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Research Article

Co-firing of brown coals and woody biomass and reburning with natural gas

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Abstract. It is a continuous imperative to establish the most efficient process of conversion of primary energy from fuel through combustion, which also has the least possible harmful effect on the environment. In this time of expressed demands for decarbonisation, it also means the affirmation of the use of renewable fuels and the indispensable application of appropriate primary measures in the combustion furnace. At the same time, the efficiency of the combustion process depends on several factors, from the type and properties of the fuel to the ambient and technological settings for the process. In this regard, with the aim of determining the static characteristics of combustion, experimental laboratory research was carried out on the combustion of mixtures of brown coal with low heating value and a high ash content with waste woody biomass and different process conditions: temperature, staged combustion air supply (air staging) and in conditions of application of a third or additional fuel (natural gas, reburning technology). Applied experimental methods included the analysis of the combustion process on the basis of input (reactants) - output (products), including the analysis of the composition of flue gases, i.e. the determination of the emission of the key components of flue gases CO_2, CO, NO_x and SO_2, as well as the analysis of the composition of slag, ash and deposits ash, i.e. assessment and evaluation of the behaviour of ash from fuel in that process. Based on the obtained research results, this paper shows the significant positive effects of the application of primary measures in the furnace - compared to conventional combustion: air staging - reduction of net CO_2 emissions during co-firing with biomass and reduction of NO_x emissions by up to 30%; reburning technology - additional reduction of CO_2 and NO_x emissions in proportion to the share of natural gas, e.g. at a combustion process temperature of 1350 °C and at a 10% energy share of natural gas during the co-firing of a mixture of brown coal and waste woody biomass, compared to the emission without the use of natural gas, a reduction of NO_x emissions by 185 mg/m_n^3 or by almost 30% was recorded. It was concluded, at the same time, the application of these primary measures in the furnace does not negatively affect the behaviour of ash from the fuel in the given settings of the combustion process.

Keywords: coal, woody biomass, natural gas, combustion, furnace, air staging, reburning technology, emission CO_2, CO, NO_x, SO_2, ash

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1. Introduction

Energy transition, which implies the introduction and intensive use of renewable energy sources with the aim of decarbonisation, i.e. reduction of CO_2 emissions, which also includes waste wood biomass, is quite a complex and technically quite demanding process. This complexity is reflected not only in the required scope and type of technical interventions that must be carried out on the existing plant, but also due to the considerable number of possible unknowns that such activities can result in in a given concept of the furnace, i.e. the boiler as a whole. The number and the weighting factors of those unknowns are functions of several variables. Those unknowns are especially noticeable during combustion of mixtures of different solid fuels and fuels with highly variable composition and properties even on a daily basis. The unknowns can also be noticed in mixtures where poor reactive and low-heat components dominate, as well as components with a high mineral mass (ash), especially in the properties and the behaviour of that mineral part of the fuel in the combustion process and the impact of that process on the environment, i.e. the emission of pollutants of flue gases. Some of these potential process problems were detected during research, the results of which are presented in the paper (Nussbaumer 2003).

Nevertheless, thanks to the knowledge and continuous work of engineers and scientists, motivated also by the imperative to implement the decarbonisation of the energy sector in the world, there are so far a very large number of examples of plants (e.g. energy and industrial boilers) adapted to the simultaneous use of different fuels in regular operation. In such plants a certain share of coal is substituted with renewable and alternative solid fuels. So, for example, the co-firing of coal and waste wood biomass or biomass residues from agricultural activity was put into regular operation in over 230 power plants throughout the European Union by the middle of the last decade (Hodžić 2016).

The necessarily reduction of NO_x emissions, compared to conventional combustion systems, can be achieved to an appropriate extent by using newer generation burners (vortex or flow *Low* NO_x burners - LNB), and by using primary measures in the furnace. These primary measures mean the simultaneous application of one or more measures, of which, in terms of reaching a technically and economically acceptable level of

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efficiency of primary energy conversion from fuel and a significant reduction of NO_x emissions, the most famous are:

- staged or zonal air supply for combustion in the wider zone of the furnace (air staging, Over Fire Air - OFA),
- staged or zonal introduction of the basic fuel into the furnace (*fuel staging*) by installing two or multi row burners, observed by the height of the furnace, and
- applying additional third fuels and their subsequent introduction into the furnace (e.g. natural gas, biogas, etc.) which establishes subsequent or delayed or delayed combustion – reburning technology.

