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STUDY INTO COMBUSTION OF SEWAGE SLUDGE AS ENERGETIC FUEL

BADANIA SPALANIA OSADÓW ŚCIEKOWYCH JAKO PALIWA ENERGETYCZNEGO

Along with the development of civilisation, it can be observed that the amount of waste of different type is growing and the preparation process for further usage of the waste or the utilization process differs. What is to be focused on is municipal sewage sludge which, due to its energetic properties, constitutes a valuable fuel. The problem of usage of municipal sewage sludge remains still unsolved, which stems both from the increasing amount of such waste, and from the lack of properly adjusted systems for thermal processing thereof. What is of an additional obstacle are the increasingly stricter legal regulations regarding disposal of sewage sludge after the year 2013; hence, it is necessary to consider various benefits resulting from thermal processing of such waste. This work presents an overview of methods of disposal of sewage sludge, taking into consideration, in particular, thermal methods including the process of combustion and co-combustion as a means of successful utilization.

The research section of the work presents the results of study into the mechanism and kinetics of combustion of sewage sludge in various conditions of the process carried out in air flow. Combustion of sewage sludge has been compared against combustion of coal and biomass.

Keywords: sewage sludge, thermal utilization, fuel combustion mechanism and kinetics

Wraz z rozwojem cywilizacji zaobserwować można postępujące powstawanie różnego rodzaju odpadów różniących się, m.in. sposobem przygotowania do dalszego wykorzystania, czy procesem utylizacji. Na szczególną uwagę zasługują komunalne osady ściekowe, które z uwagi na właściwości energetyczne stanowią cenne paliwo. Problem wykorzystania komunalnych osadów ściekowych jest nadal otwarty, a wynika to zarówno z rosnącej produkcji tych odpadów, jak i braku odpowiednio przystosowanych instalacji do termicznego ich przekształcania. Dodatkowym utrudnieniem są zaostrzające się przepisy prawne dotyczące składowania osadów ściekowych po 2013 r. skłaniające tym samym do rozważań nad korzyściami płynącymi z termicznej obróbki tych odpadów.

W pracy przedstawiono przegląd sposobów unieszkodliwiania osadów ściekowych ze szczególnym uwzględnieniem metod termicznych, głównie spalania i współspalania jako drogi do ich sukcesywnej utylizacji. W części badawczej pracy zaprezentowano wyniki badań mechanizmu i kinetyki spalania osadów ściekowych w różnych warunkach procesu prowadzonego w strumieniu powietrza. Spalanie osadów ściekowych porównano ze spalaniem węgla oraz biomasy.

Słowa kluczowe: osady ściekowe, termiczna utylizacja, mechanizm i kinetyka spalania paliw

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1. Introduction

In the year 2000, 359.8 k mg. of dry weight (d.w.) of municipal sewage sludge was created; in the year 2010, this amount increased to 526.7 k mg. of d.w. According to the 2014 waste management plan, this number will increase to 746 k mg. of d.w. A gradual increase in the amount of the above-mentioned waste is noticeable; moreover, there seems to be no optimum method of utilization thereof.

Considering various methods of sludge utilization, it is necessary to conduct an analysis of their properties, as the properties play a key role in selecting an appropriate usage methods (Gluzińska, 2009). Moreover, certain methods of waste management are excluded or limited due to applicable legal regulations. With regard to the 2014 national waste management plan (Resolution No. 217 of the Council of Ministers of 24 December 2010), it is to be assumed that the amount of sewage sludge to:

– dispose will decrease,
– process prior to introduction to the environment and transform by means of thermal methods will increase.

Furthermore, it is to be indicated that the trend will be to use biogenic substances contained in sewage sludge to the highest possible degree, paying attention, at the same time, to requirements concerning environmental, sanitary and chemical safety.

Undoubtedly, the problem is getting more and more significant and this may result from intensive works on development of a sewage system as well as on construction of new sewage treatment plants. Therefore, it is necessary to introduce an appropriate strategy based on thermal methods which have been used both in energetics and cement industry.

