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RESEARCH ON CO-COMBUSTION OF SEWAGE SLUDGE AND COAL IN OXY-FUEL CONDITIONS

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Abstract: Oxy-fuel co-combustion of municipal dried sewage sludge and coal was conducted to observe the combustion characteristics as well as pollutant emissions generated under different oxygen injection rate in oxy-fuel atmosphere in 0.1 MWt CFB reactor. As a feed gas a mixture of oxygen and carbon dioxide was used. Oxygen concentration in a feed gas varied from 21 % to 30 % per volume. The following blending ratios of sewage sludge to coal were chosen: 50 %, 30 % and 10 %. Flue gas components were on-line measured by a gas analyzer, determining CO₂, CO, SO₂, SO₃, NO₂, NO, N₂O, NH₃, HCN concentrations by non-dispersive infrared absorption. During the study the influence of oxygen concentration in the gas atmosphere and the mass fraction of sewage sludge in the fuel blend on the emission of sulfur and nitrogen compounds in the O₂/CO₂ atmosphere with varied proportions of components in the blend were determined. It was found that oxygen concentration in the gas mixture has a significant influence on the process conditions. When the oxygen concentration in the gas mixture increased, the temperature of thermal processing of fuel blends was higher. The proportion of sewage sludge also affected the obtained profiles, which was particularly visible at 21 % oxygen content in the gas mixture. Then the conversion ratios of nitrogen and sulfur contained in blending fuel to NO, NO₂, N₂O, NH₃, HCN, SO₂, SO₃ and H₂S were determined. This paper reports some of the major findings obtained from these research activities.

Keywords: sewage sludge, co-combustion, oxy-fuel, sulfur and nitrogen conversion ratio

Introduction

Although sewage sludge is a kind of waste produced as a result of sewage treatment, it can be considered as an alternative fuel if pretreated. Proper preparation of sewage sludge first of all involves the removal of water. This can be achieved through different processes, such as thickening, dewatering and drying [1]. The composition of sludge depends on the composition of the treated wastewater. The range of organic (including flammable) compounds content is quite broad, with the mean of approx. 60 %. Thus, the calorific value of dried sewage sludge is mostly between 12–22 MJ/kg [2–4]. This

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value is obviously so attractive that dry sewage sludge is used as a fuel in different technologies applied in plants obtaining energy from waste [5, 6]. The effectiveness of obtaining energy from sewage sludge may be further improved as a result of co-combustion with fossil or renewable fuels. Thus, the process can be performed, not only in installations dedicated to water and wastewater companies running sewage treatment plants, but in any installation where sewage sludge would be added to the basic fuel. Circulating fluidized bed installations are particularly well-suited for this purpose as wide range of fuel blends can be used in them, including difficult, low quality fuels. Fluidized bed boilers have low combustion temperatures, which helps to reduce emission, especially of nitrogen compounds [7]. Thanks to direct introduction of sorbents to the boiler, the technology works equally well for sulfur oxides [8]. The fact that fuel particles stay for a long time in the combustion zone with partial recirculation of incompletely burnt grains has also a positive effect on circulating fluidized bed installations, which helps to reduce the loss related to incomplete combustion.

