DOI: 10.5604/20830157.1130199

COMBUSTION OF COAL AND ALTERNATIVE FUELS IN OXY-FUEL ATMOSPHERE

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Abstract. *In this paper, results of fuel behavior during combustion of coal and alternative fuels in oxy-fuel atmosphere are presented. The objective of this work was to evaluate the dependencies between properties (ignition, explosion parameters, emissions of NO_x and SO_2) of coal and alternative fuels. The exchange of air for recycled flue gas and oxygen mixture, leads to changes of combustion behavior i.e. lower emission of NO_x, SO_2 and increased ignition delay time. Nevertheless, performed experiments do not indicate significant differences in explosion parameters among different fuels at air and 30%O_2/70%CO_2 atmosphere.*

Keywords: ignition, emission, oxy atmosphere

SPALANIE WĘGLI I PALIW ALTERNATYWNYCH W ATMOSFERZE TLENOWEJ

Streszczenie*. Artykuł przedstawia wyniki badań uzyskane w czasie realizacji procesu spalania w atmosferze oxy-fuel. Prezentowane wyniki skupiają się na określeniu takich własności jak zapłon, parametry wybuchowości, emisję zanieczyszczeń gazowych NO_x, SO_2 węgli i paliw alternatywnych. Eksperyment został wykonany na 3 metrowym pionowym reaktorze przepływowym, 20 litrowej sferycznej kuli i w 1 metrowym pionowym piecu do badania zapłonu. Zastosowanie technologii spalania w tlenie może znacząco polepszyć możliwości użytkowania paliw stałych. Eliminacja, z atmosfery spalania, azotu prowadzi do obniżenia emisji zanieczyszczeń gazowych NO_x, SO_2 oraz wzrostu czasu opóźnienia zapłonu. Niemniej, przeprowadzone eksperymenty nie wykazały wpływu atmosfery 30%O_2/70%CO_2 na parametry wybuchowości.*

Słowa kluczowe: zapłon, emisja, atmosfera oxy

Introduction

Oxy fuel combustion is one of the leading carbon capture and storage (CCS) technology. In this process, the fuel is combusted in a mixture of recycled flue gases and nearly pure oxygen, instead of air. The main attraction of this technology is production of a flue gas containing mainly CO_2 and water vapour. Since the H_2O can be easily removed by condensation, the almost pure CO_2 stream becomes suitable for compression, transport and storage.

During the last decade, the oxy fuel technologies have been significantly developed to the point where several demonstration projects have begun [11]. A number of state-of-the-art reviews have been presented [1, 7, 10]. Nevertheless, while oxy fuel conditions differ considerably from air conditions, several issues, i.e. ignition mechanism, explosion risks, SO_2 and NO_x emissions still need clarification.

The ignition of solid fuel particles is an important step of combustion mechanism due to its influence on flame stability and pollutant formation. The ignition temperature and ignition delay time are not an inherent property of the fuel, but they depends also on the operating conditions (i.e. atmosphere composition, heating rate, etc.). In oxy fuel atmosphere, poor ignition quality has been often noted during pilot scale experiments [9]. As shown in the paper [8] the ignition delay time is longer and the ignition temperature is higher in an O_2/CO_2 environment than in an O_2/N_2. Authors suggested that the longer ignition delay in O_2/CO_2 mixtures is mainly due to the higher heat capacity of CO_2. The same effect has been attributed also to endothermic char-CO_2 gasification reaction [6].

The explosion parameters of pulverized solid fuels under oxy fuel conditions are important for burner design and development, and power plant safety considerations. The amount of experimental data in the literature is very limited and ambiguous. As presented in [4] substitution of air by oxy fuel atmosphere with higher O_2 concentration increases the rate of pressure rise. On the other hand, results presented in [3] do not indicate differences between explosion parameters in air and oxy fuels atmospheres.