The increase in the level of life of people causes an increase in the amount of sewage sludge produced in our country. The predominant direction of its management in Poland is their neutralising by disposal. According to the Regulation of the Minister of Economy of 12 June 2007 (Regulation of the Minister of Economy of 12 June 2007), from 1 January 2013, disposal of sewage sludge characterized by, among others, heat of combustion less than 6 MJ/kg dry weight (Table 1). This is a very strict criterion since the said value of the heat of combustion is significantly lower as compared to most organic substances. In addition, given the restriction on the future use of sewage sludge for agricultural purposes, it can be concluded that the thermal sludge utilization is a very important issue from the environmental, technical and economic point of view. The essence of drying and combustion of sewage sludge in systems designed for this purpose is to be emphasised here, as well as co-co-combustion with coal and biomass fuels in objects of commercial power industry, that is, in power stations and gas powered generating stations. In literature (Środa et al., 2012a-d), the characteristics and issues connected with properties and utilization methods of sewage sludge are discussed extensively. An urgent need, therefore, is to conduct scientific research, enabling identification of the mechanism and determining the kinetics of the sewage sludge combustion process in a variety of process conditions.

Each of the methods of disposal of sewage sludge has both drawbacks and advantages affecting their proper application.

Taking into consideration the natural use of such waste, it is first of all necessary to pay attention to the possibility of using biogenic compounds and organic matter contained therein. In addition, taking into account costs of such undertaking, it usually turns out to be the most cost effective way of waste management. However, due to the limited knowledge about the contents of micropollutants and pathogens and their impact on human and animal food chains, the use of such methods of waste usage is quite limited.

TABLE 1

The criteria for acceptance of waste disposal in places designated for non-hazardous and neutral substances (Regulation of the Minister of Economy and Labour of 7 September 2005)

Parameter	Border value
total organic carbon (TOC)	5%
loss on ignition (LOI)	8%
combustion heat for municipal processed waste*	max. 6 MJ/kg

* it is unacceptable to mix municipal waste with inert fractions in order to obtain this parameter

Thermal methods provide a significant reduction of the input material (and at the same time their energetic usage), low sensitivity to variation in the composition of the sludge, the possibility of using recycled products and, what is important, minimising odours from the waste. The main disadvantages of these methods include, among others, high investment and operating costs, as well as problems connected with meeting emission standards (in the case of co-combustion).

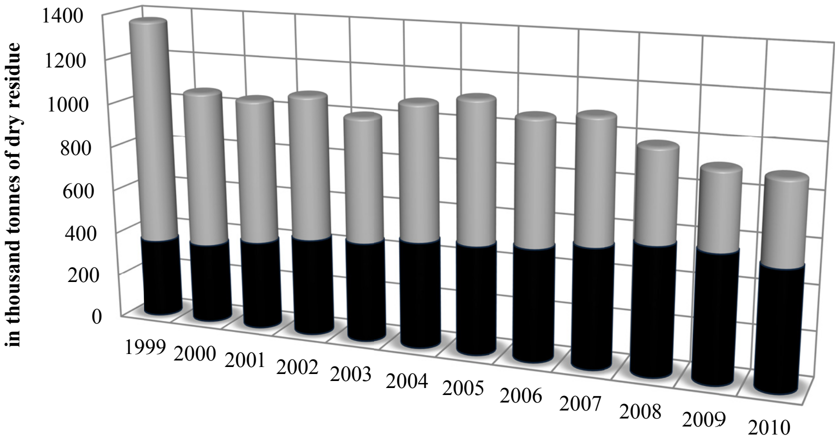
Disposal is a cheap way of waste management; however, this method is not always recommended. Among others, this results from the biological decomposition of organic matter contained in the waste, which is associated with uncontrolled emission of methane into the atmosphere. The solution to this problem may constitute recovery and combustion of methane; nevertheless, it is a costly and inefficient method. The reason for this is the large area of emission and the low concentration of methane in the atmosphere connected therewith.

