**INFLUENCE OF OVER FIRE AIR SYSTEM ON NOx EMISSIONS – AN EXPERIMENTAL CASE STUDY**

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*In this work, various combinations of the NOx emission influencing factors and their combined effects in air staging combustion on level of furnace, using OFA, were investigated in an experimental lab-scale furnace. At this, process temperature were varied in the range from 950 $^oC$ to 1450 $^oC$, excess air ratio in primary zone in the range $\lambda_1$ = 0.9 – 1.2, while distance of OFA 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 NOx emission. Results shows that an average reduction of NOx emission over tested temperature range, when using OFA against conventional air supply with OFA swiched off, is 26.5%. At this, much more NOx emission reduction for two coal blends were occured at higher temperatures – at 1350 $^oC$ and above, where an average NOx emission reduction is 32.5%. Furthermore, it was found that the NOx emission decreased with an increase in distance of OFA nozzles from the outlet level of burner until a distance of 1/3 of total furnace lengh; with further increase of the distance, NOx emission is stabilised and no further effect to NOx emission reduction was observed, while CO emission and unburnt increased.*

*Key words: combustion, excess air ratio, over fire air (OFA), $NO_x$ emission*

## 1. 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 NOx 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 OFA (Over Fire Air) - 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 NOx emissions.

Reduction of NOx emissions in comparison to conventional combustion systems can be achieved by applying a newer generation burner with lower NOx emissions (swirl or jet Low-NOx burners, LNB), then air staging combustion system incl. OFA, fuel staging of basic fuel or additional fuel (for example, natural gas or biogas) for reburning. LNB burners work on the principle of air staging combustion at the level of individual burners - which result in a significant reduction in NOx 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 NOx emissions were presented; as fuel, dried lignite was used. It has been shown that in this way there is a significant reduction in NOx emissions - 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 low-NOx burners, NOx emissions can be reduced by a fifth, but that due to the high combustion temperature this emission is still high (1036 $mg/m_n^3$ at 6% $O_2$ dry). For further reduction of the NOx emission, air staging and OFAS (over fire air system) is recommended. In works [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 $NO_x$ emissions from 421 to 180 mg/N $m^3$@6%$O_2$, an increase in CO emissions from 51 to 168 mg/N $m^3$@6%$O_2$ and a reduction in particle burnout from 81.8% to 76.5%. It was concluded that the reduction of the $O_2$ 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 NOx emissions are also shown in works [7] and [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 NOx emissions were studied widly. Costa et al, see works [12, 13], found that the sawdust reburning leads to $NO_x$ reductions comparable or even higher than those attained with natural gas reburning, while coal reburning yields much lower $NO_x$ reductions. In work [14], Hodzic et al found that over 50% of NOx 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 NOx emissions, combustion simetry 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 NOx emissions. Same authors in work [17] studied effect of primary air cone length on burner performance and NOx emissions. It was found that flame stability, performance of ignition, and burnout are significantly improved by decreasing the primary-air cone length, while NOx emissions decreased.

All aforementioned works mostly investigated influence of single factors on the NOx emissions. However, for better understanding and improvement the efects, it is important to quantify and sublimate influence on NOx emissions of variuos factors, i.e. determine combined effects of various factors on NOx 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 NOx 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.

## 2. Experimental

### 2.1. 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 NOx 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 PC 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 NOx emissions which go up to 900 mg/$m_n^3$ at 6% $O_2$ 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].

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

| Fuel | K70B20Z10 | U100 | U93B7 |
|---|---|---|---|
| ***Proximate analysis, %, as-received*** | | | |
| 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 |
| ***Ultimate analysis, %, as-received*** | | | |
| 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 |
| ***Heating value, kJ/kg, as-received*** | | | |
| Gross | 13898 | 13351 | 13446 |
| Net | 13171 | 12496 | 12510 |

For purpose of lab-scale tests, fuel test matrix is used as shown in Table 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 caol blend, usual blend of coal that is used in regualr 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 caol-biomass blend, made by mixing the coal blend U100 with the waste woody biomass B100 at mass ratio 93:7%w respectivly. 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.

