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Combustion of alternative fuel composites containing municipal sewage sludge in power boilers

Eugeniusz Orszulik

Central Mining Institute

pl. Gwarków 1, 40–116 Katowice, Poland

Abstract

Municipal waste, including sewage sludge and biomass can be a source of energy in commercial energy generation and heating. The possibility of using municipal sewage sludge in heat installations in the power industry as a composite of alternative fuels is limited by type, homogeneity and fuel properties. The article presents the possibility of using waste—code 19 08 05 stabilized municipal sewage sludge as an admixture to hard coal and lignite as well as to biomass in the form of straw and wood. Energy recovery generated from alternative fuel composites will be conducted in boilers. The properties of the fuels and emissions of pollutants into the environment are presented.

Keywords: sewage sludge, fuel, combustion, boiler, emission

1. Introduction

The search for new energy sources is driven by the continued increase in demand for fossil fuels to generate heat and electricity [1–4]. Waste—code 19 08 05 stabilized municipal sewage sludge—presents an environmental problem [5]. This stems from the increase in sediment generation resulting from the expansion of waste water systems as well as the construction and expansion of wastewater treatment plants. Known waste water treatment methods do not fully solve the problem of the recovery or disposal of municipal sewage sludge [6–8]. The choice of disposal technology of this type of waste is tightly regulated [9–15]. Methods known from the literature [1, 16–21] have not developed a way of combustion or co-combustion of municipal sewage sludge in dust boiler burners. In the present work, [22] a test has been conducted, based on managing stabilized municipal sewage sludge by thermal disposal in the D10 process [10] by co-combustion with hard coal and lignite as well as with biomass in the form of cereal straw and wood chips. The research was aimed at the possibility of using alternative fuel composites containing sewage sludge as fuel for energy boilers equipped with dust burners. The use of hard coal and lignite, biofuels such as straw and wood chips as used in the tests, their extraction and acquisition are all dependent on the economic situation [1, 23].

2. Research methodology

The research sought to determine the thermal properties and the measure the emissions of dust and gaseous substances emitted to the atmosphere and pollutants to the ground (waste slag and ash) arising during and after the process of co-combustion of

*Corresponding author
Email address: e.orszulik@gig.katowice.pl (Eugeniusz Orszulik)

composites of alternative fuels containing municipal sewage sludge as a fuel to power boilers equipped with dust burners. The following flammable mixtures were selected for testing:

- waste—code 19 08 05 stabilized municipal sewage sludge with hard coal,
- waste—code 19 08 05 stabilized municipal sewage sludge with lignite,
- waste—code 19 08 05 stabilized municipal sewage sludge with wood chips,
- waste—code 19 08 05 stabilized municipal sewage sludge with cereal straw.

Measurements and tests were carried out in accordance with the relevant regulations [24–28]. The scope of the study included the following:

- testing the physical and chemical properties of the fuels: hard coal, lignite and biomass, i.e., cereal straw, wood chips and waste—code 19 08 05 stabilized municipal sewage sludge used at the time of the tests [5];
- emission of gaseous and dust pollutants emitted to air during the combustion of flammable mixtures, analysis of the concentrations of dust and gases in the outflow gases;
- thermal measurements, i.e., the heat produced by the combustion of flammable mixtures, heat load calculation;
- determining the energy efficiency of the boiler during the combustion of flammable mixtures;
- testing slag and ash to determine the content of flammable parts and trace elements obtained after the combustion of flammable mixtures.

The tests and measurements were carried out on a test post, which was equipped with a 5 kW laboratory water boiler. The boiler was equipped with a mechanical fuel feeder, which was directly connected with a dust burner. The test post was equipped with measuring and control apparatus for continuous and periodic measurement:

- of the temperature of the water supplying the boiler,
- of the temperature of the water coming back from the boiler,
- of water pressure in the boiler,
- of the flow of water through the boiler,
- of exhaust gas composition, i.e., O_2, CO_2, CO, NO_2, SO_2,
- of the aassociated organic carbon content,
- of the hydrogen fluoride and hydrogen chloride content,
- of the concentration of dust in exhaust gas,
- of polluting substances emitted to the ground in order to determine the applicability of the products of combustion in the form of slag and ash into a group of types of land which could be utilized [29].

The boiler had a feeder for flammable mixtures, a PID controller to control the work of the boiler as regards the heating water temperature in the system. At the time of the tests, control of the combustion process of flammable mixtures and heat generation was based primarily on the maintenance of thermodynamic parameters through air supply to the combustion and analysis of the composition of the exhaust gas leaving the combustion chamber for a specified boiler load. Fig. 1 shows the layout of the measuring and control system of the test post.

2.1. Flammable mixtures used in testing

The composition of flammable mixtures was determined on the basis of the obtained research into the energy properties of the fuels, biomass and waste:

- hard coal—fine coal MII,
- lignite—fine brown coal II,
- wood chips (biomass),
- cereal straw (biomass),

