The Implementation and Efficiency of Technological Methods for Suppressing Nitrogen Oxides at Thermal Power Plants

E. Kakaras\textsuperscript{1}, A. Tumanovsky\textsuperscript{2}, V. Kotler\textsuperscript{2}, N. Koukouzas\textsuperscript{1} and E. Karlopoulos\textsuperscript{1}

\textsuperscript{1}Centre for Research and Technology Hellas / Institute for Solid Fuels Technology and Applications
\textsuperscript{4}\textsuperscript{th} km N.R. Ptolemaida-Kozani
P.O. BOX 95, 50200, Ptolemaida, Greece
Tel: +302463053842
Fax: +302463053843
E-mail: isfta@lignite.gr

\textsuperscript{2}All-Russian Thermal Engineering Institute
14/23 Avtozavodskaya str.
109280, Moscow, Russia
Tel: (095) 2753483
Fax: (095) 2347427
E-mail: vti@cnt.ru

Abstract

The problem of nitrogen oxides emissions has become important not only to designers engaged in the construction of new thermal power stations, but also to the management of power plants that have to cope with increasingly stringent sanitary requirements. In this paper, the main results obtained from recent introduction of technological methods for suppressing nitrogen oxides at thermal power plants in Russia and Ukraine are presented. By reconstructing of the furnace, which requires a significant low investment cost, investigations have shown that nitrogen oxides emissions can be reduced by 1.5 to 2 times when brown coal is used as fuel.

Nomenclature

\begin{itemize}
\item SR\textsubscript{I} \quad \text{Stoichiometric Ratio in primary combustion zone}
\item SR\textsubscript{II} \quad \text{Stoichiometric Ratio in reducing zone}
\item SR\textsubscript{III} \quad \text{Stoichiometric Ratio in reburn zone}
\item DAF \quad \text{Dry Ash Free}
\item V \quad \text{Volatile}
\item OFA \quad \text{Overfire Air}
\item UBC \quad \text{Unburned Carbon}
\item r \quad \text{Flue gas recirculation}
\item t\textsubscript{II} \quad \text{Residence time of the combustion products in the reburn zone}
\item t\textsubscript{I} \quad \text{Residence time in the reducing zone}
\item a \quad \text{Excess air}
\item a\textsuperscript{ii} \quad \text{Excess air past the furnace}
\item a\textsubscript{II} \quad \text{Excess air in the reducing zone}
\end{itemize}

1. Introduction

This paper presents the evaluation of applicability of the reburning technology on 11 Thermal Power Plants with 26 types of boiler, by a code which is called “psbl reburning”, in order to decrease the NO\textsubscript{X} emissions. For the above thermal power plants, the emitted amounts of NO\textsubscript{X} are represented in (Fig.1), in tones per year and for each plant. Annually in Russia the coal-power plants emit in the atmosphere about 300 kt of NO\textsubscript{x}, about 600 kt of SO\textsubscript{2}, about 400 kt of dust and 100 000 kt of CO\textsubscript{2} (Fig.2). ISFTA has investigated the environmental performance of the Russian coal-fired power sector in the CARNOT action programme where renovation activities in the Russian energy sector were promoted. [1]
As far as the depopulation equipment is concerned the Russian coal-fired power plants are equipped with Electrostatic Precipitators, Cyclones, Scrubbers and combinations of the above mentioned equipment. About 50% of the power plants are equipped with ESPs, about 40% with scrubbers, about 30% with cyclones and of course combinations of the above mentioned measure. (Fig.3) [1]

Figure 3. De-pollution equipment of the Russian coal-fired power sector.

The Russian coal-fired power plants utilize low and high rank coal. The name of the mine and the coal type are classified according to Russian standards. The lower Heating Value of the used Russian coals varies between 7MJ/Kg and 25MJ/Kg. The biggest part 47.74% of the annually consumed coal has LHV that varies between 15MJ/Kg and 20 MJ/Kg. Moreover 29.80% has LHV that varies between 20 MJ/Kg and 25 MJ/Kg. Finally only 3.9% of the consumed coal corresponds to low rank coal with LHV less than 10 MJ/Kg.