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

### *2.2.1. 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, Figure 1.

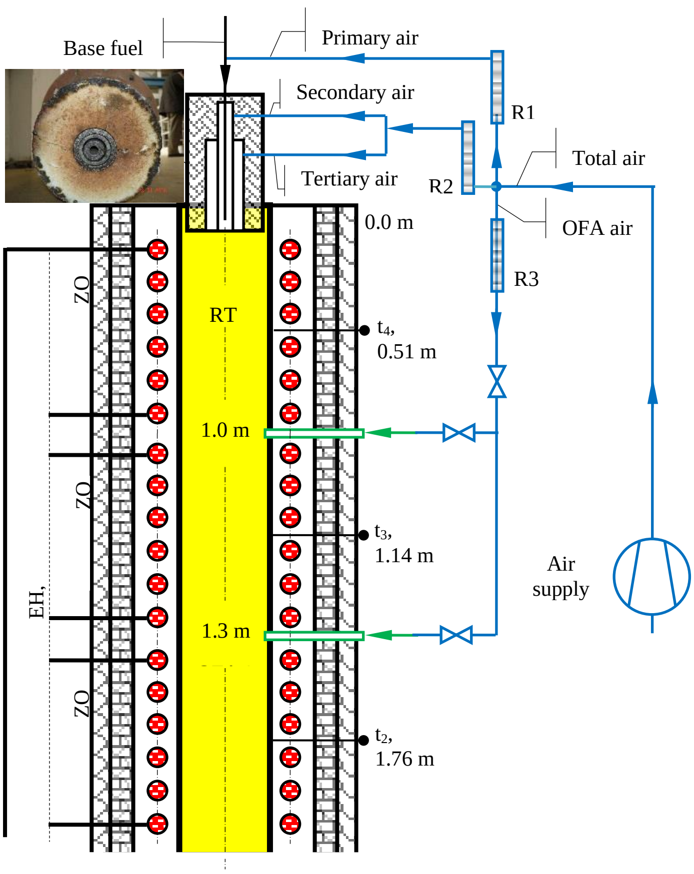


**Figure 1**. Principal scheme of part of the lab-scale furnace with indicated staging air introduction

The temperature of the reaction zone is controlled by a programmable logic controller (PLC) 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].

*2.2.2. Experimental setup 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 over fire air (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 $NO_x$ and CO ratio. Thus, in all tests, optimized $NO_x$ and CO emissions were provided if primary (carrier) air portion was set at 1.50 $m_n^3$/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 airflow rate was between 4.2 and 4.5 $m_n^3$/h, while flue gas flow rate was between 4.5 and 5.0 $m_n^3$/h. Fuel thermal load is kept at same thermal input (approximately 5 $kW_{th}$) in all the runs to provide comparison of the results. Depending on the fuel and excess air used, the total airflow rate is identified. The primary (carrier) air flow rate is set at 1.50 $m_n^3$/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 Table 2.

**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 |

Emissions of $O_2$, NO, $NO_2$, $SO_2$, CO and $CO_2$ 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.

With regard to process temperatures used, fuel K70B20Z10 is tested over temperature range of 950 – 1350 $^oC$, 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.

## 3. Results and discussion

### 3.1. Combined effect of various excess air ratios and the process temperatures on the NOx emission reduction

In this case, fuel Fuel K70B20Z10 is tested and the NOx 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 NOx emission is recorded at the lowest test temperature of 950 °C. Generally, the NOx emission increases with a rise in temperature all over the range of tested temperatures and excess air ratios. On the other hand, the NOx 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 Figure 1). In this test regime, the lowest NOx 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 $mg/m_n^3$ at 6% $O_2$ dry and is lower by about 130 $mg/m_n^3$ in relation to the classical supply of the air to the burner at the same excess air ratio; a reduction in the NOx emission for these two test regimes is about 15%, Figure 2.