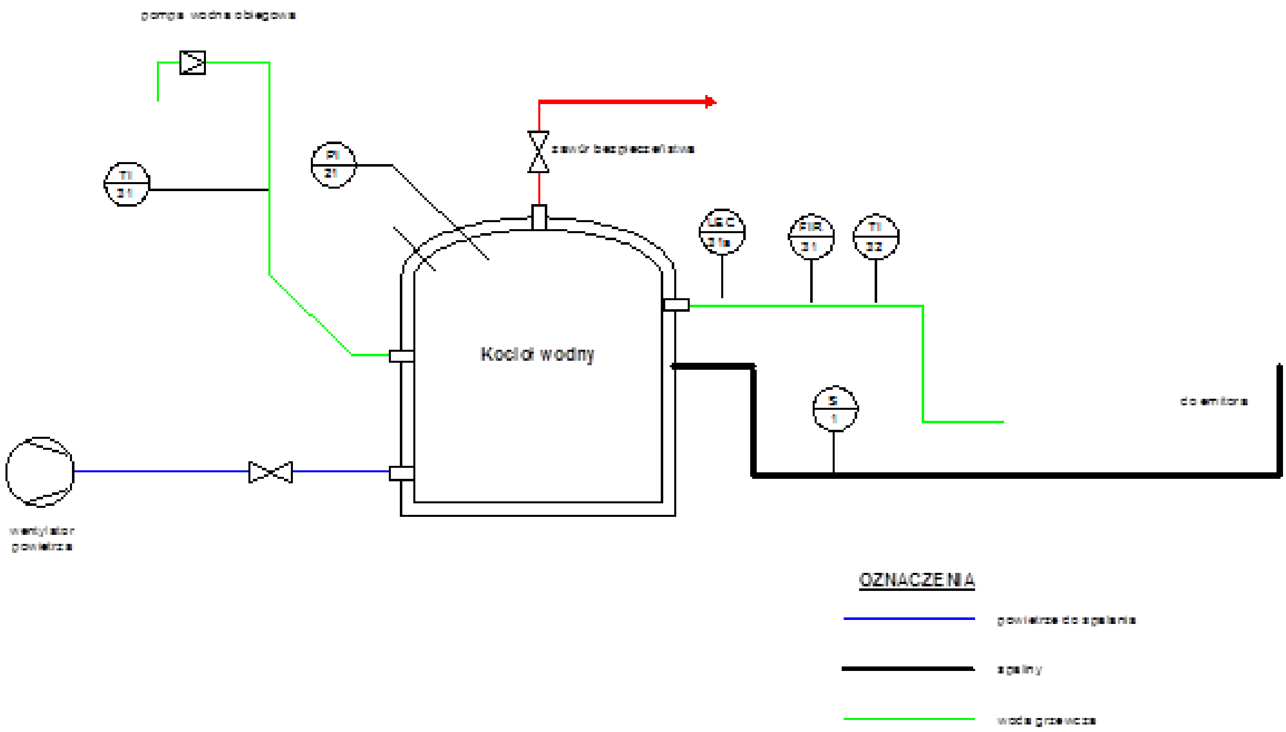

Figure 1: The post for testing the water boiler during the combustion of flammable mixtures

Table 1: Properties of the fuels used for thermal and environmental tests

Number	Specification	Fuel: hard coal	lig-nite	cereal straw	wood chips	waste—code 19 08 05 stabilized municipal sewage sludge
1	calorific value, kJ/kg	22033	8133	13218	7585	12846
2	sulfur content, %	1.02	0.47	0.39	0.02	0.93
3	ash content, %	7.21	11.07	6.55	1.21	28.48
4	moisture content, %	20.22	52.16	19.86	50.82	14.04
5	chlorine content, %	0.095	0.046	0.254	0.00	0.075

- waste—code 19 08 05—stabilized municipal sewage sludge (biomass) after drying and stabilizing.

Properties of used fuels, biomass and stabilized municipal sewage sludge as ingredients of flammable mixtures for thermal and environmental testing are presented in Table 1.

Features of the fuel, biomass and stabilized municipal sewage sludge used in the test:

- hard coal had the highest calorific value (22,033 kJ/kg), and wood chips the lowest (7,585 kJ/kg),
- hard coal had the highest sulfur content (1.02%), and wood chips the lowest (0.02%),
- lignite had the highest ash content (11.1%), and wood chips the lowest (1.21%),
- lignite had the highest moisture content (52.2%), and cereal straw the lowest (19.9%),
- cereal straw had the highest chlorine content (0.254%), and wood chips the lowest (0.00%).

Waste—code 19 08 05—stabilized municipal sewage sludge had the calorific value of 12,846 kJ/kg, which was higher than the limit set out in the Regulation of the Minister of Economy [14]. For this reason, the waste should not be stored at a dumping site.

The composition of flammable mixtures was determined after the established criteria:

- the average calorific value should be a minimum 8.0 MJ/kg,
- sulfur content should be 0.6%,
- ash content should be 15%,
- chlorine content should be 5%,
- moisture content should be 20%.

The criteria were established on the basis of the coals currently used for power generation and heating, mostly lignite in dust boilers.

Table 2 presents the results obtained from testing the fuels, biomass and stabilized municipal sewage sludge compositions of flammable mixtures, and Table 3 presents the properties of flammable mixtures used for thermal and environmental tests.

Table 2: The composition of the flammable mixtures for thermal and environmental tests

Mixture	Fuel	Waste—code 19 08 05 stabilized municipal sewage sludge
No I	hard coal—80% of the mass	20% of the mass
No II	lignite—20% of the mass	80% of the mass
No II	cereal straw—50% of the mass	50% of the mass
No IV	wood chips—15% of the mass	85% of the mass

Flammable mixtures: No I, II, III and IV meet the established criteria.

The best energy properties are obtained by flammable mixture No I—waste—19 08 05 stabilized municipal sewage sludge with hard coal. The mixture has a high calorific value (20,094 kJ/kg), low ash content of 12.50%, but a high sulfur content of 0.9%.

