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Sustainable Energy Sector Using Waste Woody Biomass and Miscanthus in the Energy Transition

Primjenom otpadne drvne biomase i Miscanthusa do održivog sektora termoenergetike u vremenu energetske tranzicije

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***Abstract* -** The thermal energy sector is very important at this time of global energy transition. From the aspect of stable energy independence, this is especially important in countries whose energy system is based on fossil fuels, especially coal. This is why decarbonisation of the energy sector is necessary, with a partial and gradual substitution of coal with renewable fuels. However, the use of these fuels is not always possible in existing plants. This refers to the establishment of energy, economic and environmentally acceptable proportion of the co-firing of these fuels, i.e. a mixture of coal and renewable fuels. The success of the establishment of this process is a function of several variables, the dominant of which are the aggregate properties of the fuel, basic and their mixtures, including the ash properties of those fuels. With the motive of contributing to a more successful implementation of the energy transition in the thermal energy sector, and with the aim of obtaining new scientific knowledge about the characteristics of the combustion of lignite and brown coal with different renewable fuels, laboratory research was carried out. In particular, different mixtures of lignite and brown coal, waste woody biomass and Miscanthus as a fast-growing energy crop were subjected to co-firing with variable process conditions. In addition to changing the composition of fuel mixtures, the test regimes included a significant change in process temperature (1250-1450 °C) and the primary measure of staged air supply to the furnace. In these combustion conditions, the emission of undesirable and harmful components into the environment, the efficiency of combustion, and the tendency of the ash from the fuel mixture to possible soiling of the heating surfaces in the furnace were evaluated - an analysis of the characteristics of the ash samples from the reaction zone and samples of the slag and ash to the furnace. Here, in both cases of co-firing, lignite and brown coal with different types of biomass, it was shown that in real conditions it is possible to establish a sustainable primary energy conversion process from fuel with a low unburnt carbon content in the slag (unburnt carbon content, UBC<1%) as well as low CO emission, below 350 mg/m_n^3. At the same time, the NO_x emission is below 320 mg/m_n^3 during the co-firing of lignite mixtures at 1250 °C, and in the case of brown coal mixtures below 740 mg/m_n^3 at 1450 °C. In both cases, the net CO_2 emission decreases in proportion to the proportion of biomass in the mixture, while the SO_2 emission is still high, at a level of up to 2500 mg/m_n^3 for lignite mixtures and up to 6400 mg/m_n^3 for brown coal mixtures. None of the treated types of biomass, up to the level of applicable content in the mixture with lignite and brown coal, does not worsen the progress of the process from the aspect of possible slagging/fouling heating surfaces in the boiler.

***Index Terms* -** Waste woody biomass, Miscanthus, Coal, Co-firing, Emissions, Ash

***Rezime* -** U aktuelnoj eri globalne energetske tranzicije naročito je važan sektor termoenergetike. Ta važnost sa aspekta postizanja i održanja stabilne energetske nezavisnosti je posebno izražena u zemljama čiji je energetski sistem baziran dominantno na bazi primjene fosilnih goriva, naročito uglja, te u uslovima globalnih poremećaja. Stoga je u tom zahtjevnom procesu dekarbonizacije termoenergetskog sektora i nužno i neminovno bar djelimično i postepeno supstituisati fosilni ugalj obnovljivim vrstama goriva. Međutim, mogućnost uvođenja i naročito uspostave energetski, ekonomski i okolinski prihvatljivog procesa sagorijevanja uglja i obnovljivih goriva u postojećim ložištima i termoblokovima nije uvijek moguća. Ukupna uspješnost uspostave takvog jednog procesa je funkcija niza varijabli, od kojih su zbirne osobine goriva, komponentnih i mješavine, uključujući i osobine pepela iz tih goriva, dominantne u tom smislu. S motivom doprinosa za uspješnije provođenje energetske tranzicije u sektoru termoenergetike, a s ciljem dobijanja novih naučnih saznanja o karakteristikama sagorijevanja lignitnog i mrkog uglja sa različitim obnovljivim gorivima, izvršena su laboratorijska istraživanja. Konkretno, sagorijevanju su podvrgnute različite mješavine lignitnog i mrkog uglja, otpadne drvne biomase i Miscanthusa kao brzorastućeg energetskog usjeva i to u promjenjivim procesnim uslovima. Osim promjene sastava mješavina goriva, ispitni režimi su uključivali značajnu promjenu procesne temperature (1250-1450 °C) i primarnu mjeru stepenovanog privoda vazduha u ložište. U tim uslovima sagorijevanja utvrđena je emisija nepoželjnih i štetnih komponenti u okolinu, efikasnost sagorijevanja, te je ocijenjena sklonost pepela iz mješavine goriva ka mogućem prljanju ogrijevnih površina u ložištu - analizirane su karakteristike čvrstih uzoraka depozita pepela iz zone reakcije kao i uzorci šljake i pepela na izlazu iz ložišta. Ovdje je u oba slučaja kosagorijevanja, i lignita i mrkog uglja sa različitim vrstama biomase, pokazano da je u realnim uslovima moguće uspostaviti održiv proces konverzije primarne energije iz goriva sa niskim sadržajem nesagorjelog ugljenika u šljaci (*unburnt carbon content*, UBC<1%) kao i niskom emisijom CO, ispod 350 mg/m_n^3. Pri tome je i emisija NO_x ispod 320 mg/m_n^3 pri kosagorijevanju mješavina lignita na 1250 °C, a kod mješavina mrkog uglja ispod 740 mg/m_n^3 na 1450 °C. U oba slučaja, neto emisija CO_2 se smanjuje srazmjerno udjelu biomase u mješavini dok je emisija SO_2 još uvijek visoka, na nivou do 2500 mg/m_n^3 za mješavine lignita a za mješavine mrkog uglja do 6400 mg/m_n^3. Ni jedna od tretiranih vrsta biomase, do nivoa primijenjenog sadržaja u mješavini sa lignitnim i mrkim ugljem, ne pogoršava odvijanje procesa sagorijevanja sa aspekta mogućeg prljanja i zašljakivanja pepela u ložištu.