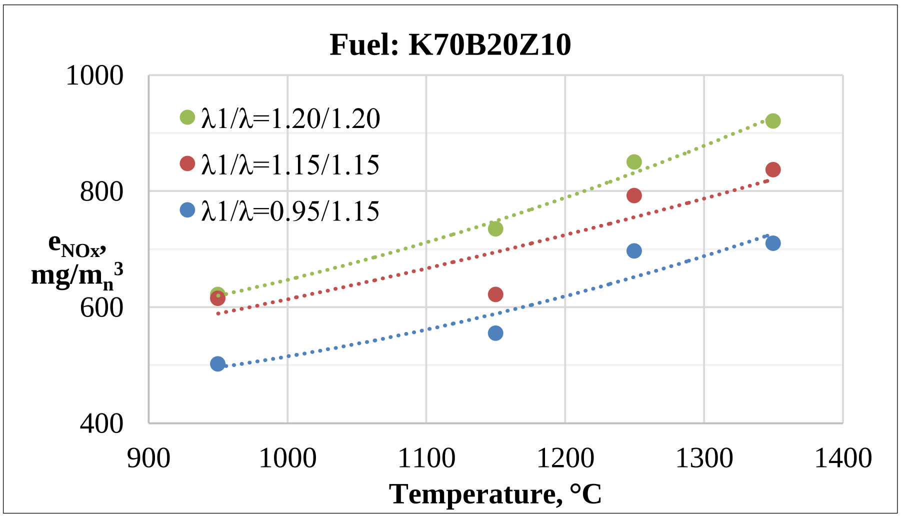


**Figure 2**. NOx emission as function of the combustion temperature and excess air ratio

Considering combined effect of the process temperature and excess air ration on NOx emission, it is important to note that the effect of decreasing excess air ratio on NOx emission is stronger when a process temperature increased.

### 3.2. 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 testred and NOx 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 NOx emissions were measured in this case. So, for example, for a combustion temperature of 1450 °C and air staging with OFA switched on, the NOx emission is, on average, 860 $mg/m_n^3$ at 6% $O_2$ dry as opposed to 1155 $mg/m_n^3$ at 6% $O_2$ dry in the conventional air supply to the burner with OFA switched off, Figure 3. In this case, the NOx emissions with OFA switched on is lower by almost 300 $mg/m_n^3$ or about 25%.

Furthermore, the NOx emission results show that, along general decreasing in NOx emission when primary zone stoichimetric ratio decreases ($e_{\lambda 1 = 0.90} < e_{\lambda 1 = 0.95}$), an effect of the decreasing primary zone stoichimetric ratio on NOx 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 NOx emissions, the efficiency of the process estimated through CO emission and unburnt is particularly important.