LNB burners also function on the principle of staged combustion air supply but for individual burners, where by separate portions of combustion air are additionally turbulent by the constructive design of channels and elements in the burner - these burners result in a significant reduction in NO_x emissions and as such are practically indispensable equipment today in the design and construction of newer energy boilers and industrial furnaces, but they are massively introduced in existing energy boilers and industrial solid fuel furnaces as a replacement for the current conventional flow-type burners (Tsumura *et al.* 2003). So, for example, Wang *et al.* (2012) presented the results of research, i.e. the effects of the use of staged combustion air supply on NO_x emissions during the combustion of dried lignite. Those investigations analysed the influence of the excess air coefficient, the distribution of that air for the combustion and the distance of the OFA air inlets into the reaction zone in relation to the burner. The results showed that NO_x emissions were significantly reduced within the given technical and technological conditions of the combustion process. Similarly, (Kuang *et al.* 2013) stated that the NO_x emission can be reduced by 20% using the appropriate Low-NO_x burners. However, this emission is still high (1036 mg/m_n^3 at 6% O_2 content in dry flue gases) due to the high combustion temperature, and application of staged or zonal air supply to the furnace - OFA is recommended in order to further reduce NO_x emission.

The positive effects of applying staged combustion air supply to the furnace, aimed at reducing NO_x emissions, are also presented (Rozendaal 1999, Kuang *et al.* 2014) - in both cases, the results are related to coal combustion, (Kazagić & Smajević 2007, Kazagić, Smajević & Duić 2010, Smajević *et al.* 2012) refer to the co-firing of coal and biomass.

Chae *et al.* (2021) presented the interesting results of research into the combustion of coal as the main fuel in the conditions of the subsequent introduction into the furnace of different types of waste wood biomass (reburning technology), with an emphasis on the application of such primary measures in the furnace on NO_x emissions, Zhou *et al.* (2010) presented NO_x emission values under conditions of application of selective non-catalytic reduction (SNCR) technology.

The efficiency of the combustion process of various solid fuels, including the level of emission of undesirable and harmful components of flue gases into the environment, depends on a number of factors, the key ones being: type and properties of fuel, mechanical preparation of fuel, coefficient of excess air and the method of supplying that air to the reaction zone and combustion temperature. Therefore, there is still a very pronounced lack of even basic knowledge about the combustion characteristics of different fuels in different process settings (Sami, Annamalai & Wooldridge 2001, Demirbas 2004, Yuan *et al.* 2021, Kim *et al.* 2022). This deficiency is particularly pronounced for low-value, low reactivity, high-ash and solid fuels prone to soiling of heating surfaces and their mixtures (Kurose, Ikeda & Makino 2001, Zevenhoven *et al.* 2012, Hurskainen & Vainikka 2016, Jenkins 2020).

By firing different mixtures of solid fuels, e.g. a mixture of coal as well as a mixture of coal and waste wood biomass (sawdust, residues from cutting wood), with different technical-technological and ambient conditions as basically defined:

- selected mean combustion temperature from a wider range of temperatures corresponding to different solid fuel combustion technologies,
- the application of the primary measure of staged combustion air supply, which includes the introduction of a portion of OFA air at different distances from the main burner (air staging), as well as
- application of natural gas as an additional, third fuel (reburning technology)

It is possible to determine the appropriate response of the combustion process through the measurement of important process parameters and their analysis, (Hodžić 2016, Hodžić, Smajević & Kazagić 2016, Madanayake *et al.* 2017, Hodžić, Kazagić & Kadić 2020). In this way, it is possible to reach relevant conclusions about the impact on the process: coefficient of excess air for combustion, places of introduction of the OFA of combustion air, applications of natural gas and consequently the impact on the emission of flue gas components into the environment, e.g. CO_2, CO, NO_x and SO_2. Based on these conclusions it is possible to quantify and sublimate the characteristics of co-firing coal with woody biomass and natural gas, including the advantages of conversion of primary energy from fuels for solid fuel pulverized combustion technology with a staged combustion air supply, (Raatikka 2011, Karampinis *et al.* 2013, Hodžić 2016). In this particular case, the total air for combustion is divided into four streams: primary, secondary, tertiary and OFA stream - the principle scheme of the experimental plant is given in Fig. 1. The results of the research on the co-firing of coal and waste woody biomass and reburning technology with natural gas are presented for this setting of the experimental plant. The final purpose of the subject research was to determine the static characteristics of fuel combustion, a mixture of brown coals of low heat value LHV<14 MJ/kg, high ash content and moisture (see Table 1) with waste woody biomass in in a reduced state and in conditions of different process temperature, excess air coefficient and method of air supply for combustion.

