Contents list available at IJRED website

Int. Journal of Renewable Energy Development (IJRED)

Journal homepage: http://ejournal.undip.ac.id/index.php/ijred

Effects on NO_x and SO_2 Emissions during Co-Firing of Coal With Woody Biomass in Air Staging and Reburning

Nihad Hodžić[a], Sadjit Metović[a,*], Anes Kazagić[b]

[a] University of Sarajevo, Faculty of Mechanical Engineering,Vilsonovo setaliste 9, 71000 Sarajevo, Bosnia and Herzegovina

[b] Elektroprivreda BiH d.d. - Sarajevo Power utility, Vilsonovo setaliste 15, 71000 Sarajevo, Bosnia and Herzegovina

ABSTRACT. Co-firing coal with different types of biomass is increasingly being applied in thermal power plants in Europe. The main motive for the use of biomass as the second fuel in coal-fired power plants is the reduction of CO_2 emissions, and related financial benefits in accordance with the relevant international regulations and agreements. Likewise, the application of primary measures in the combustion chamber, which also includes air staging and/or reburning, results in a significant reduction in emission of polluting components of flue gases, in particular NO_x emissions. In addition to being efficient and their application to new and future thermoblocks is practically unavoidable, their application and existing conventional combustion chamber does not require significant constructional interventions and is therefore relatively inexpensive. In this work results of experimental research of co-firing coals from Middle Bosnian basin with waste woody biomass are presented. Previously formed fuel test matrix is subjected to pulverized combustion under various temperatures and various technical and technological conditions. First of all it refers to the different mass ratio of fuel components in the mixture, the overall coefficient of excess air and to the application of air staging and/or reburning. Analysis of the emissions of components of the flue gases are presented and discussed. The impact of fuel composition and process temperature on the values of the emissions of components of the flue gas is determined. Additionally, it is shown that other primary measures in the combustion chamber are resulting in more or less positive effects in terms of reducing emissions of certain components of the flue gases into the environment. Thus, for example, the emission of NO_x of 989 mg/m_n^3 measured in conventional combustion, with the simultaneous application of air staging and reburning is reduced to 782 mg/m_n^3, or by about 21%. The effects of the primary measures applied in the combustion chamber are compared and quantified with regard to conventional combustion of coals from Middle Bosnian basin.

Keywords: Co-firing, coal, biomass, reburning, NO_x emissions

Article History: Received: November 5th 2017; Revised: January 6th 2018; Accepted: February 1st 2018; Available online
How to Cite This Article: Hodžić, N., Kazagić, A., and Metović, S. (2018) Experimental Investigation of Co-Firing of Coal with Woody Biomass in Air Staging and Reburning. International Journal of Renewable Energy Development, 7(1), 1-6.
https://doi.org/10.14710/ijred.7.1.1-6

1. Introduction

Greenhouse gas emissions as a cause of global warming, primarily carbon dioxide CO_2 as well as other undesirable flue gas components such as NO_x and SO_2, have been enormously increased for the last seven decades, Figure 1a. Various scenarios of temperature increase on Earth up to year 2100, out of which a critical scenario with a 2 °C increase in temperature is set, Figure 1b. Likewise, with the aim of limiting and reducing greenhouse gas emissions as the cause of global warming of the planet Earth, the measures and recommendations expressed through protocols and agreements, such as the Kyoto Protocol of 1997 and the Paris Agreement of 2015/16, will continue to evolve. The intention is to substitute the use of fossil fuels in final energy production through the application of appropriate new technical and technological measures and in particular by the introduction of renewable energy sources, thus reducing the CO_2 emissions by 40% by 2050.

