

CO-FIRING OF BIOMASS WITH PULVERISED COAL IN OXYGEN ENRICHED ATMOSPHERE

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The aim of the paper is a comparative study of co-firing high shares of wooden and agro-biomass with hard coal under oxy-fuel and air conditions in the laboratory scale reactor for pulverised fuels. The investigations of co-combustion behaviour NO_x and SO_2 emission and burnout were carried out for selected blends. Detailed investigations were concentrated on determining the effect of dosing oxygen method into the burner on NO_x emission. The paper presents the results of co-firing blends with 20 and 50% share of biomass by mass in air and oxy-combustion condition. Biomass oxy-co-firing integrated with CCS (CO_2 capture) technology could be a carbon negative technology. The reduction of NO_x emissions in the conditions of oxy-co-firing is dependent on the concentration of oxygen in the primary stream of oxidiser. A significant reduction of NO_x was achieved in the case of low oxygen concentration in the primary stream for each investigated blends. Co-firing of biomass with coal in an oxygen enriched atmosphere enhances combustion behaviour, lowers fuel burnout and as a result increases of the boiler efficiency.

Keywords: biomass, co-firing, oxy-combustion

1. INTRODUCTION

Currently the most popular option for co-firing applications is direct co-firing, where biomass and coal are utilised together in the same boiler (Grammelis et al., 2010; Livingston, 2010; Maciejewska et al., 2006; Zuwała and Sciążko, 2005). Although there are many successful co-firing systems, because of various limitations resulting from biomass properties. Some wider research in the air atmosphere for co-firing blends was conducted by many authors (Pawlak-Kruczek et al., 2006; Savolainen, 2003). Biomass fuels are usually characterised by a high moisture content, relatively low calorific value, low bulk density compared to coal, low ash melting point, chemical composition with potentially high chlorine content, hydrophilic and non-friable character.

The constraints related to co-firing can include fuel preparation, handling and storage, different combustion behaviour, possible decreases in overall efficiency, deposit formation (slagging and fouling), agglomeration, corrosion and/or erosion, and ash utilisation.

The degree of these difficulties depends on the quality and share of biomass in the fuel blend, type of combustion, the co-firing configuration of the system, and properties of coal. High moisture and volatile matter content, low calorific value have substantial impact on combustion condition resulting in boiler efficiency including high content of unburned carbon in ash.

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Combustion in an O₂/CO₂ mixture (oxyfuel) has been recognised as a promising technology for CO₂ capture as it produces a high CO₂ concentration flue gas. A review of that technology is presented in papers of Buhre et al. (2005), Chen et al. (2012), Wall et al. (2009).

The combination of oxy-fuel combustion with biomass could afford an attractive method of CO₂ reduction, because biofuels in general contribute to CO₂ reduction in comparison with fossil fuels as they are considered CO₂ neutral.

Thus, co-firing of coal and biomass is one of the methods to reduce greenhouse gas emission. The target for the carbon intensity of energy in Poland is presented in the paper (Budzianowski, 2012) and one of the solutions is solid biomass-fired power plants with CCS e.g. with oxy fuel technology. Further, biomass co-firing in oxy atmosphere could be a carbon negative technology, because the oxy-combustion is one of CCS ready technology. Additionally, co-firing of biomass with coal in oxy-fuel atmosphere can increase fuel burnout and thus also the efficiency of the boiler.

The co-firing blend of biomass with coal in the oxy-fuel has not yet been studied extensively and there are open questions prior to utilising biomass under oxy-fuel conditions. Performed oxy co-firing tests in an entrained flow reactor by Arias et al. (2008) showed that coal burnout can be improved by blending biomass in O₂/CO₂ mixtures.

A few investigations on ignition, burnout and NO_x formation for two types of biomass blends are presented in papers of J. Rianza et al. (2012), where burnout provement and decreasing trend of NO_x formation was observed. The advantages of co-firing biomass on SO₂ emission on an industrial scale is also presented in Pedersen et. al. (1996), and Zuwała and Ściążko (2010).

The aim of the paper is a comparative study of co-firing high shares of wooden or agro-biomass with hard coal under oxy-fuel and air conditions in a laboratory scale combustor for pulverised fuels. A detailed study was concentrated on minimising SO₂ and NO_x emission.