Based on the above analysis, it becomes inevitable to take advantage of thermal methods of sludge utilization. It is justified by the benefits of obtaining products that have minimal impact on the environment. Moreover, energy contained therein can be recovered by the use of synthesis gas (from gasification) or the pyrolysis oil and gas (from pyrolysis) and by the process of creation of electrical energy or heat energy (by means of combustion).

2. Sewage sludge production

Figure 1 (Environmental Protection 2000-2010) shows production of waste in the years 1999 to 2010, depending on its type. It can be seen that the amount of sewage sludge from industrial wastewater treatment plants decreased approximately threefold over the specified period of time, while the amount of sewage sludge from municipal wastewater treatment plants increased by nearly one and a half times.

Figure 2 (Environmental Protection 2000-2010) illustrated the general classification of the sewage sludge management methods along with their percentage share. As it can be seen, the most popular is natural usage, and it may be due to low financial outlays necessary for this type of sewage sludge management. However, the increased amount of heavy metals, sanitary properties and applicable legal regulations have a significant impact on the usage of this type of disposal of above-mentioned waste, thus directing it to the sludge combustion method.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
▨ sludge from industrial treatment plants	1014,1	703,3	649,6	648	562,1	611,2	638,2	563,4	555,4	411,6	345	368,4
■ sludge from municipal treatment plants	354,4	359,8	397,2	435,7	446,5	476,1	486,1	501,3	533,4	567,3	563,1	526,7

Fig. 1. Production of sewage sludge depending on its type in years 1999-2010

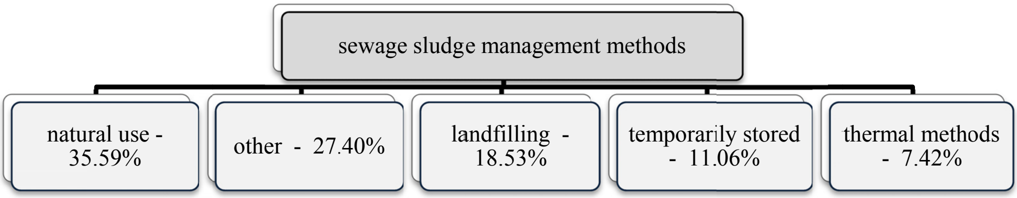


Fig. 2. Sewage sludge management methods in 2010

3. Thermal sludge disposal

Figure 3 shows the overall division of thermal methods of disposal of sewage sludge. According to the Act of 27 April 2001, (Waste Act of 27 April 2001), thermal treatment of waste constitute combustion through their oxidation, as well as other waste treatment processes (pyrolysis, gasification, plasma processes), taking into account the fact that substances formed in the course of these processes undergo combustion afterwards.

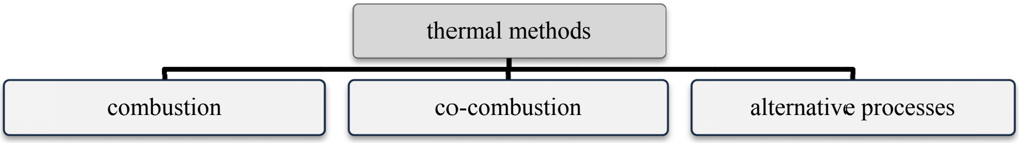


Fig. 3. Thermal methods of disposal of sewage sludge

Among alternative processes, the following can be distinguished (Bień, 2007): wet oxidation, pyrolysis and gasification (and combinations thereof) and vitrification.

