

## INFLUENCE OF OVER FIRE AIR SYSTEM ON NO<sub>x</sub> EMISSIONS An Experimental Case Study

by

**Nihad HODZIC<sup>a</sup>, Anes KAZAGIC<sup>b\*</sup>, and Sadjit METOVIC<sup>a</sup>**

<sup>a</sup> Faculty of Mechanical Engineering Sarajevo, University of Sarajevo,  
Sarajevo, Bosnia and Herzegovina

<sup>b</sup> JP Elektroprivreda BiH - Sarajevo Power utility, Sarajevo, Bosnia and Herzegovina

Original scientific paper  
<https://doi.org/10.2298/TSCI180619238H>

*In this work, various combinations of the NO<sub>x</sub> emission influencing factors and their combined effects in air staging combustion on level of furnace, using over fire air, were investigated in an experimental lab-scale furnace. At this, process temperature were varied in the range from 950 °C to 1450 °C, excess air ratio in primary zone in the range  $\lambda_1 = 0.9 - 1.2$ , while distance of over fire air nozzles from the burner outlet varied until a given distance of 2/5 of total length of furnace. Basic fuel is brown coal from Middle Bosnia coal basin, mixed in two coal blends and one coal-woody biomass blend, to combine an effect of fuel characteristics variation on NO<sub>x</sub> emission. Results shows that an average reduction of NO<sub>x</sub> emission over tested temperature range, when using over fire air against conventional air supply with over fire air switched off, is 26.5%. At this, much more NO<sub>x</sub> emission reduction for two coal blends were occurred at higher temperatures – at 1350 °C and above, where an average NO<sub>x</sub> emission reduction is 32.5%. Furthermore, it was found that the NO<sub>x</sub> emission decreased with an increase in distance of over fire air nozzles from the outlet level of burner until a distance of 1/3 of total furnace length; with further increase of the distance, NO<sub>x</sub> emission is stabilised and no further effect to NO<sub>x</sub> emission reduction was observed, while CO emission and unburnt increased.*

Key words: combustion, excess air ratio, over fire air, NO<sub>x</sub> emission

### Introduction

An appropriate excess air ratio and air distribution dictated by amounts, locations and manner of introducing certain portions of total air into the furnace, are one of the key factors influencing on efficiency of the combustion process and NO<sub>x</sub> emissions in large boilers. The application of air staging combustion system into large furnace - including proper design referred to supply of primary, secondary, tertiary air and over fire air (OFA) – is unavoidable in the design of new industrial and energy boilers today. This is also applied in reconstruction of existing coal-base power units, necessary today to increase efficiency, mitigate emissions issue and improve economy of solid-fuel based power plants. The application of this primary measure does not require significant financial investment - the cost of investing in the introduction of the air staging combustion system into the regular boiler operation is practically negligible in relation to the multiple positive effects and benefits of applying such a system, in particular the lower NO<sub>x</sub> emissions.

