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Arch. Min. Sci., Vol. 61 (2016), No 2, p. 425–442

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.1515/amsc-2016-0031

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ANALYSIS OF COMBUSTION PROCESS OF SEWAGE SLUDGE IN REFERENCE TO COALS AND BIOMASS

ANALIZA PRZEBIEGU PROCESU SPALANIA OSADÓW ŚCIEKOWYCH W ODNIESIENIU DO PALIW WĘGLOWYCH ORAZ BIOMASY

Production of sewage sludge is an inseparable part of the treatment process. The chemical and sanitary composition of sewage sludge flowing into the treatment plant is a very important factor determining the further use of the final product obtained in these plants. The sewage sludge is characterized by heterogeneity and multi-components properties, because they have characteristics of the classical and fertilizer wastes and energetic fuels. The thermal utilization of sewage sludge is necessary due to the unfavorable sanitary characteristics and the addition of the industrial sewage. This method ensures use of sewage sludge energy and return of expenditure incurred for the treatment of these wastes and their disposal. Sewage sludge should be analyzed in relation to conventional fuels (coals and biomass). They must comply with the applicable requirements, for example by an appropriate degree of dehydration, which guarantee the stable and efficient combustion.

This paper takes the issue of the combustion process of the different sewage sludge and their comparison of the coal and biomass fuels.

Keywords: sewage sludge, coal, biomass, kinetics of fuels combustion

Produkcja osadów ściekowych jest nierozłącznym elementem procesu oczyszczania ścieków. Skład chemiczny oraz sanitarny ścieków dopływających do oczyszczalni jest niezwykle istotnym czynnikiem determinującym dalsze wykorzystanie produktu finalnego uzyskiwanego w tych zakładach. Osady charakteryzuje niejednorodność oraz wieloskładnikowość, dlatego posiadają one cechy zarówno klasycznego odpadu czy nawozu, a także wartościowego paliwa energetycznego. Termiczna utylizacja osadów ściekowych jest niezbędna ze względu na niekorzystne ich cechy sanitarne, jak również dodatek ścieków przemysłowych. Ten sposób zagospodarowania osadów gwarantuje wykorzystanie zawartej w nich energii oraz zwrot nakładów finansowych poniesionych na obróbkę tych odpadów i ich zbyt. Osady ściekowe powinno się analizować w odniesieniu do tradycyjnych paliw (węgli oraz biomasy). Muszą one spełniać stosowne wymagania, poprzez np. odpowiedni stopień odwodnienia, gwarantujące ich stabilne i sprawne spalanie.

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Niniejszy artykuł podejmuje problematykę przebiegu procesu spalania osadów ściekowych o różnych własnościach, w postaci granulatu, w odniesieniu do paliw węglowych oraz biomasy.

Słowa kluczowe: osady ściekowe, węgiel, biomasa, kinetyka spalania paliw

1. Introduction

According to the Central Statistical Office (Protection of the Environment, 2000-2012) (as at 31 December 2011) Poland has over 3000 of the municipal sewage treatment plants, which serve more than 65,7% of the population, as follows:

– in the cities: 88,4%;
– in the rural areas (inhabited by about 39% of the population): 30,6%.

In Western Europe sewage plants treatment over 80% of the population.

1.1. Sewage sludge – waste or biomass?

According to the Act of 14 December 2012 (The act on waste of 14 December 2012) waste sludge is defined as substances, which the holder discards or intends to get rid of or to get rid of them is required.

In accordance with the Regulation of the Minister of Environment of 27 September 2001 (Regulation of the Minister of Environment of 27 September 2001) sewage sludge is ranked among the 19 "Waste from the plant and facilities for waste disposal, sewage treatment plants and drinking water and water for industrial purposes", in a subset of 08 "Waste treatment plant waste not otherwise specified". Waste code 19 08 05 "Fixed municipal sewage sludge."

According to the EU definition (Directive of the European Parliament and of the Council 2009/28/EC of 23 April 2009) sewage sludge must be defined as biomass.

According to the Polish standard PN-EN 12832:2004 (Polish Standard PN-EN 12832:2004) the sewage sludge is defined as a mixture of water and solids separated from various types of plants, as a result of natural or artificial processes.

1.2. Properties of sewage sludge

Characteristics of sewage sludge are discussed in the papers (Bień, 2007; Heidrich & Witkowski, 2010; Podedworna & Umiejewska, 2008; Środa et al., 2012a-c). Table 1 shows the characteristics of sewage sludge depending upon the degree of fermentation. It should be noted that with the increase of sewage sludge fermentation increases the pH value, but decreases the calorific value, which significantly affects the usefulness of this waste energy, that is considered as a fuel. On the other hand the behavior of sewage sludge ensures the stability for hygenisation.

TABLE 1

Example composition and basic properties of sewage sludge (Heidrich & Witkowski, 2010)

Proper-ties of sludge	**Unit**	**Type of sludge**					
		Primary sludge from mechanical sewage treatment	**Secondary sludge (after biofilters or activated sludge chambers)**	**Badly digested sludge**	**Weakly digested sludge**	**Well digested sludge**	**Very well digested sludge**
pH	–	5,0÷7,0	6,0÷7,0	6,5÷7,0	6,8÷7,3	7,2÷7,5	7,4÷7,8
Dry waste residue	%	4÷8 (biofilters) 0,5÷3,0 (activated sludge)	4÷12	4÷12	4÷12	4÷12	4÷12
Loss on ignition	$\%_{d.w.r.}^{*}$	60÷75	55÷80	55÷80	55÷80	45÷55	30÷45
Alkalinity	$mgCaCO_3/dm^3$ or $mmol/dm^3$	500÷1000 20÷40	55÷1000 (sometimes <500) 20÷40	100÷2500 40÷100	2000÷3500 80÷140	3000÷4500 120÷180	4000÷5500 160÷220
Volatile acids content	mg CH_3COOH/l or $mmol/dm^3$	1800÷3600 30÷60	1800÷3600 30÷60	2500÷4000 and more 40÷70	1000÷2500 15÷40	100÷1000 2÷15	< 100 < 2
General nitrogen	% N in $_{d.w.r.}^{*}$	2÷7	1,5÷50 (biofilters) 3÷10 (activated sludge)	1÷5	1÷3,5	0,5÷3,0	0,5÷2,5
General phos-phorus	% P in $_{d.w.r.}^{*}$	0,4÷3	0,9÷1,5	0,8÷2,6	0,8÷2,6	0,8÷2,6	0,8÷2,6
Potassium	% K in $_{d.w.r.}^{*}$	0,1÷0,7	0,1÷0,8	0,1÷0,3	0,1÷0,3	0,1÷0,3	0,1÷0,3
Calorific value	kJ/g $_{d.w.r.}^{*}$	16÷20	15÷21	15÷18	12,5÷16	10,5÷15	8÷10