- pyrolysis – a process of thermal conversion of organic substances contained in sewage sludge, rich in coal, taking place at a temperature of 350°C-500°C under oxygen-free conditions or with little oxygen presence. The result are products in gaseous, solid and liquid phases. Part of the liquid and gaseous products is recycled in order to meet the process heat demand (Heidrich & Witkowski, 2010; Kordylewski & Robak, 2002),
- wet oxidation – is characterized by the ability to use only mechanically compacted sludge, – not dehydrated. In the reactor, during the process execution, the temperature is maintained at about 250°C and the pressure amounts to about 40 bar. Such conditions allow oxidation of the organic matter with the use of oxygen. As a result, the following is obtained: mineralized sludge, biodegradable leachate and post-reaction gas (Chodur, 2008).
- gasification – a process of complete conversion of solid fuels in gas fuels; it takes place at a temperature of about 1000°C, in the presence of an oxidizing agent. The product of the process is hydrogen, carbon monoxide, and small amounts of methane, carbon dioxide, water vapour and nitrogen. The gas obtained can be of varying calorific value; this depends on the type of an oxidizing agent and ranges from 5 MJ/Nm^3 (for air) to 10 MJ/Nm^3 (for oxygen),
- vitrification – a process that allows changing the properties and form of the modified material. It consists in bringing (as a controlled process) energy to the substance, which decomposes at higher temperatures to form a gas phase, and then undergoes combustion and melting. The resulting product – a vitrificate is characterized by low chemical reactivity, amorphous structure, good chemical and mechanical properties, lack of toxicity and dusting (Kordylewski & Robak, 2002).

Particularly noteworthy is combustion, which is an attractive solution for sludge utilization, and this is due to: minimising odours, significant reductions in the volume of the parent substance, the possibility of further use of ash and – what is important – thermal destruction of organic toxic compounds in the waste. In addition, dry sewage sludge is an attractive fuel, and this may result from calorific value which is comparable to the calorific value of brown coal. Thus, it is reasonable to carry out combustion of this waste to recover energy contained in it, given that there have been significant improvements in combustion technology, which affects its competitiveness in relation to other waste disposal methods. Nevertheless, combustion, as any other waste management method, brings with it various problems. These include: the presence of heavy metals in ash and sticky phase at 50-60% of dry weight content in the sludge negatively affecting, at the same time, the drying process; the need for extensive treatment systems resulting from the diversity of contaminants present in sludge; the high moisture content, which sometimes causes the impossibility of autothermal combustion; in such a case, it may be necessary to provide additional fuel (Werther & Ogada, 1999).

Thermal methods used for sewage sludge disposal require adequate fuel pre-treatment, e.g. in the form of a drying process. This is particularly important in cases where sludge is characterized by a high degree of hydration (Malej, 2004) (Fig. 4).

Technologies of fluidised bed combustion of sewage sludge are the most technically developed solutions having many proven applications in the power industry, based on coal fuels (Malej, 2004; Wielgosiński & Kozłowska, 2005). They allow combustion of properly prepared sludge, partially drained if possible, and this is due to the autothermal process (Bień, 2007).