2. Technical setup of laboratory research

2.1 Experimental plant

As part of the Laboratory for Combustion of Coal and Biomass established at the University of Sarajevo - Faculty of Mechanical Engineering, Department of Energy, the experimental plant Entrained flow tube reactor, Fig. 1. The facility was built in such a way that it enables the examination of a wider range of combustion characteristics of different solid fuels with different ambient and technical-technological conditions. In Fig 1. the principle scheme of the upper part of the experimental plant and the accompanying systems for classic or conventional and staged or zonal combustion air supply to the reaction tube are indicated and highlighted. In this experimental plant it is possible to use natural gas or biogas as an additional fuel to investigate the combustion characteristics within the reburning technology, (Hodžić 2016) and (Hodžić, Kazagić & Smajević 2016, Hodžić, Kazagić & Kadić 2020, 2021).

The laboratory plant can work in a very wide interval of combustion temperature (practically from ambient temperature to max. 1560 °C) and with supply to the reaction tube of different amounts and distribution of basic solid fuel and air for combustion, including the possibility of researching reburning combustion technologies using the third/additional fuel. Basically, the research provides output data related to the efficiency of conversion of the fuel primary energy within the combustion process at the selected temperature, the intensity of

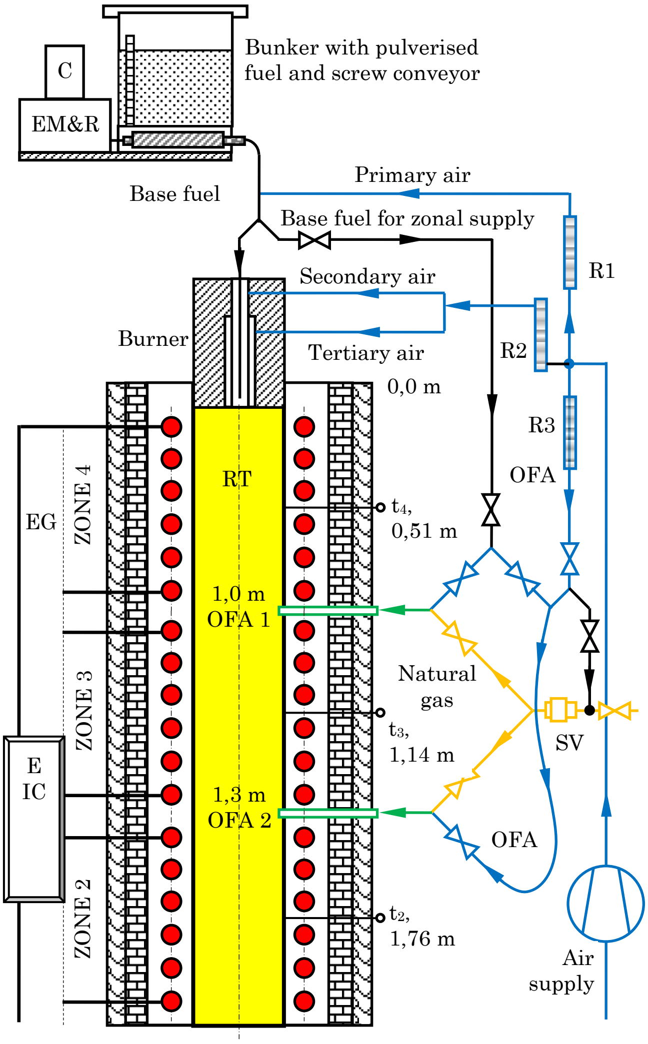

Fig. 1 Principal scheme of the experimental plant: Upper part of the experimental plant with designated systems for classical and stepped fuel supply (basic and additional fuel) and zone or stepped combustion air supply to the reaction tube (RT) - *air staging, fuel staging, reburning technology*, (Hodžić 2016)

deposition and the characteristics of ash deposits along the reaction zone. It also provided the characteristics of the slag and the ash at the exit from the reactor, and the composition of the resulting flue gases, in this particular case the content of CO_2, CO, O_2, NO, NO_2, NO_x=NO+NO_2 and SO_2, (Hodžić 2016).

2.2 Matrix of solid fuel mixtures for research

For the purpose of conducting experimental research with the aim of determining the effects of the use of natural gas on the characteristics of solid fuel pulverized combustion technology, the following matrix of solid fuel mixtures was formed, presented in the Table 1.

The symbols of the test fuels in Table 1 are:

- U100: a mixture of brown coals, which in recent years is usually burned at the Kakanj Thermal Power Plant, and which was created by mixing brown coals delivered to the thermal power plant depot from several mines (Kakanj approx. 50%, Breza, Zenica, Gračanica, Livno, Nova Bila, Banovići, ...).
- U90B10: a mixture of the previous test fuel U100 and waste wood biomass (sawdust, B100), where the mass fraction of U100 coal is 90% and wood biomass B100 is 10%. Wood biomass is a mixture of beech and spruce sawdust in a mass ratio of 1:1.