According to the information from the Polish Central Statistical Office (GUS), in 2017 municipal sewage treatment plants in Poland produced 584.5 thousand Mg d.m. of sludge. Poland is the fifth largest country within the EU countries in terms of sewage sludge production [9]. More than 100 thousand Mg d.m. of sewage sludge is a subject to thermal processing in Poland. Currently, there are 11 municipal mono-incineration plants for sewage sludge. Seven of them were established using the fluidized bed technology, and in four, sewage sludge is incinerated on a grate. These are both small- and large-scale facilities. The smallest mono-incinerator is located in Lomza and has the capacity of 1.5 thousand Mg d.m./year, whereas the Warszawa one is a giant with the capacity of 62 thousand Mg d.m./year. The most popular technology applied in four installations, i.e., in Warszawa, Kielce, Lodz and Krakow, is PyrofluidTM. In those plants, air combustion occurs in the conditions of excess air, which causes considerable carbon dioxide emission. Advanced technologies of CO₂ emission reduction are mostly connected with its capture and storage. Oxy-fuel combustion, i.e., combustion in atmosphere enriched with oxygen, is regarded as one of the key technologies in this group [10]. The oxidation factor, air, is replaced by the O₂/CO₂ mixture, leading to a higher concentration of carbon dioxide in flue gas [11]. Moreover, the flue gas recirculation prevents high temperatures (exceeding the temperature of ash fusibility) during the combustion. This technology has been studied in many publications, mainly concerning its application in coal combustion in pulverized-fuel boilers [10, 12] or fluidized bed boilers [13, 14]. Numerous studies have also been performed in which the feed fuel in the oxy-fuel combustion technology was waste, including sewage sludge [15, 16] and biomass [17, 18], as well as diverse fuel blends [19–22]. The studies focused on a number of aspects. Some of them involved the modeling of oxy-fuel combustion process in terms of heat exchange, flow aerodynamics or combustion kinetics. The impact of thermal treatment of mixtures of sewage sludge and other materials on selected chemical properties can be found in [23]. Environmental impact has also been studied in terms of pollutant emissions to the air. However, most of the studies on co-combustion of coal and sewage sludge so far have been performed in the air atmosphere, and the ones that involved oxy-fuel combustion have been carried out as thermogravimetric studies [24, 25].

This article presents the results of a study on co-combustion of municipal sewage sludge and coal in the modified O₂/CO₂ atmosphere, carried out on a large laboratory scale with a 0.1 MWt (megawatts thermal) circulation fluidized bed station. The experiments involved fuel blends with varied mass fractions of sewage sludge as well as varied oxygen concentrations in the gas mixture. They were aimed to test the influence of process temperature and oxygen concentration on gas pollution emissions in a large laboratory scale unit.

Materials and methods

Initial materials

The sewage sludge used in the experiment was collected from a wastewater treatment plant located in Czestochowa, a medium-sized agglomeration in the south part of Poland with approximately 200000 inhabitants. The treatment plant is equipped with a system of mechanical-biological sewage treatment. The character of the sludge is typical for mixed municipal-industrial sewage. The presence of heavy metals makes it impossible to use the sludge for agricultural purposes impossible; therefore, other methods are preferred. The anaerobically stabilized, dewatered and dried sludge was collected in the form of granulates with the diameter up to about 8–10 mm. Furthermore, the initial material for obtaining the sludge and coal mixtures was hard coal from the Janina mine located in Poland. Different fuel mixtures were prepared using the initial materials, with different sewage sludge mass percentages. Further they are marked as M50 (50 % of sewage sludge), M30 (30 %) and M10 (10 %). The properties of initial materials and prepared blends have been presented in Table 1. Data has been provided on a dry basis, in which the presence of water is ignored for the purposes of the calculation.

Table 1

The proximate and ultimate analyses of coal and sewage sludge

Fuel	Proximate analysis (db ^a) [%]			LHV (db ^a) [kJ/kg]	
	Volatile matter	Ash	Fixed carbon		
Coal	33.47	10.33	56.20	22531	
Sewage sludge	50.70	39.15	10.15	12542	
M10	36.16	14.27	49.57	21254	
M30	39.59	20.27	40.14	19483	
M50	43.18	25.93	30.89	18033	
Ultimate analysis (db ^a) [%]					
	C	H	N	S	O ^b
Coal	67.88	5.92	1.26	1.72	12.90 ^b
Sewage sludge	32.41	5.31	4.21	1.56	17.36 ^b