\*Corresponding author, e-mail: a.kazagic@epbih.ba

Reduction of NO<sub>x</sub> emissions in comparison to conventional combustion systems can be achieved by applying a newer generation burner with lower NO<sub>x</sub> emissions (swirl or jet low-NO<sub>x</sub> burners LNB), then air staging combustion system including. The OFA, fuel staging of basic fuel or additional fuel (for example, natural gas or biogas) for reburning. The LNB burners work on the principle of air staging combustion at the level of individual burners – which result in a significant reduction in NO<sub>x</sub> emissions and today are necessary equipment for new energy boilers which are usually with supercritical or ultra-critical parameters of steam and which require very high flexibility in operation, [1, 2]. In the paper [3], the results or the effect of the air staging including OFA on NO<sub>x</sub> emissions were presented; as fuel, dried lignite was used. It has been shown that in this way there is a significant reduction in NO<sub>x</sub> emissions and the results are related to testing the amount of OFA air and the distance of its introduction into the reaction zone relative to the burner. In the paper [4] it was stated that, with LNB, NO<sub>x</sub> emissions can be reduced by a fifth, but that due to the high combustion temperature this emission is still high (1036 mg/m<sup>3</sup> at 6% O<sub>2</sub> dry). For further reduction of the NO<sub>x</sub> emission, air staging and OFA is recommended. In works [5, 6], the performance of a pulverized-coal-fired large-scale laboratory furnace with air staging was evaluated for two primary zone stoichiometric ratios, 1.15 (unstaged flame) and 0.95 (staged flame), other operating conditions being fixed. The results revealed that the reduction in primary zone stoichiometric ratio caused a decrease in NO<sub>x</sub> emissions from 421 to 180 mg/N m<sup>3</sup> at 6% O<sub>2</sub>, an increase in CO emissions from 51 to 168 mg/N m<sup>3</sup> at 6% O<sub>2</sub> and a reduction in particle burnout from 81.8% to 76.5%. It was concluded that the reduction of the O<sub>2</sub> availability in the primary zone inhibits the NO formation, mainly via the fuel mechanism, but it affects negatively both the CO and the char oxidation processes. The same findings and similar positive effects of the air staging combustion on the reduction of NO<sub>x</sub> emissions are also shown in works [7, 8] – coal combustion; as well as in cofiring of coal and biomass, as reported in [9-11]. Reburning process and effects of use various reburning fuels and fuel particle size to NO<sub>x</sub> emissions were studied widely. Casaca and Costa [12, 13], found that the sawdust reburning leads to NO<sub>x</sub> reductions comparable or even higher than those attained with natural gas reburning, while coal reburning yields much lower NO<sub>x</sub> reductions. In work [14], Hodzic *et al.* found that over 50% of NO<sub>x</sub> emission reduction can be achieved by reburning at 0.1 cofiring, and even 67% with additional effect of reducing process temperature. With regard to influence of furnace configuration to NO<sub>x</sub> emissions, combustion symmetry factors such as dimensionless of upper furnace height, boiler nose depth, furnace arch's burner location and staged air angle were numerically studied in works [15, 16] to investigate effects to unburnt and NO<sub>x</sub> emissions. Same authors in work [17] studied effect of primary air cone length on burner performance and NO<sub>x</sub> emissions. It was found that flame stability, performance of ignition, and burnout are significantly improved by decreasing the primary-air cone length, while NO<sub>x</sub> emissions decreased.

All aforementioned works mostly investigated influence of single factors on the NO<sub>x</sub> emissions. However, for better understanding and improvement the effects, it is important to quantify and sublimite influence on NO<sub>x</sub> emissions of variuos factors, *i.e.* determine combined effects of various factors on NO<sub>x</sub> emissions. This paper deals with such a comprehensive approach, grounded on extensive tests which were recently carried out at the Faculty of Mechanical Engineering in Sarajevo, in Laboratory for Coal and Biomass Combustion. The experimental study investigated the effects to NO<sub>x</sub> emission of the air staging in furnace including primary zone stoichiometric ratio and OFA nozzles positions in terms of various distances from the burner's level, combined with fuel characteristics, the process temperature and burner configuration including various primary/secondary/tertiary air distribution.

## Experimental

### Fuel test matrix

Basic fuel used for the tests is brown coal from Middle Bosnia coal basin, mixed in two coal blends and one coal-woody biomass blend, to combine the effects of fuel characteristics variation with other influencing factors on NO<sub>x</sub> emission. Coal from the Middle Bosnia mining basin is used to be run in regular operation of coal-based power plant Kakanj, in central Bosnia, in which it is burned in pulverized coal boilers with slag tap furnaces. That combustion technology is characterized by high temperature in the furnace, especially in a melting chamber (achieving temperature level of 1450-1550 °C). It results in very high NO<sub>x</sub> emissions which go up to 900 mg/m<sup>3</sup> at 6% O<sub>2</sub> dry, even with applied primary measures. The basic characteristics of the coal are low calorific value, a high proportion of mineral and humidity and poor reactivity, [18,19].