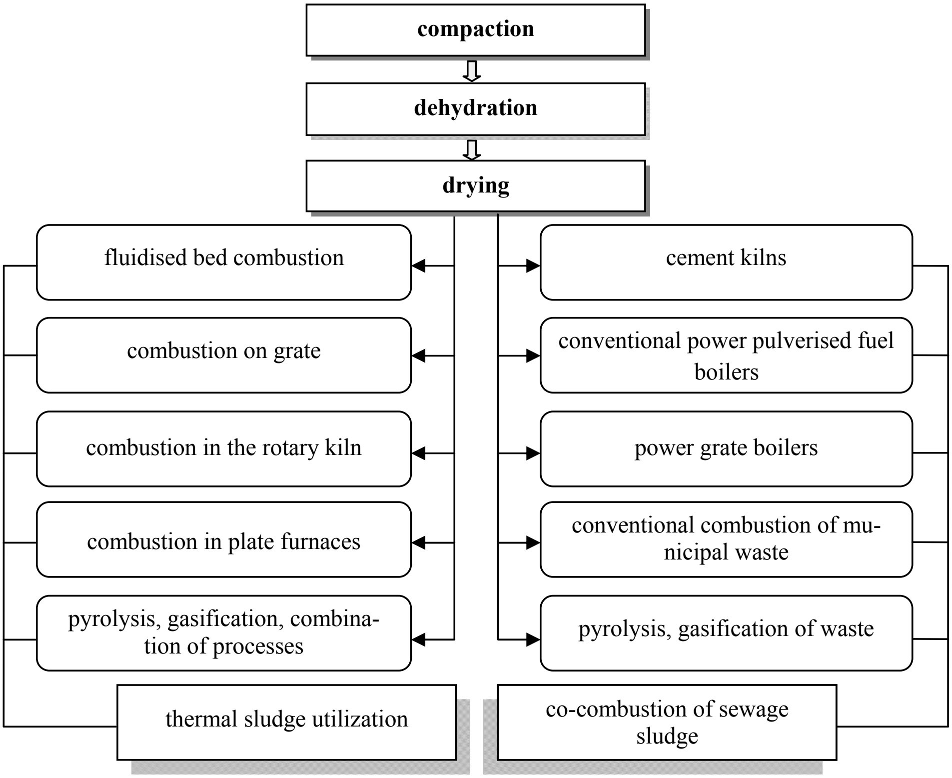


Fig. 4. Methods of drying and combustion of sewage sludge

A fluidised bed furnace, in which the sewage sludge undergoes combustion, is usually vertical and has a cylindrical shape with a diameter of 2.7-7.6 m. Besides, it is characterised by a fire-protective steel housing and features a fluid-bed, the height of which is 0.8 m in idle mode. The bed is located on a brick dome or a fire-protective grate. Air under pressure of 20-35 Pa is channelled through nozzles located in the bed supporting layer. Its purpose is to maintain the combustion process. The minimum temperature of the fluid-bed before introduction of sludge should be 700°C (Heidrich & Witkowski, 2010). In the process of fluidised combustion of sludge, sand remains suspended in the combustion chamber. This results in adequate supply of air, mixing of the bed, as well as good contact between the combusted sludge and air. Significant combustion intensity causes complete utilization of calorific value of the waste (Bień, 2007). Water evaporation and combustion of the waste occurs rapidly. Flue gases and ash leave the bed and are moved to the gas outlet located in the upper part of the furnace. Later, they are channelled through the scrubber and washed in it (Heidrich & Witkowski, 2010). An important advantage of fluidised bed combustion is low range of temperatures in the combustion chamber, which leads to low emission of NO_x, as well as a significant reduction in sulphur oxides. Examples of such a constructional solution are: a sludge incineration plant in the "Dębogórze" wastewater treatment plant in Gdynia; PYROFLUID^{TM} – a fluidised-type system for combustion of sludge; and the PYRODYN^{TM} process.

Sewage sludge combustion technologies assuming combustion in grate furnaces are characterised by simple design and high energy efficiency (Malej, 2004). The main element of such a furnace is a grate, which connects the combustion and after-combustion chambers. Parallel-flow, counter-flow or mixed combustion can take place, depending on the flow direction of exhaust gas with respect to movement of sewage sludge. Sloping grates are used most frequently (cylindrical, reciprocating, sliding); they, as a moving element of the furnace, guarantee – in the course of the combustion process – mixing of combusted material and after-combustion of flue gas in the chamber located above the grate (Podedworna & Umiejewska, 2008).

Technologies of sewage sludge combustion in a rotary kiln constitute an alternative to fluidised bed furnaces (Podedworna & Umiejewska, 2008), this is due to the total destruction of the input material. A rotary drum furnace is a ceramic tube (Heidrich & Witkowski, 2010), installed with a slight slope. The furnace rotates at a low speed to mix sludge and allow for its passing through subsequent sections responsible for drying, degassing, combustion and ash storage. The combustion process takes place at a temperature of 800-1000°C (Podedworna & Umiejewska, 2008), (Werther & Ogada, 1999). Sludge and flue gas can be channelled both as a parallel-flow and counter-flow, however, in order to reduce the risk of explosions the first system is used (Heidrich & Witkowski, 2010). In rotary furnaces, sludge of high calorific value is combusted, and this is due to large heat losses. They are used, in general, in the cement industry (Bień, 2007).

