

Effects of Primary Measures in Combustion Chamber on Co-firing of Coal with Woody Biomass

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Abstract. In this work results of laboratory research of co-firing coals from Middle Bosnian basin with waste woody biomass are presented. Pulverized combustion under various temperatures and various technical and technological conditions is performed using previously formed fuel test matrix. This is primarily related to the different mass ratio of fuel components in the mixture, the overall coefficient of excess air and the application of different primary measures in the combustion chamber. The results and analysis of the emissions of components of the flue gases are presented and discussed, which are predominantly related to the emission of CO₂, CO, NO_x and SO₂. In addition to determining the impact of fuel composition and process temperature on the values of the emissions of components of the flue gas, 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. This particularly stand out measures such as exponentiation of combustion air and the use of natural gas as the additional fuel: the emission of NO_x is reduced from a level of 837 mg/m_n³ in conventional combustion to 710 mg/m_n³ using exponentiation of combustion air, or for more than 15%, and using natural gas as additional fuel it is reduced to 450 mg/m_n³, or for more than 45%. Overall, the effects of the primary measures in the combustion chamber are mutually compared and quantified. In addition, the influence of applied primary measures in the combustion chamber on the behavior of ash in the co-firing process is analyzed. In this way, evaluation the fouling and slagging tendencies of the ash under given technical and technological conditions of co-firing coal with waste woody biomass is given.

Keywords: Co-firing · Coal · Biomass · Emissions · Ash

1 Introduction

The multidisciplinary scientific and professional public has been involved over the last 30 years, more than ever, in analyzes and finding solutions to the increasingly negative impact of emissions of flue gas components generated by the burning of fossil fuels.

These analyzes and projections for the future shorter and/or longer periods have resulted and will continue to produce measures and recommendations expressed through conventions, directives and protocols, such as the Kyoto Protocol of 1997. This protocol defines guidelines that would, after the prolongation of the Protocol's validity by 2020, reduce greenhouse gas emissions as a cause of global warming, primarily carbon dioxide CO₂ emissions that have been enormously increased for the last six decades, as well as other undesirable flue gas components such as NO_x and SO₂. In relation to the above, 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—Fig. 1 [1].

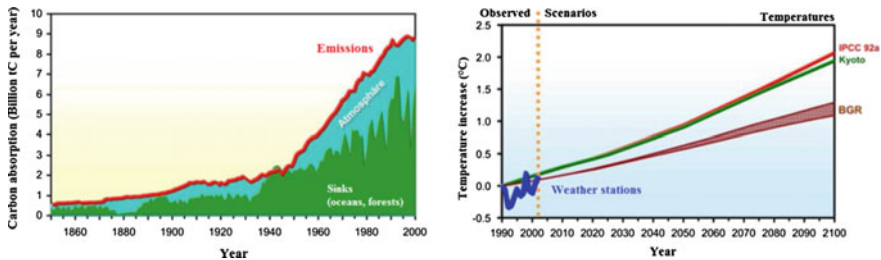


Fig. 1. CO₂ emissions and earth temperature growth scenarios [1]

There are significant coal reserves in Bosnia and Herzegovina. These are lignite and brown coal, while there is no stone coal. According to the latest estimates, the balance and exploitation reserves of coal in Bosnia and Herzegovina are about 4.5×10^9 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 [2]. The basic characteristics of these coals are: low heating value, high mineral mass and moisture content and poor reactivity.

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 CO₂ emission from thermal power plants (TPP) is still high compared to modern thermoblocks in Europe and the world. Figure 2 is a diagram of the change of specific CO₂ 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/m³ and SO₂ even over 8000 mg/m³, under the reference conditions of 6% O₂ in dry flue gases [3].

The above mentioned emission values exceed the limits prescribed by the Ordinance on emission limit values for thermal power plants (Official Gazette of FBiH No. 4/13) and the Directive 2010/75/EU—Industrial Emissions Directive (IED).