**Table 1. Proximate and ultimate analysis of the tested fuels, [20]**

Fuel	K70B20Z10	U100	U93B7
<b>Proximate analysis, %, as-received</b>			
Moisture	10.71	13.90	18.09
Ash	40.84	37.88	33.05
Volatiles	27.71	28.97	31.16
Fixed C	20.73	19.25	18.59
Combustible	48.44	48.22	48.86
<b>Ultimate analysis, %, as-received</b>			
Carbon	34.48	36.62	33.36
Hydrogen	2.33	2.60	2.52
Sulphur	2.41	2.06	1.59
Nitrogen	0.75	0.72	0.75
Oxygen	8.48	10.22	10.63
<b>Heating value, kJ/kg, as-received</b>			
Gross	13898	13351	13446
Net	13171	12496	12510

For purpose of lab-scale tests, fuel test matrix is used as shown in tab. 1.

- K70B20Z10 coal blend, mixed by coals from Kakanj (K), Breza (B), and Zenica (Z) coalmines with mass fractions in the blend at 70%w, 20%w and 10%w, respectively. The coal blend was formed after drying and grinding of component coals in a laboratory mill.
- U100 coal blend, usual blend of coal that is used in regular operation of Kakanj power station for the last few years. This mixture was formed by mixing the coals delivered to the coal depot of Kakanj power station from several coalmines, namely Kakanj, Breza, Zenica, Gracanica, Livno, Nova Bila, and Banovici. For purpose of the tests, a sample of the coal blend was extracted from behind the mills in the real drive of Kakanj power station Unit 5.
- U93B7 coal-biomass blend, made by mixing the coal blend U100 with the waste woody biomass B100 at mass ratio 93:7%w respectively. The biomass is a sawdust mix of beech and spruce mixed at an approximate mass ratio of 50:50%w. The sample of the coal-biomass blend for the tests was taken from the belt-conveyer during the co-firing operation of Kakanj power station Unit 5.

### Lab-scale furnace, experimental setup and measurements

#### Lab scale furnace

Electrically heated entrained flow tube reactor, located in the laboratory of the Faculty of Mechanical Engineering Sarajevo, Department of Energy, is used for the tests. The lab-scale furnace allows testing the characteristics of combustion of various fuels at different ambient and technological conditions. The lab-scale furnace is comprised of a 3 m length alumina-silicate ceramic tube, with a diameter of 230/200 mm, where combustion takes place, surrounded by SiC

stick-type electric heaters and three-layer insulation, fig. 1.

The temperature of the reaction zone is controlled by a programmable logic controller with thyristor units for each of the four heating zones, allowing the process temperature to be varied at will across the range from ambient to 1560 °C. The furnace is designed to operate at a wide range of process temperature, amounts and distribution of basic fuel and combustion air, including an ability to test reburning, using both basic and additional solid and gasses fuels, for example natural gas, [19].

#### Experimental set-up and measurements

The maximum power of the electrical heaters used to maintain temperature in the reaction tube is 70 kW, while nominal or thermal power of the furnace is 20 kW. Pulverized fuel is fed into the furnace by means of a volumetric feeder, mounted above the reactor. The feeder is equipped with a speed controller, allowing mass-flow in the range of 0.25-5 kg/h. Air for combustion, coming from the air blower, is divided into carrier air (primary air), secondary air, tertiary air, and OFA. The first three air portions are fed into the furnace over the swirl burner settled on the top of the reactor, so the air-fuel particle mixture flows downward. The excess air ratio was adjusted by tuning the air flow in each airline, at a constant fuel flow. Ratio of primary and secondary/tertiary air is adjusted on a swirl burner for optimal air staging in primary zone *i.e.* optimal NO<sub>x</sub> and CO ratio. Thus, in all tests, optimized NO<sub>x</sub> and CO emissions were provided if primary (carrier) air portion was set at 1.50 m<sup>3</sup>/h providing primary air ratio to be between 0.30-0.33. For air staging in the furnace, OFA varied from 0 to 0.30 of the overall amount of combustion air. The new data are reported in this work for four primary zone stoichiometric ratios, 1.15 and 1.2 for unstaged flame and 0.90 and 0.95 for staged flame. Depending on fuel and excess air ratio used, total air-flow rate was between 4.2 and 4.5 m<sup>3</sup>/h, while flue gas flow rate was between 4.5 and 5.0 m<sup>3</sup>/h. Fuel thermal load is kept at same thermal input (approximately 5 kW<sub>th</sub>) in all the runs to provide comparison of the results. Depending on the fuel and excess air used, the total air-flow rate is identified. The primary (carrier) air-flow rate is set at 1.50 m<sup>3</sup>/h for all the runs, with the rest of the air is divided into secondary and tertiary portions, approximately at a ratio of 2.5:1. No air preheating was before entering the burner. Specific fuel particle size is used as shown in tab. 2.