* $_{d.w.r.}$ – dry waste residue

1.3. Waste disposal method of sewage sludge

Figure 1. presents the sludge management in Poland. The quantity of produced different sewage sludge in our country increase and the prevailing direction of sewage sludge utilization in Poland is disposed of by landfilling. In accordance with the Regulation of the Minister of Economy of 8 January 2013 (Regulation of the Minister of Economy of 8 January 2013), from January 2013 introduced a total ban on the storage of sewage sludge characterized by, among others, heat of combustion than 6 MJ/kg of dry matter. It is a very sharp criterion indicating the restriction on the use of sewage sludge for agricultural purposes.

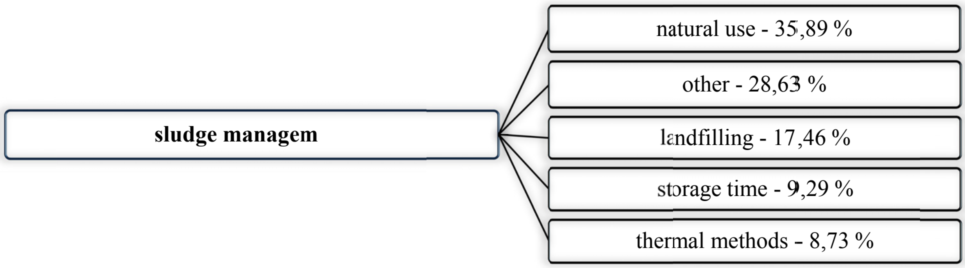

Fig. 1. Methods of sewage sludge disposal in Poland (Protection of the Environment, 2000-2012) (as at 31 XII 2011)

According to Fig. 2, sewage sludge thermally utilization in Poland is a small percentage of their disposal, but this is changing, because the thermal utilization of sewage sludge is a very important issue from the point of view of environmental, technical and economic. In other countries of the European Union thermal methods divert the greater role and they are more respected because of the controversial nature of sanitary and waste use.

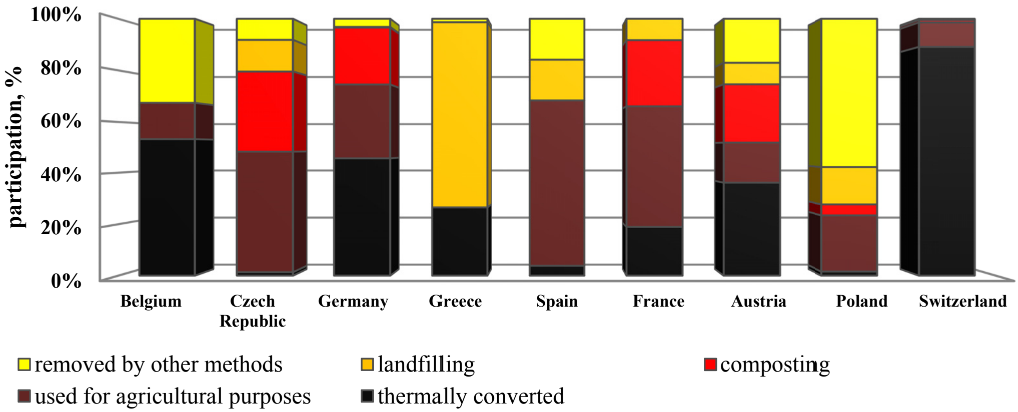

Fig. 2. The share of the different methods of disposing of sewage in some countries of the European Union (Eurostat data, 2006-2009; Protection of the Environment, 2011)

Figure 3 and 4 show the change in the use of sewage sludge in Poland in the years 1999-2011. We can observe the growing interest of thermal methods of this waste.

Figure 5. shows the thermal treatment of sewage sludge. Particularly note worthy co-combustion of the waste from the fuel basic, which is very important from the point of view of environmental protection. Figure 6 illustrates location plants in Poland, where there is the thermal utilization of sewage sludge. Should be highlighted here: 11 mono-incineration be distinguished sewage sludge, 20 thermal sewage sludge drying, 12 solar sewage sludge drying, 9 cement plants with lines of alternative fuels.