LHV – lower heating value, ^a db: dry basis, ^b oxygen calculated

Experimental stand

The investigations were carried out on a 0.1 MW_t circulating fluidized bed (CFB) test stand modified for oxy-fuel combustion. The unit consists of a 0.1 m inner diameter (I.D.), approximately 5.0 m tall combustion chamber, connected via a crossover section to a 0.25 m I.D. hot cyclone. Solids separated in the cyclone return to the combustion chamber via a 0.075 m I.D. downcomer and a non-mechanical loopseal. The unit is provided with four heaters, three around the combustion chamber and one around the downcomer. These furnaces are used to heat the unit to (or beyond) the ignition point of the fuel being used. Fluidizing oxygen-enriched air (PA) is supplied through a common-rail fitted with four nozzles at the bottom of the combustion chamber. This gas is preheated with the help of two heaters installed in series.

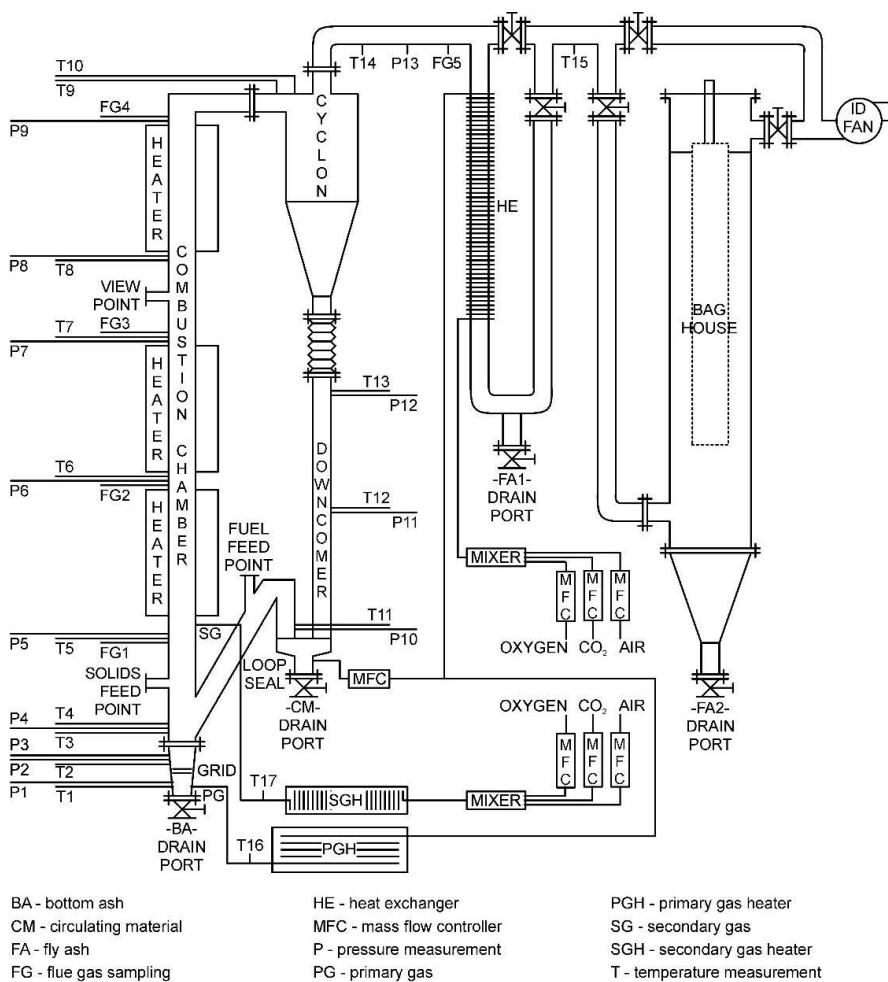


Fig. 1. Scheme of laboratory unit of 0.1 MW_t CFB

The fuel blend is fed continuously by a screw feeder above the primary air nozzles. A single fabric filter baghouse, installed downstream of the cyclone, is used for ultimate flue gas particulate clean-up. The baghouse may be by-passed if necessary. Flue gas leaving the baghouse (or by-passing the baghouse) is vented with the help of an ID fan to the atmosphere, through a stack. The test rig is equipped with a developed data acquisition system for temperature (T) and pressure (P or DP) measurements as well as a number of ports for flue gas (FG), bottom ash (BA), fly ash (FA) and circulating material (CM) sampling. The fluidization material was quartz sand with the Sauter diameter of 178 μ m and an absolute density of 2562 kg/m^3 . The pressure drop over the riser was kept stable in the range of 2500 Pa. The fuel flux was changed to keep excess oxygen ratio constant at 1.15 as well as the inlet gas flux was changed to keep the fluidization velocity constant at 3.2 m/s. The oxygen injection rate in oxy-fuel conditions was varied from 21 % to 30 %. The combustion tests were conducted in O_2/CO_2 with the