Table 1
Basic characteristics of test fuels

Fuel/Label	U100	U90B10	K70B20Z10
Moisture, %	13.90	14.67	10.71
Ash, %	37.88	34.14	40.84
Volatiles, %	28.97	32.49	27.71
C_{fix}, %	19.25	18.70	20.73
Combustible, %	48.22	51.18	48.44
Carbon, %	32.62	33.25	34.48
Hydrogen, %	2.60	2.84	2.33
Sulphur, %	2.06	1.87	2.41
Nitrogen, %	0.72	0.67	0.75
Oxygen, %	10.22	12.57	8.48
HHV, kJ/kg	13,351	13,572	13,898
LHV, kJ/kg	12,496	12,655	13,171

Source: Hodžić 2016

- K70B20Z10: a mixture of brown coals from three mines, Kakanj, Breza and Zenica, where the mass content of the component coals in the mixture is 70%, 20% and 10%.

All mixtures of solid fuels are thermally and mechanically prepared - dried and ground in operational or laboratory conditions and with a known granulometric analysis of the grind.

2.3 Basic settings of test regimes

The test solid fuels from Table 1 were subjected to experimental combustion research with staged supply of combustion air to the furnace, including separate supply/application of natural gas as an additional fuel. The test regimes are defined and carried out in the range of process temperatures that correspond to the combustion temperature in real operation of all boilers in the assembly Thermal Power Plant Kakanj - the technology of combustion of pulverised fuel with dry removal of the slag from the furnace: 1350 - 1450 °C.

This research is set to gain as much knowledge as possible about the process of combustion of coal and biomass mixtures with air staging and reburning with natural gas. A special emphasis is put on the emission of undesirable components from flue gases into the environment, primarily the emission NO_x, and the behaviour of fuel ash within such combustion process. Combustion test regimes with natural gas as an additional fuel were performed with 5% and 10% energy share of gas in the mixture. These natural gas combustion tests were assigned the following designations from the perspective of total fuel: UPn, UB(90)Pn i KBZ(70)Pn, were where "n" indicates the energy share of the natural gas in the total heat input to the furnace through the fuel.

In all air staging test regimes, the total coefficient of excess air was 1.15, while the distribution of that total air was with the ratio λ_1/λ=0.95/1.15 - i.e. a sub-stoichiometric amount of air λ_1= =0.95 is supplied to the burner through the primary, secondary and tertiary streams, while the remainder is OFA air stream, $\Delta\lambda$=0.20.

3. Results and discussions

3.1. Emission of components in flue gases

Combustion characteristics of the previous solid test fuels, mixtures of brown coals and mixtures of these coals with waste wood biomass, in terms of the emission of polluting components in flue gases (CO_2, NO_x and SO_2 components) during classic or conventional combustion where the total amount of air for combustion through three separate portions to the burner, are given in the Table 2 - see also Ma *et al.* 2007, Pestaño & Jose 2016 and Fakudze & Chen 2022. The emission values of these components in flue gases produced during combustion with staged or zonal combustion air supply are listed in the Table 3.

Table 2
Emissions of CO_2, CO, NO_x and SO_2 with conventional combustion (λ_1/λ=1.20/1.20) and a process temperature of 1350 °C

	U100	U90B10	K70B20Z10
CO_2, kg/m_n^3	0.258	0.264	0.256
CO, mg/m_n^3	15	12	16
NO_x, mg/m_n^3	941	931	938
SO_2, mg/m_n^3	5,750	5,484	5,588

Source: Hodžić (2016).

Table 3
Emission of CO_2, CO, NO_x and SO_2 with staged combustion with zonal combustion air supply (λ_1/λ=0.95/1.15) and a process temperature of 1350 °C

	U100	U90B10	K70B20Z10
CO_2, kg/m_n^3	0.255	0.259	0.258
CO, mg/m_n^3	18	14	14
NO_x, mg/m_n^3	665	670	710
SO_2, mg/m_n^3	5,646	5,480	5,958

Source: Hodžić (2016).