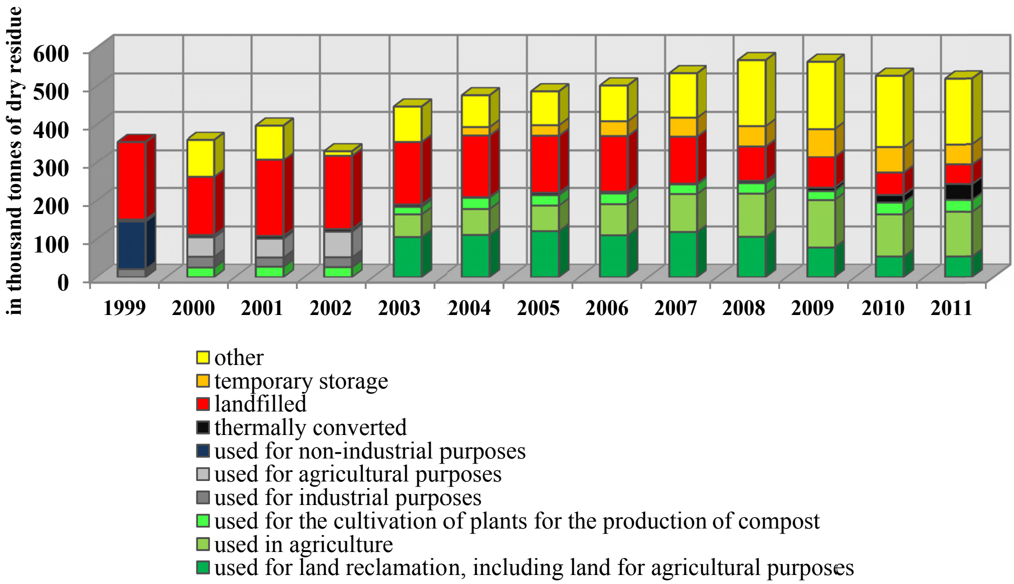

Fig. 3. Proceeding with sludge from municipal sewage treatment plants in the years 1999-2011 (Protection of the Environment, 2000-2012)

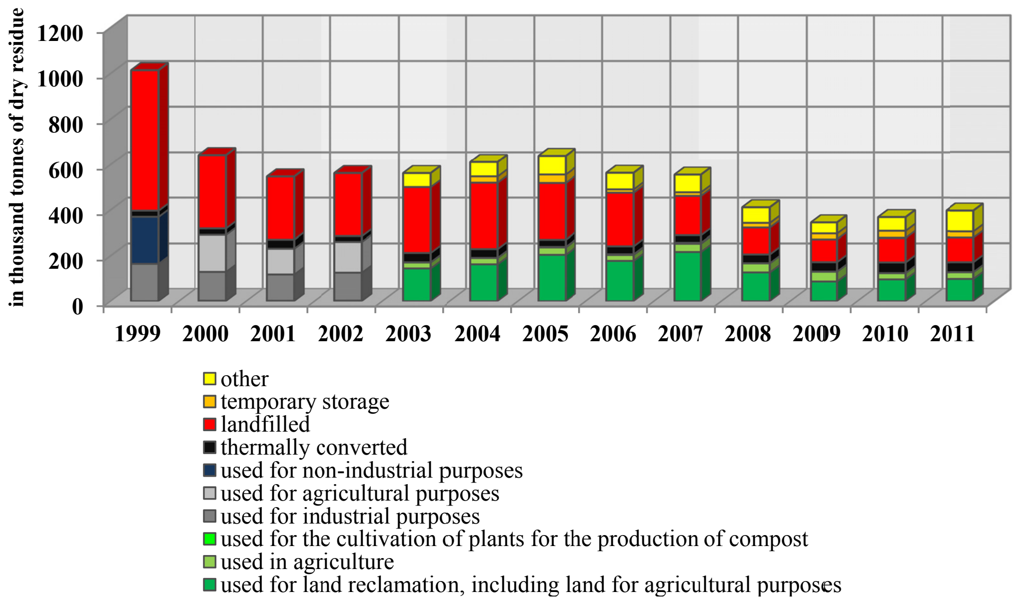

Fig. 4. Proceeding with sludge from industrial sewage treatment plants in the years 1999-2011 (Protection of the Environment, 2000-2012)

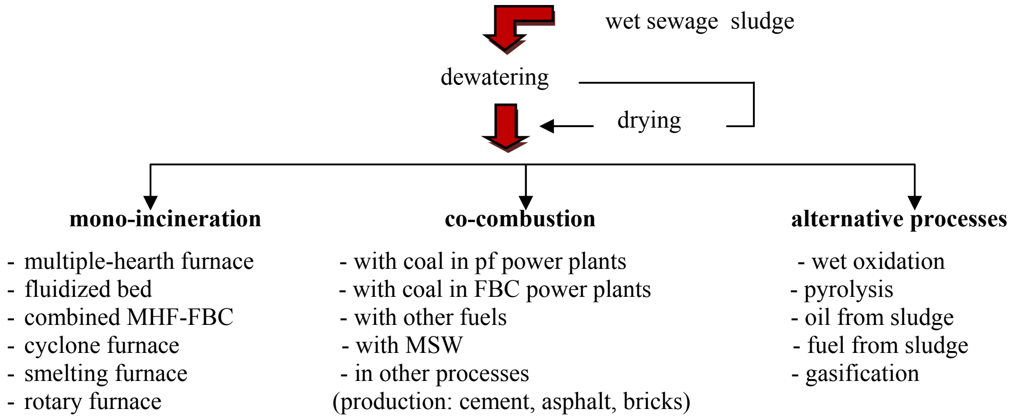

Fig. 5. Methods for thermal treatment of sewage sludge (Werther & Ogada, 1999)

Fig. 6. Thermal utilization of sewage sludge in Poland (Bień, 2013)

Table 2 shows that a full cost-incineration of sludge from waste is over 60% degree of dryness. This may be due to what product we want to achieve. Since the aim is to obtain granules of suitable mechanical strength of the above compounds, it should have suitable moisture content. However, in the case of sludge process is viable at a degree of drying of 35 to 45%. About this, in turn, may determine the type of dryer that we use in the preparation of sludge for further disposal.