Emissions of O<sub>2</sub>, NO, NO<sub>2</sub>, SO<sub>2</sub>, CO, and CO<sub>2</sub> are measured by a TESTO 350XL instrument. Flue gas temperature is measured at the point in the partially insulated outlet tube where the gas sample is taken for emissions measurement. The processes in the flue gas line is frozen; there is no post combustion from the reactor to the TESTO 350XL instrument. With regard to measurement of emissions, the measurement error is estimated for the NO emission to be at 2.6%, [20]. The aforementioned facts should be taken into account in considering the results presented here.

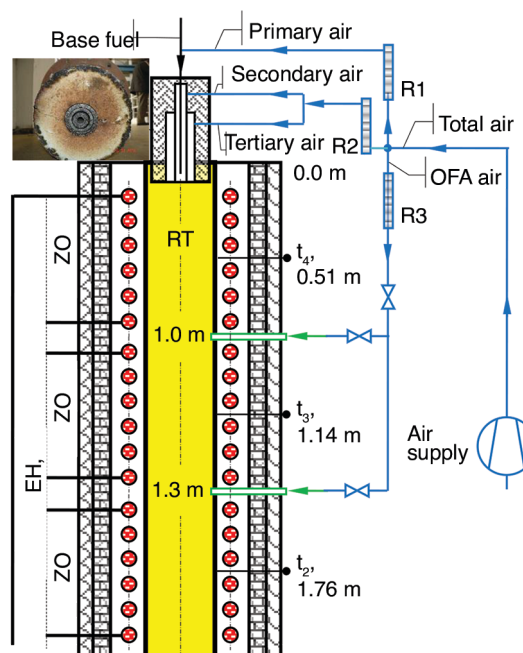


Figure 1. Principal scheme of part of the lab-scale furnace with indicated staging air introduction

With regard to process temperatures used, fuel K70B20Z10 is tested over temperature range of 950-1350 °C, while fuels U100 and U93B7 were tested over the temperature range 1350-1450 °C, which corresponding to conditions of PC boilers with slag tap furnace; that technology was applied to all units in the Kakanj power station, of which the units 5 and 6 (2 × 118 MW) and unit 7 (230 MW) are still in operation.

**Table 2. Fuel particle size distribution**

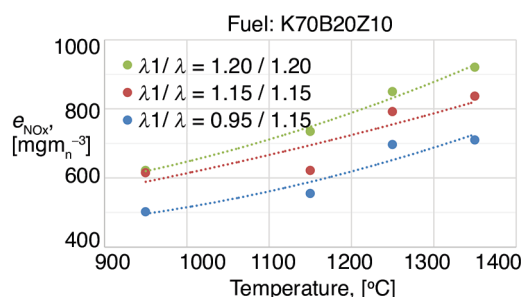
Fuel particle size, [%]	K70B20Z10	U100	U93B7
>1.00 mm	0.00	0.04	0.45
>0.50 mm	1.80	0.66	2.39
>0.20 mm	25.82	18.50	18.15
>0.09 mm	21.70	34.70	35.24
<0.09 mm	50.69	46.11	43.77