2. DESCRIPTION OF THE TESTS

Co-firing tests were carried out using an isothermal flow reactor being a main unit of test facility shown in Figure 1. The reactor has a five controlled heating zones equipped with electrical heaters (20kW total power). A heating section has a length of 2.5 m and the inner diameter of combustion chamber is 0.135m. The maximum uniform temperature of the reactor is 1250°C.

The geometry of the burner which was used in the tests is presented in Figure 2. This type of burner has three inlet channels. Any configuration of fuel supply can be tested. One type of fuel feeding system and two oxidising streams (primary, and secondary) were selected. For the co-firing tests two variants of O₂ injection were performed: the first where the O₂ concentration was the same in both streams, and the second where different ratios O₂/CO₂ in primary and secondary stream were adjusted (data of both variants are presented in Table 1). The composition of primary stream in the second mode was O₂/CO₂ = 6/94% (vol.). The rest of oxygen was added to the second stream of oxidised mixture to obtain the total concentration of O₂/CO₂ in the furnace at 20/80% by vol. (Oxy20) and 30/70% by vol. (Oxy30).

The temperature of inlet oxidisers was 60°C for the primary stream where the fuel is supplied and 150°C for the secondary stream. The air for reference tests was characterised by humidity near 2%. For the tests which were run with O₂/CO₂ atmosphere the mixture O₂/CO₂ equal to 20%/80% and 30%/70%, was prepared by gas mixer. Fuel feeder was installed at the top of the reactor. The weight of the fuel transported to the burner was measured. The concentration of NO_x, SO₂, CO, O₂ and CO₂ was measured by gas analysers (Ultramat 23, Oxymat).

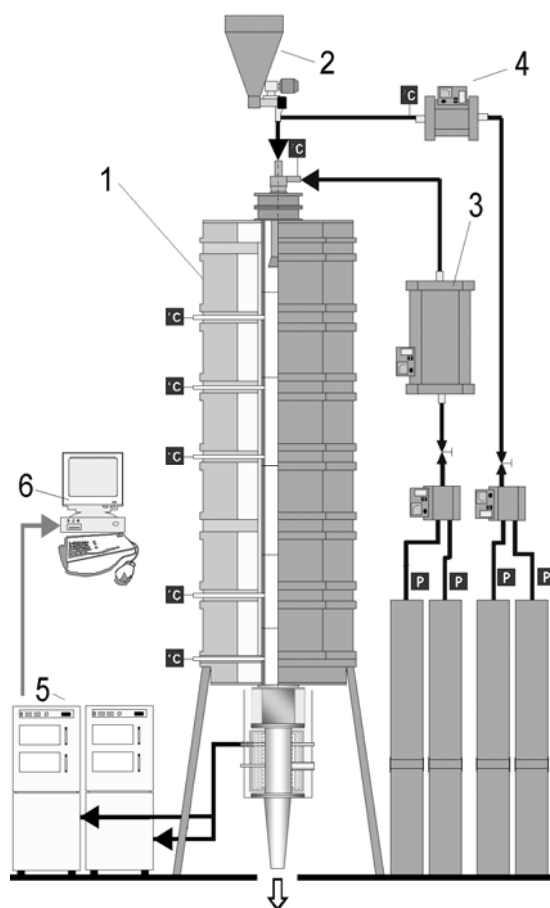


Fig. 1. The scheme of IFR set-up;
 1 – IFR, 2 – feeder, 3 and 4 – heaters, 5 – gas analysers, 6 – data acquisition

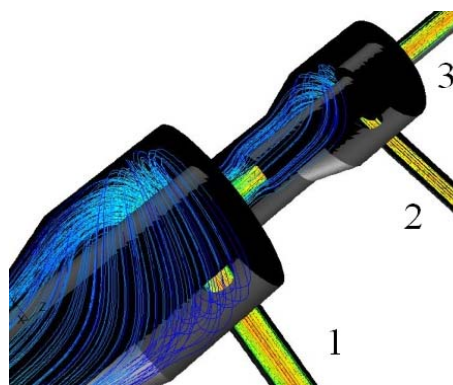


Fig. 2. The burner geometry and flow visualisation

A numerical modelling of the fuel flow in burner (inlet 1st and 2nd) and reactor was examined. Simultaneously the flow at the outlet of burner was recorded by a high speed camera. A different flow distribution along the burner and in the burner outlet was tested to obtain the homogeneous mixture flow. The results from experimental section were analysed by image analysis software. Numerical modelling supported by experimental results gives uniform pulverised coal distribution in the case 2, where inlet 1st and 2nd were used. The Figure 3 presented below shows a comparison of the obtained pictures from a high speed camera and numerical modelling of pulverised coal flow in reactor.