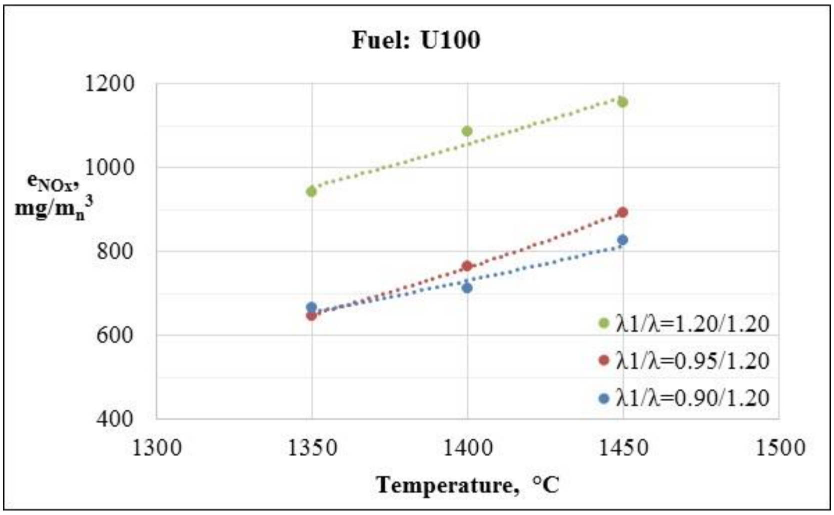


**Figure 3**. Fuel U100: $NO_x$ emissions as function of combustion temperature, excess air ratio and OFA portion, position of over fire air intake: OFA1

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

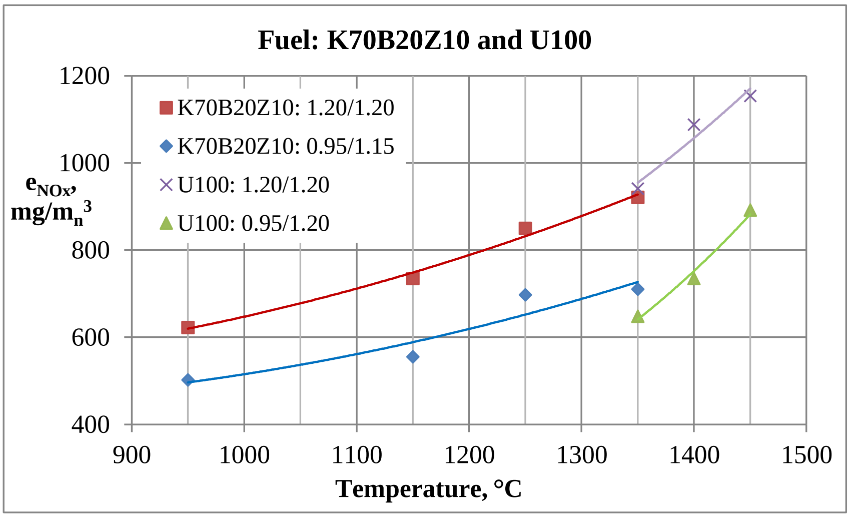


**Figure 4**. Trend of NOx emission values depending on the temperature and mode of combustion air distribution

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

Analogously to the previously presented, and for the same test settings, the following figure presents the NOx 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 NOx emissions in the co-combustion of coal and woody biomass are at the same level of NOx emissions as in coal combustion - comparing the regimes with the same combustion temperature, the same excess air ratio and the same air supply mode, Figure 5, [20]. It is worth mentioning that decreasing primary zone stoichiometric ratio in air staging in furnace produced higher reduction in NOx emission at higher process temperatures.

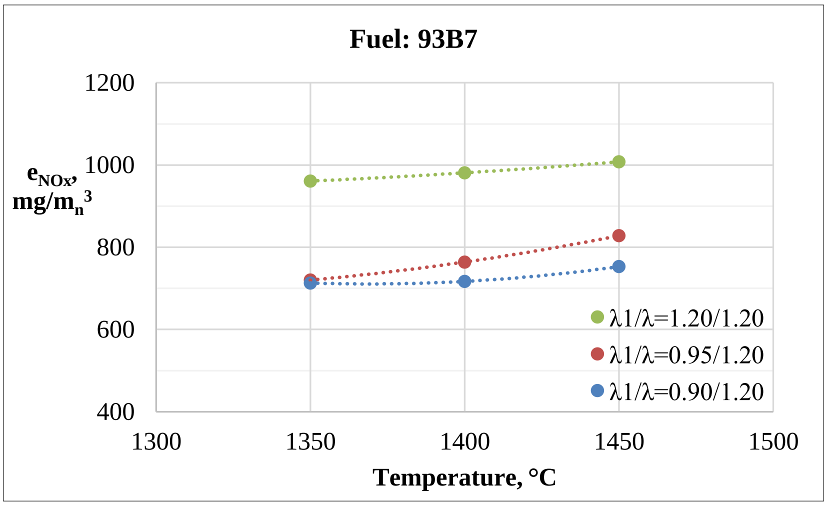


**Figure 5**. $NO_x$ emissions as function of combustion temperature and primary zone stoichiometric ratio, Fuel U93B7, position of over fire air nozzle: OFA1