following contents of mixture components: 21 % $\text{O}_2/79$ % CO_2 , 25 % $\text{O}_2/75$ % CO_2 and 30 % $\text{O}_2/70$ % CO_2 , thus simulating flue gas recirculation. Emissions of pollutants (CO_2 , CO , SO_2 , SO_3 , NO_2 , NO , N_2O , NH_3 , HCN , H_2O , HCl , HF) from the combustion were measured using a measurement system based on the Gamet DX-4000 analyzer, a unit based on the Fourier Transform Infrared Spectroscopy (FTIR). No additives were added for sulphur capture.

Conversion ratios of molecular nitrogen and sulfur

The calculation methodology of conversion ratio of molecular nitrogen contained in fuel to NO_x is based on the following equation:

$$\text{CR}_{\text{N} \rightarrow \text{NO}_x} = \frac{\frac{N_{\text{fg}}^{\text{NO}_x}}{C_{\text{fg}}^{\text{CO}_2 + \text{CO}}}}{\frac{N_f}{C_f}} \quad [-] \quad (1)$$

where: molar ratio of N_2 (fixed in NO_x)/C (fixed in $\text{CO}_2 + \text{CO}$) in flue gas:

$$\frac{N_{\text{fg}}^{\text{NO}_x}}{C_{\text{fg}}^{\text{CO}_2 + \text{CO}}} = \frac{0.5[\text{NO}_x]}{10^4[\text{CO}_2] + [\text{CO}]} \left[\frac{\text{kmol}_{\text{N}_2}}{\text{kmol}_{\text{C}}} \right] \quad (2)$$

and, molar ratio of N_2/C in fuel:

$$\frac{N_f}{C_f} = \frac{\frac{N}{28}}{\frac{C}{12}} \left[\frac{\text{kmol}_{\text{N}_2}}{\text{kmol}_{\text{C}}} \right] \quad (3)$$

and: $CR_{N \rightarrow \dots}$ – a conversion ratio of nitrogen to gaseous compounds (HCN, NH_3 , NO, NO_2 , N_2O); N_{fg} – molar fraction of nitrogen fixed in gaseous compound (HCN, NH_3 , NO, NO_2 , N_2O) in flue gas; N_f – nitrogen molar fraction in fuel; C_{fg} – molar fraction of carbon fixed in gaseous compound (CO , CO_2) in flue gas; C_f – carbon mass fraction in fuel.

In case of calculating the sulfur conversion ratio the following equation was used:

$$CR_{S \rightarrow SO_2} = \frac{\frac{S_{fg}^{SO_2}}{C_{fg}^{CO_2+CO}}}{\frac{S_f}{C_f}} \quad [-] \quad (4)$$

where: molar ratio of S (fixed in SO_2)/C (fixed in $CO_2 + CO$) in flue gas:

$$\frac{S_{fg}^{SO_2}}{C_{fg}^{CO_2+CO}} = \frac{[SO_2]}{10^4 [CO_2] + [CO]} \left[\frac{\text{kmol}_S}{\text{kmol}_C} \right] \quad (5)$$