## Results and discussion

### *Combined effect of various excess air ratios and the process temperatures on the NO<sub>x</sub> emission reduction*

In this case, fuel Fuel K70B20Z10 is tested and the NO<sub>x</sub> emission is given as function of the combustion temperature (950, 1150, 1250, and 1350 °C) and the various primary zone stoichiometric ratios (1.20, 1.15, and 0.95). In relation to the process temperature, as expected, the lowest NO<sub>x</sub> emission is recorded at the lowest test temperature of 950 °C. Generally, the NO<sub>x</sub> emission increases with a rise in temperature all over the range of tested temperatures and excess air ratios. On the other hand, the NO<sub>x</sub> emission is lower for lower values of the total excess air ratio:  $e_{\lambda=1.15} < e_{\lambda=1.20}$ . In test regimes with unstaged flame ( $\lambda_1/\lambda = 1.15/1.15$  and  $\lambda_1/\lambda = 1.20/1.20$ ), the air enters the burner as primary, secondary and tertiary air. In contrast to these test modes, the test mode with staged flame ( $\lambda_1/\lambda = 0.95/1.15$ ) is with the total excess air ratio  $\lambda = 1.15$ , but with the portion of air added through OFA nozzles in furnace at a given distance behind the burner (in this case placed at the distance of 1.0 m from the burner exit or at 1/3 of the total furnace length – OFA1, see fig. 1). In this test regime, the lowest NO<sub>x</sub> emissions were measured for all the combustion temperatures, in relation to the conventional air supply to the burner. For example, at a combustion temperature of 1350°C and in the case of air staging with OFA, the emission is 710 mg/m<sup>3</sup> at 6% O<sub>2</sub> dry and is lower by about 130 mg/m<sup>3</sup> in relation to the classical supply of the air to the burner at the same excess air ratio; a reduction in the NO<sub>x</sub> emission for these two test regimes is about 15%, fig. 2.

Considering combined effect of the process temperature and excess air ration on NO<sub>x</sub> emission, it is important to note that the effect of decreasing excess air ratio on NO<sub>x</sub> emission is stronger when a process temperature increased.



**Figure 2. The NO<sub>x</sub> emission as function of the combustion temperature and excess air ratio**

### *Combined effect of air staging in furnace at various primary zone stoichiometric ratios and the process temperatures on the NOx emission reduction*

In this case fuel U100 is tested and NO<sub>x</sub> emissions are given depending on the combustion temperature (1350, 1400, and 1450 °C) and various primary zone stoichiometric ratios:  $\lambda_1/\lambda = 0.90/1.20$ ,  $\lambda_1/\lambda = 0.95/1.20$  and  $\lambda_1/\lambda = 1.20/1.20$  (unstaged flame *i.e.* OFA switched off). Due to higher combustion temperatures, in comparison with the previous coal blend, even more NO<sub>x</sub> emissions were measured in this case. So, for example, for a combustion temperature of 1450 °C and air staging with OFA switched on, the NO<sub>x</sub> emission is, on average, 860 mg/m<sup>3</sup> at 6% O<sub>2</sub> dry



as opposed to 1155 mg/m<sub>n</sub><sup>3</sup> at 6% O<sub>2</sub> dry in the conventional air supply to the burner with OFA switched off, fig. 3. In this case, the NO<sub>x</sub> emissions with OFA switched on is lower by almost 300 mg/m<sub>n</sub><sup>3</sup> or about 25%.

Furthermore, the NO<sub>x</sub> emission results show that, along general decreasing in NO<sub>x</sub> emission when primary zone stoichiometric ratio decreases ( $e_{\lambda 1 = 0.90} < e_{\lambda 1 = 0.95}$ ), an effect of the decreasing primary zone stoichiometric ratio on NO<sub>x</sub> emission reduction is stronger when process temperature increases. It does not mean that the combustion modes with  $\lambda 1/\lambda = 0.90/1.20$  are generally more favorable than the air staging regimes with  $\lambda 1/\lambda = 0.95/1.20$ . Namely, in the overall assessment of the combustion process of a given fuel, in addition to the NO<sub>x</sub> emissions, the efficiency of the process estimated through CO emission and unburnt is particularly important.

When compared NO<sub>x</sub> emission results for the previous two fuels over the temperature range tested, it can be concluded that the rate of change in NO<sub>x</sub> emissions is higher when the coal is burnt under temperature equal or higher than 1350 °C, fig. 4. This is in accordance with the Zeldovich mechanism of temperature influence at the rate of the chemical reaction of thermal NO generation.