Table 1. The ratio of O₂/CO₂ concentration in first and second examined variant

I - first variant			
Inlet	atmosphere O ₂ /CO ₂ % (vol.)		
	AIR	Oxy20	Oxy30
1	AIR	20/80	30/70
2	AIR	20/80	30/70
3	-	-	-
II - second variant			
Inlet	Atmosphere O ₂ /CO ₂ % (vol.)		
	AIR	Oxy20	Oxy30
1	AIR	28/72	44/56
2	AIR	6/94	6/94
3	-	-	-

The results obtained from high speed camera pictures and numerical flow modelling reveal that the best mixing was achieved in the second case presented above.

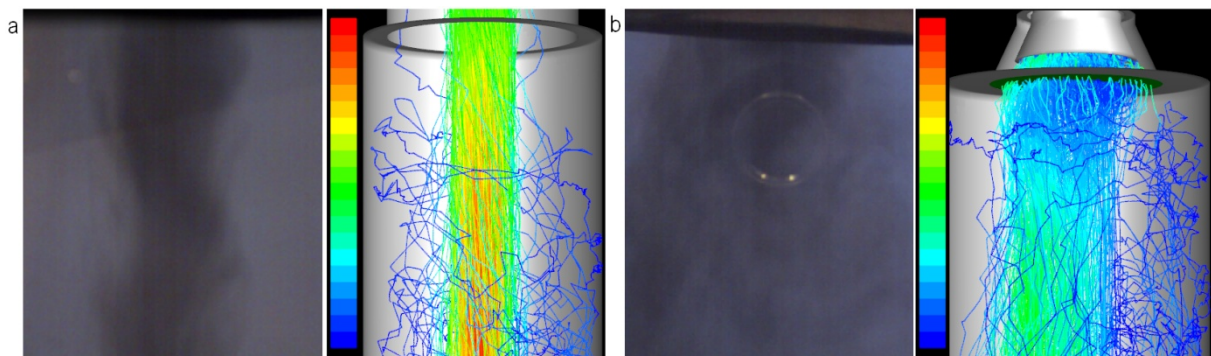


Fig. 3. View and visualisation of the burner outlet flow; a) – inlet 1 and 3; b) – inlet 1 and 2

3. FUEL CHARACTERISTIC

Hard coal and two types of biomass including agrobiomass are studied in this work: hard coal from coal mine Janina, micronised straw and wooden pellets. Each type of fuel is commonly used in boiler furnaces. Proximate and ultimate analysis results of the fuel and ash are reported in Tables 2, 3 and 4.

Table 2. Proximate analysis and heating values of selected fuels as received

Fuel	M ^{AR}	A ^{AR}	HHV ^{AR}	LHV ^{AR}	VM ^{daf}
	%	%	MJ/kg	MJ/kg	%
Hard Coal	13.23	4.96	25.23	23.96	30.64
Straw	5.88	2.98	18.01	16.72	77.96
20% Straw + 80% H.C.	11.71	4.31	24.00	22.76	-
50% Straw + 50% H.C.	9.22	3.17	21.30	20.01	-
Wood	6.74	0.55	19.29	17.95	75.19
20% Wood + 80% H.C.	12.84	3.77	23.77	22.50	-
50% Wood + 50% H.C.	10.11	2.25	21.75	20.46	-

Table 3. Ultimate analysis of the selected fuels (dried ash free)

Fuel	C ^{daf}	H ^{daf}	N ^{daf}	S ^{daf}
	%	%	%	%
Hard Coal	73.60	5.26	1.44	0.81
Straw	47.54	5.78	0.69	0.07
20% Straw + 80% H.C.	67.80	5.19	1.30	0.71
50% Straw + 50% H.C.	55.96	5.52	0.91	0.50
Wood	49.60	5.82	0.17	0.02
20% Wood + 80% H.C.	68.53	5.23	1.20	0.58
50% Wood + 50% H.C.	58.08	5.47	0.73	0.49