### 3.4. Effect of distance OFA nozzles from burner exit to NOx emission

For the fuel U93B7, NOx emission as function of the position of OFA nozzles in furnace i.e. the distance from the burner exit is shown in Figure 6.

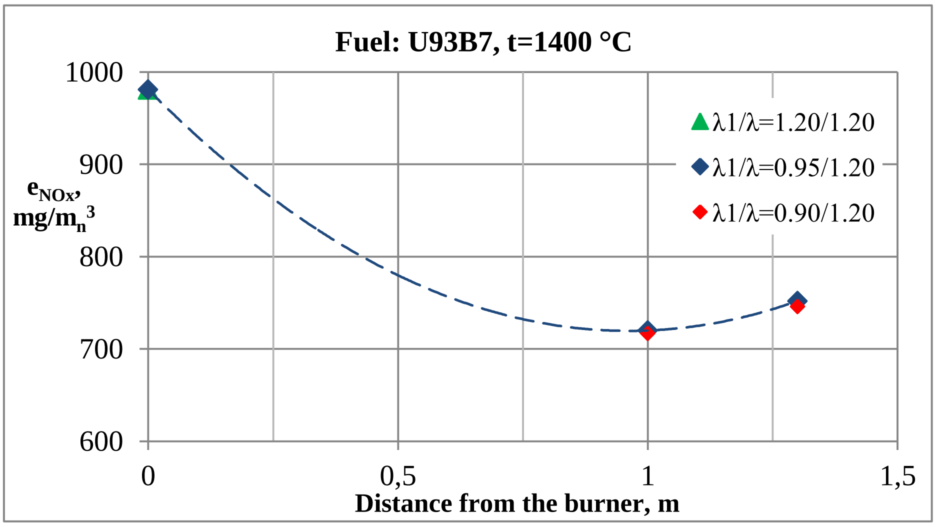


**Figure 6**. $NO_x$ emissions as a function of position of OFA nozzle in furnace

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 NOx 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, Figure 6. By a simultaneous supply of the over fire air at both positions (both OFA1 and OFA2) it can be concluded that the NOx emissions are practically at the same level as in the case of the use of the position 2 (OFA2), Figure 6. On the base of these results, it can be concluded that NOx 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 NOx emission is stabilized and there is no further effect of increasing the distance of OFA nozzle in order to reduce the NOx emission, while CO emission and unburnt increase.

## 4. Conclusions

The experimental study investigated the effects to NOx 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 NOx emission factor than fuel composition. When process temperature decreased from 1350 °C to 950 °C, an average NOx emission decrease of almost 300 mg/$m_n^3$ was recorded, which is a reduction of more than one third. NOx 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 $NO_x$ 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 NOx emission, it was found that the effect of decreasing excess air ratio on NOx emission is stronger when a process temperature increased. Generaly, when used excess air ratio of 0.95 against 1.2, other operation parameteres being fixed, much more NOx emission reduction for two tested coal blends were occured at higher temperatures – at 1350 $^{o}$C and above, where an average NOx emission reduction of 32.5% is observed against an average 26.5% of the reduction recorded over the entire temperature range 950 – 1450 $^{o}$C. It is worth mentioning that, both for coal blends and coal-biomass blend tested, a decrease of primary zone stoichiometric ratio in air staging in furnace produced higher reductions in NOx emission at higher process temperatures. Finally, it was found that the NOx 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 lengh; with further increase of the distance, NOx emission is stabilised and no further effect to NOx 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.

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