The worst energy properties are obtained by flammable mixture No II—waste—code 19 08 05 stabilized municipal sewage sludge with lignite. It has a very low calorific value (8,112 kJ/kg), low ash content of 13.55% and sulfur of 0.43% and a high moisture content of 46.71%. The properties of mixture No II are comparable to the lignite burned in BOT power plants.

The chlorine content in flammable mixtures No I, II, III and IV is very low, which will require maintenance of the combustion process to ensure that the temperature of the exhaust gases is above 850°C for at least 2 seconds [30, 31].

Table 3: Properties of the flammable mixtures for thermal and environmental testing

Number	Specification	Flammable mixture			
		No I	No II	No III	No IV
1	calorific value, kJ/kg	20,094	8,112	13,315	8,070
2	sulfur content, %	0.90	0.62	0.43	0.08
3	ash content, %	12.50	14.74	13.55	3.20
4	moisture content, %	21.02	46.71	25.64	47.67
5	chlorine content, %	0.070	0.049	0.018	0.024

2.2. *Determining the energy efficiency of the boiler during the combustion of flammable mixtures*

Boiler energy efficiency [32] at the time of the combustion of flammable mixtures was determined by the definition for the tested combustible mixture, taking into account the supplied energy flow as the chemical energy contained in the mixture:

$$\eta = \frac{Q_N}{Q_Z} \tag{1}$$

where: Q_N—flow of the energy brought out, kW; Q_Z—flow of supplied energy, kW.

Boiler efficiency determined by the formula (1) refers to a specific point of the boiler heat load (at the time of measurement). Stream energy brought out from the water boiler:

$$Q_N = \dot{m}\,(h_2 - h_1) \tag{2}$$

where: Q_N—determined thermal useful power, kW; $\dot{m}$—hot-water mass flow, kg/s; h_2—enthalpy of water at the average temperature of outflow, t_2, kJ/kg; h_1—enthalpy of water at the average temperature on inflow, t_2, kJ/kg.

The stream of energy supplied to the boiler:

$$Q_Z = \dot{m}\left[(H_{(N)} + h_F) / (1 - l_u) + J_{(N)A}\right] \tag{3}$$

where: Q_Z—flow of supplied energy, kW; $\dot{m}$—flow of fuel mass, kg/s; $H_{(N)}$—the calorific value of fuel at reference temperature, t_r, kJ/kg; h_F—fuel enthalpy: $h_F = c_F\,(t_F - t_r)$, kJ/kg; c_F—proper heat capacity of fuel, kJ/kg/K; t_F—fuel temperature, °C; t_r—reference temperature, °C; l_u—non-burnt fuel flow mass to flow of supplied fuel mass ratio: $l_u = m_{Fu}/m_{Fo}$; $J_{(N)A}$—enthalpy of combustion air: $J_{(N)A} = \mu_A C_{pA}\,(t_A - t_r)$, kJ/kg; C_{pA}—proper heat capacity of air, kJ/kg/K; μ_A—air mass to fuel mass ratio; t_A—air temperature at the border of the balance cover, °C .

2.3. *Study of solid products—slag and ash obtained after the combustion of flammable mixtures*

The chemical composition of the solid waste obtained after the combustion of flammable mixtures—slag and ash—was tested for trace elements [33]. The concentrations of heavy metals in the samples were compared to the soil and land standards contained in the Regulation of the Minister of the Environment [24] with regard to (current and planned land development) groups of types of land where they can be stored.

3. The results of the tests and measurements from co-combustion of flammable mixtures

3.1. *Combustion of flammable mixture No I*

A study of the combustion of flammable mixture No I—stabilized municipal sewage sludge with hard coal was carried out for a heat load laboratory boiler of 85 ± 5%. Thermal-emission tests were aimed at determining the energy efficiency of the boiler and the emission values occurring during the combustion of flammable mixture No I. The thermal-emission test results for flammable mixture No I are presented in Table 4. At the time of the thermal-emission test, the Table 7 contains which values were obtained.

values:

Table 4: Thermal-emission test results obtained during combustion of flammable mixtures

Mixture	Water temperature, °C		Water	Energy	Water pressure	Fuel	Coefficient of	Boiler	Boiler	content of combustible
No	Supply	Return	flow, kg/h	generated, kW	in the boiler, bar	consumed, kg/h	air excess λ	load, %	efficiency ,%	parts in ash and slag, %
I	46.70	65.45	21.51	0.5	0.1	0.15	1.38	86	79.65	42.09
II	43.70	61.48	43.06	1.01	0.1	0.45	1.33	80	62.22	42.09
III	45.12	63.12	14.56	0.33	0.1	0.16	1.25	83	61.8	10.33
IV	45.12	63.12	14.56	0.33	0.1	0.16	1.25	83	61.8	10.33

Table 5:

No	Unit	O_2,%	CO_2,%	SO_2*/	NO_2*/	CO*/	Dust*/	OGC*/	HCL	HF
I	mg/m^3	11.3	9.5	1105.7	146.3	457	30	0.15	13	p.o
	kg/h			0.012	0.002	0.005	0.003	0.00000	0.00014	p.o
II	mg/m^3	13.0	7.8	211.8	134.8	1098.6	122	0.89	8	p.o
	kg/h			0.002	0.001	0.010	0.003	0.00014	0.00008	p.o
III	mg/m^3	12.8	7.6	637	217	966	565	2.5	3	p.o.
	kg/h			0.002	0.001	0.010	0.003	0.00000	0.00005	p.o.
IV	mg/m^3	16	4.7	396	297	902	233	0.26	758	p.o.
	kg/h			0.003	0.002	0.006	0.016	0.00000	0.005	p.o.