and, molar ratio of combustible S/C in fuel:

$$\frac{S_f}{C_f} = \frac{\frac{S}{32}}{\frac{C}{12}} \left[\frac{\text{kmol}_S}{\text{kmol}_C} \right] \quad (6)$$

and: $CR_{S \rightarrow \dots}$ – conversion ratio of combustible sulfur to gaseous compounds (H_2S , SO_2 , SO_3); S_{fg} – molar fraction of sulfur fixed in gaseous compound (H_2S , SO_2 , SO_3) in flue gas; S_f – combustible sulfur molar fraction in fuel.

This methodology presented in [26] was used as to ensure the independence of obtained emission results from potential changes in the technical composition of fuel (moisture and ash proportions and the division of organic substance into volatile matter and breeze), losses from incomplete and/or imperfect combustion and the uncertainty of measurements of fuel and gases (O_2/CO_2) flows. That methodology assumes that flammable nitrogen and flammable sulfur are evenly distributed both in the volatile matter and in the coke.

Results and discussion

Effects of CO_2 concentration and sludge blending ratio on process temperature

Figure 2 presents the distribution of temperature in the riser depending on the concentration of oxygen in the gas mixture (21, 25 and 30 %) and mass fraction of

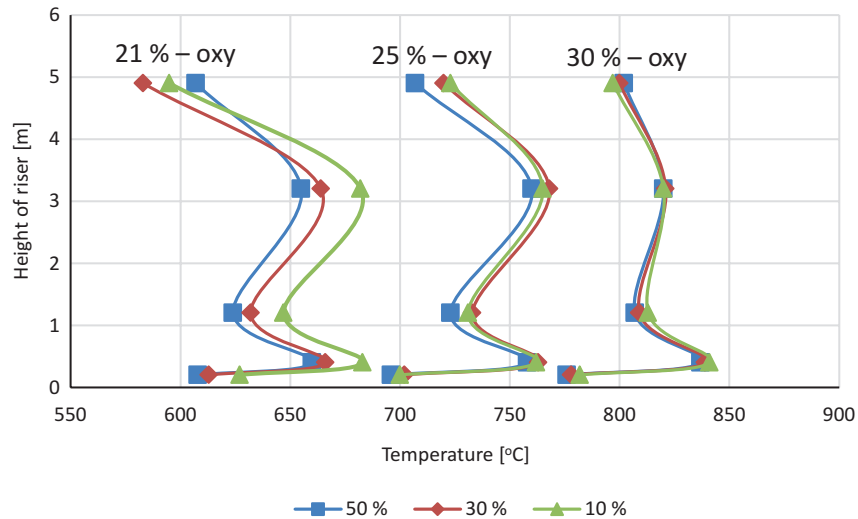


Fig. 2. Temperature profiles along the height of the riser at different oxy conditions

sewage sludge in the fuel blend (50, 30 and 10 %). As we can see in Table 1, the calorific value of coal is almost twice as high as that of sewage sludge. Since lower ratios of sludge in the fuel blend resulted in higher calorific values of the fuel introduced to the combustion chamber, the temperature of the process increased as the amount of sludge in the blend decreased.

The highest temperatures were obtained at the point of introducing the fuel to the column. Sewage sludge has a higher content of volatile matter than coal, which is released in lower temperature range. This is in agreement with the findings published in [27], proving that adding biomass considerably affects the temperature of fuel ignition, reducing it as a result of a high reactivity and high content of volatile matter in the biomass. Adding biomass to coal makes its ignition quicker and better.