Ključne reči **-** otpadna drvna biomasa, Miscanthus, ugalj, kosagorijevanje, emisije, pepeo

I INTRODUCTION

Decarbonization of the energy sector is a necessary imperative. In this sense, increasingly strict requirements lead to at least partial substitution of fossil fuels with renewable and/or alternative fuels. This need is particularly pronounced in the field of thermal energy in developing countries whose energy system is based on the use of their own coal resources as a primary energy carrier. The energy transition from fossil to renewable fuels is happening gradually due to the pronounced complexity of implementation, but also the need for a safe and stable energy system. This complexity is reflected in the very demanding technical and economic interventions on the existing energy plants. According to the projection, the transition process will last for some time, especially in countries that have yet to enter the transition process of the energy sector on a larger scale, approximately two or three decades - Bosnia and Herzegovina (BiH) is such an example of a country. In order to replace fossil fuels and carry out the transition in a sustainable way, the focus of research is on environmentally acceptable fuels while increasing the efficiency of primary energy use. The category of promising renewable fuels primarily includes biomass, either as waste from agricultural, forestry or wood-processing activities. In this regard, research into the possibility of co-firing of different types of coal and a wide range of different types of biomass is very current in this period and practically throughout the world. In addition to research that is directed and determined by the technological settings of combustion in the existing furnaces of a very large number of different versions of energy plants, research is also intensively carried out in the direction of the development of new, cleaner combustion technologies. The development of such new combustion technologies belongs to the development of the so-called of Clean Coal Technologies (CCT), which provides a global scientific contribution aimed at mitigating the increase in average temperature and climate change on the planet Earth, including local and national level contribution to a cleaner environment, as already defined by the goals of the United Nations Agenda for Sustainable Development 2030, [1], as well as the Green Agenda of the EU and the Balkans, [2]. In connection with the above, including taking into account the fact that the energy system of BiH is based predominantly on domestic coal (about 2/3 of the total electricity produced in BiH is produced as part of thermal power plants on lignite and brown coal), in BiH it is neither realistic nor it is fair to expect a drastic reduction in the use of the most important domestic energy resource, coal, in a shorter period of time. This is also discussed in the long-term energy strategy of Bosnia and Herzegovina, where the commitment to the use of domestic coal in the future is clearly demonstrated [3]. The situation is quite similar in other countries in the Balkans. On the other hand, the goals of the European Union (EU) are clear and defined by the European Green Deal initiative, which is a commitment to complete cli-mate neutrality by 2050, which was also confirmed in the annual report of the International Energy Agency for last year, [4-5]. BiH, on its way to the EU, must respect and adapt to the global market and trends that tend towards clean energy. The European Green Deal initiative is also a great opportunity for the energy transition of BiH and other countries, i.e. monitoring the trend of clean energy production, which was also discussed by regional experts in the subject area, [6]. The trend of switching electricity production from coal to renewable energy sources is a rather slow, investment-demanding and long-term process. Because of this, but also because of the current representation and especially because of the stability and reliability of production, including a fairly stable price even in conditions of market disturbances, coal as the primary energy source in thermal power plants is projected to remain an important resource in the energy system in the coming period. At the same time, due to competition and increasingly strict requirements regarding the overall reduction of negative impact on the environment, coal-based electricity producers are forced to monitor and adopt new technologies. Therefore, in addition to a higher degree of utilization, these plants should also be classified as plants with a significantly lower burden on the environment based on the polluting components in the flue gases. At the same time, this prolongs the use of fossil fuels for a certain period of time in which a further alter-native or replacement for fossil fuels with other sources of energy should be found. New technologies - Clean Coal Technologies (CCT), also include technologies with additional renewable or alternative fuel/co-firing, e.g. co-firing of coal with waste woody biomass (residues after felling and wood processing, small branches, sawdust). These fuels are considered renewable and neutral from the aspect of origin and combustion process, i.e. CO_2 generation, [7-8]. Emission CO_2 from conventional coal-fired thermal power plant boilers in Bosnia and Herzegovina are extremely high - on average above 950 kg/MWh. In addition, coals from Bosnia and Herzegovina generally belong to low heating value and poor reactivity coals, and the ash from these coals is very prone to slagging and fouling of heating surfaces in boilers. In the short-term and medium-term plans of the EU, on whose path BiH is also, co-firing of coal with biomass and/or fuel generated from municipal waste (fuels of the professional nomenclature SRF/RDF - *Refuse Derived Fuel / Solid Recovered Fuel*) is one of the most promising applications - see also [9-11]. Renewable fuels in energy and industrial boilers must meet several criteria, such as appropriate energy potential, availability of supply throughout the year, appropriate chemical composition and humidity to reduce transport costs and contribution to thermal power, and adequate price. Woody residues, as biomass, represent a fuel that meets all these criteria. In addition to the known significant reserves of coal, whose balance and exploitation reserves according to the latest estimates amount to about $4{,}5\times10^9$ t, [12], Bosnia and Herzegovina also has signify-cant biomass potential - it is estimated that the total annual technical energy potential of biomass residues amounts to more than 33 PJ, which is equivalent to more of 3 million tons of BH lignite, [9], [13]. The use of biomass and fuel from waste has been in use in technologically developed countries for a long time and with further expansion of that use. Namely, the partial use of biomass replaces a certain amount of coal in the production of electricity and heat, reduces the amount of undesirable and harmful gases, in the context of decarbonization, primarily CO_2, because about 98% of the total CO_2 emission at the world level originates from the burning of fossil fuels, and 30 % to 40% of that CO_2 emission is caused by burning coal, [14-15]. Every year, burning coal produces more than 14 billion tons of carbon dioxide (CO_2), which is released into the atmosphere, of which CO_2 is mostly generated during the production of electricity, [16], [17]. In the paper [18], it is stated that the negative greenhouse effect is mainly contributed by CO_2 with a share of more than 55%. Therefore, obtaining specific scientific and socially useful data on the possibilities of such application of domestic fuel resources (combination of the application of lignite and brown coal, waste wood biomass and/or energy crops in the co-combustion process) represents a more than sufficient motivational basis for research - see also [13], [14], [17] and [19]. Specifically, in this case, different mixtures of lignite and brown coal, waste wood biomass and Miscanthus as a fast-growing energy crop were subjected to combustion under variable process conditions.