The reduction of emissions is an important environmental issue due to the NO_x and SO_2 contribution to acid rain formation. Many of researchers [5, 7, 10] indicated that oxy fuel combustion conditions may decrease the NO_x emission intensity due to: (1) lower partial pressure of N_2, (2) different radical and gas compositions within and around the char particles and (3) reburning of recycled flue gas containing NO. As shown in [2] the SO_2 emission intensity does not change significantly under oxy fuel and air conditions. However, recycling of flue gasses may increase the SO_2 concentration in the furnace and raise potential corrosion issues.

The aim of this paper is to examine the behaviour of various coals and alternative fuels during the oxy fuel combustion and to compare obtained results with data possessed in referenced air atmosphere. The principal objective of the study is to determine the impact of oxy fuel conditions on the ignition mechanism, explosion risks and SO_2 and NO_x emissions.

1. Fuel samples

Eight fuels were selected for the research, i.e. hard coals Janina and Sobieski, lignites Turów and Bełchatów, alternative fuels: wood pellet (PelD), sunflower pellet (PelS), sewage sludge (OsadS) and solid recovery fuel (SRF). The chosen alternative fuels represent three groups, defined according to source and origins: wood/woody biomass (PelD), herbaceous/agricultural biomass (PelS) and solid waste (OsadS and SRF). Physicochemical properties of investigated fuels differ substantially and are summarized in Tab. 1.

Table 1. Proximate and ultimate analyses of fuel (on air dried basis)

					Proximate analyses
Fuel	W	A	V	FC	FR
	%				-
Janina	3.1	8.6	32.7	55.6	1.70
Turów	2.0	17.5	46.6	33.8	0.73
Sobieski	3,7	10,4	33,0	52,9	1,60
Bełchatów	4,4	16,1	44,4	35,0	0,80
PelS	2.1	2.7	73.5	21.7	0.30
PelD	4.5	1.3	78.3	15.9	0.20
OsadS	3.3	42.3	46.5	7.8	0.17
SRF	3.5	17.0	68.3	11.2	0.16
					Ultimate analyses
Fuel	C	H	N	S	O
	%				
Janina	75.7	4.3	1.2	1.2	5.9
Turów	59.0	4.8	0.5	1.3	14.8
Sobieski	76,0	4,1	1,2	1,6	2,9
Bełchatów	55,2	4,5	0,6	1,8	17,4
PelS	51.9	5.7	0.7	0.1	36.8
PelD	52.1	6.5	0.4	0.1	35.2
OsadS	29.8	4.0	3.8	2.3	14.5
SRF	51.3	6.6	0.7	0.2	20.6

Comparing to coals, alternative fuels contain high amount of volatiles and lower fuel ratio FR. Moreover, sewage sludge and SRF contain high amount of ash, caused by the process of their production. The ratio between fractions of the proximate analysis is shown on the Fig. 1. All of the investigated alternative fuels are characterized by the fuel ratio lower than 0.5, thus the predominant form of combustion is gas – phase oxidation of the volatile matter. Fuel ratio lower than unity, may increase the fire and explosion risks during combustion and co-combustion of these fuels. Particularly exposed to the hazard of fire and explosion are the feeding and the preparation systems. Nevertheless, high amount of volatiles (low fuel ratio) may promote ignition and increase flame stability.

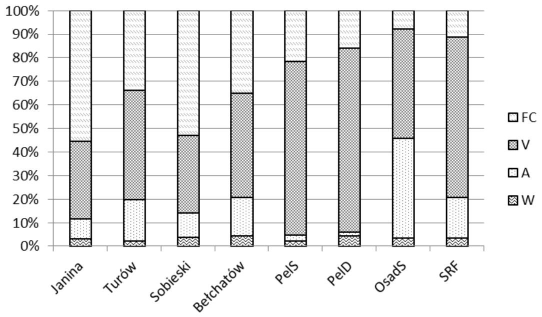

Fig. 1. Proximate analyses diagram

2. Results

2.1. Ignition of coal particle suspension in oxy-fuel atmosphere

Ignition measurements in oxy-fuel (O_2/CO_2) atmosphere were performed using monodisperse coal dust clouds experimental technique. An electrically heated vertical furnace (Fig. 2) coupled with optical particle detection has been applied to study the ignition of clouds of pulverized coal. The experimental program involved the variation of furnace temperatures, T_g (ranging from 400°C to 900°C), type of atmosphere (air, oxy 30%O_2/70%CO_2) and fuel type.