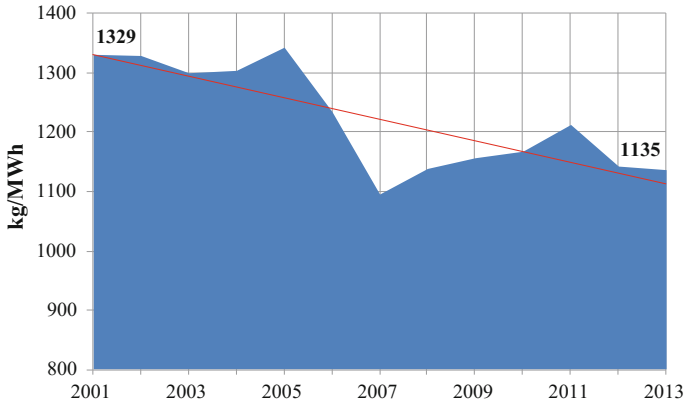


Fig. 2. Specific CO₂ emission in thermoblocks of EP BiH in the period 2001–2013 [3]

According to the results of the research carried out at the Mechanical Engineering Faculty in Sarajevo under the ADEG project, 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 [4], which is equivalent to more than 3 million tons of BiH lignite.

Due to the need for further reduction of CO₂ 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).

Reduction of NO_x emissions, compared to conventional combustion systems, can be adequately achieved by using burners of newer generations (vortex Low-NO_x burners), over fire air supply (OFA), staging primary fuel supply and using additional fuel (e.g. natural gas, reburning).

2 Aim of the Work and Fuel Test Matrix

The subject of this paper is co-firing of coal with waste woody biomass, 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. In this way, it is possible to determine the influence of different primary measures in the combustion chamber on co-firing coal with woody biomass, with particular reference to emissions of pollutants, e.g. CO, CO₂, NO_x and SO₂.

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). In the regimes with reburning technology, gas was used as an additional fuel (label P)—Table 1 [5].

Table 1. Test fuel matrix

| No. | Fuel/label | Weight ratio (%m) or energy content ration (%e) | |
|-----|------------|-------------------------------------------------|----|
| 1. | U | U 100% | %m |
| 2. | B | B 100% | %m |
| 3. | U95B5 | U:B=95:5 | %m |
| 4. | U93B7 | U:B=93:7 | %m |
| 5. | U90B10 | U:B=90:10 | %m |
| 6. | UB(95)P5 | UB(95):P=95:5 | %e |
| 7. | UB(95)P10 | UB(95):P=90:10 | %e |

Co-firing of coal with woody biomass was carried out at process temperatures of 1350, 1400 and 1450 °C with staging air supply 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 (O₂, CO, CO₂, NO, NO₂, NO_x and SO₂) were measured. In addition, sampling of deposits, slags and ashes from selected test regimes and sampling sites enabled the determination of the burnout degree. 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, the propensity of ash to fouling boiler heating surfaces.

3 Results and Discussion

It has been found that NO_x emissions during co-firing are at the emission levels of the combustion of coal blends without biomass, there is practically no change in this emissions by increasing the fraction of woody biomass in the blend. The average difference in NO_x emissions depending on the mode of combustion air supply is 250 mg/m_n³; for the classic air intake the emission is 942 mg/m_n³, while it is 692 mg/m_n³

for the staging air intake, Fig. 3. On the other hand, the sulfur content decreases proportionally with the fraction of the woody biomass in the mixture. Although SO₂ emission results are indented, it can still be concluded that the SO₂ emissions decrease with the increase of the biomass fraction in the mixture. On the other hand, based on the results of the measurements it can be concluded that SO₂ emissions do not practically depend on the mode of the air intake—the emissions are high and at process temperature of 1350 °C are on an average of about 5300 mg/m_n³, Fig. 3.

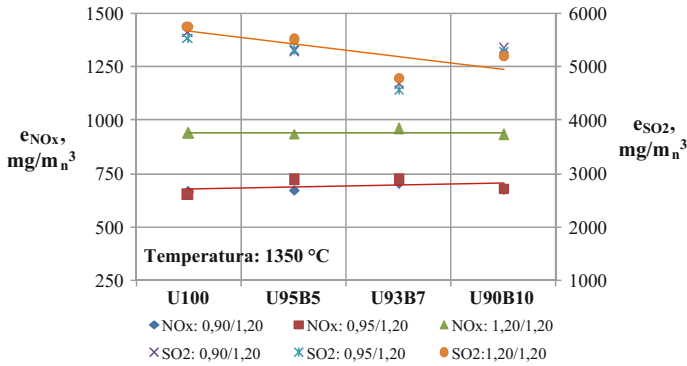


Fig. 3. NO_x and SO₂ emissions during co-firing of coal with woody biomass at process temperature of 1350 °C