*/—with oxygen content of 10% in the exhaust gas in the contractual conditions at a temperature of 273 K and pressure of 101.3 kPa and the boiler heat

Table 7:

Specification	Result	Permissible	values per	PN-EN 303-5
Boiler efficiency in accordance with PN-EN 303-5			81	
Concentration of dust and			Class	
gaseous substances emitted into the air, %		3	4	5
dust, mg/m^3	30	150	60	40
OGC, mg/m^3	0.15	80	30	20
sulfur dioxide, mg/m^3	1106	-	-	-
nitrogen dioxide, mg/m^3	146	-	-	-
carbon monoxide, mg/m^3	457	3000	1000	500

Table 6:

No	Energy generated, kW	Fuel consumed, kg/h	Boiler load, %	Boiler efficiency, %
I	0.5	0.15	86	80
II	1.01	0.45	80	62
III	0.33	0.16	83	62
IV	0.25	0.196	80	73

Thermal and emission values of the boiler obtained during combustion of flammable mixture No I were compared against the maximum permissible emission concentrations contained in standard PN-EN 303-5: 2012 [28]—see Table 7.

Emission values obtained during the test combustion of flammable mixture No I (waste—code 19 08 05 stabilized municipal sewage sludge with hard coal) meet class 5 (highest) emission value requirements with regard to PN-EN 303-5: 2012 standard [28]. Solid product tests—slag and ash—obtained from the combustion process of flammable mixture No I were aimed at identifying factors with a view to assessing potential use as raw materials in the construction industry or farming. The results of analysis of solid product—ash and slag—obtained from the combustion process of flammable mixture No I are provided in Table 8. Table 9 shows a comparison of the concentrations of trace elements obtained in testing. The obtained concentrations were compared to the soil and land standards contained in the Regulation of the Minister of the Environment [24].

The test results presented in tables 8 and 9 for the tested sample of the waste—slag and ash obtained after the combustion of flammable mixture No I contain values higher than the maximum permissible concentrations for soil and land quality standards with regard to surface land assigned to groups A and B [24]. The sample meets the requirements of Group C land development—industrial, mining and transport areas, developed at a depth of 0.3...15 m bgl. [24].

Table 8: Trace element content of the solid product—ash and slag—obtained after the combustion of flammable mixture No I

Trace element	Obtained value,	mg/kg
Silver, Ag	<2	<2
Arsenic As	<2	<2
Barium Ba	3052	692
Cadmium Cd*	2	<2
Cobalt Co *	28	6
Chrome Cr *	153	35
Copper Cu *	113	26
Manganese, Mn	580	132
Molybdenum Mo	3	<2
Nickel Ni *	104	24
Lead Pb *	128	29
Rubidium, Rb	99	22
Antimony, Sb	<2	<2
Tin, Sn	11	2
Strontium, Sr	486	110
Vanadium, V	113	26
Zinc, Zn *	404	92

/*as per the Regulation of the Minister of the Environment [24]

3.2. *Test combustion of flammable mixture No II*

Test combustion of flammable mixture No II—stabilized municipal sewage sludge with lignite was carried out for a heat load laboratory boiler of 85±5%. The thermal-emission tests were aimed at determining the energy efficiency of the boiler and the emission values occurring during the combustion of flammable mixture No II. The thermal-emission test results of flammable mixture No II were shown in Table 4.

At the time of the thermal-emission test the following values were obtained as in Table 5.

*/—with oxygen content of 10% in the exhaust gas in the contractual conditions at a temperature of 273 K and pressure of 101.3 kPa

and the boiler heat values are given in Table 6.

Thermal and emission values of the boiler obtained during combustion of flammable mixture No II were compared against the maximum permissible emission values contained in standard PN-EN 303-5: 2012 [28], see Table 10.

Table 9: Maximum permissible concentrations in the soil or land, compared against the results obtained from analyses of the test sample of the solid product—ash and slag—from combustion of flammable mixture No I

Element	Land *			Value determined for flammable mixture No I
	Group A	Group B	Group C	
	Depth in m bgl			
		0...0.3	0...2.0	
	mg/kg s.m.			
I Metals				
As	20	20	60	<2
Ba	200	200	1000	692
Cd	1	4	15	<2
Co	20	20	200	6
Cr	50	150	500	35
Cu	30	150	600	26
Mo	10	10	250	<2
Ni	35	100	300	24
Pb	50	100	600	29
Sn	20	20	350	2
Zn	100	300	1000	92

Table 10:

Specification	Result	Permissible	values per	PN-EN 303-5
Boiler efficiency in accordance with PN-EN 303-5			62	
Concentration of dust and			Class	
gaseous substances emitted into the air, %		3	4	5
dust, mg/m^3	122	150	60	40
OGC, mg/m^3	1	80	30	20
sulfur dioxide, mg/m^3	212	-	-	-
nitrogen dioxide, mg/m^3	135	-	-	-
carbon monoxide, mg/m^3	1099	3000	1000	500

Table 11: Trace element content of the solid product—ash and slag—obtained after the combustion of flammable mixture No II

Marking	Marked value,	mg/kg
Silver, Ag	<2	<2
Arsenic As	36	5
Barium Ba	1311	194
Cadmium Cd*	6	<2
Cobalt Co *	72	11
Chrome Cr *	357	53
Copper Cu *	127	19
Manganese, Mn	575	85
Molybdenum Mo	<2	<2
Nickel Ni *	248	37
Lead Pb *	195	29
Rubidium, Rb	67	10
Antimony, Sb	<2	<2
Tin, Sn	<2	<2
Strontium, Sr	887	131
Vanadium, V	83	12
Zinc, Zn *	269	40

Emission values obtained during the tests of the combustion of flammable mixture No II (waste—code 19 08 05 stabilized municipal sewage sludge with lignite) meet class 3 (lowest) emission value requirements with regard to PN-EN 303-5: 2012 standard [28]. Solid product tests—slag and ash—obtained from the combustion process of flammable mixture No II were aimed at the identifying factors with a view to assessing potential use as raw materials in the construction industry or farming. The results of the analyses are provided in Table 12 provides a comparison of the concentration values of trace elements in combustion tests of flammable mixture No II against the soil and land standards contained in the Regulation of the Minister of the Environment [24].