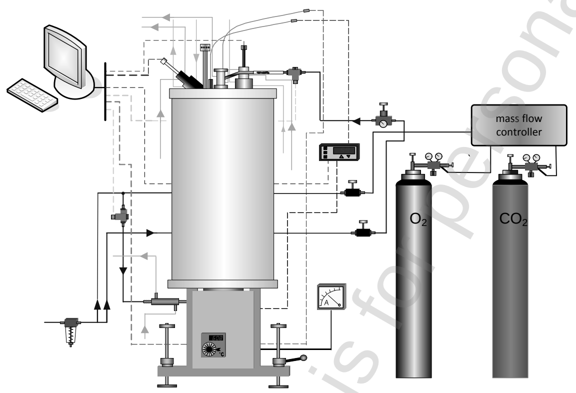

Fig. 2. Vertical furnace diagram

A series of experiments were undertaken to determine the sensitivity of the cloud ignition delay time to adjustable experimental variables – the furnace temperature and oxy-fuel (O_2/CO_2) atmosphere. The variation of the ignition delay time with respect of the furnace temperatures for fuels is reported in Fig. 3.

As shown in the Figure 3, ignition temperature and ignition delay time vary depending on the fuel type. Regardless of the atmosphere composition, the lowest ignition parameters were measured for biomass PelS, PelD and for lignites Turów, Bełchatów. On the other hand, long ignition delay time and high ignition temperature were obtained for hard coal Janina, Sobieski and sewage sludge OsadS.

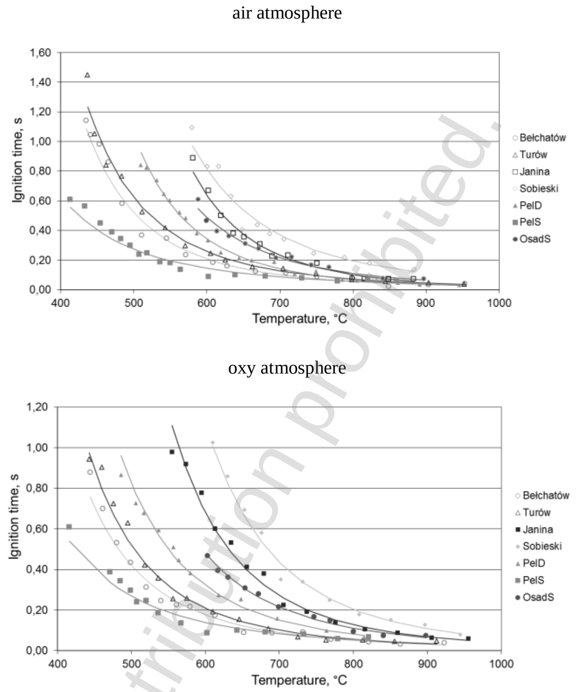

Fig. 3. Ignition characteristics for fuels in different atmosphere

In order to investigate the impact of atmosphere composition on ignition parameters, results obtained for air and 30%O_2/70%CO_2 are summarized in Tab. 2.

Table 2. Ignition parameters of fuels

Fuel	Air		30%O_2/70CO_2	
	MTI_c, °C	t_{z650}, s	MTI_c, °C	t_{z650}, s
Janina	555	0,37	581	0,42
Turów	437	0,178	443	0,142
Sobieski	580	0,536	610	0,682
Bełchatów	435	0,142	444	0,123
PelD	498	0,2147	507	0,2345
PelS	403	0,1100	412	0,1841
OsadS	588	0,3176	593	0,3518

Obtained results revealed that exchanging air for 30%O_2/70%CO_2 atmosphere, in general, leads to slight decrease of ignition temperature (MTI_C) and to increase of ignition delay time (t_{z650}). The highest difference between ignition temperature in air and oxy fuel conditions, measured for hard coal Sobieski, was 30°C, the mean difference calculated for all investigated fuels was about 15°C. For 5 of 7 analysed fuels, presence of O_2/CO_2 mixture increase ignition delay time by average about 0,06s. For lignite Turów and Bełchatów oxy fuel conditions decrease the ignition delay time by 0,04s and 0,02s respectively.