The total and net CO₂ emissions due to combustion of woody biomass as renewable fuel are shown in Fig. 4. By increasing the fraction of woody biomass, the emission of the net CO₂ emission is linearly reduced and it is 0.233 kg/m_n³ with 10% of biomass in the mixture. Some more increased CO emissions during co-firing coal with biomass compared to firing only coal, especially at 10% biomass fraction, can be

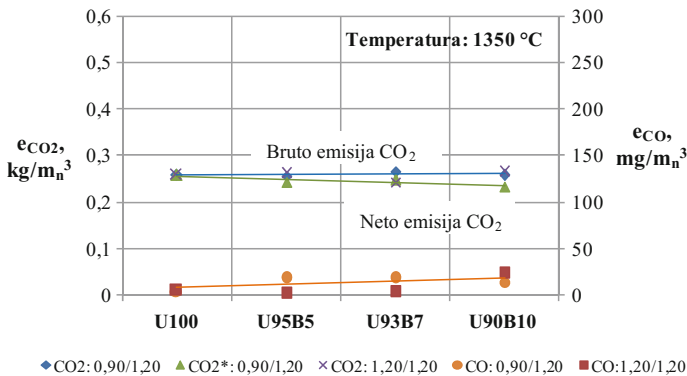


Fig. 4. CO₂ and CO emissions during co-firing of coal with woody biomass at process temperature of 1350 °C

related to granulation of the biomass that is not mechanically treated (minced)—a certain fraction of biomass particles with size of up to 4 mm, Fig. 4.

With the increase in combustion temperature the NO_x and SO_2 emissions also increase. Thus, average NO_x emissions at temperatures of 1400 and 1450 °C: 750 and 800 mg/m_n^3 respectively, and SO_2 emissions under these conditions: about 5000 and 5200 mg/m_n^3 respectively. Even in these test regimes, it has been confirmed that NO_x emissions are practically unchanged with the increase of the biomass fraction in the mixture and that the SO_2 emission decreases proportionally with the increase of the biomass fraction in the mixture—Fig. 5.

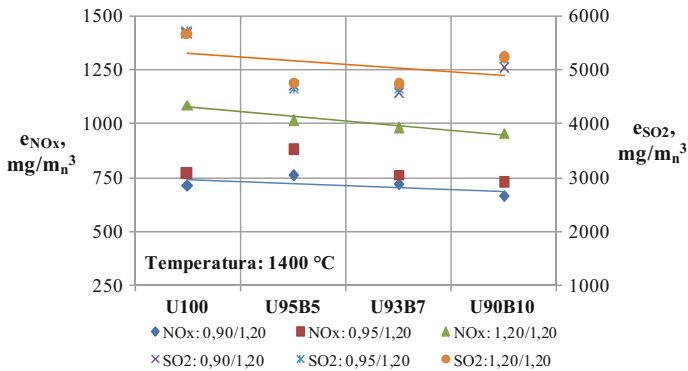


Fig. 5. NO_x and SO_2 emissions during co-firing coal with woody biomass at process temperature of 1400 °C

The dependence of NO_x and SO_2 emissions from the place of introduction of OFA air into the furnace or reactor is shown in the following figure. Specifically, here are the results of co-firing coal with 7% woody sawdust at 1400 °C and with different options for introducing OFA air into the reaction pipe: OFA 1 at a distance of 1 m from the burner outlet, then OFA 2 at a distance of 1.3 m and the OFA 1 and 2 option—simultaneous OFA air intake at both levels. The results show that the NO_x emissions, in this case, are smallest when the OFA air is introduced at position 1, while it is slightly higher in the case of position 2. When the OFA air supplied at both positions (1 and 2) in the same time, it can be concluded that the emissions NO_x are practically at the same level as when using position 2 for OFA air intake. In any case, these emissions—no matter which of the positions for OFA air intake is used—are significantly lower than emissions without OFA air. On the other hand, using OFA air does not affect the SO_2 emissions and is practically equal to emissions without OFA air—in this case the average is over 4800 mg/m_n^3 , Fig. 6.