Multi-fuel operation of coal fired power stations, running co-firing different kind of biomass with coal, is nowadays mainly done to provide fuel mix diversity in order to reduce CO_2 emissions, improve security of supply and reduce operational costs by fuel cost optimization. In the last decade, significant progress was made in the utilization of biomass in coal-fired power plants. Over 250 units worldwide have either tested or demonstrated co-firing of biomass or are currently co-firing on a commercial basis, as reported by KEMA (Kema 2009). Coal is often replaced with up to 30% of biomass by weight in pulverised coal based power plants, as in Belgium, Canada, Denmark, Finland, the Netherlands, Sweden, United Kingdom,

*)Corresponding author: metovic@mef.unsa.ba

Germany, Poland and the United States. Most of these projects refer to co-firing biomass with high-rank coal (both bituminous and anthracite), while availability of projects on biomass co-firing with low-rank sub-bituminous coal and lignite is scarcer, like the project involving Greek lignite reported by Kakaras (Karakas *et al.* 2000). Furthermore, progress is made in application of different types of municipal solid waste as a fuel in coal-based power plants (solid recovered fuel - SRF or refuse derived fuel - RDF, including their gasification), or even co-firing with sewage sludge (Wischnewski *et al.* 2006). The work used a drop tube furnace to evaluate the combustion behaviour and ash properties of biomass, waste derived fuels, pine and coal. Kupka et al. (2008) investigated the ash deposit formation during the process of co-firing coal with sewage sludge, saw-dust and refuse derived fuels in a drop tube furnace, to optimize biomass co-firing blends (Kupka *et al.* 208). Williams et al. (2012) investigated the emission of pollutants from solid biomass fuel combustion (Williams *et al.* 2012).

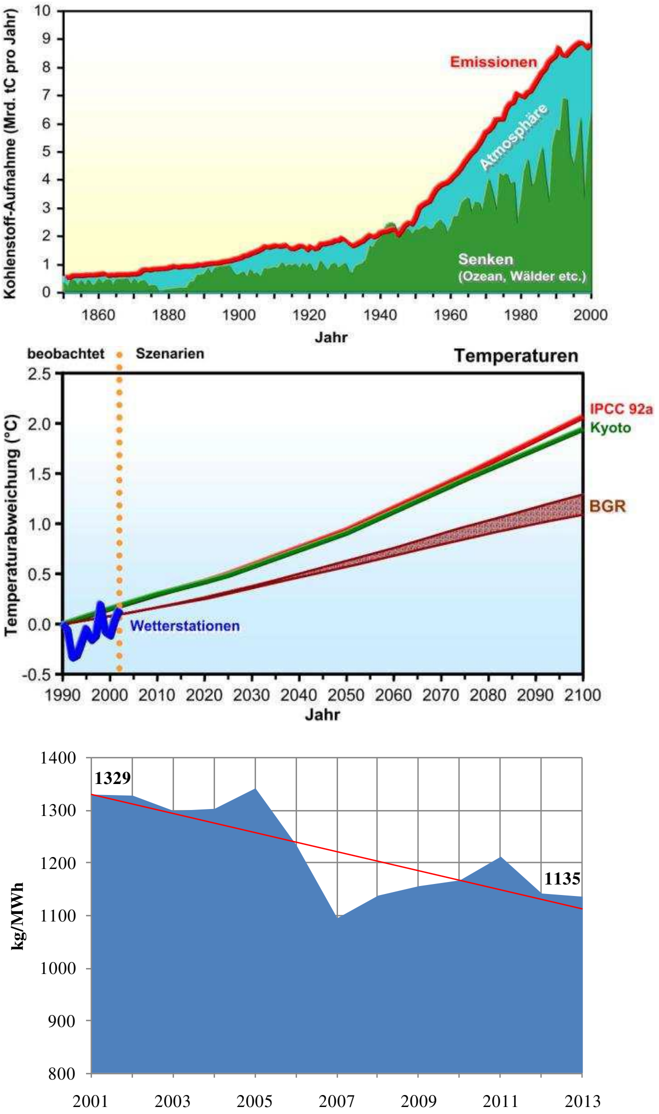


Fig. 1 a) CO_2 emission on the planet Earth (Data Base VGB), b) temperature increase scenarios (Data Base VGB), c) specific CO_2 emission of TPP-units in EP BiH in 2001-2013, (Hodžić *et al.* 2015)

Bosnia and Herzegovina has significant coal reserves (lignite and brown coal). According to the latest estimates, the balance and exploitation reserves of coal in are about $4.5 \cdot 10^9$ t, of which about 40% refers to brown coal and about 60% to lignite. However, the quality of coal in Bosnia and Herzegovina is significantly different from one basin to another and even from one mine to another within the same mining basin. The basic characteristics of these coals are: low heating value, high mineral mass and moisture content and poor reactivity (Study EP BIH 2014).