2. Classical and Simplified reburning

At the end of the 1970s and the beginning of the 1980s, in the United States and Japan, almost simultaneously, studies of a new technology for flame combustion were started. The objective was to suppress nitrogen oxide (NOx) emissions. This new technology was called the reburning process. In Russia, this technology is called three-stage combustion. The essence of this technology is intensification of the reduction of nitrogen oxides by hydrocarbons and possibly by radicals that contain nitrogen. The latter are formed in zones where combustion takes place with a deficiency of oxidizer.

The combustion technology that is implemented by the classical and simplified reburning is as follows. About 80 – 90% of the fuel, with the ordinarily used excess air that ensures stable inflammation and efficient combustion, is delivered to the main burners. The rest of the fuel (natural gas, or some other highly reactive fuel) is delivered to additional burners with a high deficit of air for the excess air coefficient to decrease to 0.9 – 0.95 after this fuel is mixed with the combustion products of the main flame. The nozzles for tertiary air blow are located above the fuel input. The tertiary air is necessary to complete the combustion process.

Using this combustion technology in industrial boilers corroborated the possibility of a great reduction of nitrogen oxides into molecular nitrogen N2, which is harmless.

This method demands the following three zone to be provided in the furnace chamber volume.

- Primary combustion zone, SR1 ≥ 1
- Reducing zone where supplementary fuel firing provides for SR2 ≤ 1
- Reburn zone where injection of tertiary air provides for SR3 = SRb

For the above zones, the stoichiometric ratio (SR) must be determined by the flow of coal, burner air, natural gas and OFA. In general, the SRs in all three zones should be at the lowest acceptable values to maintain the highest possible efficiency consistent with gas reburning technology. Flue gases recirculation (r) was initially used for natural gas injection because theory suggested that the mass flow was needed to provide momentum to and mixing of the injected natural gas.

The specialists of VTI use two alternatives of the reburning technology. In the classical one, gas burners are installed to form a special reducing zone (this alternative was applied in a 300 MW power unit at the Ladyzhino district power plant). In the simplified alternative, the reducing zone is formed because of the decrease in excess air in the upper tier burners (the 150 MW unit at the Dobrotvory district power plant, the TP-230 boiler at the Stupino CHP plant of the Moscow power system). [2,3]

For the first time, the classical reburning process was realized by the VTI on the 300 MW unit of Ladyzhino TPP in 1989-1992 in cooperation with the ABB Combustion Engineering (USA), Ladyzhino TPP (Ukraine), and Yuzhtechenergo (Ukraine). [4]

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At the Ladyzhino district power plant, the TPP-312 boiler has a furnace with liquid slag removal and 16 vortex burners are installed countercurrently in two tiers at the front and the back waterwalls.
When reconstructing the boiler, the main burners were not changed. Additional rectangular gas burners were installed countercurrently at the front and the back waterwalls with a slight downward inclination. The nozzles for tertiary air blow were placed above the additional burners at the front and the back waterwalls as well (Fig. 5). The results of tests conducted on the TPP-312 boiler which was reconstructed in accordance with the three-stage combustion scheme, showed that the boiler operates reliably and efficiency in a wide range of loads.

When 6 to 16% of natural gas and 8 to 10% of recirculating gases are delivered to the additional burners, the NO\textsubscript{x} concentration downstream of the boiler was equal to 500 – 570mg/m\textsuperscript{3}. Before reconstruction, the NO\textsubscript{x} concentration in the flue gases varied from 1100 to 1200mg/m\textsuperscript{3}, depending on the excess air. In tests after reconstruction, when the secondary air flowrate to the main burners was reduced to its rated value of a=1.05, the NO\textsubscript{x} concentration decreased to approximately 400mg/m\textsuperscript{3}. (Fig.4)

Figure 4. The results of tests on TPP-312 boiler at Ladyzhino Plant

The example of using the simplified three-stage combustion technology is the reconstruction of the TP-230 boiler at CHP plant 17 of the Moscow power system. This boiler furnace has solid slag removal and four shaft windows for coal dust-air mixture located at the front waterwall.

The boiler was tested only after reconstruction was over. Therefore, the nitrogen oxide concentration in the base regime (before reconstruction) was estimated using the data obtained for the CHP as a whole. In accordance with this data, the NO\textsubscript{x} concentration in the flue gases constitutes 300 – 390mg/m\textsuperscript{3} when burning natural gas and 1025 mg/m\textsuperscript{3} when burning Moscow basin coal.

The secondary air nozzles are mounted inside these windows. In turn, the natural gas nozzles are placed inside the secondary air nozzles (Fig.6).