The test results presented in tables 11 and 12 for the tested sample of the waste—slag and ash obtained after the combustion of flammable mixture No II, contain values higher than the maximum permissible concentrations for soil and land quality standards with regard to surface land assigned to groups A and B [24]. The tested sample meets the requirements of Group C land development—industrial, mining and transport areas, developed at a depth of 0.3...15 m bgl. [24].

3.3. Test combustion of flammable mixture No III

Test combustion of flammable mixture No III—stabilized municipal sewage sludge with cereal straw was carried out for a heat load laboratory boiler of 85 ± 5%.

The thermal-emission tests were aimed at determining the energy efficiency of the boiler and the emission values occurring during the combustion of flammable mixtures No III. The thermal-emission test results of flammable mixture No III were shown in Table 4.

At the time of the thermal-emission study the following values were obtained as in Table 5 and the boiler heat values are given in Table 6.

Thermal and emission values of the boiler obtained during combustion of flammable mixture no III were compared against the maximum permissible emission concentrations contained in standard PN-EN 303-5: 2012—see Table 13.

Emission values obtained during the tests of the combustion of flammable mixture No III (waste—code 19 08 05 stabilized municipal sewage sludge with cereal straw) meet class 3 (lowest) emission value requirements with regard to PN-EN 303-5: 2012 standard [28].

Solid product tests—slag and ash obtained from the combustion process of flammable mixture NO III—were aimed at identifying factors with a view to assessing potential use as raw materials in the construction industry or farming. The results of the analysis are provided in Table 14.

Table 15 provides a comparison of the concentration values of trace elements in the solid product—slag and ash—obtained in combustion tests of flammable mixture No III against the soil and land standards contained in the Regulation of the Minister of the Environment [24].

Results of tests contained in Tables 14 and 15 for the tested sample of waste—slag and ash obtained after the combustion of flammable mixture No III—waste—code 19 08 05 stabilized municipal sewage

Table 12: Maximum permissible concentrations in the soil or land, compared against the results obtained from analysis of the test sample of the solid product—ash and slag—from combustion of flammable mixture No II

Element	Land * Group A	Group B	Group C	Value determined for sample: flammable mixture No II
	Depth in m bgl			
		0–0.3	0–2.0	
	mg/kg s.m.			
I Metals				
As	20	20	60	<2
Ba	200	200	1000	50
Cd	1	4	15	194
Co	20	20	200	<2
Cr	50	150	500	11
Cu	30	150	600	53
Mo	10	10	250	19
Ni	35	100	300	85
Pb	50	100	600	<2
Sn	20	20	350	37
Zn	100	300	1000	29

/*by the Regulation of the Minister of the Environment dated 9 September 2002 on soil and ground quality standards—Dz. U. 02.165.1358 (Journal of Laws 02.165.1358).

Table 13:

Specification	Result	Permissible	values per	PN-EN 303-5
Boiler efficiency in accordance with PN-EN 303-5			73	
Concentration of dust and	Class			
gaseous substances emitted into the air, %		3	4	5
dust, mg/m^3	233	150	60	40
OGC, mg/m^3	0	80	30	20
sulfur dioxide, mg/m^3	396	–	–	–
nitrogen dioxide, mg/m^3	297	–	–	–
carbon monoxide, mg/m^3	902	3000	1000	500

Table 14: Trace element content of the solid product—ash and slag—obtained after the combustion of flammable mixture No III

Marking	Marked value,	mg/kg
Silver, Ag	<0.02	<0.19
Arsenic, As	<0.02	<0.19
Barium, Ba	<0.005	<0.047
Cadmium, Cd *	<0.02	<0.19
Cobalt, Co *	<0.02	<0.19
Chrome, Cr *	<0.02	<0.19
Copper, Cu *	0.04	0.37
Manganese, Mn	<0.05	<0.47
Molybdenum, Mo	<0.05	<0.47
Nickel, Ni *	<0.02	<0.19
Lead, Pb *	<0.02	<0.19
Rubidium, Rb	<0.02	<0.19
Antimony, Sb	<0.02	<0.19
Tin, Sn	0.03	0.28
Strontium, Sr	<0.02	<0.19
Vanadium, V	<0.02	<0.19
Zinc, Zn *	<0.005	<0.047

Table 15: Maximum permissible concentrations in the soil or land, compared against the results obtained from analysis of the test sample of the solid product—ash and slag—from combustion of flammable mixture No III

Element	Land *			Value determined for sample: Flammable mixture No III
	Group A	Group B	Group C	
	Depth in m bgl			
		0–0.3	0–2.0	
	mg/kg s.m.			
	I Metals			
As	20	20	60	<0.19
Ba	200	200	1000	<0.19
Cd	1	4	15	<0.047
Co	20	20	200	<0.19
Cr	50	150	500	<0.19
Cu	30	150	600	<0.19
Mo	10	10	250	0.37
Ni	35	100	300	<0.47
Pb	50	100	600	<0.47
Sn	20	20	350	<0.19
Zn	100	300	1000	<0.19