II EXPERIMENTAL RESEARCH SETTINGS

Primary fuels: Laboratory research pulverized-fuel combustion technology was carried out for mixtures primary fuels: brown coal and lignite with two different type of woody biomass, waste woody biomass and energy crop Miscanthus. The designations, basic description and characteristics of primary fuels are given below in Table 1:

- LC, a mixture of lignite coals from the Šikulje and Dubrava mines (mines from the area of the Tuzla mining basin, Bosnia and Herzegovina) in a 50:50 mass ratio - the mixture was formed in laboratory conditions after drying and grin-ding the two listed component lignite coals.
- BC, a mixture of brown coals that have been delivered and burned in Kakanj TPP for many years. These are brown coals from mines in the area of the central Bosnian mining basin, BiH. More precisely, these are the Kakanj, Breza, Zenica, Gračanica, Livno and Nova Bila mines. Grinding of this coal mixture was extracted directly from the boiler unit 6 in Kakanj TPP - from the coal dust channel behind the mills. At the same time, the mass fraction of coal from the Kakanj mine in the mixture is about 55%.
- WB, waste woody biomass, small sawdust - the mixture is formed from beech and spruce sawdust in a ratio of 50:50.
- MI, Miscanthus, a fast-growing energy crop extracted from a sample plot of an agricultural plantation in Butmir, BiH. Miscanthus (MI) and waste woody biomass (WB) were ground in a laboratory mill after drying.

Table 1. Basic characteristics of primary fuels, [20]

Fuel	**LC**	**BC**	**WB**	**MI**
Moisture, %	3.27	12.04	41.82	12.33
Ash, %	38.28	36.98	0.39	4.28
Volatiles, %	33.64	29.90	48.98	71.40
C_{fix}, %	24.79	20.94	8.83	11.99
Combustible, %	58.45	50.98	57.80	83.39
Carbon, total, %	38.72	35.42	28.79	42.60
Hydrogen, %	2.95	2.64	3.54	4.79
Sulphut, combustible, %	0.90	1.09	0.06	0.11
Nitrogen, %	0.86	0.62	0.11	0.11
Oxygen, %	15.02	11.21	25.29	35.78
Gross, HHV, kJ/kg	14,870	14,018	10,846	15,361
Net, LHV, kJ/kg	14,187	13,198	9,155	14,090

LC - lignite coal, BC - brown coal, data after partial drying..

WB - waste woody biomass, MI - Miscanthus, data for delivery condition.

The basic characteristics of mixtures of lignite and brown coal are high moisture and ash content in the delivery state (especially lignite), poor reactivity and low heating value. The key characteristics of both types of biomass are significant moisture content, especially in the case of waste woody biomass, relatively low ash content and a significant share of volatiles and total combustible materials. Favourable features of these types of biomass are the very low content of sulphur and nitrogen, Table 1.

Test regimes: By mixing mixtures of lignite and brown coal (LC or BC) and a certain type of biomass (WB and/or MI) in the appropriate selected ratio by mass, three mixtures of coal and biomass were formed, which were separate, as well as mixtures of lignite and brown of coal, subjected to combustion in the appropriate technical and technological conditions, Table 2. These conditions basically refer to the chosen appropriate process temperature - 1250 °C for combustion lignite and mixtures of lignite and biomass, and 1450 °C for combustion brown coal and its corresponding mixtures with biomass. The process temperature of 1250 °C basically corresponds to the pulverized-fuel combustion technology with dry bottom furnace - applied on all boilers within the Tuzla TPP, while the temperature of 1450 °C corresponds to the technology applied on the current boilers within the Kakanj TPP - pulverized-fuel combustion technology with slag tab furnace. In addition, all test regimes included a total coefficient of excess air for combustion of λ=1.15 and a staged supply of that air to the combustion chamber (air staging), where the subsequent flow of that air (OFA - Over Fire Air) was, OFA=$\Delta\lambda=\lambda-\lambda_1$=0.20, Table 2. Under these conditions, in the actual operation of unit 6 within the Tuzla TPP and all units in the Kakanj TPP, the subject mixtures of lignite (LC) and brown coal (BC) are burned.