Table 2 and Table 3 shows that the CO_2 emission is constant ($\bar{e}_{CO2}$=0.258 kg/m_n^3) for all test (gross CO_2 emission is also given for co-firing regimes), and it can be seen that the combustion process is well organized (CO emission is always below 20 mg/m_n^3), while NO_x emission at:

- co-firing of coal and wood biomass practically at the emission level when combustion the coal mixture, regardless of the method of air supply for combustion,
- staged combustion is on average lower by around 250 mg/m_n^3 or by around 27% compared to the emission during conventional combustion - see Figure 2,

while the SO_2 emission is extremely high and practically at the same level in all considered combustion regimes - that is, regardless of the proportion of woody biomass in the mixture with coal and the method of supplying the total air for combustion, where the mean value of that emission is $\bar{e}_{SO2}$=5650 kg/m_n^3.

In the processes of co-firing of a mixture of coal and wood biomass (U90B10), the net emission of CO_2 is lower compared to the emission during the combustion of only coal and this percentage is equal to the mass share of biomass in the mixture with coal - see also (Priyanto *et al.* 2016. and Issac *et al.* 2020). By introducing the subject solid fuels and natural gas into the combustion process as an additional, i.e. reburning fuel, in the already established conditions of staged air supply for combustion, an additional reduction of CO_2 emissions and especially NO_x emissions occur at the same time. The reduction

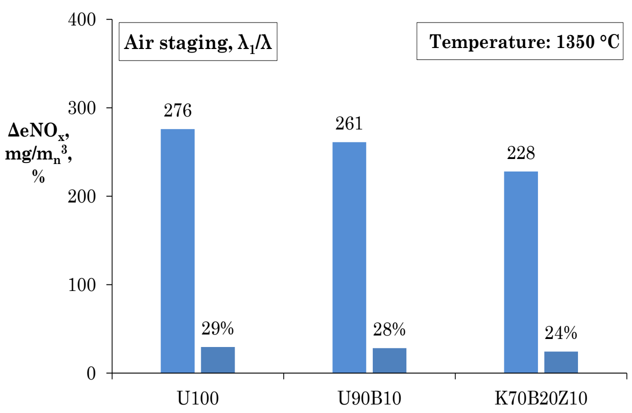

Fig. 2 Absolute and relative reduction of NO_x emissions during staged combustion (air staging) compared to conventional solid fuel pulverized combustion

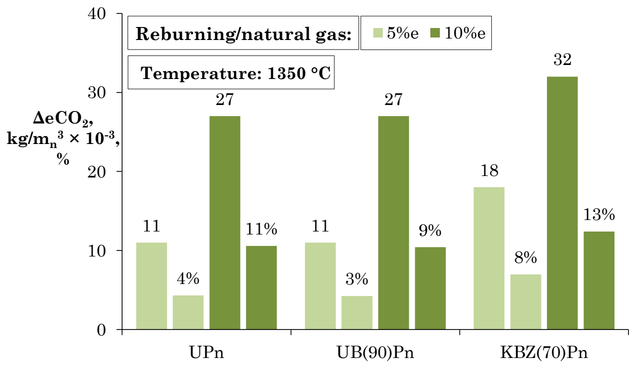

Fig. 3 Absolute and relative reduction of gross CO_2 emissions during reburning combustion with natural gas compared to air staging regimes of solid fuel pulverized combustion

of CO_2 emissions, in this case, is a consequence of the significant introduction of hydrogen (H_{2n}, n=1, 2, 3, ...), as a constituent fuel element in the hydrocarbons that make up natural gas, into the combustion process. Such positive effects of reducing CO_2 emissions in reburning modes of combustion with natural gas, with 5% and 10% of the energy share of gas in the total energy introduced into the furnace through fuel, compared to air staging modes, are shown in Fig. 3.

The positive effects of additional NO_x emission reduction in reburning combustion modes are presented in Figure 4. So, for example, NO_x emission during combustion of U100 coal mixture during reburning with 5%e gas is 545 mg/m_n^3 and by 120 mg/m_n^3 or 18% lower compared to the emission during air staging combustion mode, while the same emission at 10% e of the energy share of gas is lower by more than 170 mg/ m_n^3 or by 26%. Under these conditions of reburning combustion with natural gas, the situation is similar when burning a mixture of coal and wood biomass (fuel mark: UB (90)Pn) - specifically, at 10% of the gas, the NO_x emission is 485 mg/m_n^3 and lower by 158 mg/m_n^3 or by 29%. In these regimes, the NO_x emission during the co-firing of coal and biomass is practically at the level of the emission during the combustion of coal alone, even during reburning combustion with natural gas, as well as during air staging combustion regimes. Compare the reduction of NO_x emissions with air staging regimes for fuels U100 and U90B10 in Fig. 2, and then for the same fuels UPn and UB(90)Pn, in order to compare emissions during reburning combustion. Somewhat different values of NO_x emission during the combustion of the K70B20Z10 coal mixture, both with air staging and with reburning combustion, can be related to the granulation of this mixture. This mixture was formed in the laboratory, unlike the other two mixtures which are taken from the mills in operation