Though the reconstruction and modernization of thermoblocks in EP BiH (Public Enterprise Electric Utility of Bosnia and Herzegovina) has been achieving certain results in the sense of improving energy efficiency, due to the obsolete technology of existing thermoblocks and relatively low heating value of domestic coals, the specific CO_2 emission from thermal power plants (TPP) is still high compared to modern thermoblocks in Europe and the world. Figure 1c is a diagram of the change of specific CO_2 emissions from TPPs of EP BiH in the period 2001-2013 - relative emission reduction of almost 15% as a result of significant financial investments - but still high: about 1140 kg/MWh.

In addition, the firing of coal mixtures in TPP Kakanj in these conditions results in high emissions of other pollutants, eg. NO_x emissions are typically in the range of 700÷1000 mg/ m_n^3 and SO_2 even over 8000 mg/ m_n^3, under the reference conditions of 6% O_2 in dry flue gases (Hodžić *et al.* 2015). The above mentioned emission values exceed the limits prescribed by the Ordinance on emission limit values for thermal power plants (Official Gazette of Federation of Bosnia and Herzegovina No. 4/13) and the Directive 2010/75/EU - Industrial Emissions Directive (IED).

Results of the research carried out at the Mechanical Engineering Faculty - University of Sarajevo under the ADEG project, show that biomass could be the second most significant renewable energy source after hydro potential - it is estimated that the total annual technical energy potential of biomass remains in BiH is more than 33 PJ (ADEG 2007), which is equivalent to more than 3 million tons of BIH lignite.

Due to the need for further reduction of CO_2 emissions, in current research in the world focus is especially on exploring these phenomena in the combustion of various coal blends and co-firing coal with different types of biomass. The application of one or more primary measures at the same time in the combustion chamber/combustion zone is an inevitable technical and technological setting. These studies have resulted in the introduction of co-firing in 230 TPPs in the EU. In addition to the various technical solutions for the use of biomass in co-firing, the significant introduction of different types of biomass (waste biomass, energy crops) and gaseous fuels (natural gas, biogas) into the combustion process with coal as the base fuel of the thermal power plant, depending on availability and economic eligibility, represents the multi fuel concept (MFC).

2. Aim of the work and fuel test matrix

Co-firing of coal with waste woody biomass is the subject of this paper, ie. the determination of the characteristics, behavior and characteristic phenomena of this co-firing in different ambient and technological conditions. This applies primarily to the application of primary measures in the combustion chamber aimed at reducing emissions (for example, different mass and/or energy partaking of component fuels in the mix, different temperature conditions/regimes, gradual combustion by zonal fuel and/or air supply, additional combustion using natural gas - reburning technology). This is achieved by combusting mixture of component fuels in the experimental plant: an automatically controlled coal and biomass pipe reactor, where it is possible to achieve process temperatures ranging from ambient temperatures up to 1560 °C and varying the excess air coefficient with the possibility to vary air and fuel distribution (Hodžić 2016) - Figure 2.

In the work the results of the exploration of the co-firing coals from Middle Bosnian mining basin (label U) with waste woody biomass (spruce and beech sawdust in weight ratio 1:1, label B) by staging the combustion of the base fuel are discussed. In the Table 1 the overview of test regimes under conditions of pulverized combustion technology with wet bottom ash discharge is given.

Co-firing of coal with woody biomass was carried out at process temperatures of 1350, 1400 and 1450 °C with air staging and excess air coefficient of 1.20. During test regimes, the process temperature, fuel consumption, air flow (primary, secondary/tertiary and OFA), as well as the composition of flue gas (O_2, CO, CO_2, NO, NO_2, NO_x i SO_2) were measured. Based on the measured and analyzed samples of combustion products, the characteristics of the co-firing process are determined, for example the efficiency of applying one or more primary measures in the combustion chamber to the emissions of flue gas components.