Table 4. Ash characteristic of hard coal and biomasses

Oxides	Hard Coal	Wood	Straw
Ashing temp.	815 °C	600 °C	600 °C
SiO ₂	45.72	55.90	68.34
Al ₂ O ₃	18.12	7.90	0.00
Fe ₂ O ₃	19.23	6.57	0.99
Mn ₃ O ₄	0.04	0.44	0.32
TiO ₂	0.58	0.56	0.01
CaO	4.55	10.91	2.79
MgO	2.52	4.56	1.19
Na ₂ O	1.01	3.78	0.58
K ₂ O	1.81	9.38	25.79
SO ₃	6.44	-	-

The co-firing tests were conducted for blends with biomass share equal to 20 and 50% (by mass). An excess oxygen was in the range of 1.0 – 1.6 and a fuel flow adjusted from 0.05 to 0.6 g/s, reactor wall temperature was 1200 °C. Fuel was milled separately into diameter $d < 0.5\text{mm}$. The particle size distribution of the fuels is presented in Figure 4. The initially prepared fuel blends were supplied with the primary stream to the burner.

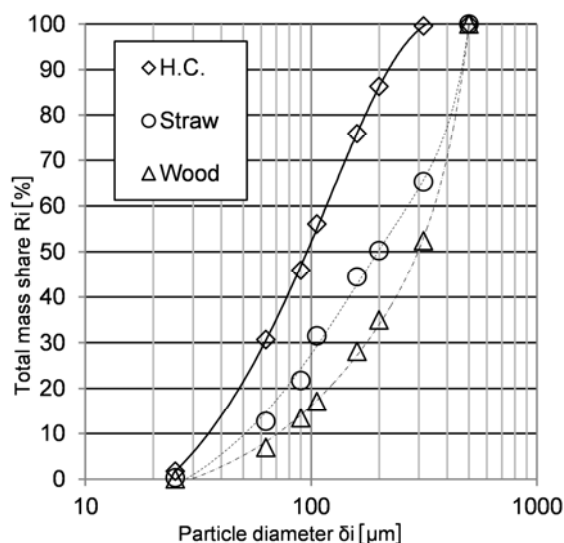


Fig. 4. Particle size distribution

Oxygen concentration in the oxy atmosphere and two oxygen injection modes was investigated on the burnout effect, emission results, and combustion stability. Moreover the effect of biomass contribution on NO_x and SO₂ emission was analysed.

3. THE EFFECT OF BIOMASS SHARE AND O₂/CO₂ RATIO ON SO₂ AND NO_x EMISSION FOR THE FIRST VARIANT OF OXYGEN INJECTION MODE

Analysis of NO_x and SO₂ emission results from the tests of oxy- co-firing for four blends (20% and 50% share of wood and straw with hard coal) was performed. The tests were performed to evaluate the effect of the atmosphere composition where both primary and secondary oxidizer streams had the same O₂/CO₂ ratio on NO_x and SO₂ emission level.

The SO₂ emission in Oxy20 atmospheres for two biomasses share at different excess oxygen is showed in Figure 5. Increasing biomass share in the blend lowers SO_x emission compared to pulverised coal combustion for oxy-co-firing atmosphere (Oxy20). A similar effect occurs for oxy-cofiring at 30/70% ratio of oxygen to carbon dioxide (see Fig. 7). It mainly results from low content of sulphur in biomass. The nearly constant concentration of sulphur dioxide above excess oxygen = 1.1 was obtained for all the investigated fuels as can be seen in Figure 5. It would seem that SO₂ emission would be lower for blend with 20% share of wood than for that of 20% share of straw blend, because of S content in the blends. However, the results show that in Oxy20 and Oxy30 atmosphere sulfur conversion to gaseous form from blend with 20% wooden biomass is greater than for the straw case (Fig. 7).