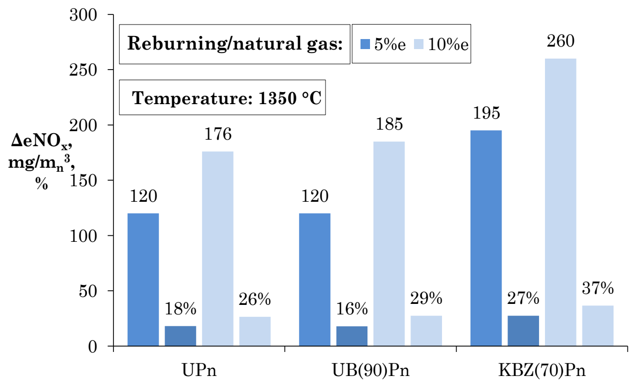

Fig. 4 Absolute and relative reduction of NO_x emissions during reburning combustion with natural gas compared to air staging modes of solid fuel pulverized combustion

of the Unit 5 of Kakanj thermal power plant, and contains a higher share of larger fractions of grinding, e.g. the residue on the 200 μm and 500 μm sieves is:

$R_{200}=25{,}82\%>R_{200opt}=(5\div10)\%$, $R_{500}=25{,}82\%>R_{500opt}<1\%$.

NO_x emission measured during air staging and reburning combustion modes are presented in Fig. 5. In order to make a comparative analysis of the previously presented research results of the same test fuels U100, UP10 and UB(90)P10 at the combustion temperature of 1350 °C, the share of natural gas was 10%., and the combustion temperature - in reburning modes is varied. The values of NO_x emissions during the combustion of the basic test fuels U90B10 and K70B20Z10 in the air staging combustion mode temperature of 1350 °C, and for the KBZ(70)P10 fuel in the reburning combustion mode are indicated in Fig. 5. The NO_x emission for the U100 coal mixture in the reburning mode of combustion at a temperature of 1450 °C is $e_{UP10}=615$ mg/m$_n^3$, which is 30% lower emission compared to the comparative emission in the air staging mode of combustion. Also, during the co-firing of a mixture of brown coal and waste wood biomass in these reburning combustion conditions and at the same temperature of 1450 °C, the emission of $e_{UB(90)P10}=600$ mg/m$_n^3$ was measured, which is practically for the same 30% less compared to emission during combustion of only U100 coal mixture, $e_{U100}=866$ mg/m$_n^3$, Hodžić 2016, Orooji *et al.* 2021, Li *et al.* 2022.

During reburning test regimes, the impact of natural gas on SO_2 emission was also analysed, (Figure 6). Figure 6 shows the measured SO_2 emission values and they are given in comparison for the air staging and reburning combustion regimes of the subject test fuels at 5%e and 10%e share of natural gas in the heat input to the furnace.

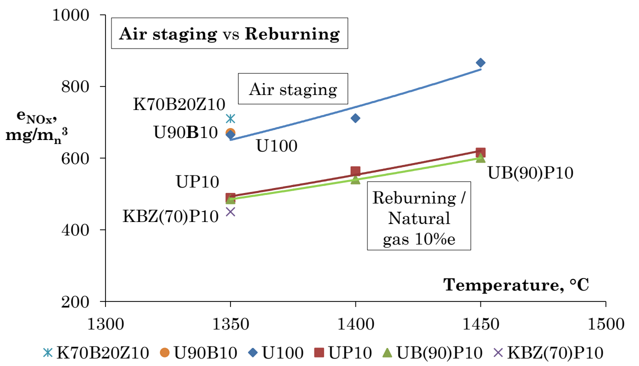

Fig. 5 Effects of natural gas application on NO_x emissions at variable process temperature and combustion of solid fuels of different composition - *reburning technology*

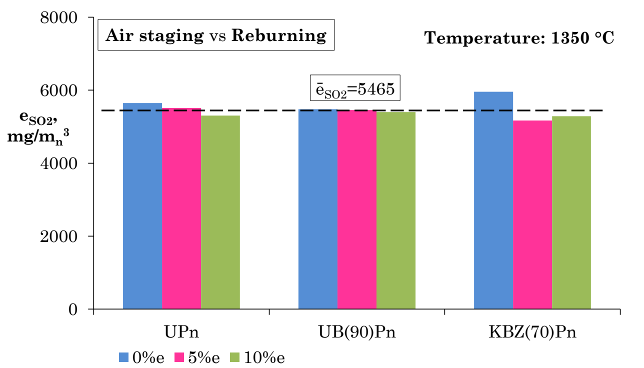

Fig. 6 SO_2 emission during air staging and reburning combustion modes at a process temperature of 1350 °C