In multi-level furnaces, sludge is channelled into the upper part of the hearth, where the drying process takes place. Then slowly, it is pushed towards the centre, and then moves to the next lower hearth, in which the scrapers move it towards the edges. Subsequently, the sludge goes down to the third hearth and, again, is moved towards the centre. The the highest temperature is in the middle hearths. At this point, the sludge is combusted as well as the additional fuel which is necessary to warm up the furnace and to maintain the process. The preheated air is introduced into the lowest hearth, next, it is heated during the ascent through the middle hearths, where sludge combustion takes place. Further, the air is cooled by giving up heat to dry sludge introduced to the upper hearth (Heidrich & Witkowski, 2010).

When choosing sewage sludge combustion technology, the BAT principle is to be obeyed; it determines the need for choosing technology of the highest available level of technology, as well as engineering and environmental protection (Pająk & Wielgosiński, 2003). In systems designed primarily for combustion of sewage sludge, the fluidised-bed technology is considered BAT. And this results from the high combustion efficiency and low volume of flue gas produced in these systems (Gromiec & Koć, 2009).

Among the technologies that assume combustion of sewage sludge by co-combustion with different types of fuels, the following can be distinguished (Heidrich & Witkowski, 2010; Pająk & Wielgosiński, 2003; Wielgosiński, 2002):

- co-combustion of municipal waste – it is an attractive solution from the point of view of the possibility of using part of the flow of heat from the process of combustion of municipal waste for sludge drying. It is important in this case that the municipal waste has a higher calorific value,
- co-combustion of sewage sludge in rotary furnaces in the cement industry – it has many benefits which result from the combustion temperature, which reaches 2000°C; time of existence of gases in high temperature; very high heat capacity of the furnace; and non-waste technology; the burnt charge is of alkaline type and binds acidic components present in the exhaust gases – they become incorporated into the structure of the clinker.

These benefits co-combustion of sewage sludge in rotary furnaces in the cement industry indicate that such devices are ideal for the process of disposal of organic compounds most resistant to temperature (Broszura, 2006). However, in order to make sewage sludge an interesting fuel for the cement industry, it is to be characterised by an appropriate calorific value, which should equal, upon drying, at least 11.5 MJ/kg
(according to "Lafarge") or 14 MJ/kg (according to other cement plants). An important assumption is also the chlorine content not exceeding 5% of weight of introduced sewage sludge (Rosik-Dulewska, 2008),

– co-combustion of sewage sludge with coal in power plants – it is characterized by the fact that the proportion of sewage sludge in the fuel designated to combustion should not exceed 5% (although it is sometimes recommended to increase their the value to 10-25% of the fuel). Sludge designated to combustion in systems based on hard coal is to be dried to 90% of dry weight, while the content of dry weight in brown coal can be reduced.

The problem of properties, methods of disposal of sewage sludge, its combustion and co-combustion with other fuels, as well as the impact of these processes on the environment is currently of the highest importance and widely is widely discussed in the literature, both national and international, including (Bień & Westalska, 2008; Bień & Gandor, 2010; Moroń et al., 2012; Werle, 2010, 2011; Li et al., 2009; Werther et al., 1995; Słowik et al., 2011; Pająk, 2010, 2012; Werther & Ogada, 1999; Xiao et al., 2009; Xiao et al., 2010; Li et al., 2010; Nadziakiewicz & Kozioł, 2003).

The literature emphasizes that the existing experimental studies carried out on operating units recommend that the amount of sewage sludge in the fuel stream does not exceed 5%. Foreign experience shows, however, that it is possible to use up to 30% of mass of sewage sludge in a fuel mixture (Li et al., 2009).