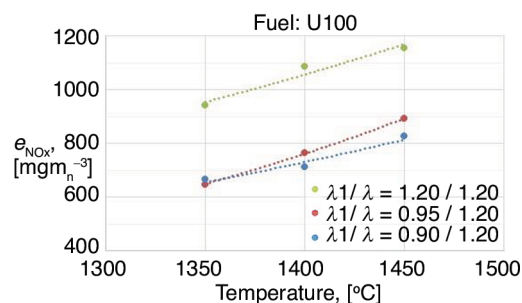


Figure 3. Fuel U100: NO<sub>x</sub> emissions as function of combustion temperature, excess air ratio and OFA portion, position of over fire air intake: OFA1

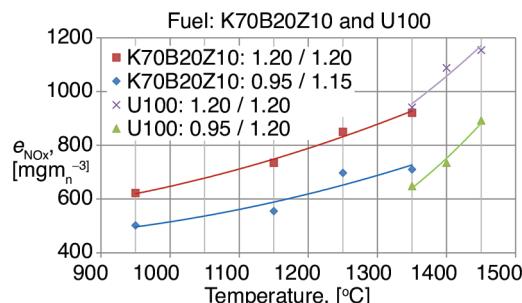


Figure 4. Trend of NO<sub>x</sub> emission values depending on the temperature and mode of combustion air distribution

#### *Combined effect of air staging in furnace at various primary zone stoichiometric ratios and the process temperatures on the NO<sub>x</sub> emission reduction*

Analogously to the previously presented, and for the same test settings, the following figure presents the NO<sub>x</sub> emission for co-combustion of coal and waste woody biomass – U93B7. Practically, the same conclusions can be drawn in this case, with an addition that NO<sub>x</sub> emissions in the co-combustion of coal and woody biomass are at the same level of NO<sub>x</sub> emissions as in coal combustion - comparing the regimes with the same combustion temperature, the same excess air ratio and the same air supply mode, fig. 5, [20]. It is worth mentioning that decreasing primary zone stoichiometric ratio in air staging in furnace produced higher reduction in NO<sub>x</sub> emission at higher process temperatures.

#### *Effect of distance OFA nozzles from burner exit to NO<sub>x</sub> emission*

For the fuel U93B7, NO<sub>x</sub> emission as function of the position of OFA nozzles in furnace i.e. the distance from the burner exit is shown in fig. 6.

In particular, the results are given for a process temperature of 1400 °C and for different positions of OFA nozzles in the reaction tube: OFA1 at a distance of 1 m from the burner exit, or at

1/3 of the total length of furnace, then OFA2 at a distance of 1.3 m from the burner exit or at 2/5 of total length of furnace and combined supply of the over fire air through OFA1 and OFA2 *i.e.* simultaneous supply of the OFA air at both given levels.

The results show that the NO<sub>x</sub> emission, in this case, is the lowest in the supply of the over fire air at position OFA1, while it is stabilised in the case of supply at position OFA2, fig. 6. By a simultaneous supply of the over fire air at both positions (both OFA1 and OFA2) it can be concluded that the NO<sub>x</sub> emissions are practically at the same level as in the case of the use of the position 2 (OFA2), fig. 6. On the base of these results, it can be concluded that NO<sub>x</sub> emissions decreases with an increase in distance of the OFA nozzle from the burner exit (as also found in work [21]) but only until a certain distance which is, in this case, at about 1/3 of the total furnace length. After that distance, the NO<sub>x</sub> emission is stabilized and there is no further effect of increasing the distance of OFA nozzle in order to reduce the NO<sub>x</sub> emission, while CO emission and unburnt increase.