The impact of oxygen concentration in the gas mixture on the temperature profile in the combustion chamber is evident. As the oxygen concentration in the gas mixture increased, the temperature of fuel blends thermal processing also grew. The lowest temperatures were obtained using a gas mixture with 21 % oxygen, and the highest, for 30 % of oxygen. The difference between temperatures in temperature profiles for different values of oxygen concentration in the mixture was more than 150 °C. For 30 % oxygen concentration in the gas mixture, the temperature profile is practically identical for all the fuel blends. Differences in temperature profiles along the combustion chamber for the fuel blends used in the study are more evident at lower concentrations of oxygen in the gas mixture and hence, lower temperatures of the process. The differences are particularly clear for the process using the 21 %O₂/79 %CO₂ gas mixture. The higher the content of sewage sludge in the fuel blend, the lower the resultant temperature of thermal processing.

Influence of oxygen concentration and mass fraction of sludge on pollutant emissions

In air combustion, the mechanism of nitrogen compounds formation may be threefold: the thermal mechanism of NO formation (Zeldovich mechanism), rapid NO formation, and the fuel-based mechanism [28]. Generally, it is assumed that the fuel-based mechanism is the main cause of nitrogen compounds emission, estimated even at 80–100 %. The remaining 20 % is the result of the thermal mechanism. The rapid formation mechanism is negligible [29]. As for the oxy-fuel combustion, the available literature points to a possible reduction of nitrogen compounds emissions by at least 30 % in comparison to air combustion [30, 31], although some authors argue that as a result of higher amount of oxygen, and hence higher temperature, the fuel-based mechanism of nitrogen compounds formation will be enhanced and the emission will be higher [31, 32]. However, total NO_x emission in relation to the calorific value of fuel in the oxy-fuel combustion process was significantly lower. The thermal mechanism does not occur due to the lack of air nitrogen in the combustion atmosphere (it is replaced by CO_2).

The results of the degree of fuel nitrogen conversion to compounds such as NO, NO_2 , N_2O , NH_3 and HCN for each fuel blend and different oxygen concentrations in the O_2/CO_2 atmosphere have been presented in Table 2.

Table 2

Nitrogen conversion ratio to NO – ($\text{CR}_{\text{N} \rightarrow \text{NO}}$), NO_2 – ($\text{CR}_{\text{N} \rightarrow \text{NO}_2}$), N_2O – ($\text{CR}_{\text{N} \rightarrow \text{N}_2\text{O}}$), NH_3 – ($\text{CR}_{\text{N} \rightarrow \text{NH}_3}$), HCN – ($\text{CR}_{\text{N} \rightarrow \text{HCN}}$)

Fuel blend	$\text{CR}_{\text{N} \rightarrow \text{N}_2\text{O}}$ [%]	$\text{CR}_{\text{N} \rightarrow \text{NO}}$ [%]	$\text{CR}_{\text{N} \rightarrow \text{NO}_2}$ [%]	$\text{CR}_{\text{N} \rightarrow \text{NH}_3}$ [%]	$\text{CR}_{\text{N} \rightarrow \text{HCN}}$ [%]
Conversion ratio N – 21 % O_2 /79 % CO_2					
M10	3.67	1.96	1.36	21.43	5.19
M30	8.93	2.78	0.17	19.92	7.46
M50	1.17	0.00	0.29	24.23	5.93
Conversion ratio N – 25 % O_2 /75 % CO_2					
M10	18.86	7.05	0.05	0.89	0.61
M30	15.51	3.95	0.04	0.38	0.85
M50	16.81	3.54	0.02	0.22	0.93
Conversion ratio N – 30 % O_2 /70 % CO_2					
M10	11.10	2.15	0.00	0.00	1.07
M30	10.12	2.42	0.00	0.00	1.29
M50	10.03	2.02	0.00	0.01	2.09