/*per the Regulation of the Minister of the Environment dated 9 September 2002 on soil and land quality standards—Dz. U. 02.165.1358 (Journal of Laws 02.165.1358);

sludge with cereal straw showed values lower than the maximum permissible concentrations for soil and land quality in relation to surface grounds assigned to groups A, B and C [24]. The sample meets the requirements for application in development of land:

1. Group A:
   (a) land in a protected area under the regulations of the Water Law,
   (b) areas subject to protection under nature protection regulations, if maintaining the current level of land pollution does not pose a threat to human health or the environment—for these areas, the concentrations are in accordance with standards resulting from the current state;
2. Group B: land classified as agricultural land except land under ponds and ditches, forest land, land with a high amount of woods and bushes, waste land as well as built-up and urbanized land, with the exception of industrial land, mining areas and transport areas;
3. Group C: industrial, mining and transport areas;

developed to a depth of 0.3...15 m bgl. [24].

3.4. Test combustion of flammable mixture No IV

Test combustion of flammable mixture No IV, stabilized municipal sewage sludge with wood chips was carried out for a heat load laboratory boiler of 85 ± 5%.

The thermal-emission tests were aimed at determining the energy efficiency of the boiler and the emission values occurring during the combustion of flammable mixture No IV. The thermal-emission test results of flammable mixture No IV are shown in Table 4.

Table 17: Trace element content of the solid product—ash and slag—obtained after the combustion of flammable mixture No IV

Element	Flammable mixture Value,	No IV mg/kg
Silver, Ag	<0.02	<0.19
Arsenic, As	0.12	1.16
Barium, Ba	<0.005	<0.048
Cadmium, Cd *	<0.19	1.84
Cobalt, Co *	0.25	2.42
Chrome, Cr *	<0.02	<0.19
Copper, Cu *	0.15	1.45
Manganese, Mn	<0.05	<0.48
Molybdenum, Mo	<0.05	<0.48
Nickel, Ni *		0.3
Lead, Pb *	<0.02	<0.19
Rubidium, Rb	<0.02	<0.19
Antimony, Sb		<2
Tin, Sn	0.03	0.29
Strontium, Sr	<0.02	<0.19
Vanadium, V	0.12	1.16
Zinc, Zn *	<0.005	<0.048

At the time of the thermal-emission study the following values were obtained as in Table 5 and the boiler heat values are given in Table 6.
Thermal and emission values of the boiler obtained during combustion of flammable mixture No IV were compared against the maximum permissible concentrations contained in standard PN-EN 303-5: 2012 [28]—see Table 16.

Emission values obtained during the tests of the combustion of flammable mixture No IV (waste—code 19 08 05 stabilized municipal sewage sludge with wood chips) meet class 3 (lowest) emission value requirements with regard to PN-EN 303-5: 2012 standard [28].
Solid product tests—slag and ash obtained from the combustion process of flammable mixture NO IV—were aimed at identifying factors with a view to assessing the solid product—ash and slag for potential use as a raw material in the construction industry or farming. The results of the analyses are provided in Table 17.
Table 18 shows a comparison of the solid products—ash and slag obtained in tests of concentrations of trace elements from the combustion process flammable mixture No IV. The obtained metal concentrations were compared against the soil and land standards contained in the Regulation of the Minister of the Environment [24].
The test results presented in Tables 17 and 18 for the tested sample of the waste—slag and ash obtained after the combustion of flammable mixture No IV, contain values lower than the maximum permissible concentrations for soil and land quality standards with regard to surface land assigned to groups A, B and C [24]. The sample meets the requirements for application areas of land development:

1. Group A:
   (a) land in a protected area under the regulations of the Water Law,
   (b) areas subject to protection under nature protection regulations, if maintaining the current level of land pollution does not pose a threat to human health or the environment—for these areas, the concentrations are in accordance with standards resulting from the current state;
2. Group B: land classified as agricultural land except land under ponds and ditches, forest land, land with a high amount of woods and bushes, waste land as well as built-up and urbanized land, with the exception of industrial land, mining areas and transport areas;
3. Group C: industrial areas, mining areas, transport areas;

developed to a depth of 0.3...15 m bgl. [24].

4. Conclusion

- Test results obtained during the combustion of flammable mixture No I (waste—code 19 08 05 stabilized municipal sewage sludge with hard coal) met class 5 (highest) emission value requirements with regard to the PN-EN 303-5: 2012 standard [28]. Other flammable mixtures

Table 16:

Specification	Result	Permissible	values per	PN-EN 303-5
Boiler efficiency in accordance with PN-EN 303-5			73	
Concentration of dust and			Class	
gaseous substances emitted into the air, %		3	4	5
dust, mg/m^3	233	150	60	40
OGC, mg/m^3	0	80	30	20
sulfur dioxide, mg/m^3	396	-	-	-
nitrogen dioxide, mg/m^3	297	-	-	-
carbon monoxide, mg/m^3	902	3000	1000	500

Table 18: Maximum permissible concentrations in the soil or land, compared to the results obtained from analysis of the test sample of the solid product—ash and slag—from combustion of flammable mixture No IV