Table 1
Test regimes with staging combustion of the base fuel

Fuel label*	**Process temperature, °C**			**Coefficient of excess air, λ_1/λ**	**Fuel staging, %m**
	1350	1400	1450	0,90/1,20	
U100	+	+	+	+	5 and 10
U95B5	+	+	+	+	
U93B7	+	+	+	+	
U90B10	+	+	+	+	

*eg. U95B5 means 95% coal, 5% waste woody biomass (sawdust) in the mixture

3. Results of the investigation

NO_x emissions for the case of combustion with staging base fuel, at a process temperature of 1350 °C and for two different percentages of base fuel introduced into the combustion chamber (5 and 10% by weight), are shown in Figure 3a.

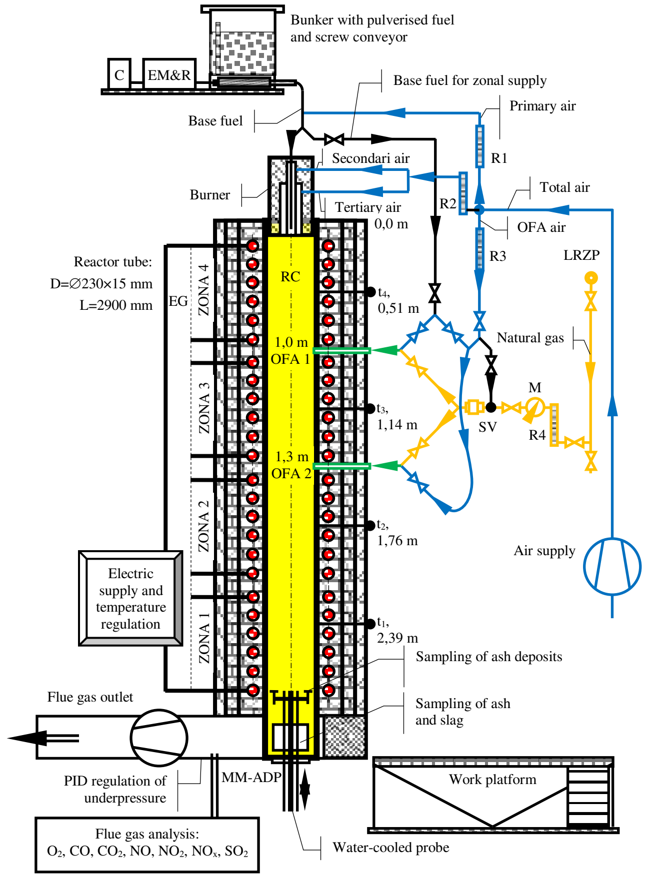


Fig. 2 Principal scheme of the experimental plant (Hodžić 2016)

Generally, NO_x emissions are reduced. In the case of fuel staging of 5% NO_x emissions are 630 mg/m_n^3 in average or by about 5% lower (relative) than the emissions for combustion without fuel staging. In the case of fuel staging of 10% NO_x emissions are in average 570 mg/m_n^3, which is an average emission reduction of almost 100 mg/m_n^3 or close to 15% (relative), (Hodžić *et al.* 2016). The effects of applying 10% of the basic fuel stage to the NO_x emission depending on the process temperature, for the fuels of different composition, are presented in Figure 3b. For example, at temperature of 1450 °C for coal (U100), this emission decreased from 892 to 694 mg/m_n^3 (more than 22%) relative to the emission at the same temperature, quantity and mode of air supply but without fuel staging. It should be noted that in these test regimes there was a significant increase in CO content in flue gases, for example U100: 686 mg/m_n^3 at 1350 °C and 140 mg/m_n^3 at 1450 °C. The effect of the staged fuel intake into the reaction zone on SO_2 emissions is shown in Figure 3c. These emissions, recorded during test regimes for different fuel compositions and for base fuel staging of 5% and 10%, are practically at the SO_2 emission level as in the case of combustion without fuel staging (U100, 0% m). In average, this emission is around 5500 mg/m_n^3 for both tested percentages of the base fuel staging (Hodžić *et al.* 2016).