To reduce to a minimum the amount of work necessary for reconstruction, the power station selected the simplified three-stage combustion scheme.

This scheme calls for a decrease in the outlet cross-section of the channel, which delivers air nozzles at the front and the back waterwalls.

After introducing simplified three-stage combustion, several operating conditions were checked. When the tertiary air gate valves were closed, the NO\textsubscript{x} concentration was equal to 280 mg/m\textsuperscript{3} when burning natural gas and to 730-750 mg/m\textsuperscript{3} when burning coal. In this case, the NO\textsubscript{x} was suppressed only as a result of redistribution of the excess air between the upper and the lower part of the main flame.

A second series of tests was conducted with the tertiary air gate valves open by 50%. In these tests, the NO\textsubscript{x} concentration decreased to 185 mg/m\textsuperscript{3} when burning natural gas and to 580 mg/m\textsuperscript{3} when burning brown coal. In the last series of tests, when the tertiary air valves were fully open, that is, with the rated scheme of...
3. Applicability of reburning technology in Russia and Ukraine.

Considering the available successful implementation of both the simplified and classical reburning process, the VTI administration takes an active part in EC International project “Application of reburning for NOx abatement in Russia and CIS”.

At the first step, the information had been collected on the boilers steam output installed in the Russia Federation, Kazakhstan and Ukraine. The composite tables incorporated 40 TPPs of the Russian Federation (218 boilers of total electrical capacity of 30890 MW), 15 TPPs in the Ukraine (95 boilers, 23300 MW) and 10 TPPs in the Kazakhstan (61 boilers, 10400 MW).

Next based on the sufficiency of the obtained information, 11 TPPs of the Russian Federation, 3 TPPs in the Ukraine and 3 TPPs in the Kazakhstan had been selected. Some TPPs have two or even three phases of construction with different equipment, therefore, the final list contained 11 TPPs with 26 types of boilers.

For the above 26 boilers, the predictions were carried out using the “Psbl Reburning” code to assess the technical feasibility of reconstruction by the reburning scheme.

The capacity of the boilers for which the calculations had been made, varied from 320 to 1650 t/h practically firing all grades of coals produced in Russia, as well as Donetsk anthracite culm, Lvov-Volynsk coals (Ukraine) and CC Ekibstauz coal (Kazakhstan). The list includes the wet and dry bottom, opposite, front and tangential fired boilers.

To provide for 50% NOx reduction, it was adopted that in the case of the gas reburning the main burners will be supplied with 85% of coal, and additional burners with 15% of natural gas. The latter burners are to be supplied with the recirculation gases taken past the economizer (about 10%).

At TPP having no possibility of the round the year natural gas supply, the main burner will use 80% of coal at normal excess air coefficient, while additional burners will use 20% of the same coal at lean-air coefficient.

In using direct-fired systems, the additional burners were fed with the coal-mixture only. For example, the burner was equal to the share of the primary air. In the case of the indirect-fired systems, the above coefficient was adopted at 0.25-0.35 versus characteristics of the coal fired.

The coefficient for the reducing zone (above the additional burners) was calculated based on the fuel and air input, accounting for not only controlled air but the furnace inleakage and recirculation gases as well.

The amount of the air required to be fed as tertiary air was calculated in the fractions from SR as the difference between the excess air past the furnace and in the reducing zone.

$$Δα = α_T − α_{II}$$

The location for the injection of the additional fuel was taken considering the complete combustion of volatile matter and about 90% burnup on the DAF basis. In so doing, the configuration of the furnace lower portion (for the determination of the active combustion zone) and VDAF had been taken into account.

The reducing zone combustion products residence time in the base option of the predictions was taken at 400ms. It had been done on the basis on numerous experimental investigations showing that further increment in reburning efficiency becomes insignificant, but the amount of the incomplete combustion products (CO, H2) in the furnace outlet flue gases increases with increasing final UBC (refer to the diagrams in Figs. 8 and 9 obtained on fire test facilities [5,6] and on large utility boiler [7]).

The selected time tII enables the calculation of the location of tertiary air nozzles and, hence, of tIII the residence time of the combustion products in the reburn zone. For example, the furnace upper section, from the level of the tertiary air injection to the platen superheater lower elevation.