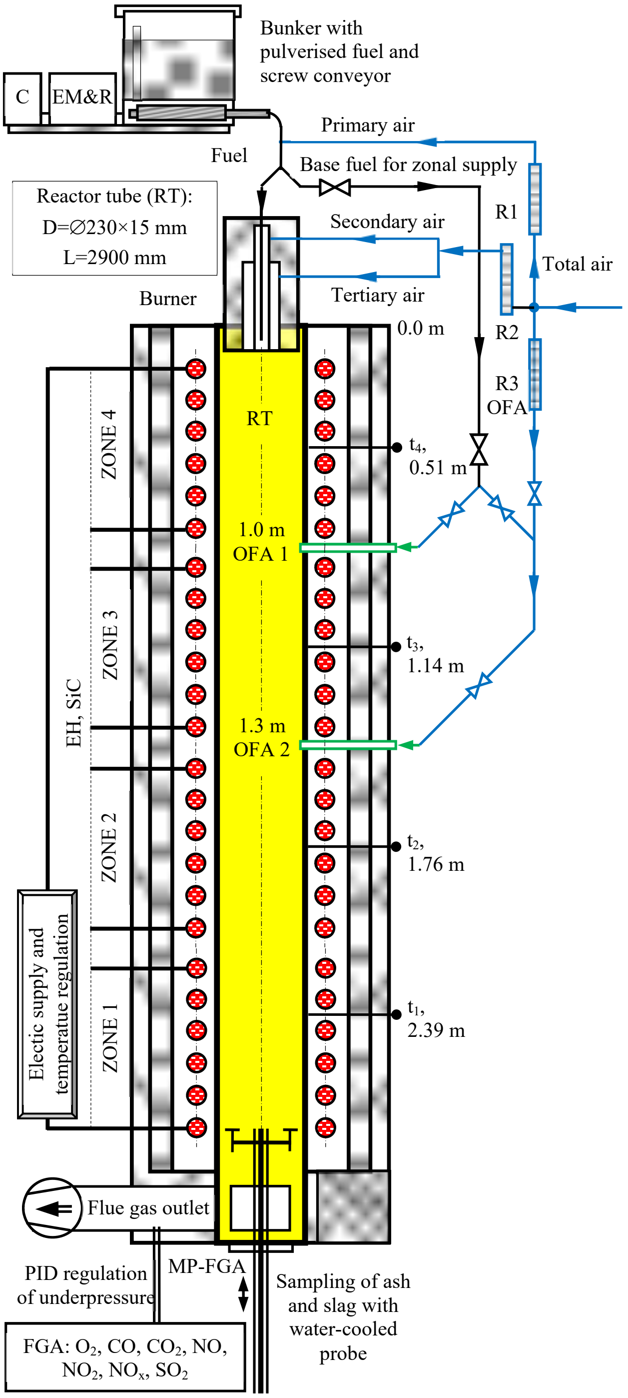

Figure 1. Principal scheme of part of the lab-scale furnace with indicated staging introduction of combustion air, [13]

In all test co-firing regimes, flue gas composition was continuously analyzed, on the basis of which the pollutant emission was determined: $NO+NO_2=NO_x$, SO_2, CO_2 and CO - the emission of all flue gas components was expressed in relation to the reference oxygen content in with dry flue gases, for O_{2ref}=6%, [21], - see also the principle scheme of the plant given in Figure 1.

In addition, during the test regimes, samples of ash deposits in the combustion chamber and samples of slag and ash at the exit from the combustion chamber were extracted and then analyzed. Considering the different bulk density of the test fuel mixtures, for each of them the characteristic of the fuel dispenser was previously determined so that the measurement results obtained during the research could be correlated with fuel consumption (kg/h), i.e. with the thermal load of the furnace based on the heat input through fuels (kW), [13].

Table 2. Test fuel mixtures and test regime settings

	Air staging λ_1/λ=0.95/1.15	
	Temperature 1250 °C	Temperature 1450 °C
No.	Designation and composition of the fuel mixture by mass	
1.	LC	BC
2.	LC:WB=85:15	BC:MI=93:7
3.	LC:WB:MI=80:13:7	BC:WB=85:15
4.	LC:WB:MI=75:15:10	BC:WB=75:25

LC - lignite, BC - brown coal, WB - waste woody biomass, MI - Miscanthus

Lab-scale furnace: An Automatic Controlled Tubular Reactor with electric SiC heaters is used for research. It was installed in the Solid Fuel Combustion Laboratory at the University of Sarajevo - Faculty of Mechanical Engineering, Figure 1 - see also [13], [17], [22-23]. At the facility, it is possible to research the combustion characteristics of different solid fuels at different temperatures and technological conditions. In short, the plant is designed to operate at a wide temperature interval (from ambient temperature to 1560 °C) and in conditions of different amounts and distribution of basic fuel and combustion air, including the ability to test reburning using both basic and additional solid and gasses fuels, for example natural gas. During the research, data concerning the efficiency of combustion, the deposit intensity and the characteristics of deposits from the reaction zone are obtained, as well as slag and ash at the reactor outlet. The emission of flue gas components O_2, CO, CO_2, NO, NO_2, NO_x and SO_2, HF, HCl, etc. are measured - [13], [17].