TABLE 2

The degree of pre-drying of sludge as a function of the final development
(Heidrich & Witkowski, 2010; Skalmowski, 2006)

Way development	**Degree of drying**			**Purpose of drying**
	30÷40%	**60÷90%**	**above 90%**	
agriculture	uneconomic for reasons technical and economic	profitable	profitable	facilitate the transport and storage; stabilization and hygienization (above 90%)
combustion special furnaces	profitable (35÷45%)	uneconomic for reasons technical and economic	cost-effective (dryness the total solid part of the mixture to prepare the undried sludge containing 35÷45% $_{d.w.r.}$ before introduction into the furnace)	autothermal combustion
common combustion waste	uneconomic for reasons technical and economic	profitable	profitable	facilitate the exploitation of furnace, transport and storage
* $_{d.w.r.}$ – dry waste residue				

The issue of ownership, the methods of disposal of sewage sludge, their combustion and co-combustion with other fuels, as well as the effect of these processes on the environment is at the present time very important and widely described in the literature, both the national and the international, including: (Bień & Westalska, 2008; Bień & Gandor, 2011; Moroń et al., 2012; Werle, 2010, 2011; Li et al., 2009; Werther et al., 1995; Słowik et al., 2011; Pająk, 2010, 2012).

It emphasizes the specific behavior of sewage sludge combustion process, mainly resulting from the substantial hydration and the high content of mineral and volatiles matter.

Experiments on the sewage sludge combustion apply mainly the thermogravimetric researches, which designed to determine the kinetic parameters. It emphasizes the high reactivity and the low devolatilization temperature of these fuels, significantly lower than coal.

It should be emphasized basic differences between sewage sludge and conventional fuels, namely in the case of sewage sludge: high moisture and ash content and low calorific value, much of the content of harmful substances such as chlorine, sulfur, metals, excess emissions: CO, SO_2, NO_x, dust, WWA, dioxins and furans in the combustion process (Górski & Zabawa, 2008). The combustion of sewage sludge has both advantages and disadvantages, which should not be overlooked. The main advantages of the combustion of sewage sludge are: minimizing odors, a significant reduction in the volume of the starting material, the possibility of further use of fly ash, thermal destruction of organic, toxic ingredients, calorific value comparable to lignite (Werther & Ogada, 1999). The defects should however include: the presence of heavy metals in the ash and viscous phase (at 50-60% of the dry matter in the sediment), which affect the drying process; specific after treatment systems resulting from the diversity of contaminants present in the sediments. High moisture content affects the lack of auto-thermal combustion (the need to provide additional fuel) (Werther & Ogada, 1999).

Noteworthy combustion of sewage sludge in a fluidized-bed boilers. It has its own characteristics:

- high combustion efficiency and low gas volume (Gromiec & Koć, 2009),
- the possibility of mechanically dewatered sludge, partially dried and granulated (Pająk, 2003; Pająk & Wielgosiński, 2003),
- Germany: most of the mono-combustion installation (80%) using a fluidized-bed furnace (Podewils, 2012),
- Germany: the possibility of combustion materials containing much ballast the lower heating value (researches show that the systems work reliably for 30 years) (Podewils, 2012),
- German Regulation 17.BlmSchV: the ability of the maximum admixture of 25% of the sewage sludge to the primary fuel (Podewils, 2012),
- Japan: combustion of sewage sludge – a priority by the thermal utilization (Solmaz, 1999).

Combustion of sewage sludge in a fluidized bed furnace eliminates the need for deep drainage and drying of the fuel. Combustion in a circulating fluidized bed meets the tough conditions that we must overcome to efficiently and ecologically use these fuels.

Co-combustion of sewage sludge with other fuels is carried out:

- in rotary kilns in the cement industry
  - sewage sludge must have sufficient heating value, which should be dried at least 11,5 MJ/kg (according to the "Lafarge") or 14 MJ/kg (according to other cement plants). Another assumption is also the chlorine content exceeding 5% by weight placed on sewage sludge (Rosik-Dulewska, 2008),
  - thermal treatment of sludge in cement is a promising solution, resulting in the possibility of using waste heat for drying wet sludge and ash used to produce clinker (Stasta et al., 2006).
- with coal in power plants
  - participation of sewage sludge in the fuel to combustion should not exceed 5% (although sometimes it is suggested to increase their share to as high as 10%). The precipitate is directed to the combustion systems based on coal to be dried to 90% dry matter, while the brown coal – up to 25 (Heidrich & Witkowski, 2010; Skalmowski, 2006),
  - during co-combustion of sewage sludge with coal and wood (which are the basic fuel of EU) is not exceeded emissions (CO, NO_x and SO_2) in the case of participation of sewage sludge in a mixture of primary fuel, not exceeding 25% (Leckner et al., 2004).

2. Experimental studies

2.1. Characteristics of fuels used in researches

Table 3 shows the analysis of selected chemical properties of sewage sludge used in the study. Table 4 presents the elementary and technical analysis of sewage sludge in reference to coal and biomass. It should be noted the content of volatile matter and carbon in fuels and their calorific value significantly affect the combustion process.

TABLE 3

Analysis of selected chemical properties of sewage sludge used in the study

Rate	**Unit**	**Result research granules A**	**Result research granules B**	**Result research granules C**	**Permissible content heavy metals in municipal sewage sludge, according to Regulation Minister of the Environment of 13 July 2010. (for use in agriculture and land reclamation for agricultural purposes)**
Reaction	unit pH	7,4	7,0	7,8	
Water content	%	4,60	7,00	14,7	
Loss on ignition	%	55,6	64,2	56,4	
Ammonium	$\%_{\text{d.w.r.}}$ *	0,17	0,27	0,38	
Kjeldahl nitrogen	$\%_{\text{d.w.r.}}$ *	3,9	5,1	4,1	
Phosphorus	$\%_{\text{d.w.r.}}$ *	3,0	3,2	3,3	
Calcium	$\%_{\text{d.w.r.}}$ *	4,7	3,1	4,9	
Magnesium	$\%_{\text{d.w.r.}}$ *	0,53	0,67	0,73	
Cadmium	$\text{mg/kg}_{\text{d.w.r.}}$ *	5,9	2,3	< 1	to 20
Chromium org.	$\text{mg/kg}_{\text{d.w.r.}}$ *	340	160	80	to 500
Copper	$\text{mg/kg}_{\text{d.w.r.}}$ *	360	470	210	to 1000
Nickel	$\text{mg/kg}_{\text{d.w.r.}}$ *	190	97	19	to 300
Lead	$\text{mg/kg}_{\text{d.w.r.}}$ *	160	62	12	to 750
Mercury	$\text{mg/kg}_{\text{d.w.r.}}$ *	0,61	0,50	0,48	to 16
Zinc	$\text{mg/kg}_{\text{d.w.r.}}$ *	2400	950	1000	to 2500