In general, when burning in these conditions and considering the level of that emission, there is a practically insignificant reduction in SO_2 emissions. So, for example, the mean SO_2 emission value for all combustion regimes is still quite high and amounts to $\bar{e}_{SO2}=5465$ mg/m$_n^3$, while in the reburning combustion regime with 10% natural gas, this emission is on average $\bar{e}_{SO2\text{-}R10\%}=5330$ mg/m$_n^3$, and the lower the emission by $\Delta\bar{e}_{SO2}=135$ mg/m$_n^3$ or by only $\Delta\bar{e}_{SO2}=2{,}5\%$ (Hodžić 2016, Orooji *et al.* 2021).

3.2. Ash behaviour in the combustion process

When choosing a solid fuel combustion technology, knowledge of the physicochemical properties of fuel ash, including knowledge about the behaviour of that ash in the combustion process established in a defined temperature and technical-technological setting, is of key importance. These findings are particularly important when selecting and designing new combustion chambers for known fuel, as well as when expanding the fuel portfolio in an existing furnace, e.g. when introducing biomass or fuel from municipal waste into co-firing regimes with coal. In this research, the behaviour of the mineral part from the fuel (ash) was monitored and quantified along with the measurements of the emissions of the key components in the flue gases. The given ambient and technical-technological settings of the solid fuel pulverized combustion (mixture of brown coal and brown coal and waste woody biomass), both under air staging combustion conditions and during reburning combustion technology with natural gas were analysed.

In this regard, for the purpose of a visual assessment of the condition and form and appropriate chemical analysis, samples of ash deposits collected during combustion on a water-cooled probe and uncooled ceramic tablets were taken from the reaction tube, including samples of slag and dry ash with bottom of the reactor, i.e. from the flue gas transport pipe to the environment. As an example, Figure 7 shows the extracted ash deposit from a water-cooled probe and from an uncooled ceramic tablet during air staging combustion of K70B20Z10 coal mixture and at a combustion temperature of 1350 °C - see also Kazagić & Smajević 2007, Jing *et al.* 2016. For the same coal mixture and under the same combustion conditions, Figure 8 shows samples of slag from the bottom of the furnace and dry ash from the flue gas discharge pipe to the environment.

From the solid samples in Figures 7 and 8, it can be concluded that in these overall combustion conditions, different forms and characteristics of deposits or slag appear, depending on the place of removal, or the position of the heating surface in the furnace/boiler in real operation. At the same time, the deposits on the uncooled surfaces and the slag at the bottom of the firebox are larger, hard and firmly attached to the substrate.

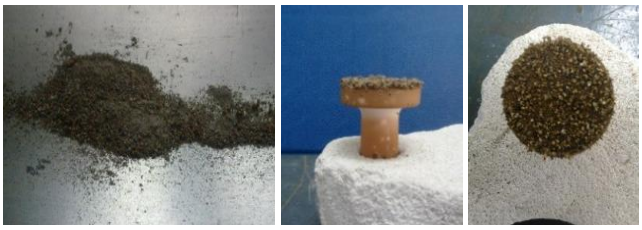

Fig. 7 Air staging, K70B20Z10, 1350 °C; left: deposit with water-cooled probe - loose state with a granular structure that is very easily and completely separated from the probe, in the middle and right: deposit from an uncooled ceramic tablet - compact cylindrical form with larger fused grains, dominantly yellow-black in colour, tightly bound for the tablet and it is necessary to use a significant shearing force at the joint site to remove the deposit from the surface of the ceramic tablet

Fig. 8 Air staging, K70B20Z10, 1350 °C; left: slag from the bottom of the reactor - the dominant form of larger, fused, hard and irregularly shaped pieces, the application of significant force is required to break the slag into small pieces, right: ash from the flue pipe - very fine granulations, grey in colour and very expandable

Comparative presentation of changes in the chemical composition of ash in the combustion process from the fuel entering the furnace to the exit of slag and ash from the furnace, is given in the Figure 9. The changes are result of mutual interaction and redistribution of those components in the ash in different states on its way through the furnace and the boiler to the sampling site or separation, is given in the Figure 9.