2.2. Dust explosion characteristic in oxy-fuel atmosphere

Ignition of fuels dust cloud leads to the explosion. To cause the explosion, three conditions must be fulfilled, i.e. proper dust concentration, access to oxygen and a source of explosion (embers, fire). Knowledge about characteristics of the explosion is important due to prevention (lower explosive limit, LEL) and providing information on the consequences (maximum explosion pressure p_{max}, maximum rate of pressure rise $(dp/dt)_{max}$, the K_{st} parameter). The explosion behavior was determined using 20 litre – sphere presented in Fig. 4.

Results obtained for investigated fuels are presented in Fig. 5 and Tab. 3.

It may be concluded that biomass and sewage sludges are characterized by lower explosion parameters than coals and lignites but their explosion tendency is similar. This can be explained by the high content of volatiles and low onset temperature of devolatilization (from range 200-400°C).

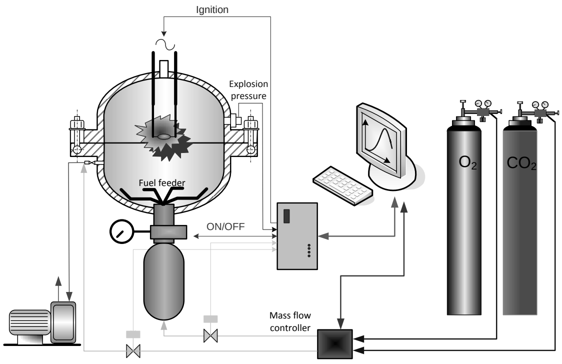

Fig. 4. 20 litre – sphere diagram

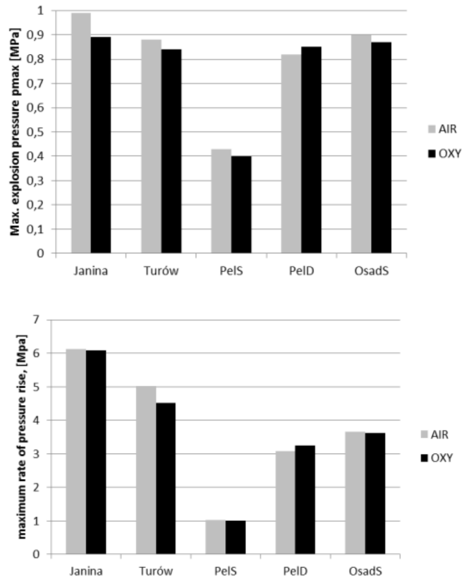

Fig. 5. Comparison of explosion parameters for investigated fuels

Regardless of the fuel type, no significant impact of the atmosphere composition on the explosion parameters was found. The maximum explosion pressure for all investigated fuels varies form 0,43 MPa to 0,99 MPa, and from 0,45 MPa to 0,96 MPa in air and oxy fuel atmosphere respectively. The maximum rate of pressure rise was equal from 3,61 MPa/s to 21,74 MPa/s in air and from 3,56 MPa/s to 21,43 MPa/s in 30%O_2/70%CO_2. The K_{st} parameter, describing the maximum rate of pressure rise in 1m^3 vessel when a dust is ignited, differs from 1,06 MPa m/s to 6,18 MPa m/s in air and from 1,01 MPa m/s to 6,09 MPa m/s in oxy fuel atmosphere.