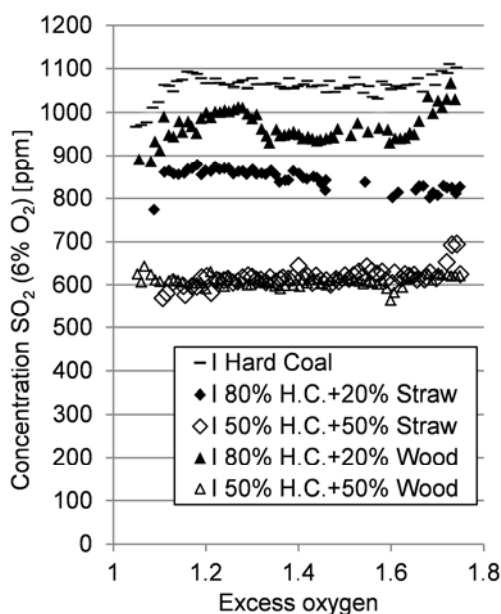


Fig. 5. The effect of biomass share and excess oxygen on the SO₂ emission in Oxy20 atmosphere – variant I

The higher SO₂ emission from co-firing of blend with 20% share of wooden biomass than from co-firing of blend with 20% share of straw can result from the retention of sulfur in ash. The retention of sulphur is about 54% higher for straw-coal blend compared to wood coal blend which can be seen in Figure 6. This effect can result from very high content of potassium in straw ash.

The 50% share of biomass decreases the concentration of SO₂ to the same degree for both agro and wooden biomass, compared to pulverised coal combustion. The sulfur retention in ash from straw –coal blend in this case is by 36% higher than that from wood-coal blend.

For both oxy-combustion condition Oxy20 and Oxy30 the emission of SO₂ from co-firing blend with 20% biomass is 50 – 150 mg/MJ lower than that from pulverised coal combustion in the same atmosphere. Interestingly, for blends with 50% share of biomass SO₂ emission is 240 – 320 mg/MJ lower than that from coal combustion.

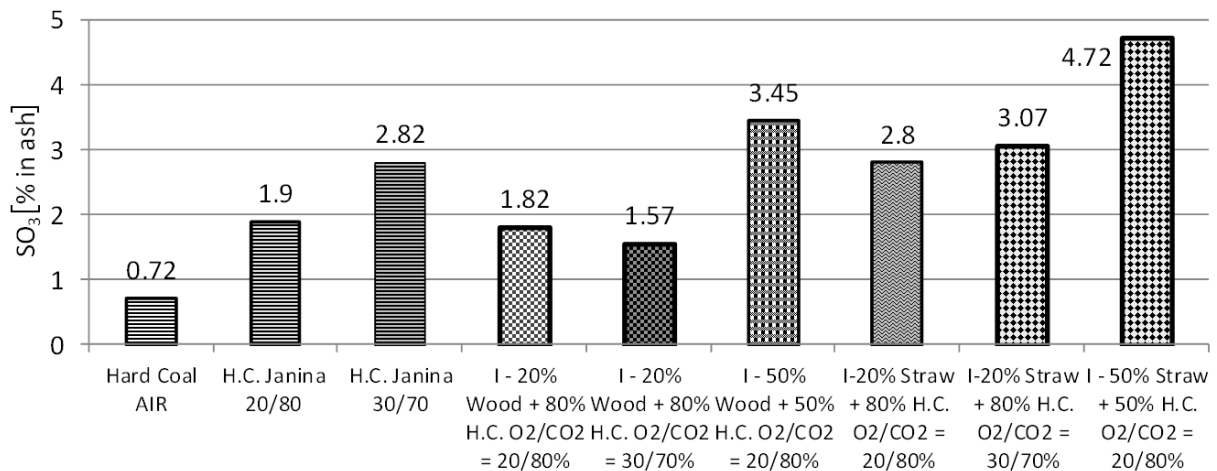


Fig. 6. Average value of SO₃ in ash from hard coal combustion and blend of wood and straw with hard coal oxy- co-firing (first variant)

For Oxy20 atmosphere and the first variant of oxygen injection the results of SO₂ emission (mg/MJ) are comparable with air atmosphere (see Fig.7). Whereas in oxy30 atmosphere SO₂ emission (mg/MJ) is generally higher than that in air atmosphere. This effect may be due to a higher temperature of combustion in the oxygen concentration of 30%. For combustion of hard coal and co-firing of hard coal, blends with 20% of straw and wood, and 50% straw and wood SO₂ emission in Oxy30 atmosphere is greater in comparison to the air atmosphere respectively by 10%, 6%, 19%, 4% and 11% (see Fig. 7).