If the calculated tIII turned out to be greater than 600ms, the conclusion was that the boiler is adapted for application of reburning, otherwise special measures are required.

The basic results of the predictions using the “Psbl Reburning” code are given in Table 1.

The multivariate predictions based on Psbl Reburning code indicated that the reducing zone SR (which practically defines the degree of NOx reduction at constant residence time tIII) depends on a great extent on the boiler operating parameters. In Fig.8 predicted values of SRII at constant tIII are illustrated with varying main burner SR, furnace inleakage, flue gas recirculation in
additional burners, and excess air past the boiler (for example, $O_2$ content in recirculation gases).

Figure 8. $NO_x$ emission versus reducing zone residence time $t_{II}$: 1) experiments at the test facility firing Uttal coal [5]; 2) Mitsui Badcock Energy Limited (MBEL) test results.

Figure 9. Concentration $NO_x$ and UBC versus $SR_{II}$ at Longannet unit 600 MW [6]

The predictions were made for the TPP-312 boiler with the main and additional fuel being Donetsk coals and natural gas respectively.

4. Conclusions

In table 1, the predicted values are given. The following conclusions can be made for the applicability of the reburning technology.

For 16 out of 26 boilers, the natural gas reburning was applied, and for 10 boilers applied the coal by coal reburning (due to no natural gas at the TPP)

Out of 26 boilers, 11 boilers have dry-bottom furnaces, and 15 boilers have wet-bottom furnaces. The former boilers are designed at supercritical pressure where the two-stage combustion is undesirable due to danger of enhanced high temperature corrosion of the furnace walls in the active combustion zone.

Most of the boilers can be reconstructed for reburning taking account the parameters: the reconstruction of the furnace facilities ensures sufficient residence time for the reducing zone ($400ms$) and reburn zone ($>600ms$), the $SR$ in the reducing zone being generally at $0.92-0.96$ enabling of about 2 times reduction of $NO_x$ emissions (Fig.9).

The exceptions are TP-80 boilers (Mosenergo CHP plant 22 and Lenenergo Pervomaiskaya CHP plant 140 and BKZ-500 boilers (Kransnoyarsk CHP plant 2 and Novo-Irkutsk CHP plant). In the first case, the problem is with rather high elevation of the burners (at TP-80 boilers, the burners axes are on 11490mm elevation while at the adjacent TP-87 boilers of the same capacity at the 9150mm elevation). In the second case (BKZ-500 boiler), the cause is, first, due to large burner flue gas recirculation ($r>25\%$) and, second, low rate of heat release in the active combustion zone, as result of which the axis of the burner upper tier was found to be at 19260mm elevation.

The diagrams explains wide variations of the flue gases $NO_x$ concentration after the reconstruction of the TPP-312 boiler (Ladyzhino TPP). With wide open secondary air dampers, the main burner $SR$ increased to 1.15, the reducing zone $SR$ approached 1.0 which caused $C_{NOx}$ rise to 500-600mg/m$^3$. With reduced secondary air flow, the design excess air coefficient were reached burner $SR=1.05$ and $SR_{II}=0.96$. In such experiments, the boiler outlet flue gas $NO_x$ concentration was reduced to 400-420mg/m$^3$ which is a rather good result for the wet-bottom boilers.

The effect of the introducing various methods of staged combustion in boilers can reduce $NO_x$ emissions by 2 to 4 times when natural gas is burned and by 1.5 to 2 times when fuel oil and black and brown coals are burned.
<table>
<thead>
<tr>
<th>№</th>
<th>TPS or CHP</th>
<th>Title of boilers</th>
<th>Gas reburn (GR) or Coal by Coal reburning (CbC)</th>
<th>Capacity of boiler, MWth</th>
<th>Share of fuel (%) main/reburn burners</th>
<th>SR in zones</th>
<th>( \tau ) (ms) in burnout zone</th>
<th>Applicability (A) or not applicability (NA)</th>
<th>Level of reburn burners (RB) and OFA (mm)</th>
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<td>1278</td>
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Table 1. Evaluation of the Applicability of the Reburning Technology

*) Calculation is made for a single furnace of two-boiler single turbine unit

**) Calculation is made for a half furnace
Figure 8. Boiler TPP-312, Bituminus Coal, Gas reburns. $\text{SR}_{\text{II}}$ versus main parameter of boiler operation with $t_{\text{II}} = 400$ ms (constant)
References