III RESEARCH RESULTS AND DISCUSSION

The investigation of the characteristics of co-firing on the macro principle of input-output, that is, reactants-products, as previously mentioned, was carried out at different process temperatures, at 1250 °C and 1450 °C. During the test regimes, the composition of flue gases was continuously analysed with the aim of determining the level of emissions of pollutants, and samples of ash deposits from the reaction zone/furnace, as well as samples of slag and ash at the exit from the incinerator, were also taken. These samples were then subjected to visual, chemical (CA) and ash characteristic temperature (AFT) analysis. In connection with the above, the obtained research results were presented separately - according to the type of basic fuel (lignite and brown coal) or according to the process temperature of combustion of that fuel.

a) Lignite coal LC and biomass, t=1250 °C:

Emission of pollutants, deposit, slag and ash

Figure 2 shows the results of NO$_x$ and SO$_2$ emissions measured during the co-firing of a mixture of lignite LC, waste woody biomass WB and the fast-growing energy crop Miscanthus MI. The emission of NO$_x$ during co-firing is at the level of the measured emission during the combustion of LC lignite mixture, i.e. at the level of 310 to 320 mg/m$_n^3$ and with small variations de-pending on the type and content of biomass in the mixture with lignite - this fact has been scientifically known for a long time and was also confirmed in these studies. In particular, the NO$_x$ emission during combustion of LC lignite mixture is 320 mg/m$_n^3$, while the average NO$_x$ emission during co-firing with biomass is 315 mg/m$_n^3$. In addition, compared to the current NO$_x$ emission at unit 6 in TE Tuzla, these emissions are at the same level, which is again additional evidence of the adequately established key settings of research at the laboratory plant in relation to real operation. These are, first of all, the mean process temperature, the coefficient of excess air for combustion and the application of the primary measure of staged supply of that air in the furnace.

In terms of SO$_2$ emissions, the total sulphur content and especially the combustible sulphur content in the LC lignite mixture (S$_{tot}$= 1.57%, and S$_{com}$=0.90%) when burning that fuel at a relatively lower process temperature of 1250 °C results in an expected SO$_2$ emission at the level of 2,360 to close to 2,500 mg/m$_n^3$, which is comparable to the emission from a real plant when burning the subject lignite mixture LC. At the same time, it can be seen that the mentioned relatively lower temperature of the process favours a better binding of sulphur to the alkali from the ash. Here too, it is additionally visible that there is no significant change in SO$_2$ emission with regard to the type and content of biomass in the mixture with lignite - the emission decreases quite slightly with the increase in the proportion of biomass in the mixture. So, for example, SO$_2$ emission during co-firing with a total of 25% biomass (15% waste woody biomass and 10% Miscanthus) in a mixture with lignite is only 150 mg/m$_n^3$ lower (or only 6%) compared to the emission when burning a mixture of LC lignite under the same conditions, e$_{LC-SO2}$=2,490 mg/m$_n^3$, Figure 2.

Due to the relatively lower combustion process temperature, the slightly less favourable granulation of both types of biomass compared to the LC lignite mixture, and the greater mass content of biomass in the mixture with LC (biomass content in the mixture from 15% to 25%), slightly higher CO emissions were measured here at co-firing in relation to the emission during the combustion of the LC lignite mixture, Figure 3 - see the CO emission values at the biomass content in the mixture of 15%, 20% and 25%:300 mg/m$_n^3$, 320 mg/m$_n^3$ and 346 mg/m$_n^3$.

That CO emission during combustion of LC is at the level of 130 mg/mn3. This is certainly connected with slightly lower NOx emissions and especially CO2 emissions in co-firing regimes with a proportion of biomass in the mixture ≥20%, Figure 3. More specifically, in co-firing with 25% biomass in the mixture (of which 15% is WB and 10% MI) emission of NOx and CO2 is 310 mg/mn3, and 0.253 kg/mn3. It should also be emphasized here that the structure of the MI ground, compared to the ground of WB, is different, it is more fibrous, and that the rest of the MI fraction on a sieve with a perforation of 1 mm is 0.83%, while through a sieve with a perforation of 90 µm passed 14.03% of MI fractions, [20].

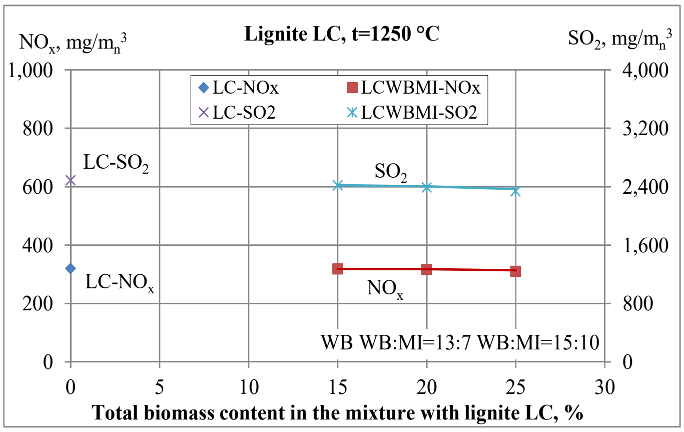

Figure 2. NOx and SO2 emissions for the lignite coal LC, woody biomass WB and Miscanthus MI

