of the char fraction of the fuel. These reactions occur much more slowly than the reactions involving the volatile species. This conversion can be controlled by reducing oxygen availability during the initial stages of combustion. Techniques such as controlled fuel-air mixing and staged combustion provide a significant reduction in NO_x emissions by controlling stoichiometry in the initial devolatilization zone.[6]

III. NO_x EFFECTS

Although NO_x is represented a family of seven compounds, nitrogen dioxide (NO₂) is considered by Environmental Protection Agency U.S. to be the most prevalent form of NO_x in the atmosphere that is generated by human activity [2]. NO₂ is not only an important air pollutant by itself, but also reacts in the atmosphere to form ozone (O₃) and acid rain. Nutrient enrichment problems (eutrophication) occur in bodies of water when the availability of either nitrates or phosphates becomes too large. As a result, the ratios of nitrogen to phosphorus, silicon, and iron and other nutrients are altered. This alteration may induce changes in phytoplankton, produce NO_x or toxic brown or red algal blooms (which are called "red tides"), or stimulate other plant growth. [2] The algal blooms and plant growth produce a shadow and cause the death of other plants in the water, which depletes the oxygen content of the water (hypoxia) when the plants die, sink, and decay. Such eutrophication can make the bottom strata of water uninhabitable for both marine animals (such as fish and shellfish) and aquatic plants. It can progress to virtually the complete depth of the water. It is estimated that between 12% and 44% of the nitrogen loading of coastal water bodies comes from the air. [2] Inland lakes are also affected in this way.

Another dimension of the problem is that high temperature combustion can convert sulfur in fuel to SO₂ and SO₃. While SO₂ is toxic and forms sulfurous acid when dissolved in water, SO₃ is both toxic and hygroscopic (moisture absorbing) and forms sulfuric acid by combining with moisture in the atmosphere.[5] SO₂ and SO₃ form sulfites and sulfates when their acids are neutralized. Both of these acids can form solid particles by reacting with ammonia in air. SO₂ and SO₃ also contribute to pH (acidity) changes in water, which can adversely affect both land and aquatic life. Therefore, both NO_x and SO_x from combustion can kill plants and animals. [2]

IV. NO_x CONTROL

NO_x control Methods have ranged on six principal control methods, with technologies being developed for each of those methods.

1. *Reducing peak temperature through combustion control:* Reducing combustion temperature means avoiding the stoichiometric ratio (the exact ratio of chemicals that enter into reaction). Essentially, this technique dilutes calories with an excess of fuel, air, flue gas, or steam. Combustion controls use different forms of this technique and are different for fuels with high and low nitrogen content. [3] Several methods have been utilized for reducing the peak temperature for NO_x control. These include:

- a. Flue Gas Recirculation (FGR)
- b. Natural Gas Reburning
- c. Low NO_x Burners (LNB)
- d. Combustion Optimization
- e. Burners Out Of Service (BOOS)
- f. Less Excess Air (LEA)
- g. Inject Water or Steam
- h. Over Fire Air (OFA)
- i. Air Staging
- j. Reduced Air Preheat
- k. Catalytic Combustion

2. *Reducing residence time at peak temperature :* Reducing residence time at high combustion temperatures can be done by ignition or injection timing with internal combustion engines. It can also be done in boilers by restricting the flame to a short region in which the combustion air becomes flue gas. [3] This is immediately followed by injection of fuel, steam, more combustion air, or recirculating flue gas. This short residence time at peak temperature keeps the vast majority of nitrogen from becoming ionized.

3. *Chemical reduction of NO_x:* This technique provides a chemically reducing (i.e., reversal of oxidization) substance to remove oxygen from nitrogen oxides. [1] Some examples utilizing this method include:

- a. Fuel Reburning (FR)
- b. Low NO_x Burners (LNB)
- c. Selective Catalytic Reduction (SCR)
- d. Selective Non-Catalytic Reduction (SNCR)

4. *Oxidation of NO_x with subsequent absorption:* This technique intentionally raises the valence of the nitrogen ion to allow water to absorb it (i.e., it is based on the greater solubility of NO_x at higher valence). [3] This is accomplished either by using a catalyst, injecting hydrogen peroxide, creating ozone within the air flow, or injecting ozone into the air flow. Non-thermal plasma, when used without a reducing agent, can be used to oxidize NO_x. A scrubber must be added to the process to absorb N₂O₅ emissions to the atmosphere. Any resultant nitric acid can be either neutralized by the scrubber liquid and then sold (usually as a calcium or

ammonia salt), or collected as nitric acid.[4] Examples of this method being employed are as follows:

- a. Non-Thermal Plasma Reactor
- b. Inject Oxidant

5. *Removal of nitrogen Oxygen Instead Of Air:* This is accomplished by removing nitrogen as a reactant either by: (1) using oxygen instead of air in the combustion process; or (2) using ultra-low nitrogen content fuel to form less fuel NO_x. (3) Eliminating nitrogen by using oxygen tends to produce a rather intense flame that must be subsequently and suitably diluted. This method also includes reducing the net excess air used in the combustion process because air is 80% nitrogen. Using ultra-low-nitrogen content fuels with oxygen can nearly eliminate fuel and prompt NO_x. [3]

6. *Using a sorbent:* Sorption, both adsorption and absorption -- Treatment of flue gas by injection of sorbents (such as ammonia, powdered limestone, aluminum oxide, or carbon) can remove NO_x and other pollutants (principally sulfur). There have been successful efforts to make sorption products a marketable commodity. This kind of treatment has been applied in the combustion chamber, flue, and baghouse. This method uses either adsorption or absorption followed by filtration and/or electrostatic precipitation to remove the sorbent. [4]

A. NO_x control in combustion stage

Approximately 75% of the NO_x formed during conventional PC firing is fuel NO_x; the remainder is primarily thermal NO_x. Consequently, the most effective combustion countermeasures are those limiting fuel NO_x formation. Fuel NO_x is formed by oxidation of fuel bound nitrogen during devolatilization and char burnout. High oxygen availability and high flame temperatures during devolatilization encourage the conversion of volatile-released nitrogen to NO_x. The most effective means of reducing fuel-based NO_x formation is to reduce oxygen (air) availability during the critical step of devolatilization. Additional air must then be added later in the process to complete char reactions and maintain high combustion efficiency. Oxygen availability can be reduced during devolatilization in two ways. One method is to design the burner(s) to supply all of the combustion air, but in a manner which limits the rate of air introduction to the flame. Only a fraction of the air is permitted to mix with the coal during devolatilization. The remaining air is then mixed downstream in the flame to complete combustion. Burners employing this technique (low NO_x burners) can reduce NO_x emissions by 30 to 60% relative to uncontrolled levels.

Air Staging: A second method of reducing oxygen availability during the early phase of combustion is to remove a portion of the combustion air from the burners and introduce it elsewhere in the furnace. This method is

referred to as air staging. Reducing the airflow to less than stoichiometric (theoretically required for complete combustion air flow) conditions can further reduce NO_x emissions. This deeper staging minimizes NO_x formation, but inevitably results in more unburned or partially burned fuel leaving the burner zone. The remaining theoretical air and excess air must then be supplied through air staging ports (NO_x ports or OFA ports).

Fuel Staging: Another method of reducing NO_x emissions is referred to as reburning or fuel staging. This control technique destroys NO_x after it has formed. Fuel staging involves introducing the fuel into the furnace in steps. Typically, the bulk of the fuel is burned in the furnace at near stoichiometric conditions. The balance of the fuel, with a limited amount of air, is then injected to create a reducing zone part way through the combustion process. The reducing conditions form hydrocarbon radicals, which strip the oxygen from previously formed NO_x, thereby reducing overall NO_x emissions. The balance of the air necessary to complete the combustion is then added.#

B. Post-combustion reduction

With current and proposed regulations, it is economically logical to consider NO_x controls that achieve the lowest emission levels possible. Additional NO_x control techniques can be applied downstream of the combustion zone to achieve the further reductions. These post-combustion control systems are referred to as selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR). In either technology, NO_x is reduced to nitrogen (N₂) and water (H₂O) through a series of reactions with a reagent (or reagents) injected into the flue gas. The most common reagents used in commercial applications are ammonia and urea for both SCR and SNCR systems.

Selective catalytic reduction: Selective catalytic reduction technology is currently the most effective method of post-combustion NO_x reduction.[11] In the SCR process, a catalyst facilitates a chemical reaction between NO_x and a reagent (usually ammonia) to produce nitrogen and water vapor. While the reactions are exothermic, the temperature rise across the catalyst is typically negligible due to the low NO_x concentrations. The ammonia (NH₃) is injected into the hot flue gas through an injection grid, the flue gas with the ammonia passes across the catalyst surface, and the NO_x reactions occur within the micropores of the catalyst. Nitrogen oxides are present in flue gas in the form of both NO and NO₂ with NO being the greater; however, NO₂ is preferentially reduced in this process [7].