The results refer to the air staging combustion of the K70B20Z10 coal mixture at a temperature of 1350 °C where the deposit is removed from uncooled ceramic tablets. It is well known research findings that in the combustion process there can be a redistribution of components in slag and ash in relation to the composition of ash from the fuel (Kazagić & Smajević 2007, Rizvi *et al.* 2015, Oladejo *et al.* 2020). The results presented in Fig. 9 show that this also occurs in this case. A significant redistribution of the components in the deposit and slag, dependant on the composition of the ash from the K70B20Z10 coal mixture (before the combustion process) is visible. During the combustion process there was a significant change in the share of the components K_2O, CaO, Al_2O_3 and Fe_2O_3 in the deposit, while there was a significant change in the share of Na_2O, CaO, Al_2O_3, Fe_2O_3 and especially the SiO_2 component in slag.

Similar to the previous one, Figure 10 shows samples of deposits from uncooled ceramic tablets and slag from the bottom of the furnace during co-firing of a mixture of coal and waste wood biomass U95B5 in the conditions of reburning technology with 5% natural gas and at a process temperature of 1400 °C - fuel designation and examination regime UB(95)P5. Solid samples of deposits and slag taken from the combustion regime with different shares of biomass in the mixture and at the same process temperature, are compared. Similar larger molten deposits are noticeable and it can be concluded that the intensification of slagging at this combustion temperature cannot be associated with the share of wood biomass in the mixture as well as with the use of natural gas.

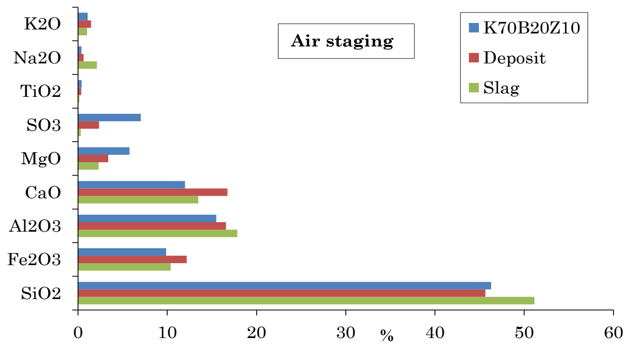

Fig. 9 Comparative presentation of the chemical composition of ash from the K70B20Z10 coal mixture (before the combustion process), ash deposits from uncooled ceramic tablets and slag from the bottom of the reactor (after the combustion process) at a combustion process temperature of 1350 °C

Fig. 10 Reburning, UB(95)P5, 1400 °C; left: deposit from an uncooled ceramic tablet - larger molten deposits are noticeable, right: slag from the bottom of the reactor - loose with coarser grain granulation and with visible hard molten pieces - the situation is almost identical in the test regimes during reburning combustion with 10% of natural of gas to which the fuel and combustion regime designations U90P10 and UB(95)P10 are attached.

Although the initial formation of larger molten ash deposits at the combustion temperature of 1400 °C can further escalate, due to accumulation of new layers on the initial molten deposits and formation of the stepped structure of the deposits, it can still be concluded that the use of natural gas does not negatively influence the combustion process regarding the behaviour of the ash, Purbasari, Samadhi & Bindar 2016, Yustanti, Muharman & Mursito 2022).

4. Conclusion

The results of this research show significant positive effects of application of air staging as the primary measure in the furnace. In such conditions, it is possible to establish an efficient combustion process with negligible share of CO in flue gases and with small, acceptable share of combustible matter in the slag and ash. There is no change in NO_x emission while changing the composition of fuel and maintaining other combustion parameters. The average NO_x emission at the combustion temperature of 1350 °C is more than 25% lower comparing to the emission during conventional combustion. NO_x emission during co-firing of coal and woody biomass is the same as during coal combustion. Unlike the fuel composition, the combustion temperature proved to have much more influence on NO_x emission, an increase in the temperature of Δt=100 °C causes an increase in NO_x of Δe_{NOx}=200 mg/m_n^3. Applying the air staging as a primary measure, it is possible to decrease the NO_x emission up to 30%. However, this primary measure does not contribute to the reduction of SO_2. Emission of SO_2 is insignificantly decreased with the increase of the share of woody biomass in the fuel mixture, and it does not depend on the air supply to the furnace. Increase in the share of woody biomass in the fuel mixture proportionally decreases net emission of CO_2.

Emission of CO is very low during the natural gas reburning regimes. During these combustion conditions NO_x emission is reduced for 40%, the reduction being proportional to the share of natural gas. Natural gas does not influence the emission of SO_2. Primary measures in the furnace (air staging and natural gas reburning) do not affect adversely the process of formation and the composition of the ash and deposits. Therefore, these measures do not make worse the tendency of the base fuel ash for slagging of the furnace and boiler walls.

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