Table 3. Explosion parameters of investigated fuels

Fuel	maximum explosion pressure		maximum rate of pressure rise, $(dP/dt)_{max}$		the K_{st} parameter	
	MPa		MPa/s		MPa m/s	
	Air	OXY	Air	OXY	Air	OXY
Janina	0,99	0,89	21,54	21,43	6,13	6,09
Turów	0,88	0,84	17,64	15,87	5,02	4,51
Sobieski	0,92	0,85	17,92	18,26	5,10	5,19
Bełchatów	0,94	0,82	21,74	10,38	6,18	2,95
PelD	0,82	0,80	9,62	9,82	2,74	2,79
PelS	0,43	0,45	3,61	3,56	1,06	1,01
OsadS	0,90	0,96	13,68	13,12	3,89	3,73

2.3. NO_x and SO_2 emission in oxy-fuel atmosphere

Predicting of the NO_x and SO_2 emission during the combustion of fuels is more difficult than for coal. Some fuels such as SRF may have lower nitrogen content, what can result lower NO_x emission. Sewage sludges have higher nitrogen content than typical coal, but the emission of NO_x does not depend only on the nitrogen content in the fuel, but also on the path of emission and combustion temperature. If the greater part of the nitrogen is emitted with the volatile matter, it will results in lower emission of NO_x, especially for combustion in Low-NO_x burners. Furthermore, NO_x is created by the thermal reaction between nitrogen and oxygen. Hence, higher moisture content in sewage sludges may decrease the maximum flame temperature and thereby reduce thermal NO_x formation. Evaluation of the emission of sulfur and nitrogen oxides was performed in the 3 meter long Plug Flow Reactor, where fuel and blend were combusted. Fig. 6 shows the entire rig.

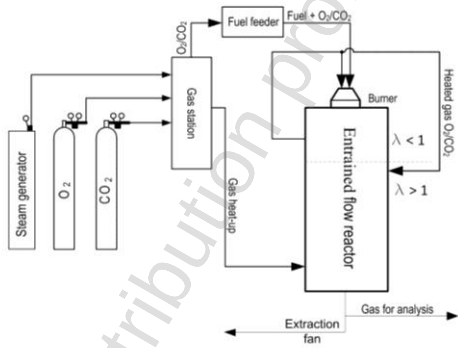

Fig. 6. Gas installation diagram

In the second stage of experiment, fuels were combusted in oxy fuel atmosphere containing 30%O_2 and 70%CO_2. Emissions of NO_x and SO_2 in oxy and air fuel atmosphere for Janina are shown in Fig. **7**. For chosen experiment conditions it was showed that emission of $NO_{\mathbf{x}}$ and SO_2 is higher in oxy fuel atmosphere than in air (in mg/m^3). However, the volume of flue gases from oxy fuel combustion is reduced due to higher content of O_2 and higher density of CO_2 than N_2.

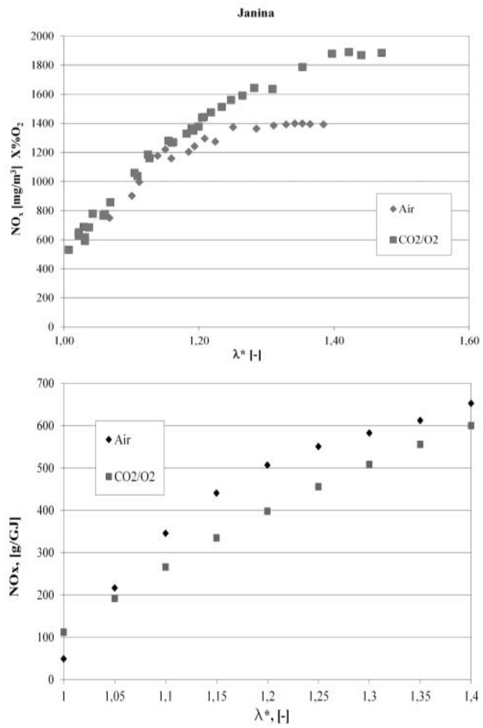

Fig. 7. NO_x emission versus fuel equivalence ratio in oxy and air fuel atmosphere

Taking into account lower volume of flue gases, the overall emission of NO_x during oxy fuel combustion is lower than air condition combustion (Fig. 8) (in g/GJ). The NO_x reduction is thought to be the result of non-NO_x formation via fixation of atmospheric nitrogen. Similar to NO_x case, the SO_2 emission per energy input of coal in oxy fuel atmosphere is lower than in air.