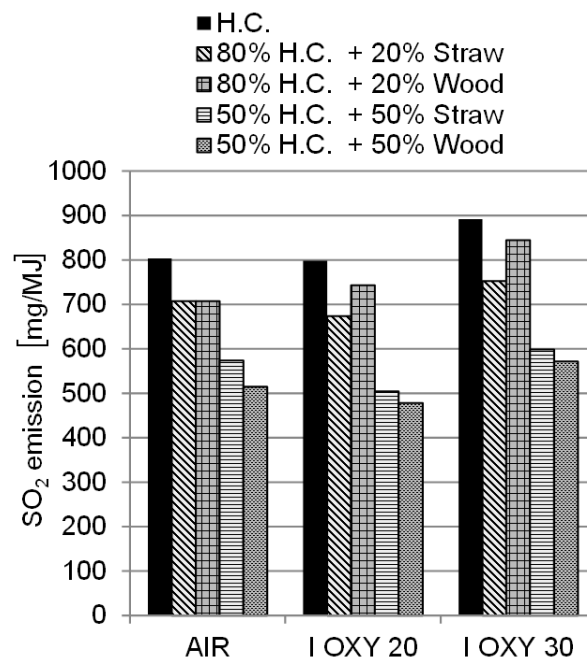


Fig. 7. The effect of biomass share and oxy atmosphere on SO₂ emission (excess oxygen = 1.25)

The NO_x emission level for air atmosphere did not change significantly with the change of biomass share, which is consistent with previous reports (Pawlak-Kruczek, 2010; Pawlak-Kruczek et al., 2010).

A similar dependence was obtained under Oxy20 and Oxy30 conditions at the first oxygen injection variant except lower NO_x emission for wooden blend with 50% share in Oxy20 and Oxy30 (see Fig.8).

A comparison of NO_x emission (mg/MJ) obtained from combustion of hard coal and blends of biomass (20, 50%) with hard coal in air and Oxy20 and Oxy30 atmospheres is presented in Figure 8. Figure 8 shows that NO_x emission (mg/MJ) from oxy combustion of hard coal and oxy-co-firing of blend hard coal with biomass is lower than that in air atmosphere for both O₂/CO₂ ratios of 20 and 30%.

However, in Oxy30 atmosphere NO_x emission is increasing related to Oxy20 atmosphere. In Oxy20 atmosphere NO_x emission is reduced compared to that in the air atmosphere by 20%, 11%, 15%, 23%, 37% respectively for hard coal, 20% and 50% for straw-blend, while 20% and 50% for wooden blend.

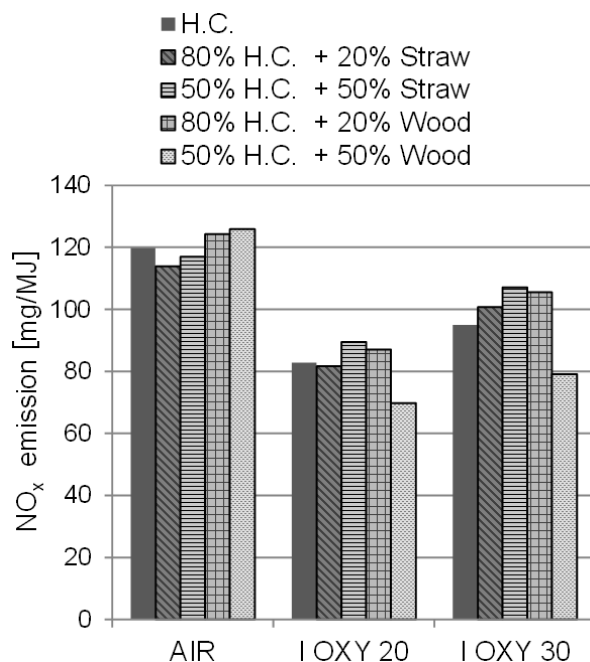


Fig. 8. The effect of biomass share and oxy atmosphere on NO_x emission (excess oxygen = 1.25) for the first variant of oxygen injection

4. THE EFFECT OF O₂/CO₂ RATIO IN PRIMARY AND SECONDARY OXIDISER STREAM ON SO₂ AND NO_x EMISSION FROM CO-FIRING BLENDS

An analysis of NO_x and SO₂ emission results from oxy- co-firing where primary and secondary oxidising streams differed O₂/CO₂ ratio for two blends with 20% and 50% share of wood and straw with hard coal was performed. The objective of this study was to reduce O₂ concentration in the primary stream for two reasons. A lower O₂ concentration decreases the explosion risk of pulverised blends, and presumably decreases NO_x formation in the primary reaction zone. Values of NO_x obtained for the second variant were generally lower than those for the first one.