Regarding the possibilities of reduction of NO_x emissions, the previous results of research and knowledge are of key importance for the design of future but also possible reconstruction of existing boilers, in particular the furnaces for the choice of a place/zone of staging air intake in the combustion zone. This certainly has an impact on the design and choice of boiler accessories.

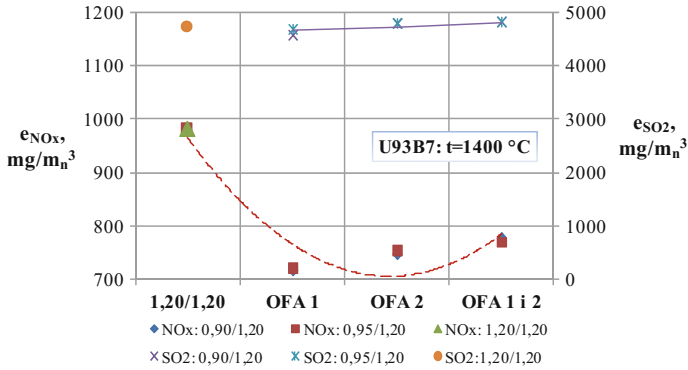


Fig. 6. NO_x and SO₂ emission dependence of the OFA air introduction place

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 Fig. 7. For example, at a temperature of 1450 °C for coal (U100), this emission decreased from 892 to 694 mg/m_n³ or more than 22% relative to the emission at the same temperature, quantity and mode of air supply but without fuel staging. However, it should be noted that in these test regimes there was a significant increase in CO content in flue gases [6, 7], for example U100: 686 mg/m_n³ at 1350 °C and 140 mg/m_n³ at 1450 °C.

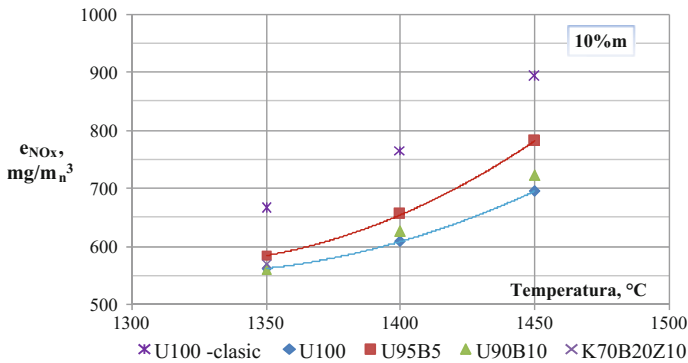


Fig. 7. Impact of the temperature on NO_x emissions with staging combustion of fuel with different composition

The use of natural gas as an additional fuel (reburning technology) results in an additional reduction in NO_x emissions relative to the emissions previously presented while applying staged basic fuel intake into combustion zone.

The NO_x emission during co-firing coal with biomass (U95B5) when applying different primary measures in furnace, including the efficiency of these measures by

reducing this emissions compared to the emission with conventional combustion is presented in Fig. 8—the results refer to the temperature of 1450 °C [8].

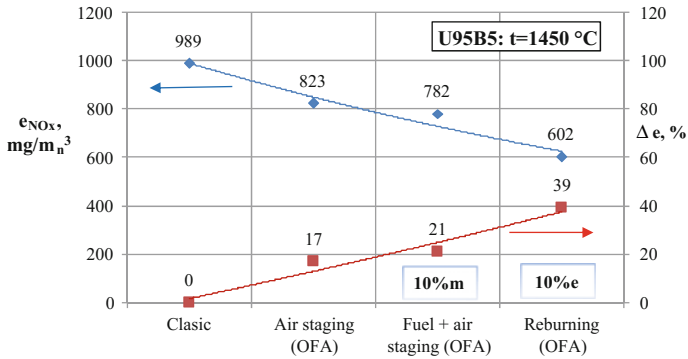


Fig. 8. Efficiency of primary measures at temperature of 1450 °C: fuel U95B5

Efficiency of primary measures by staging the base fuel and using natural gas as additional fuel is weakening with rising process temperatures. Namely, the efficiency of the basic fuel staging at 1450 °C is 21% compared to 32% at 1350 °C, while the efficiency of natural gas utilization for those temperatures is 39% and 46% respectively. Thereby, the difference in efficiency of the application of combustion air staging for the observed combustion temperature is the smallest [9].