* d.w.r. – dry waste residue

TABLE 4

Technical and elementary analysis of fuels used in studies

Fuel type	***Technical analysis***				***Elementary analysis***				
	Humidity content	**Content of volatile elements**	**Ash content**	**Heat of combustion**	**Content of coal element**	**Content of hydrogen element**	**Content of nitrogen element**	**Content of oxygen element**	**Content of total sulphur**
	W^a	V^a	A^a	Q_i^a	C_t^a	H_t^a	N^a	O_d^a	S_t^a
	%	%	%	kJ/kg	%	%	%	%	%
Brown coal	14,46	37,11	18,42	16165	43,16	3,08	0,55	19,81	0,52
Hard coal	2,66	30,90	2,36	31198	79,33	4,33	1,27	9,75	0,30
Anthracite	1,50	3,00	2,50	39350	93,00	1,70	0,06	1,01	0,23
Biomass (Grinding grain)	8,27	70,53	4,55	15825	40,90	6,07	2,73	37,30	0,18
Sewage sludge A	4,94	51,44	36,44	12574	30,77	3,92	4,26	18,23	1,44
Sewage sludge B	5,31	52,59	32,46	13801	32,43	4,30	5,47	18,42	1,61
Sewage sludge C	6,74	46,40	38,16	11104	27,50	3,72	4,24	18,73	0,91

2.2. Test stand and measurement methods

The experimental nature of the study conducted in a wide scope required preparation of a test stand and development of appropriate measurement methods. The combustion chamber (Fig. 7) was made of a ceramic block, inside which there were heating elements of the total power of 4,4 kW mounted in special grooves; they were necessary to obtain the desired temperature in the vicinity of fuel. The chamber was thermally insulated and covered with stainless steel sheet. As a temperature sensor in the measurement stand a NiCr-Ni thermocouple co-operating with a temperature controller was used. At 1/3 height of the combustion chamber there was a visualization glass of dimensions of 70×80 mm, allowing observation of the fuel combustion process. In the side wall of the combustion chamber there was a test entrance through which a fuel sample was fed on a chassis. Gases formed as a result of the fuel combustion process were taken into the stack through the expansion chamber and flue gas exhaust.

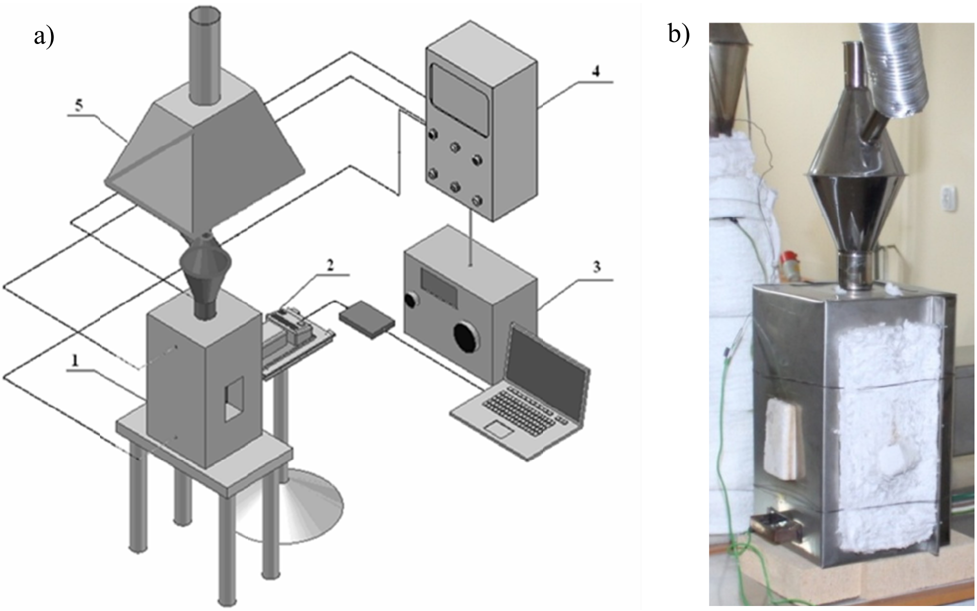

Fig. 7. Diagram of combustion chamber for fuel samples (no air intake): 1 – combustion chamber, 2 – measuring system, 3 – power controller, 4 – temperature control system, 5 – flue gas exhaust

The study consisted in observing and recording the process of fuel sample combustion placed in a specially shaped "basket" made of Pt-PtRh10 thermocouples, located in two thin quartz tubes, which were also the extension arm of an electronic laboratory scales (Mensor WM 002) of a measurement range up to 20 g and accuracy of 1 mg (Fig. 8). Such a design of the measurement system enabled registering changes in temperature inside and on the surface of the fuel sample and registering weight loss during the combustion process. One of the welds of the Pt-PtRh10 thermocouple was in fact in the fuel, while the second thermocouple weld, bent in the shape of a supporting "basket", touched the underside of the fuel surface. Fuel sample was introduced into the combustion chamber by means of a specially designed chassis. In order to register study results, thermocouples and the scales were connected to a measurement card connected to a computer.