NO_x emission for low concentration of oxygen equal to 6% in primary oxidiser stream at the final oxygen concentration of 20% dependent on oxygen excess is presented in Figure 9. A comparison of results of NO_x and SO₂ emission for the first and second variant of oxygen injection into burner shows that NO_x emission is significantly lower and also SO₂ emission is lower for the second variant (which is visible in Figures 10 and 11). A high reduction of SO₂ and a significant reduction of NO_x were obtained, excluding the emission from hard coal combustion and blend with 50% share of wood co-fired in atmosphere Oxy30. NO_x emission for the air atmosphere (mg/MJ) is higher than that in Oxy20

atmosphere. For all the fuels a similar - NO_x concentration upward trend is visible (Fig. 9), which was measured for the first and second variant of O₂ injection.

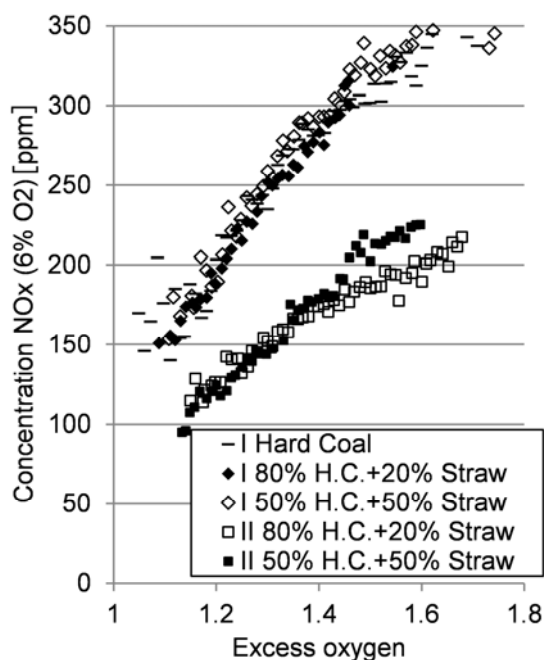


Fig. 9. The effect of O₂/CO₂ ratio in primary stream, and excess oxygen on NO_x emission in Oxy20 atmosphere (comparison of I and II variant)

Figures 10 and 11 present the percentage value of SO₂ and NO_x reduction in Oxy20 and Oxy30 atmospheres. The value of sulphur dioxide reduction was calculated as a ratio of the difference of SO₂ emissions (mg/MJ) obtained from co-firing and SO₂ emission from combustion of hard coal (mg/MJ) to SO₂ emission from combustion of hard coal under the same atmosphere. This reduction ratio exhibits the effect of biomass share in the blend on SO₂ reduction degree in each atmosphere. For the second variant i.e. under condition of oxygen depletion in primary oxidiser stream NO_x and SO₂ emissions are lower than those in first variant. The rich zone at burner outlet vicinity, where there is an evolution of volatile matter, favours reduction formation of NO_x as well as retention of sulfur in ash.

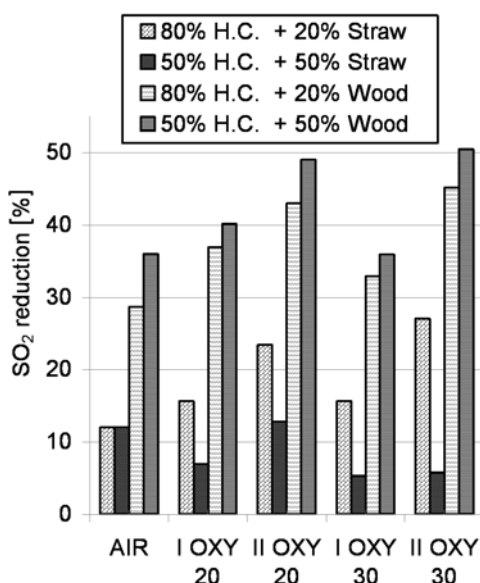


Fig. 10. The effect of oxy atmosphere and various O₂/CO₂ ratios in primary stream of oxidizer in the burner on SO₂ emission reduction compared to SO₂ emission from hard coal combustion. Comparison of I and II variant