With 21 % concentration of oxygen in the feed gas, the results showed that fuel nitrogen mostly converts into ammonia (NH_3). Nitrogen conversion into hydrogen cyanide HCN was also visible, which is typical of the decomposition of cyanides under the influence of moisture and carbon dioxide. This was also a proof that the process of

formation and destruction of nitrogen oxides was not complete at the outlet of the combustion chamber. Nitrogen conversion into NO and NO₂ in those conditions was low. Approximately 30 % of fuel nitrogen converted into the above-mentioned gaseous compounds and N₂O, and the remainder, into molecular nitrogen. This resulted from the conditions of the combustion process, in which the process temperature did not exceed 730 °C. As oxygen concentration in the gas mixture grew, the degree of conversion of fuel nitrogen clearly changed towards NO and N₂O, which are the basic compounds into which nitrogen contained in the blend of sewage sludge and coal converts. The conversion into NO₂, NH₃ and HCN was low. The nitrile group CN, which converted into an isocyanate group NCO when passing through the oxidation zone, under the influence of temperature gradually converted into NO and N₂O. Conversion of fuel nitrogen into NO₂ is imperceptible, which may mean that in the upper zone of combustion NO₂ releases oxygen in accompanying reactions, and hence this compound is not detected in the flue gas. This is in agreement with the findings of the study described in [33], involving oxy-fuel combustion of coal. In this case, the dominant direction of fuel nitrogen conversion at the combustion of the studied fuel blends was nitrous oxide.

Regarding the emission of sulfur compounds, literature describes possible reduction of sulfur dioxide [34, 35], its increase [36], or even no differences between oxy-fuel and air combustion [37].

The results of the experiments have been presented in Table 3, containing the rate of conversion of flammable sulfur from the fuel into compounds such as SO₂, SO₃ and H₂S for each fuel blend and the variable proportion of oxygen in O₂/CO₂.

Table 3

Sulfur conversion ratio to SO₂ – (CR_{S→SO₂}), SO₃ – (CR_{S→SO₃}), H₂S – (CR_{S→H₂S})

Fuel blend	CR _{S→SO₂} [%]	CR _{S→SO₃} [%]	CR _{S→H₂S} [%]
Conversion ratio S – 21 %O ₂ /79 %CO ₂			
M10	36.41	0.29	10.62
M30	15.03	0.53	15.15
M50	32.57	0.02	6.68
Conversion ratio S – 25 %O ₂ /75 %CO ₂			
M10	72.84	0.31	3.71
M30	82.16	0.22	2.75
M50	86.28	0.06	6.16
Conversion ratio S – 30 %O ₂ /70 %CO ₂			
M10	85.60	0.23	2.69
M30	78.13	0.42	2.63
M50	73.34	0.60	3.09

Sulfur from the fuel mostly converted into sulfur dioxide. With 21 % concentration of oxygen in the gas mixture, 36 % of sulfur converted in that direction. Trace amounts

of sulfur converted into SO_3 , and much more, into H_2S (6–15 %). This was unfavorable because hydrogen sulfide may be bound into alkaline sulfides, which may have a negative effect on the composition of ash. Unfortunately, when the oxygen content in the mixture was 21 %, more than 50 % of sulfur in the fuel did not take part in the combustion process, which probably resulted from low combustion temperature. It is possible that in those process conditions the gaseous products of sulfur combustion were bound by alkaline compounds from the ash. However, even in case of 25 % oxygen content in the gas mixture, the conversion of flammable sulfur into sulfur dioxide was significantly improved. Conversion into sulfur trioxide was still negligible, and conversion into H_2S was a bit lower. A further increase in oxygen concentration in the gas mixture did not result in a visible increase in the degree of sulfur conversion into SO_2 . At 30 % of oxygen content, the rate of $\text{CR}_S \rightarrow \text{SO}_2$ conversion was 73–88 %. Still, only a little sulfur converted into SO_3 . Although temperature conditions and higher oxygen content should promote the oxidation of sulfur into sulfur trioxide, the rate of conversion was the lowest of all the analyzed cases. Regarding the content of sewage sludge in the fuel blend, no clear tendency was found in terms of the rate of conversion of sulfur related to the amount of sludge in the blend. Usually, the content of sulfur in sewage sludge is higher than in coal. In the analyzed case, both components were associated with a similar sulfur content, which has been presented in Table 1. At 30 % oxygen content, the highest rate of conversion was achieved for 10 % of sewage sludge, while at 25 % of oxygen in the gas mixture, the highest rate was achieved for 50 % of sludge.