Element	Land *			Value determined
	Group A	Group B	Group C	for sample:
	Depth in m bgl			Flammable mixture
		0–0.3	0–2.0	No IV
	mg/kg s.m.			
I Metals				
As	20	20	60	<0.19
Ba	200	200	1000	1.16
Cd	1	4	15	<0.048
Co	20	20	200	1.84
Cr	50	150	500	2.42
Cu	30	150	600	<0.19
Mo	10	10	250	1.45
Ni	35	100	300	<0.48
Pb	50	100	600	<0.48
Sn	20	20	350	0.3
Zn	100	300	1000	<0.19

/* per the Regulation of the Minister of the Environment dated 9 September 2002 on soil and land quality standards—Dz. U. 02.165.1358 (Journal of Laws 02.165.1358);

No II, III and IV, met the requirements of class 3 (lowest) emission value requirements with regard to the PN-EN 303-5 standard [24]. The limiting factor for flammable mixtures No II, III and IV was dust emissions. The laboratory boiler used for testing was not equipped with a dust collector; otherwise satisfactory emission results would have been obtained that comply with accepted standards of emissions [13];

- Testing of the waste (ash and slag) obtained from the combustion of flammable mixtures qualify it for development in land areas at a depth of 0.3–15 m bgl. [24]:

  - Group A:

    (a) land in a protected area under the regulations of the Water Law,

    (b) rareas subject to protection under nature protection regulations, if maintaining the current level of land pollution does not pose a threat to human health or the environment—for these areas, the concentrations are in accordance with standards resulting from the current state;

  - Group B: Land classified as farming land with the exception of land under ponds and under ditches, forests as well as land with a high amount of trees and bushes, wasteland as well as built-up and urbanised land with the exception of industrial, mining and transport areas;

  - Group C: industrial, mining and transport areas for flammable mixture No IV—waste—code 19 08 05 stabilized municipal sewage sludge with wood chips and for flammable mixture No III—waste—code 19 08 05 stabilized municipal sewage sludge with cereal straw. Flammable mixtures: No I—waste—code 19 08 05 stabilized municipal sewage sludge with hard coal and No II—waste—code 19 08 05 stabilized municipal sewage sludge with lignite, qualify to apply to land development in the areas of:

  - Group C: industrial, mining and transport areas, developed at the depth of 0.3–15 bgl.

- Using the basic component—municipal sewage sludge as a composite of alternative fuels will:

  - save primary fuels: hard coal and lignite,
  - comply with permissible emission standards of dust and gaseous substances to the air,
  - lead to the production of slag and ash that comply with land development standards for land types in Groups A, B, and C [24].

- Using composites of alternative fuels containing municipal sewage sludge in the power generation sector, will not require major changes to boilers and will comply with the conditions for thermal conversion of wastes set down in the Regulation of the Minister of Economy [31].

References

[1] M. Czop, M. Kajda-Szcześniak, Paliwa z odpadów źródłem energii odnawialnej, Archives of Waste Management and Environmental Protection 15 (2) (2013) 83–92.

[2] G. H. Eduljee, Waste incineration and the environment, Royal Society of Chemistry, London, 1994, Ch. Organic micropollutants emmissions from waste incineration.

[3] J. Goldemberg, S. T. Coelho, Renewable energy–traditional biomass vs. modern biomass, Energy Policy 32 (6) (2004) 711–714.

[4] A. Demirbas, Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues, Progress in energy and combustion Science 31 (2) (2005) 171–192.

[5] Rozporządzenie Ministra Środowiska z dnia 27 września 2001 r. w sprawie katalogu odpadów Dz.U.01.112.1206 [Regulation of the Minister of Environment dated 27 September 2001 on waste catalogue - Journal of Laws 01.112.1206].

[6] K. Środa, A. Kijo-Kleczkowska, H. Otwinowski, Methods of disposal of sewage sludge, Archives of Waste Management and Environmental Protection 15 (2) (2013) 33–50.

[7] K. Środa, A. Kijo-Kleczkowska, H. Otwinowski, Thermal disposal of sewage sludge, Inżynieria Ekologiczna 28 (2012) 67–81.

[8] J. Milewski, K. Michalska, A. Kacprzak, Dairy biogas as fuel for a molten carbonate fuel cell – initial study, Journal of Power Technologies 93 (3) (2013) 161–168.

[9] Ustawa z dnia 27 kwietnia 2001r. Prawo Ochrony Środowiska Dz.U.01.62,627 [Law dated 27 April 2001 Environmental Law - Journal of Laws 01.62,627], (consolidated text Journal of Laws 08.25.150 dated 23.01.2008).

[10] Ustawa z dnia 14.12.2012r. o odpadach Dz.U.13.21 [Law dated 14 December 2012 on waste - Journal of Laws 13.21].

[11] Rozporządzenie MŚ z dnia 24.08.2012r. w sprawie poziomów niektórych substancji w powietrzu Dz.U.12.1031 [Regulation of the Minister of Environment dated 24 August 2012 on permissible substance degree in the air - Journal of Laws 12.1031].

[12] Rozporządzenia MŚ z dnia 26.01.2010r. w sprawie wartości odniesienia dla niektórych substancji w powietrzu Dz. U. 10.16.87 [Regulation of the Minister of Environment dated 26 January 2010 on reference values for some substances in the air, Journal of Laws 10.16.87].

[13] Rozporządzenia MŚ z dnia 22 kwietnia 2011r. w sprawie standardów emisyjnych z instalacji Dz.U.11.95.558 [Regulation of the Minister of Environment dated 22 April 2011 on standards for emissions from installations - Journal of Laws 11.95.558].