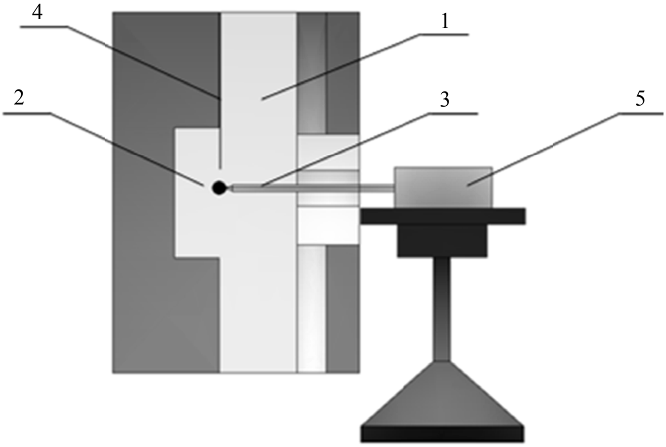

Fig. 8. Diagram of the measurement system: 1 – combustion chamber, 2 – fuel sample, 3 – Pt-PtRh10 thermocouples, 4 – NiCr-Ni thermocouple, 5 – scale

The research material forming sewage sludge was taken from a wastewater treatment plant in a large urban-industrial agglomeration. Sludge is created in a process line, in which the sludge together with the primary sludge, upon concentration, get to an oxygen-free digestion chamber in order to undergo the process of stabilization. Next, the sludge is dehydrated mechanically and dried to form hygienic granules of moisture content below 10%. Sewage sludge samples are in the form of spherical granules obtained from the wastewater treatment plant.

Coal and biomass samples were in the form of briquettes made using a briquetting machine prepared specifically for the test. For this purpose, it was necessary to prepare biomass and coal dust by grinding and sieving the fuel through a sieve (below 100 mm). The essence of the issue of combustion of coal fuel, also in form of coal-water slurry fuel, as well as its co-combustion with biomass under a variety of process conditions, was described, among others in the following works: (Kijo-Kleczkowska, 2009, 2010, 2011, 2012; Kijo-Kleczkowska et al., – in print; Pelka et al., – in print).

2.3. Experimental studies results

Studies indicated that high content of volatile matter in the fuel intensifies the initial stages of combustion, distinguished by more intensive reacting of the fuel, as evidenced by the change in mass of fuel mileage.

The fuel, upon introduction to a high-temperature unit (combustion chamber), slightly changes its size (depending on the type of fuel) in the subsequent stages of combustion, due to evaporation of water, release of volatiles and after-combustion of solid substances. Fuel formed from anthracite burns flamelessly, in contrast to fuels having lower content of carbon element.

The shortest combustion process takes place in case of fuels characterized by a lower carbon content and high proportion of volatiles.

Registering of the process of combustion of fuels indicated that the moment, when the surface of fuel reaches the maximum temperature corresponds to the moment when the volatile components emitted from the fuel are combusted upon ignition of degassed carbonising agent, which is visible as a "peak" in the graph illustrating temperature changes on the surface of the fuel. Analyzing the changes in temperature and mass of fuel samples with a diameter of 7,5 mm, at a temperature of 850°C (Fig. 9-15), it can be stated that upon introduction of fuel into the combustion chamber, its ignition takes place via the volatiles emitted from the fuel. From the moment of fuel ignition by means of volatiles, fuel surface temperature increases intensively, to eventually obtain the maximum value. Fuel ignition by means of volatiles also leads to an increase in temperature inside the fuel.

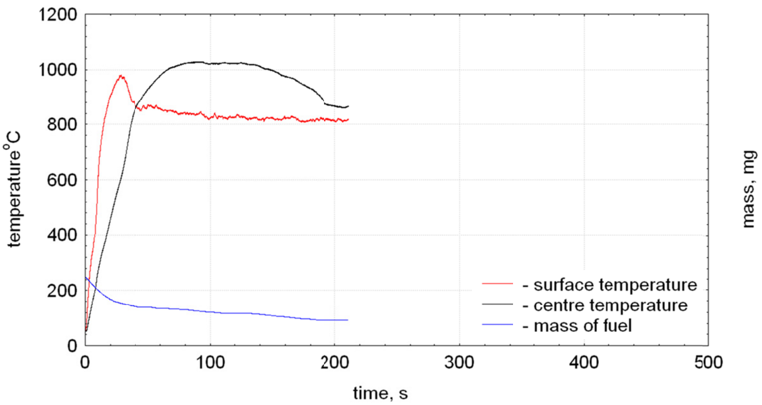

Fig. 9. The course of changes of surface and centre temperature and mass loss of sewage sludge A

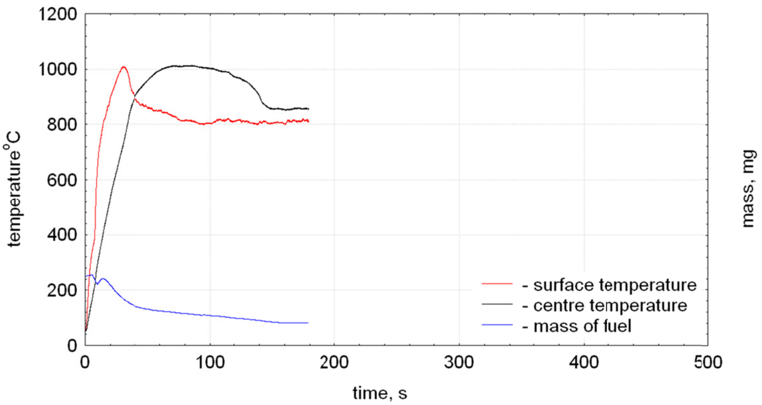

Fig. 10. The course of changes of surface and centre temperature and mass loss of sewage sludge B