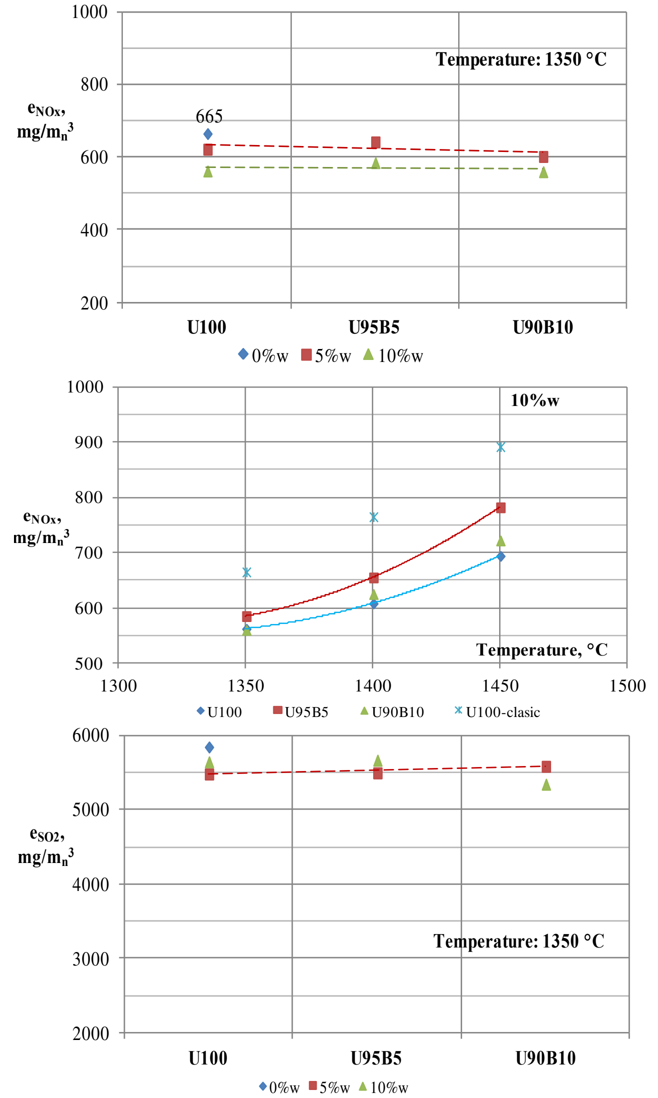


Fig. 3 a) NO_x emission during staged combustion of fuels of different composition under the same ambient conditions, b) The influence of the temperature on NO_x emission during staged combustion of fuels of different composition, c) SO_2 emission during staged combustion of fuels of different composition under the same ambient conditions

As mentioned earlier, during the staging of the base fuel, there is a significant increase in CO emissions in relation to the emissions without fuel staging. Compared are CO emissions measured during the combustion of the same fuel, at the same temperature, with the same coefficient of excess air and for the same mode of air supply. The reason for this is shorter path of combustion of fuel particles (coal and/or biomass) which were subsequently introduced into the combustion zone. In case of introducing the base fuel to the OFA 1 intake position, the available combustion path is about 2/3 of the particle combustion path as in the case the fuel is introduced directly into the burner (Hodžić 2016). Increased CO emission is particularly pronounced at the lower combustion test temperature (1350°C) and for fuel with larger granulation fractions (about or above 1 mm), e.g. fuel U90B10 (Figure 4a). The CO emission is quite high and at temperatures of about 1450°C is still above 200 mg/ m_n^3 in average.