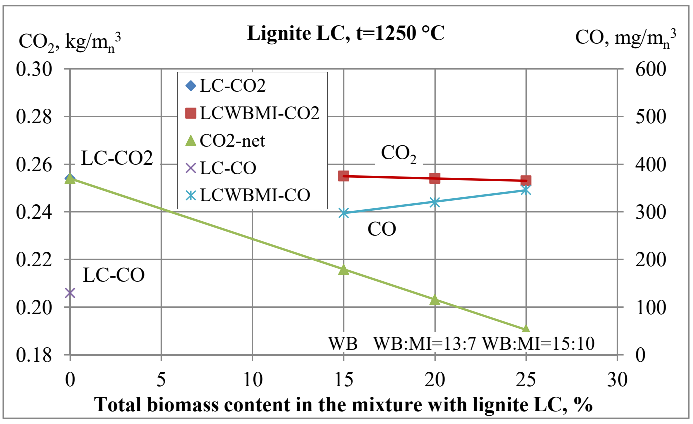

Figure 3. CO2 and CO emissions for the lignite coal LC, woody biomass WB and Miscantus MI

When designing a furnace and choosing a combustion technology, it is essential to know a wider range of properties of ash from fuel, especially the properties with regard to the ash's propensity for fouling and slagging. Therefore, for a more reliable assessment of the behaviour of ash in the combustion process, it is necessary, in addition to the assessment through classic empirical criteria based on the composition of the ash, to supplement this knowledge beforehand through laboratory or operational rese-arch. These findings in the current era of decarbonization are equally important for existing plants when there is a need to introduce renewable fuels into operation. In this regard, the following Figure 4 shows the results of the chemical analysis of the composition of ash from a mixture of lignite and the composition of slag resulting from the co-firing of that LC with 15% of WB (LC:WB=85:15) and LC with 15% WB and 10% MI (LC:WB: :MI=75:15:10). Biomass in a mixture with LC not only changes the total ash in the mixture (reduces it), but also changes the chemical composition of that ash. In addition to that, during the combustion process there is an overcomposition of components from the ash in terms of location and structure of the solid sample. From Figure 4 it is evident that MI in the mixture, compared to WB, mitigates the reduction of SiO_2 and Fe_2O_3, while it contributes to the increase of CaO, MgO, Na_2O and K_2O components - see also [13], [17-18], [24-25].

As a result of the change in the chemical composition of the ash by adding biomass to the mixture with LC, the physical properties of the ash and thus the characteristic temperature of the ash also change. In this case, the content of SiO2, which significantly determines these characteristic temperatures, is 59.01% in lignite, slightly below 7% in WB, and almost 68% in MI - [13], [20], [25].

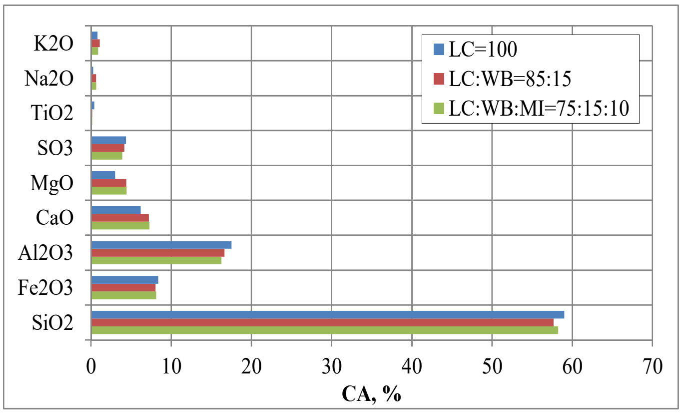

Figure 4. Chemical analysis (CA) of ash from LC lignite and slag during co-firing with different types and content of biomass

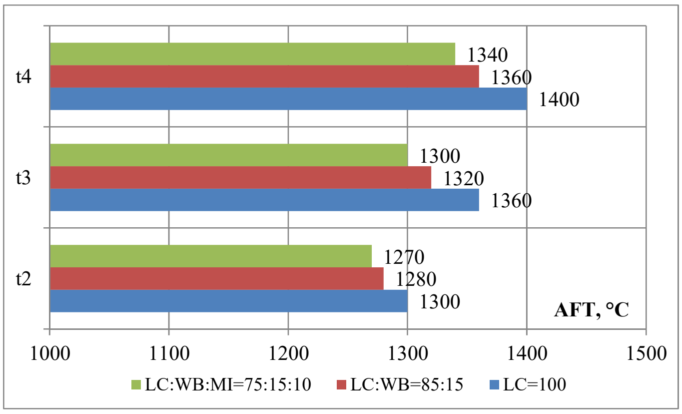

Figure 5. Ash fusion temperature (AFT) from lignite coal LC and slag during co-firing LC with types and content of biomass in the mixture; t2 - softening, t3 - hemisphere, t4 - flowing

In addition, there is also a significant difference in the content of Fe_2O_3 in the component fuels - this content is 8.38% in LC, only 1.05% in WB, and 4% in MI. The difference in Al_2O_3 content is even more pronounced - it is 17.53% in LC, 0.23% in WB and only 0.1% in MI. On the contrary, the content of CaO, MgO, Na_2O and K_2O compounds is significantly higher in biomass ash, especially in waste wood biomass. All this, in general, with an increase in the content of either one or both types of biomass, contributes to a decrease in the characteristic ash temperatures in the fuel mixture, Figure. 5.

Furthermore, regardless of the type and content of biomass in the lignite mixture, all samples of ash deposits from the furnace formed during co-firing regimes in the given process settings are loose - the deposit can be easily removed from the ceramic tablet already at a smaller tilt of the tablet, due to gravity, Figure 6.