## Conclusions

The experimental study investigated the effects to NO<sub>x</sub> emission of the air staging in furnace including primary zone stoichiometric ratio and distances of OFA nozzles from the burner exit, combined with fuel characteristics, burner configuration including various primary/secondary/tertiary air distribution and the process temperatures. The combustion temperature has been shown to be a significantly more influential NO<sub>x</sub> emission factor than fuel composition. When process temperature decreased from 1350 °C to 950 °C, an average NO<sub>x</sub> emission decrease of almost 300 mg/m<sup>3</sup> was recorded, which is a reduction of more than one third. The NO<sub>x</sub> emissions from co-combustion of coal with waste woody biomass are at the same level as in combustion of the coal blends. With regard to the air staging at the level of burner, and considering all tests, optimized NO<sub>x</sub> and CO emissions were provided if primary (carrier) air ratio to be between 0.30-0.33, with the rest of air coming into burner divided into secondary and tertiary portions at a ratio of 2.5:1. With regard to combined effect of excess air ratio and process temperature on NO<sub>x</sub> emission, it was found that the effect of decreasing excess air ratio on NO<sub>x</sub> emission is stronger when a process temperature increased. Generally, when used excess air ratio of 0.95 against 1.2, other operation parameters being fixed, much more NO<sub>x</sub> emission reduction for two tested coal blends were occurred at higher temperatures – at 1350 °C and above, where an average NO<sub>x</sub> emission reduction of 32.5% is observed against an average 26.5% of the reduction recorded over the entire temperature range 950-1450 °C. It is worth mentioning that, both for coal blends and coal-biomass blend tested, a decrease of primary zone stoichiometric ratio in air

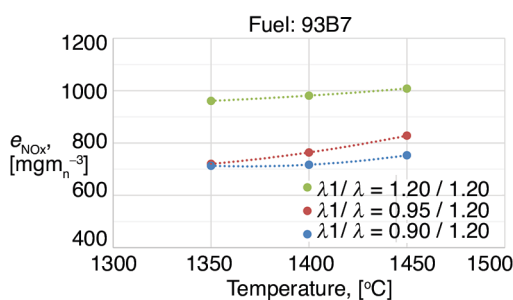


Figure 5. The NO<sub>x</sub> emissions as function of combustion temperature and primary zone stoichiometric ratio, Fuel U93B7, position of over fire air nozzle: OFA1

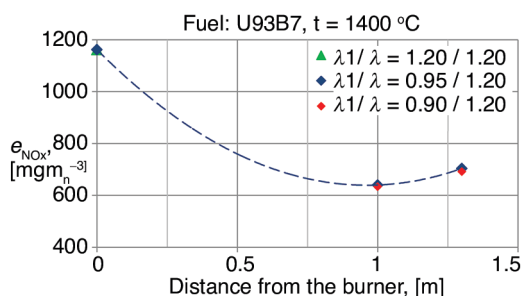


Figure 6. The NO<sub>x</sub> emissions as a function of position of OFA nozzle in furnace

staging in furnace produced higher reductions in NO<sub>x</sub> emission at higher process temperatures. Finally, it was found that the NO<sub>x</sub> emission decreased with an increase in the distance of OFA nozzles from the burner exit until a distance at about 1/3 of the total furnace length; with further increase of the distance, NO<sub>x</sub> emission is stabilised and no further effect to NO<sub>x</sub> emission reduction was observed, while CO emission and unburnt increased.

Reported results may certainly have an impact on the design, selection and costs of the accompanying boiler equipment.

### Acknowledgment

Authors acknowledge with thanks to Faculty of Mechanical Engineering of University in Sarajevo for their kind support in performing the tests.