Selective noncatalytic reduction technology: There are currently two basic selective noncatalytic reduction (SNCR) processes available. [12]An ammoniabased system and a urea-based technology have been developed and commercially operated for many years. Although there are distinct differences to each technology, the

overall processes are similar and will be presented as the same in the following sections. While the current emphasis in NO_x control has centered on the SCR technology, SNCR is an effective control technology for certain applications or in combination with combustion and control system techniques. NO_x reduction reaction SNCR technologies inject a reducing agent into NO_x-laden flue gas within a specific temperature zone. In addition, it is important to properly mix the reagent with the flue gas. Finally, the mixture must have adequate residence time at temperature for the reduction reactions to occur. The application of SNCR technology to boilers which by design have the suitable gas temperatures in the upper furnace is an attractive use of the technology.[12] Examples of this boiler type are those applied to municipal solid waste and biomass firing. The SNCR system consists of storage and handling equipment for the ammonia or urea, equipment for mixing the chemical with the carrier (compressed air, steam or water), and the injection equipment. Much of the equipment is similar to the SCR storage and handling equipment. The key component, the injection system, consists of nozzles generally located at various elevations on the furnace walls to match the expected flue gas operating temperature. The number and location of the nozzles are established by the supplier and are based on obtaining good reagent distribution within the flue gas. One major difference between the ammonia and urea based processes is that the ammonia is usually injected into the gas stream in a gaseous state, whereas the urea is injected as an aqueous solution. The urea technology requires a longer residence time for reactions due to the time required to vaporize the liquid droplets once they are in the gas stream. Aqueous ammonia systems may also be injected as a liquid with additional residence time required for vaporization [12].

References

- [1] Selective Catalytic Reduction Control of NO_x Emissions, SCR Committee of Institute of Clean Air Companies, November 1997
- [2] Nitrogen Oxides: Impacts on Public Health and the Environment, EPA 452/R-97-002
- [3] Summary of NO_x Control Technologies and Their Availability and Extent of Application, EPA 450/3-92-004
- [4] Sourcebook: NO_x Control Technology Data, EPA 600/2-91-029
- [5] Put a Lid on NO_x Emissions, J. Czarnecki, C. Pereira, M. Uberoi, K. Zak, Pollution Engineering, November 1994
- [6] Nitrogen Oxides Control Technology Fact Book, Leslie L. Sloss, Noyes Data Corp., 1992
- [7] Selective Catalytic Reduction Control of NO_x Emissions, SCR Committee of Institute of Clean Air Companies, November 1997
- [8] "Standard Practice for Calculating Heat Value, Compressibility Factor, and Relative Density of Gaseous Fuel," ASTM 3588-98, Annual Book of ASTM Standards, Vol. 05.06, September, 2003.
- [9] Elliot, M.A., Ed., *Chemistry of Coal Utilization*, Second Supplemental Volume, Wiley, New York, New York, 1981.
- [10] Zeldovich, Y.B., "Oxidation of Nitrogen in Combustion and Explosion," *Academic des Sciences de L'URSS Comptes Rendus (Doklady)*, Vol. 51, No. 3, pp. 217-220, January 30, 1946.
- [11] "Selective Catalytic Reduction (SCR) Controls to Abate NO_x Emissions," A white paper prepared by the SCR Committee of the Institute of Clean Air Companies, Inc. (ICAC), Washington, D.C., November, 1997.
- [12] "Selective Non-Catalytic Reduction (SNCR) for Controlling NO_x Emissions," A white paper prepared by the SNCR Committee, of

the Institute of Clean Air Companies, Inc. (ICAC), Washington, D.C., May, 2000.

- [13] "TECHNICAL EIA GUIDANCE MANUAL FOR THERMAL POWER PLANTS" (PDF). Ministry of Environment and Forests, Government of India. 2009.
- [14] "Economics of Coal and Gas Based Energy". Third Wave Solutions. 2012.
- [15] "Monthly All India Installed Generation Capacity Report" May2014.
- [16] "Key World Energy Statistics". International Energy Agency. 2013.