Figure 6. Samples of deposits of ash from the furnace and slag at the exit from the furnace during the co-firing of LC lignite with different types and content of biomass in the mixture – see also [9] and [25]

And all the slag samples taken at the exit from the furnace are in a loose state and without the appearance of initial fused particles - the slag particles are slightly larger during co-firing compared to the combustion of the lignite mixture. Overall, for treated mixtures up to 25% biomass content by mass in the applied co-firing conditions, there is no occurrence of ash slagging in the furnace, Figure 6, [20].

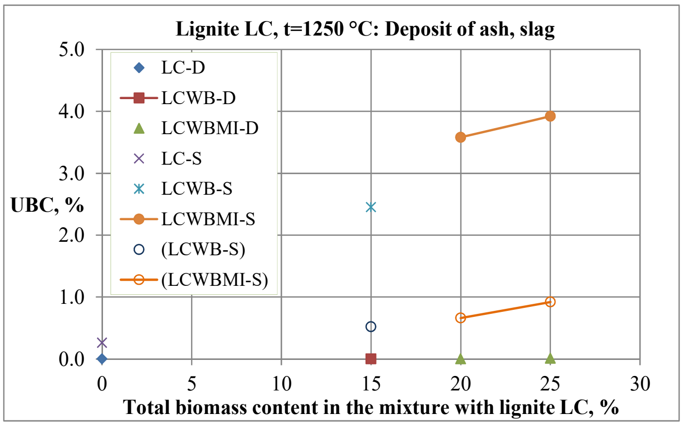

Figure 7. Unburnt carbon content (UBC) in deposit and slag samples from LC lignite co-firing with different types and biomass content in the mixture

Regarding the efficiency of the combustion process, observed through the content of combustible substances in the slag and ash samples at the exit from the furnace, the research results show that it is possible to establish a practically acceptable combustion, Figure 7.

It primarily shows the measured very low carbon content, or even equal to 0, in the ash deposit samples from the combustion chamber. The slightly higher values of the carbon content in the slag obtained in the co-firing regimes with ≥20% biomass in the mixture indicate that in the treated combustion conditions there is an insufficiently long path or insufficient time for a more complete combustion of larger fuel particles, specifically biomass, i.e. that in the given settings there is no conditions for a more efficient combustion phase. However, by changing the thermal load of the combustion chamber, i.e. by reducing the consumption of the same fuel mixtures by 50%, this indicator of combustion efficiency improves significantly - in Figure 7, see the results of the UBC analysis of slag for those combustion regimes, labels: (LCWB-S) and (LCWBMI-S) where UBC<1%. Additionally, in the conditions of real operation with in-flight combustion and in the case of significant heat loss, it is possible to reduce it to a practically acceptable level (below 2%) by introducing an additional grate for afterburning - establishment of combined combustion.

b) Brown coal BC and biomass, t=1450 °C:
Emission of pollutants, deposit, slag and ash

In contrast to the previous case, this process temperature basically corresponds to the pulverized-fuel combustion technology with slag tab furnace. In this regard, Figure 8 shows the results of NO_x and SO_2 emissions during combustion of brown coal BC and co-firing of different types and proportions of biomass with brown coal. Considering that the temperature of the process is high, consequently the binding of sulphur to the alkali from the ash is also lower, which with a rather high content of sulphur in the basic mixture of brown coal BC (S_{com}=1.09%), generates SO_2 emissions at the expected high level and in the range of 6,000 to 6,400 mg/m_n^3. Nevertheless, these are slightly lower SO_2 emissions compared to the same emission during the combustion of the BC brown coal mixture, where this emission is at the level of around 6,800 mg/m_n^3. As for the NO_x emission, it can be noted that this emission during co-firing is in the range between 700 and 740 mg/m_n^3, which is somewhat lower compared to the NO_x emission measured during the combustion of a mixture of brown coals e_{BC}=750 mg/m_n^3 - in real terms in the operation of block 6 of the Kakanj TPP, that emission is in the range of 750÷850 mg/m_n^3. Therefore, the co-firing of coal and biomass practically does not reduce the level of NO_x emissions, or the reduction is very slight compared to the combustion of only brown coal - see also [17-18].

As expected, relatively low CO emissions (<150 mg/m_n^3), were measured here, primarily due to the high combustion temperature in all regimes, Figure 9.

At the same time, it is noticeable that the CO emission increases with the increase in biomass content in the mixture with coal. This phenomenon can be linked to a significantly higher content of volatiles in the biomass (WB has almost 50%, and MI over 70%) compared to BC coal (<30%), as well as to the grinding quality of certain primary fuels in the mixture - at both types of biomass have a significantly higher content of larger slag fractions compared to brown coal. E.g. the share of brown coal fractions that passed through the 90 µm sieve is 50.41%, while it is 13% for MI and only 5% for WB. However, this emission trend also corresponds well to the NO_x emission trend for all test mixtures. On the other hand, in accordance with the necessary and current decarbonization, it is very important to point out here that the net emission of CO_2 during the co-firing of fossil coal with biomass decreases in proportion to the content of biomass in the mixture.