NO_x reduction is presented as a ratio of difference NO_x (mg/MJ) measured in oxy condition and NO_x emission (mg/MJ) measured in air to NO_x emission (mg/MJ) measured in air. The oxy atmosphere and oxygen concentration in primary oxidiser stream (oxygen injection mode) effect on NO_x reduction is visible for each studied blend and hard coal. The second variant of oxygen injection into the burner seems to be more advantageous for co-firing taking into account NO_x and SO₂ emission levels. The low concentration of oxygen in primary stream of oxidizer has significant influence on NO_x emission for co-firing and hard coal combustion.

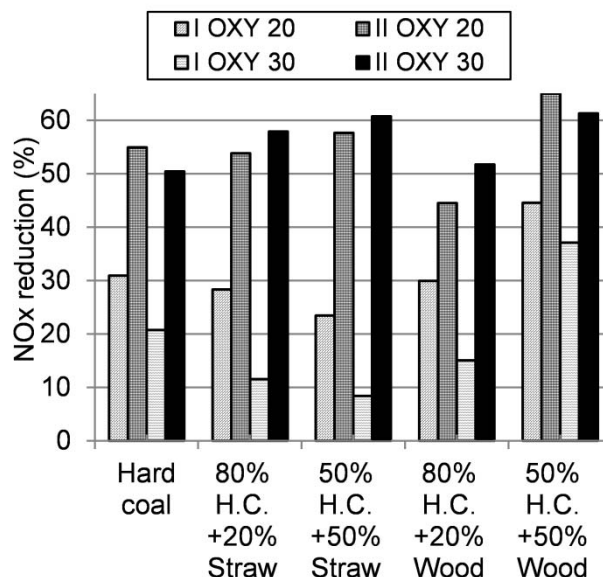


Fig. 11. The effect of oxy atmosphere and various O₂/CO₂ ratios in primary stream of oxidizer in the burner on NO_x emission reduction relative to NO_x emission from hard coal combustion in air condition

From co-firing of biomass with hard coal blends in the oxy atmosphere a high rate of burnout above 96% for both shares of biomass and both O₂ injection modes was obtained. Generally oxy co-firing yields lower values of burnout losses than air co-firing.

4. CONCLUSIONS

Sulphur dioxide and nitrogen oxide emissions from co-firing of mixtures of two different biomasses (20% and 50% by mass) and hard coal shares were studied under oxy- combustion conditions. A minimum emission of NO_x, SO₂ and high burnout from oxy co-firing biomass with hard coal can be achieved by controlling the injection oxygen method to the burner. The increase of biomass share in the blend with hard coal lowers SO₂ emission in each oxygen atmosphere. However, this effect is not so visible for NO_x emission. The oxygen injection mode has a significant effect on NO_x emission under each oxy atmosphere (Oxy20, Oxy30).

The oxy-fuel technology is characterised by a high recirculation rate of flue gases, thus the proper oxygen injection to the recirculating flue gases could diminish SO₂ and NO_x emission from co-firing. The degree of SO₂ reduction increases with increasing biomass share in blend, in comparison with pulverised coal combustion in each investigated atmosphere. A significant reduction of NO_x is achieved for the second variant of O₂/CO₂ ratio in primary stream (above 60% reduction in comparison with air atmosphere). It is the effect of presence of an oxygen deficient combustion zone at the first stage of combustion in comparison to the first variant. High volatile matter and small particle size of the solid fuel in the rich zone just after burner decreases NO_x formation. The rich zone at burner outlet vicinity

where there is an evolution of volatile matter favours a reduction of NO_x formation as well as retention of sulphur in ash.

It was found that any biomass share in the studied blends would improve the burnout. The effect of low concentration of oxygen in the primary oxidiser stream is noticeable especially for NO_x emission and it is much more significant than the effect of biomass share in blend. However, in the first variant i.e. an equal oxygen concentration in primary and secondary streams of oxidiser, SO₂ and NO_x emissions for co-firing at Oxy30 atmosphere are slightly higher than those for Oxy20.

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