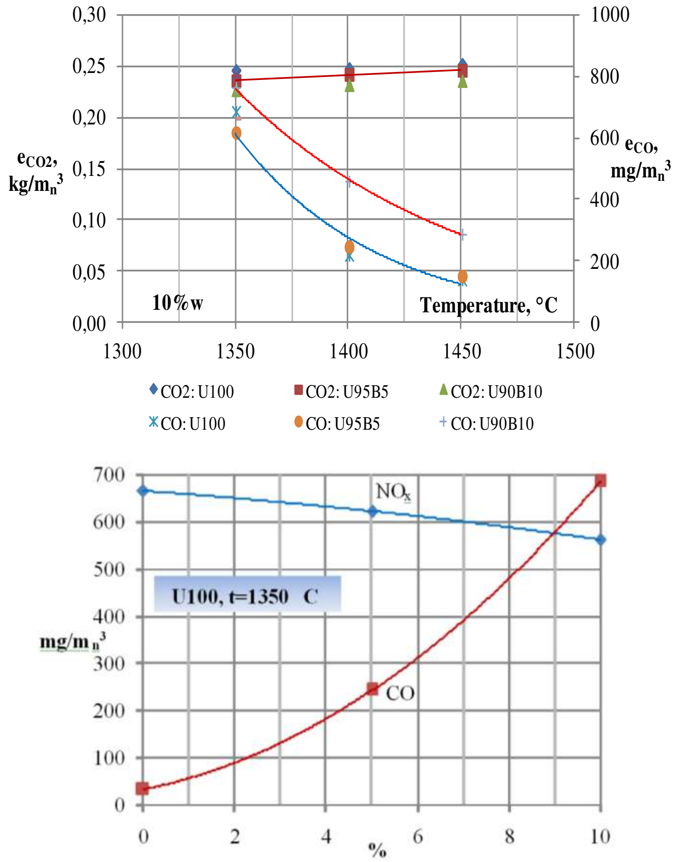
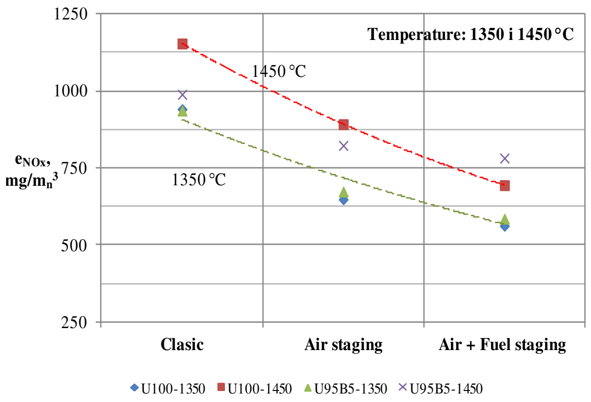


Fig. 4 a) CO_2 and CO emission during staged combustion for fuels of different composition, b) Increase of CO emission with the fraction of staged fuel

The test regimes with staging the base fuel were followed by a lower CO_2 emission compared to emissions without fuel staging (Figure 4a). This is particularly evident at temperature of 1350 °C: average CO_2 emission is 0.238 mg/ m_n^3. Further, the CO_2 emission is slightly increasing with increased combustion temperature and at 1450 °C the average emission is 0.247 mg/ m_n^3. Average emission during co-firing of different mixtures without fuel staging is 0.257 mg/ m_n^3 (Hodžić *et al.* 2016).

Obtained results and knowledge are very important in the design of new but also in the reconstruction of existing boilers of TPPs in terms of introducing staged fuel combustion. It is clear that the advantages of fuel staging in terms of NO_x emission reduction are generally followed by potential disadvantages that are reflected through increased CO emissions in flue gases, and increased content of burnable matter in ash during these combustion regimes. This has shown that the choice of the position of subsequent introduction of staged fuel is very important and has an opposite effect on NO_x emissions and combustion efficiency: for example, at combustion temperature of 1350°C, NO_x emission is decreased by 15% (relative) and CO emission is increased by over 20 times with staged intake of base fuel U100 at approx. 1/3 of the combustion chamber height (Figure 4b).

4. Efficiency comparison of each applied primary measure in the combustion chamber to the NO_x emission



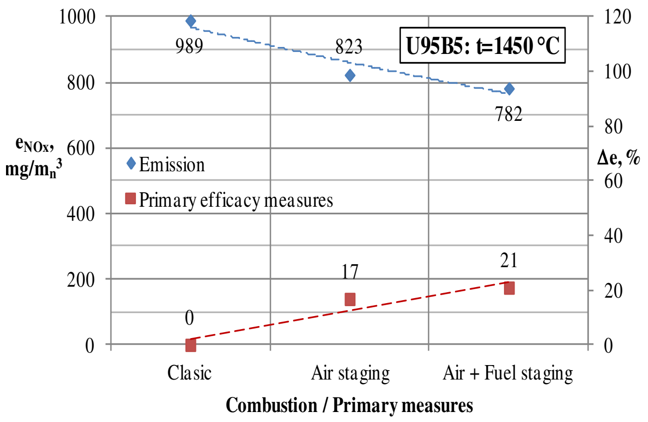


Fig. 5 a) NO_x emission while applying various primary measures in combustion chamber, b) Efficiency of primary measures at temperature of 1450 °C: fuel U95B5