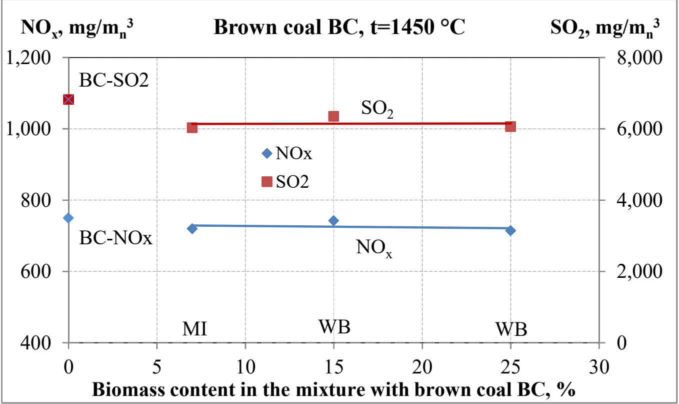

Figure 8. NOx and SO2 emissions for the brown coal BC, woody biomass WB and Miscanthus MI

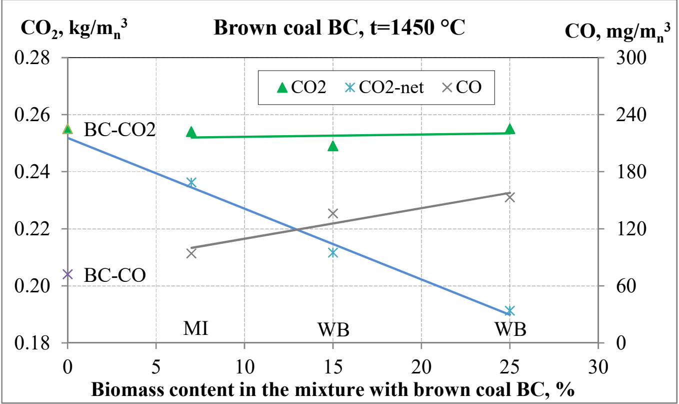

Figure 9. CO2 and CO emissions for the brown coal BC, woody biomass WB and Miscantus MI

Figure 10. Samples of deposits and slag during co-firing of biomass with coal BC - see also [22]

In this set of test regimes, samples of ash deposits from the furnace as well as samples of slag at the exit from the furnace were excluded, Figure 10. In this case, the ash deposit is always in a molten state and upon cooling it creates a hard and hard-to-separate deposit from the surface of the ceramic tablet, which in laboratory research represents the uncooled surface in the furnace. In contrast, the sample of the formed deposit from the slightly rounded tip of the probe, which is constantly cooled by water, has a completely loose granular structure. Furthermore, in all samples of slag from the bottom of the hearth, a significant proportion of larger fused pieces is visible, which is a regular occurrence in the burning of BC brown coal. From the above, it can be concluded that, from the aspect of ash properties, it is possible to efficiently co-firing with unhindered removal of slag in a liquid state - the ash spillage temperature from brown coal BC is 1350 °C. Therefore, it is clear that even during co-firing, the occurrence of slagging is possible - practically to the same extent and in the same manner as during the combustion of the brown coal BC. The carbon content in the deposit is on average almost 0%, and in the slag below 0.5%.

IV CONCLUSION

The research results clearly show that treated renewable and CO_2 neutral fuels, waste woody biomass and Miscanthus as a fast-growing energy crop are suitable and promising for application with the aim of at least partial decarbonization and the establishment of a sustainable thermal energy sector in the current time of energy transition. This is especially important for developing countries whose energy system is based predominantly on the use of their own coal resources. Research has shown that in different technological combustion conditions, it is possible to use treated types of biomass unhindered, up to 25% of the mixture with lignite or brown coal. As CO_2 - neutral fuels, the use of these types of biomass generally reduces net CO_2 emissions in proportion to its share in the coal mixture. In this particular case, it was shown that stable and smooth combustion of the fuels in question can be performed with acceptable and enviable energy efficiency - CO emission below 350 mg/m_n^3 with UBC<1%. More precisely, such an efficient process of conversion of primary energy from fuel can be established in existing furnace with pulverized-fuel combustion technology, regardless of the mode of removal of slag from the combustor, dry or liquid. At the same time, in real conditions, it is possible to further improve the efficiency of the combustion process with high-quality thermal and mechanical fuel preparation. The emission of NO_x during co-firing is at the emission level when burning the basic mixture of coal, lignite or brown coal, and practically does not depend on the type and content of biomass in the mixture. Specifically, under the given combustion conditions, the NO_x emission for lignite mixtures is at the level of 320 mg/m_n^3 and for brown coal mixtures up to 740 mg/m_n^3. Further, the SO_2 emission is practically quite high in both cases. It mainly depends on the combustion temperature and sulphur content, especially combustible in the basic fuel - in lignite or brown coal, and almost insignificantly on the type and content of biomass in the mixture with coal. When burning lignite mixtures, the SO_2 emission is up to 2,500 mg/m_n^3, and with brown coal mixtures up to 6400 mg/m_n^3 - brown coal has a fairly high content of total sulphur, 2.46%. Although the content of biomass in the mixture with coal directly changes the chemical and physical properties of the total ash in the mixture, the results of the research show that the co-firing of the fuels can be carried out smoothly under the established conditions and from the aspect of the behaviour of the ash from the mixture in the process. More precisely, the presence of these two types of biomass does not worsen the process in terms of slagging/fouling heating surfaces in the boiler. For the combustion of mixtures with lignite, all solid samples of ash deposits removed from the combustion zone, as well as all samples of slag and ash at the exit from the furnace, in a loose and highly dispersed state without initial fused particles, which are a prerequisite for the intensification of unwanted contamination of heating surfaces. Also, the presence of biomass, when co-firing with brown coal, does not worsen the basic behaviour of coal ash.

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