### References

- [1] Tsumura, T., *et al.*, Reducing the Minimum Load and NO<sub>x</sub> Emissions for Lignite-Fired Boiler by Applying a Stable-Flame Concept, *Applied Energy*, 74 (2003), 3-4, pp. 415-424
- [2] Wang, J., *et al.*, The Effect of Air Staged Combustion on NO<sub>x</sub> Emissions in Dried Lignite Combustion, *Energy*, 37 (2012), 1, pp. 725-736
- [3] Kuang, M., *et al.*, Experimental Study on Combustion and NO<sub>x</sub> Emissions for a Down-Fired Supercritical Boiler With Multiple-Injection Multiple-Staging Technology Without Overfire Air, *Applied Energy*, 106 (2013), June, pp. 254-261
- [4] Kuang, M., *et al.*, Evaluation of Staged Air and Overfire Air in Regulating Air-Staging Conditions Within a Large-Scale Down-Fired Furnace, *Applies Thermal Engineering*, 67 (2014), 12, pp. 97-105
- [5] Rozendaal, M., Impact of Coal Quality on NO<sub>x</sub> Emissions from Power Plants, Ph. D. Thesis, Delft University of Technology, Delft, The Netherlands, 1999
- [6] Ribeirete, A., Costa, M., Detailed Masurinements in a Pulverized-Coal-Fired Large-Scale Laboratory Furnace With Air Staging, *Fuel*, 88 (2009), 1, pp. 40-45
- [7] Kazagic, A., Smajevic, I., Experimental Investigation of Ash Behavior and Emissions During Combustion of Bosnian Coal and Biomass, *Energy*, 32 (2007), 10, pp. 2006-2016
- [8] Kazagic, A., *et al.*, Selection of Sustainable Technologies for Combustion of Bosnian coals, *Thermal Science*, 14 (2010), 3, pp. 715-727
- [9] Kazagic, A., Smajevic, I., Synergy Effects of Co-Firing of Wooden Biomass with Bosnian Coal, *Energy*, 34 (2009), 5, pp. 699-707
- [10] Smajevic, I., *et al.*, Co-Firing Bosnian Coals With Woody Biomass: Experimental Studies on a Laboratory-Scale Furnace and 110 Mwe Power Unit, *Thermal Science*, 16 (2012), 3, pp. 789 - 804
- [11] Nareddy, S., *et al.*, NO<sub>x</sub> Reductions Achieved Through Air Staging in Cyclone Fired Boilers, *Proceedings*, 32. International Clearwater Coal Conference, Clearwater, Flo., USA, 2008
- [12] Casaca, C., Costa M., Detailed Measurements in a Laboratory Furnace With Reburning, *Fuel*, 90 (2011) 3, pp. 1090-1100
- [13] Casaca, C., Costa, M., NO<sub>x</sub> Control Through Reburning Using Biomass in a Laboratory Furnace: Effect of Particle Size, *Proceedings of the Combustion Institute*, 32 (2009)2, pp. 2641-2648
- [14] Hodzic, N., *et al.*, Influence of Multiple Air Staging and Reburning on NO<sub>x</sub> Emissions During Co-Firing of Low Rank Brown Coal With Woody Biomass and Natural Gas, *Applied Energy*, 168 (2016), Apr., pp. 38-47
- [15] Kung, M., *et al.*, Establishing an Overall Symmetrical Combustion Setup for a 600 MW<sub>e</sub> Supercritical Down-Fired Boiler: A Numerical and Cold-Modeling Experimental Verification, *Energy*, 14 (2018), Mar., pp. 208-225
- [16] Kuang, M., *et al.*, Effect of Burner Location on Flow-Field Deflection and Asymmetric Combustion in a 600 MW<sub>e</sub> Supercritical Down-Fired Boiler, *Applied Energy*, 206 (2017), Nov. pp. 1393-1405
- [17] Ti, S., *et al.*, Influence of Primary Air Cone Length on Combustion Characteristics and NO<sub>x</sub> Emissions of a Swirl Burner from a 0.5 MW Pulverized Coal-Fired Furnace With Air Staging, *Applied Energy*, 211 (2018) Feb., pp. 1179-1189
- [18] Smajevic, I., Hodzic, N.: Operating Experience at the Kakanj Power Plant in the Combustion of the Heavily Polluting Bosnian Coal, (in German), *Proceedings*, 32. Power Plant Technical Colloquium - Use of Difficult Fuels in Power Plants, Dresden, Germany 2000., pp. 151-160
- [19] Hodzic, N., *et al.*, Concept of Co-Firing Coal With Biomass and Natural Gas - On Track of Sustainable Solution for Future Thermal Power Plants, *Thermal Science*, 20 (2016), 4, pp. 1171-1184



- [20] Hodzic, N., Research Into Co-Combustion of Coal With Biomass Aimed at Reducing Emissions by Primary Measures in Furnace (in Bosnian), Ph. D. thesis, Faculty of Mechanical Engineering, University in Sarajevo, Sarajevo, BIH, 2016
- [21] Ribeirete, A., Costa M., Impact of the Air Staging on the Performance of a Pulverized Coal Fired Furnace, *Proceeding of the Combustion Institute*, 32 (2009), 2, pp. 2667-2673