Efficiency of applied primary measures (%) in the combustion chamber is reflected through decrease of NO_x emission compared to the emission of conventional combustion. In this case, the test regimes were performed with the staging of the base fuel and the combustion air at the same time (simultaneous application of two primary measures in the combustion chamber). Significant emission reduction is noticeable at temperature of 1450 °C, from 1154 mg/m_n^3 to 615 mg/m_n^3, or for almost 50%. The results refer to NO_x emissions for combustion of coal U100, Figure 5a. The emission of NO_x during co-firing of coal with biomass (U95B5) while applying various primary measures in combustion chamber is shown in Figure 5b. In the same figure the efficiency of these measures by reducing emissions compared to the emissions of conventional combustion is shown. The results refer to the combustion temperature of 1450 °C, (Hodžić 2016).

From the results shown in Figure 5a it comes to the conclusion that the efficiency of primary measures by staging the air and/or the base fuel is weakened while increasing the process temperature. Specifically, the efficiency of staging the base fuel at temperature of 1450 °C is 21% compared to 32% at 1350 °C, (Hodžić *et al.* 2017, Hodžić *et al.* 2015).

5. Conclusions

According to the results of the research, the following conclusions are emphasized:

- The NO_x emission during co-firing coal with waste woody biomass is at the level of emission when the mixture of coals only is combusted. There is practically no change in this emission with the change of woody biomass fraction in the blend. Depending on the delivery mode of the combustion air the average NO_x emission difference is 250 mg/m_n^3. For conventional air supply the average emission is 942 mg/m_n^3, while in the case of air staging it is 692 mg/m_n^3.
- The SO_2 emission is slightly reduced with the increase of the fraction of the woody biomass in the blend and practically does not depend on the way of combustion air supply. These emissions are high and generally exceeding 5000 mg/m_n^3.
- With increasing the fraction of the woody biomass in the blend net CO_2 emission is proportionally reduced, which at 10% of the biomass is 0.233 kg/m_n^3.
- The NO_x emission depends on the location of the OFA air into the combustion chamber. Thus, the NO_x emission is minimal when supplying OFA air at position 1 (1 m from the burner outlet level or 1/3 of the length of the reaction tube), while it is slightly higher in the case of the supply at position 2 (1.3 m from the burner outlet level or at more than 1/3 of the total length of the reaction tube). With the simultaneous supply of OFA air to both positions (1 and 2), the NO_x emissions are practically the same as in the case of supply at position 2. The location of the OFA air supply (positions 1 and 2) does not affect the SO_2 emission value.
- Co-firing coal with woody biomass with air staging results in not only lower net CO_2 emission, but also in lower NO_x emission up to about 25% in relation to emission without the application of this primary measure in the combustion chamber.
- Results of laboratory and on-site research show that regimes of co-firing coal with woody biomass generally have a positive effect on the operation of TPP Kakanj, especially through reduction of CO_2 emission and the possibility of achieving financial benefits.
- NO_x emission is reduced in the case of combustion with fuel staging. This reduction is proportional to the part of the fuel that is introduced into the reaction zone afterwards. In the case of feul staging of 10%m and temperature of 1350 °C, the reduction of NO_x emissions is about 100 mg/m_n^3 or 15% on average compared to emissions of combustion without fuel staging.
- With increasing the combustion temperature, the efficiency of this primary measure is also increasing in terms of NO_x emission. For example, at a temperature of 1450 °C for fuel U100, this emission decreased from 892 mg/m_n^3 to 694 mg/m_n^3 or more than 22% relative to the emission at the same

temperature, quantity and mode of air supply but without fuel staging.

- In the case of combustion with staged base fuel intake significant increase in CO content in flue gases appears, for example for the fuel U100: 686 mg/ m_n^3 at temperature of 1350°C and 140 mg/ m_n^3 at 1450°C. This phenomenon requires finding the optimum solution that will make the combustion process economically viable and environmentally acceptable regarding the levels of NO_x and CO emissions. This implies finding the best ratio of the staged fuel brought into the combustion zone (%) on the one side and the place of introduction of the staged fuel in comparison to the primary combustion zone/burner on the other side.
- SO_2 emissions recorded during test regimes for different fuel compositions and for base fuel staging of 5% and 10%, are practically at the SO_2 emission level as in the case of combustion without fuel staging. In average, this emission is around 5500 mg/ m_n^3 for both tested percentages of the base fuel staging.