Generally, by adding wood biomass to the coal mixture, the base and acid numbers of this mixture increases. With the fraction of woody biomass in the mixture up to 10%, the base and acid number ratio is slightly increasing in relation to the coal mixture, so practically the coal-biomass mixture in the spreadsheet ($R_{B/K-t}$) remains in the zone with strong tendency to fouling/slagging [5].

4 Conclusion

Air staging:

- NO_x emissions in co-firing coal with waste woody biomass is at the emission level at combustion of coal blend. There is practically no change in this emission with the change in the fraction of woody biomass in the mixture. The average difference in NO_x emissions depending on the mode of combustion air is $250 mg/m_n^3$; for the classical air intake the average emission is $942 mg/m_n^3$, while for the leveled air intake it is $692 mg/m_n^3$.
- The SO_2 emission is slightly reduced by increasing the fraction of woody biomass and practically does not depend on the mode of combustion air intake—the emissions are high and generally over $5000 mg/m_n^3$.
- By increasing the fraction of woody biomass in the mixture, the CO_2 net emission is

proportionally reduced, which at the 10% biomass in the blend is 0.233 kg/m_n^3 .

- The NO_x emission also depends on the location of the OFA air in the combustion chamber. So the NO_x emission is smallest when the OFA air is supplied at 1/3 of the length of the reaction tube/combustion chamber). The location of the OFA air intake (positions 1 and 2) does not affect the SO_2 emission value.

Fuel staging:

- In the case of combustion with a fuel staging NO_x emission is reduced—this reduction is proportional to the part of the fuel that is introduced into the reaction zone afterwards. In the case of fuel staging of 10%*m* and temperature of $1350 \text{ }^\circ\text{C}$, the reduction of NO_x emissions is about 100 mg/m_n^3 or 15% on average with respect to emissions for combustion without fuel staging.
- For combustion with staged base fuel intake significant increase in CO content in flue gases appears, for example U100: 686 mg/m_n^3 at $1350 \text{ }^\circ\text{C}$ and 140 mg/m_n^3 at $1450 \text{ }^\circ\text{C}$. 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.

Reburning technology:

- Combustion with natural gas as additional fuel results in an additional reduction in NO_x emissions—this reduction is proportional to the fraction of natural gas that is introduced into the reaction zone at a later stage. For example, when coal is co-fired with biomass under these conditions (UB (95) P10) and at temperature of $1450 \text{ }^\circ\text{C}$, the measured emission is 602 mg/m_n^3 , which is 30.5% less than emission with U100, that is 866 mg/m_n^3 .
- In combustion regimes with natural gas, the CO emission is very low, especially during co-firing at temperatures above $1400 \text{ }^\circ\text{C}$, where this emission is virtually negligible: below 5 mg/m_n^3 .

Evaluation of the efficiency of primary measures in the combustion chamber—the effects of the application of primary measures in combustion chamber for fuels U100 and U95B5 for process temperatures ranging from 1350 to $1450 \text{ }^\circ\text{C}$:

- By using natural gas in combustion of coal U100 at temperature of $1450 \text{ }^\circ\text{C}$, the emission of NO_x decreased to 615 mg/m_n^3 or by almost 50% compared to the emission of conventional combustion: 1154 mg/m_n^3 .
- Efficiency of primary measures by staging the base fuel and using natural gas as additional fuel weakens with rising process temperatures. Efficiency of the staging basic fuel at $1450 \text{ }^\circ\text{C}$ is 20.9% compared to 31.9% at $1350 \text{ }^\circ\text{C}$, while the efficiency of natural gas utilization for those temperatures is 39.1% and 46.2% respectively. In doing so, efficiency of the application of staging combustion air is practically the same for both observed combustion temperatures.

- Despite the increase of the base and acid number ratio with the addition of woody biomass to the coal mixture, it has been shown that utilization of wood biomass in the process gives even positive effects in the formation of more abundant deposits of ash.

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