Conclusion

The article presents the findings of a study concerning the process of combustion of sludge and coal blends at a large laboratory 0.1 MWt circulating fluidized bed station. The study involved assessing the influence of oxygen concentration in the gas atmosphere and the mass fraction of sewage sludge in the fuel blend on the emission of sulfur and nitrogen compounds in the O_2/CO_2 atmosphere with varied proportions of components in the blend. Based on those experimental tests major results have been summarized as follows.

1. Oxygen concentration in the gas mixture had a significant influence on the process conditions at the chosen study site. The temperatures of thermal processing of fuel blends were higher with oxygen injection rate ranged from 21 % to 30 %.
2. Since lower ratios of sludge in the fuel blend resulted in higher calorific values of the fuel introduced to the combustion chamber, the temperature of the co-combustion increased as the amount of sludge in the blend decreased.
3. The values of sulfur conversion ratio to sulfur dioxide were relatively high and exceeded the level of 80 %. The conversion ratio to SO_3 was negligible.
4. With 21 % concentration of oxygen in the feed gas, fuel nitrogen mostly converted into ammonia (NH_3). Nitrogen conversion into hydrogen cyanide HCN was visible. Generally, nitrogen conversion into NO and NO_2 was low. As oxygen concentration in the gas mixture grew, the degree of conversion of fuel nitrogen clearly changed towards

NO and N₂O. Conversion into NO₂, NH₃ and HCN was low. The dominant direction of fuel nitrogen conversion was nitrous oxide.

Acknowledgements

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BADANIA WSPÓLSPALANIA MIESZANEK OSADOWO-WĘGLOWYCH W WARUNKACH OXY-SPALANIA

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Abstrakt: W ramach prac badawczych przeprowadzono proces współspalania komunalnych osadów ściekowych oraz węgla na wielkolaboratoryjnym stanowisku z cyrkulacyjną warstwą fluidalną CWF o mocy 0,1 MW_t. Ich celem było rozpoznanie procesu ze szczególnym zwróceniem uwagi na emisję zanieczyszczeń generowanych w trakcie procesu. Badanie przeprowadzono w zmodyfikowanej atmosferze O₂/CO₂, gdzie stężenie tlenu zmieniano w zakresie od 21 % do 35 % objętościowo. Termicznemu przekształceniu poddawano mieszanę osadowo-węglową, gdzie masowy udział osadów ściekowych wynosił odpowiednio 50 %, 30 % i 10 %. Składniki spalin mierzono on-line za pomocą analizatora gazów, określając stężenia związków takich jak CO₂, CO, SO₂, SO₃, NO₂, NO, N₂O, NH₃, HCN, H₂O, HCl, HF za pomocą niedyspersyjnej absorpcji w podczerwieni. Analizowano wpływ stężenia tlenu w atmosferze gazowej i frakcji masowej osadów ściekowych w mieszance paliwowej na emisję związków siarki i azotu w atmosferze O₂ / CO₂ przy różnych proporcjach składników w mieszance. Stwierdzono, że stężenie tlenu w mieszaninie gazowej ma znaczący wpływ na warunki realizowanego procesu, a udział masowy osadów ściekowych wpływa na rodzaj substancji emitowanych do atmosfery. Stąd dla poszczególnych warunków procesu wyznaczono współczynniki konwersji azotu i siarki zawartych w mieszance paliwa na składniki gazowe NO, NO₂, N₂O, NH₃, HCN, SO₂, SO₃ i H₂S.

Słowa kluczowe: osady ściekowe, współspalanie z węglem, spalanie tlenowe, współczynnik konwersji siarki i azotu