Acknowledgements

The authors acknowledge with thanks to EPBiH power utility for their kind cooperation and support.

References

ADEG - Advanced Decentralised Energy Generation Systems in Western Balkans (2007) Projekt FP6 - *Final Report*, National Technical University of Athens, Institut IVD Stuttgart, Fakultet Strojarstva i Brodogradnje Zagreb, Mašinski fakultet Sarajevo, Institut Vinča, IST Portugal.

Data base *VGB*, 06-2010, 09-2012.

Hodžić, N. (2016) *Istraživanje kosagorijevanja uglja i biomase usmjereno na smanjenje emisija primarnim mjerama u ložištu*, PhD Thesis, Universtity of Sarajevo, Mechanical Engineering Faculty.

Hodžić, N., Kazagić, A., & Smajević, S. (2015) *Motiv za uvođenje u praksu kosagorijevanja uglja i drvne biomase u TE Kakanj - iskustva iz probnog pogona podržana laboratorijskim istraživanjima*, 12. Savjetovanje bosansko-hercegovačkog komiteta Cigré, Neum, Bosna i Hercegovina.

Hodzic, N., Kazagic, & A., Smajevic, I. (2016) Influence of multiple air staging and reburning on NOx emissions during co-firing of low rank brown coal with woody biomass and natural gas, *Applied Energy* 168, 38–47.

Hodžić, N., Metović, S., Džaferović, E., & Kazagić, A. (2017) *Woody Sawdust and Miscanthus Co-firing - Towards more Sustainable Solution for Low-rank Coal - a Lab-scale Investigation*, 8th European Combustion Meeting (ECM 2017), Dubrovnik, Croatia.

Hodžić, N., Metović, & S., Kazagić, A. (2017) *Effects of primary measures in combustion chamber on co-firing of coal with woody biomass*, The International Symposium on Advances in Mechanical Engineering – ISAME, NINTH (9th) days of BHAAAS in Bosnia and Herzegovina, Teslić.

Hodžić, N., Smajević, I., & Kazagić, A. (2015) *Mitigation Ash-related Problems by Cofiring Coal with Woody Biomass in Case of Kakanj Thermal Power Plant* - Experimental and Trial Run, 23rd European Biomass Conference And Exhibition (EUBCE 2015), Wienna, Austria.

Kakaras, E., (2000) *Low emission co-combustion of different waste wood species and lignite derived products in industrial power plants*, XXXII Krafwerkstechnisches Colloquium: Nutzung schwieriger Brennstoffe in Kraftwerken, Dresden, p. 37-46.

KEMA (2009) Technical status of biomass co-firing, IEA Bioenergy Task 32, Netherlands.

Kupka, T., Mancini, M., Irmer, M., & Weber, R. (2008) Investigation of ash deposit formation during co-firing of coal with sewage sludge, saw-dust and refuse derived fuel, *Fuel*, 87(12), 2824-2837.

Rozendaal, M. (1999) *Impact of coal quality on NOx emissions from power plants.* Delft: Delft University of Technology.

Uticaj kvaliteta uglja na troškove proizvodnje električne energije i cijenu uglja - Study EPBIH (2014); Naručilac: JP Elektroprivreda BiH d.d. Sarajevo, Izvršilac: Mašinski fakultet Sarajevo i Rudarski institut d.d. Tuzla, Sarajevo.

Wang, Y., Wang, X., Hu, Z., Li, Y., Deng, S., Niu, B., & Tan, H. (2015) NO Emissions and Combustion Efficiency during Biomass Co-firing and Air-staging, *Bio Resources*,10(3), 3987-3998.

Williams, A., Jones, J.M., Ma, L., & Pourkashanian, M., (2012) Pollutants from the combustion of solid biomass fuels, *Progress in Energy and Combustion Science*, 38(2), 113-137.

Wischnewski, R., Werther, J., & Heidenhof, N., (2006) Synergy Effects of the Co-combustion of Biomass and Sewage Sludge with Coal in the CFB Combustor of Stadtwerke Duisburg AG., *VGB Power Tech*, 86(12), 63-70.