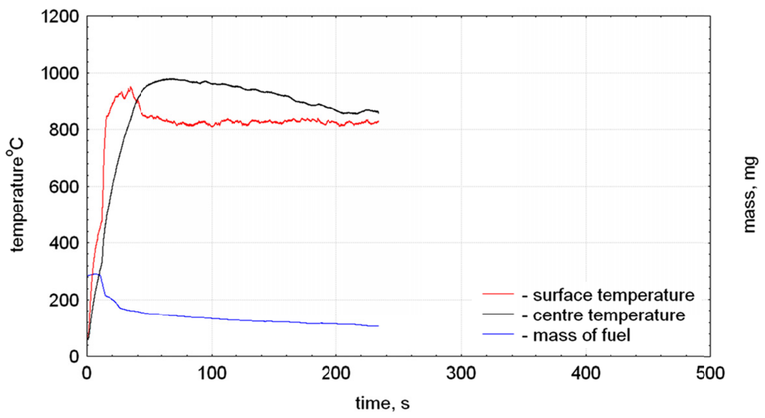

Fig. 11. The course of changes of surface and centre temperature and mass loss of sewage sludge C

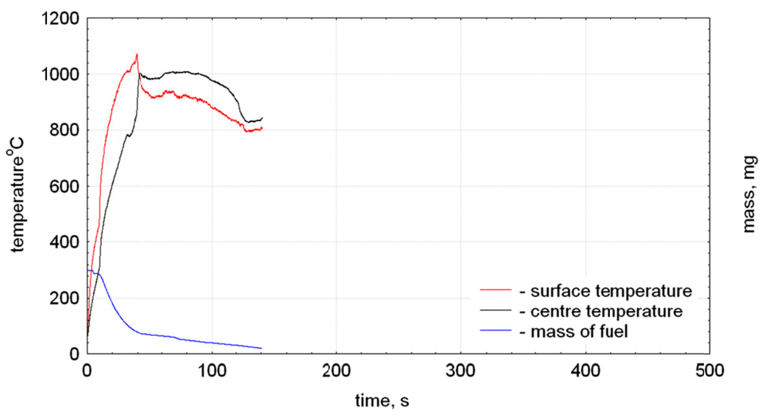

Fig. 12. The course of changes of surface and centre temperature and mass loss of biomass

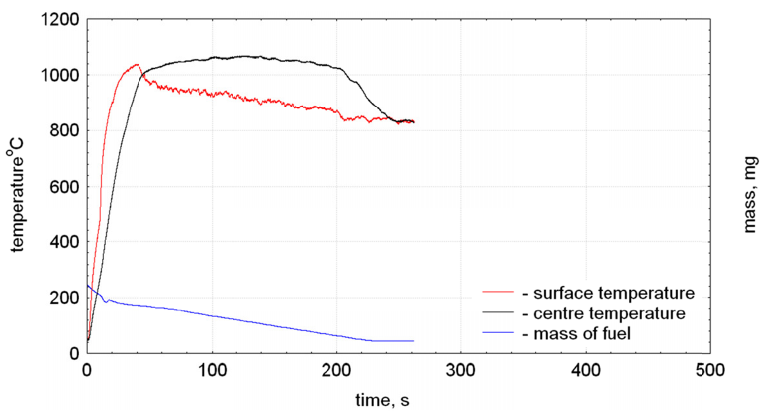

Fig. 13. The course of changes of surface and centre temperature and mass loss of brown coal

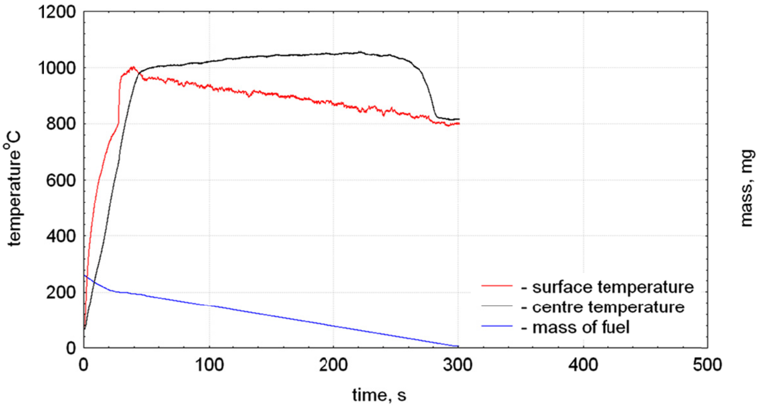

Fig. 14. The course of changes of surface and centre temperature and mass loss of hard coal

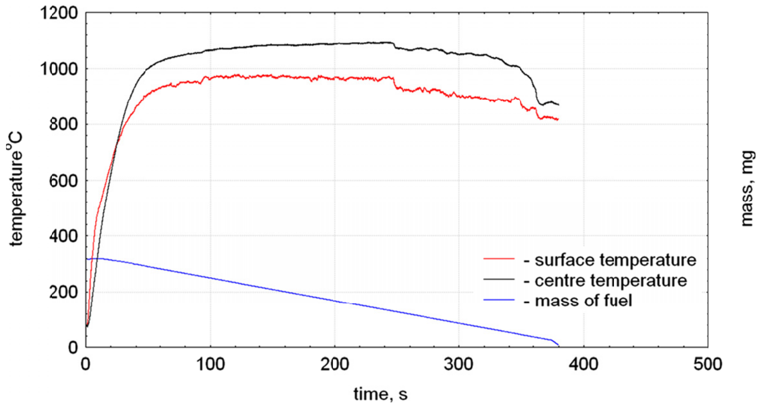

Fig. 15. The course of changes of surface and centre temperature and mass loss of anthracite

Studies into sewage sludge as well as coal and biomass showed much greater intensity of the process of combustion of sewage sludge and biomass as compared to coal, by, among others, lowering the ignition temperature (Fig. 16). The high content of volatiles matter and lower content of moisture in fuel lead to shorting of ignition time of fuel.

In the case of sewage sludge and biomass, degassing and combustion of volatile matter is an important step in the process of combustion. High content of moisture and oxygen in the sewage sludge and biomass makes the zone of combustion of volatiles emitted from the fuel more extensive in comparison to coal. The high content of volatiles matter and lower content of carbon element in fuel and its lower caloric value lead to decreasing of average temperature of fuels combustion (Fig. 17).