[14] Rozporządzenia Ministra Gospodarki i Pracy z dnia 07 września 2005r. w sprawie kryteriów oraz procedur dopuszczenia odpadów do składowania na składowisku odpadów danego typu Dz.U.05.186.1553, [Regulation of the Minister of Economy and Labour dated 7 September 2005 on criteria and procedures of permissions for waste collection at particular types of landfills, Journal of Laws 05.186.1553].

[15] Rozporządzenia Ministra Środowiska z dnia 09 września 2002 r. w sprawie standardów jakości gleby oraz standardów jakości ziemi Dz. U. 02.165.1358 [Regulation of the Minister of Environment dated 9 September 2002 on the soil and land quality standards, Journal of Laws 02.165.1358].

[16] J. Fieducik, A. Gawroński, Sewage sludge drying and combustion as a method of its utilization based on the example of incineration plant in olsztyn, Zeszyty Naukowe Politechniki Rzeszowskiej. Budownictwo i Inżynieria Środowiska 271 (57) (2010) 147–154.

[17] J. Girczys, K. Rećko, The possibilities of mutual management of sewage sludge and waste coal slime, Inżynieria i Ochrona Środowiska 4 (1) (2001) 107–116.

[18] T. Pająk, Combustion and co-combustion of sewage sludge - basic determinants, Przegląd Komunalny 1 (2003) 35–38.

[19] T. Pająk, G. Wielgosiński, Contemporary technologies of sewage sludge drying and combustion – criteria and determinants of technology choice, in: II Międzynarodowa i XIII Krajowa Konferencja Naukowo – Techniczna n.t. Nowe spojrzenia na osady ściekowe. Odnawialne źródła energii, Czestochowa, 2003, pp. 491–500.

[20] J. W. Wandrasz, M. Kozioł, M. Landrat, W. Ścierski, A. J. Wandrasz, Possibility of sludge co-combustion from sewage-treatment plants jointly with coal in stoker boilers, Gospodarka Paliwami i Energią 8 (2000) 10–15.

[21] G. Wielgosiński, Combustion, co-combustion and drying of sewage sludge, Przegląd Komunalny 1 (2002) 10–15.

[22] GIG documentation of research and development work-No 582 0777 3-323.

[23] Ochrona Środowiska 2000–2010. Główny Urząd Statystyczny. Informacje i Opracowania Statystyczne, Warszawa (2010).

[24] Rozporządzenie Ministra Środowiska z dnia 09 września 2002 r. w sprawie standardów jakości gleby oraz standardów jakości ziemi Dz.U.02.165.1358 [Regulation of the Minister of Environment dated 9 September 2002 on the soil and land quality standards, Journal of Laws 02.165.1358].

[25] Rozporządzenia Ministra Gospodarki i Pracy z dnia 07 września 2005r. w sprawie kryteriów oraz procedur dopuszczenia odpadów do składowania na składowisku odpadów danego typu Dz.U.05.186.1553, [Regulation of the Minister of Economy and Labour dated 07 September 2005 on criteria and procedures of permissions for waste collection at particular types of landfills, Journal of Laws 05.186.1553].

[26] Rozporządzenie MŚ z dnia 04.11.2008r., w sprawie wymagań w zakresie prowadzenia pomiarów wielkości emisji oraz pomiarów ilości pobranej wody Dz.U.08.206.1291 [Regulation of the Minister of Environment dated 4 November 2008 on requirements concerning measurements on volume of emission and collected water - Journal of Laws 08.206.1291].

[27] PN-Z-04030-7:1994 standard “Measurement of dust concentration and flow in waste gases using the gravimetric method.” - flow, gas physical parametres, dust emission measurements.

[28] PN-EN 303-5: 2002 standard, (Part5 : Heating boilers for solid fuels, hand and automatically stocked, with a nominal heat of up to 500 kW - Terminology, requirements, testing and marking.).

[29] Rozporządzenie MŚ z dnia 19.11.2008r., w sprawie rodzajów wyników pomiarów prowadzonych w związku z eksploatacją instalacji lub urządzenia i innych danych oraz terminów i sposobów ich prezentacji Dz.U.08.215.1366 [Regulation of the Minister of Environment dated 19 November 2008 on types of results of measurements carried out because of installation or device exploitation as well as other data terms and ways of their presentation, Journal of Laws.08.215.1366].

[30] Rozporządzenie Ministra Gospodarki z dnia 29 stycznia 2002r. w sprawie rodzajów odpadów innych niż niebezpieczne oraz rodzajów instalacji i urządzeń, w

których dopuszcza się ich termiczne przekształcenie, Dz.U.02.18.176 [Regulation of the Minister of Economy dated 29 January 2002 concerning other waste types than dangerous and types of installations and devices where their thermal transformation is allowed, Journal of Laws 02.18.176].

[31] Rozporządzenie Ministra Gospodarki, Pracy i Polityki Społecznej z dnia 22.12.2003r. zmieniające rozporządzenie w sprawie wymagań dotyczących procesu termicznego przekształcenia odpadów, Dz.U.03.1.2 [Regulation of the Minister of Economy, Labour and Social Policy dated 22 December 2003 amending the regulation concerning the requirements on the process of thermal transformation of waste, Journal of Laws 03.1.2].

[32] PN-EN 303-5: 2002 standard, (Part 5 : Heating boilers for solid fuels with manual and automatic charge, with a nominal power of up to 500 kW - Terminology, requirements, testing and marking.).

[33] J. Lasek, K. Głód, K. Kazalski, M. Janusz, B. Wilk, Evaluation of models for estimation of heating values of solid fuels and their test in full-scale combustion chambers. part i: Modeling and study of fuel analysis procedures, Rynek Energii 104 (1) (2013) 95–103.