The emission reduction is proportional to the share of alternative fuel. Figure 9 shows the degree of conversion of fuel sulfur to SO_2 in the flue gas. It presents that the lower emission was noted in the case of oxygen-enriched atmosphere and the emission of sulfur compounds is directly proportional to the amount of elemental sulfur.

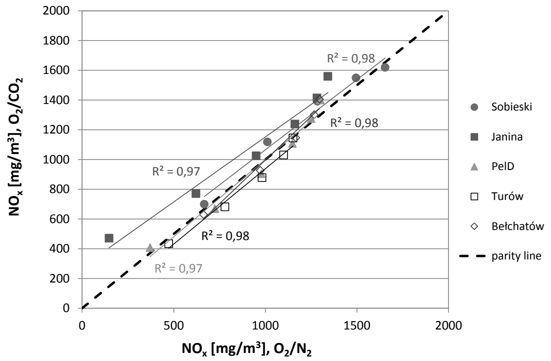

Fig. 8. The rate of conversion NOx emissions in oxy and air fuel atmosphere

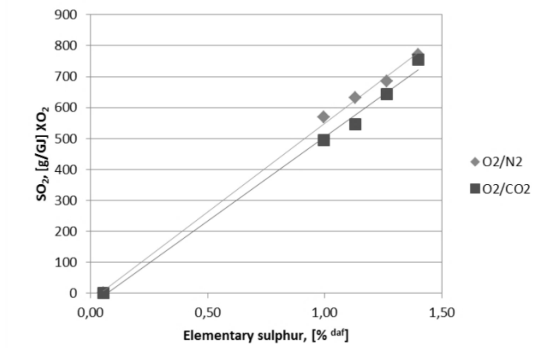

Fig. 9. The rate of conversion NO_x emissions in oxy and air fuel atmosphere

3. Conclusion

Analysis shows that the use of coals and alternative fuels in oxy-fuel combustion technology is possible and does not pose a risk than the use of these fuels in conventional systems. The obtained results have confirmed the following facts:

1) ignition parameters depends on the fuel type, the lowest ignition parameters were measured for biomass and lignites, the highest ignition parameters were obtained for hard coals and sewage sludge;
2) exchanging air for $30\%O_2/70\%CO_2$ atmosphere, in general, leads to slight decrease of ignition temperature (MTI_C) and to increase of ignition delay time (t_{z650}). The differences in ignition temperature and ignition delay time are a consequence of the higher density and heat capacity of CO_2 than N_2. The impact of CO_2 presence is visible even though the reactivity of the fuel-oxidizer mixture in oxy fuel conditions is higher (due to higher concentration of oxygen);
3) biomass and sewage sludges are characterized by lower explosion parameters than coals and lignites but their explosion tendency is higher. This can be explained by the high content of volatiles and low onset temperature of devolatilization;
4) regardless of the fuel type, no significant impact of the atmosphere composition on the explosion parameters (the maximum explosion pressure, the maximum rate of pressure rise, the K_{st} parameter) were found;
5) the overall emission of NO_x related to energy input (in g/GJ), during oxy fuel combustion is lower than air condition combustion. The NO_x reduction is thought to be the result of non – NO_x formation via fixation of atmospheric nitrogen;
6) the emission of SO_2 related to energy input (in g/GJ), during oxy fuel combustion is lower than air condition combustion ant it is proportional to the amount of elemental sulfur. The SO_2 reduction is a result of fixation of sulfur in the ash.

Acknowledgements

Scientific work was supported by the National Centre for Research and Development, as Strategic Project PS/E/2/66420/10 "Advanced Technologies for Energy Generation: Oxy-combustion technology for PC and FBC boilers with CO_2 capture". The support is gratefully acknowledged.

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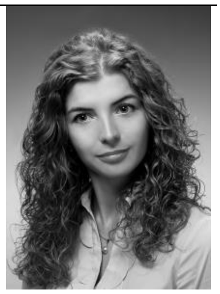

otrzymano/received: 2014.07.04 *przyjęto do druku/accepted: 2014.07.17*