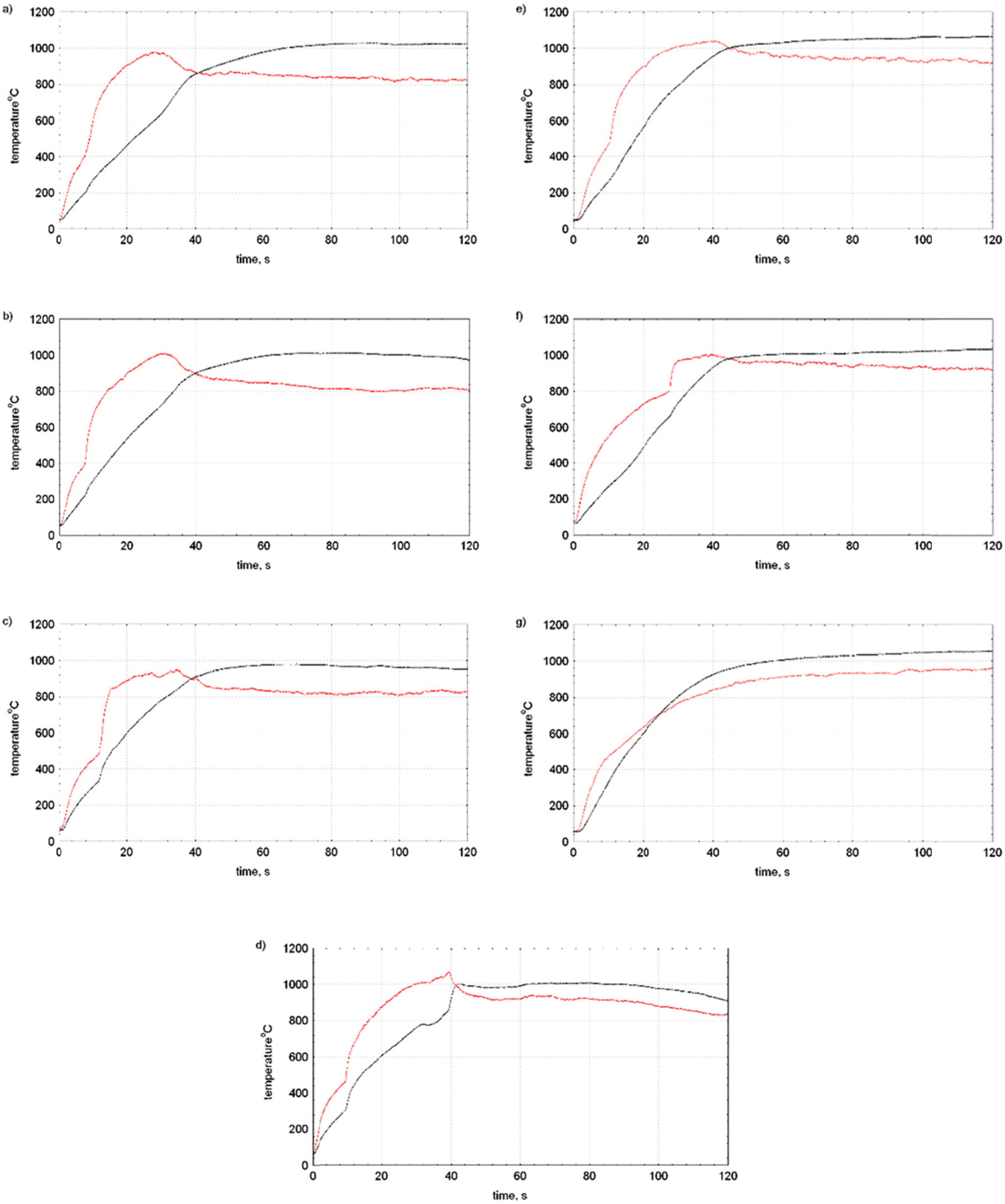

Fig. 16. Influence of fuel type on its ignition by means of volatiles
a – sewage sludge A, b – sewage sludge B, c – sewage sludge C, d – biomass, e – brown coal, f – hard coal, g – anthracite

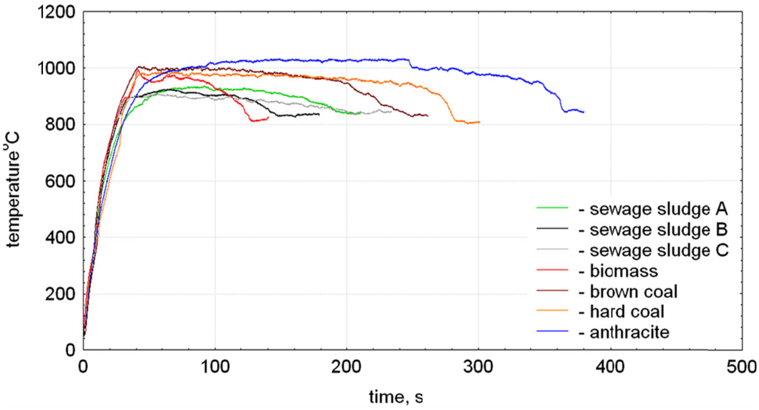

Fig. 17. An average temperature of fuels combustion

3. Conclusions

The experimental research and analysis of its results led to the following conclusions:

1. The shortest combustion process takes place in case of fuels characterized by a lower carbon content and high proportion of volatiles.
2. The composition and properties of the biomass and sewage sludge lead to intensification of the combustion process, resulting in, among others, reducing the fuel ignition temperature, compared to coal.
3. The high content of volatiles matter and lower content of moisture in fuel lead to shorting of ignition time of fuel.
4. The high content of volatiles matter and lower content of carbon element in fuel and its lower caloric value lead to decreasing of average temperature of fuels combustion.

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