Authors emphasize the specificity of behaviour of sewage sludge in the combustion process, mainly resulting from substantial hydration, and the high content of mineral and volatile elements. These experiments relate mainly to thermogravimetric studies designed to determine kinetic parameters. What is emphasised is the high reactivity and low temperature of degassing of such type of fuels, which is much lower than in case of carbon (Bień & Gandor, 2011; Werther et al., 1995). Another paper (Werle, 2011) presents a theoretical analysis of the possibility of co-combustion of municipal sewage sludge with hard coal in power stations (WR-25, CFB-420 and OP-230 boilers). The analysis takes into account different mass fraction of sewage sludge in the tested fuel blend (0%-20%) and a wide range of changes in air ratio l in the combustion chamber (1.1-1.5). Based on obtained results, an ecological analysis of co-combustion of sewage sludge was also conducted as well as an economic assessment of the undertaking. It was found that an increase in the mass fraction of the sewage sludge in the fuel blend causes a significant reduction in CO_2 emissions to the atmosphere. It was also shown that combustion of the above-mentioned fuels in a fluidised-bed boiler was characterized by the smallest decline in performance in comparison with other analysed units.

Due to the fact that in Poland there are as many as 11 (Fig. 5) working systems using sewage sludge as energy fuel (Pająk, 2010, 2012), further development of technologies discussed herein is to be expected in our country as well as the dominance of co-combustion of sewage sludge with other fuels in operating power plants.

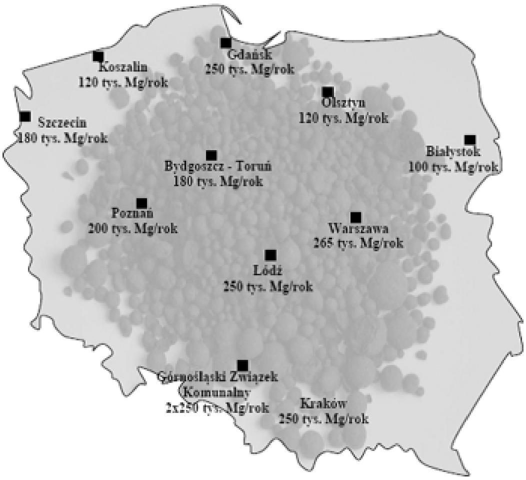


Fig. 5. Distribution of systems for mono-combustion of sewage sludge in Poland (Pająk, 2010)

4. 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. Test stand (Fig. 6) built using two ceramic blocks (1, 13). In the ceramic block (13) a gas heater was installed; the heater was made of three spirals of power of 2 kW each placed in six quartz tubes. These tubes were built into a quartz tube, heat insulated by means of a fibre material Al_2O_3 (5) and covered with stainless steel sheet. The test chamber (1) of height of 65 cm constituted a quartz tube, placed vertically in a ceramic block, which was additionally equipped with a heating coil of power of 2.2 kW to eliminate heat loss. In the ceramic block (13) a test entrance was made (100 mm above the grate) and a sight-glass was installed to allow visual observation of the combustion process. The whole was covered with stainless steel. In order to achieve the desired temperature at the measurement place and eliminate heat loss, the combustion chamber was also enclosed with segments of heaters with a capacity of 2.2 kW, insulated thermally and covered with a stainless steel sheet. By installing a special expansion chamber made of stainless steel sheet (6) above the combustion chamber it was possible to carry out measurements of pollutants emission during the process of combustion of a fuel sample. Compressed air is fed into a quartz tube in the ceramic block (13) using a float flow meter (11). A temperature control system in this test stand was based on two Lumel RE3 microprocessor controllers connected to two NiCr-Ni thermocouples (8), operating independently in the combustion chamber and in the gas heater, and controlling operation of the three-phase Lumel RI31 power controller (10) supplying power to the main heating elements (gas heater).

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. 7). Such a design of the measurement system enabled registering changes in temperature inside and on the surface of the

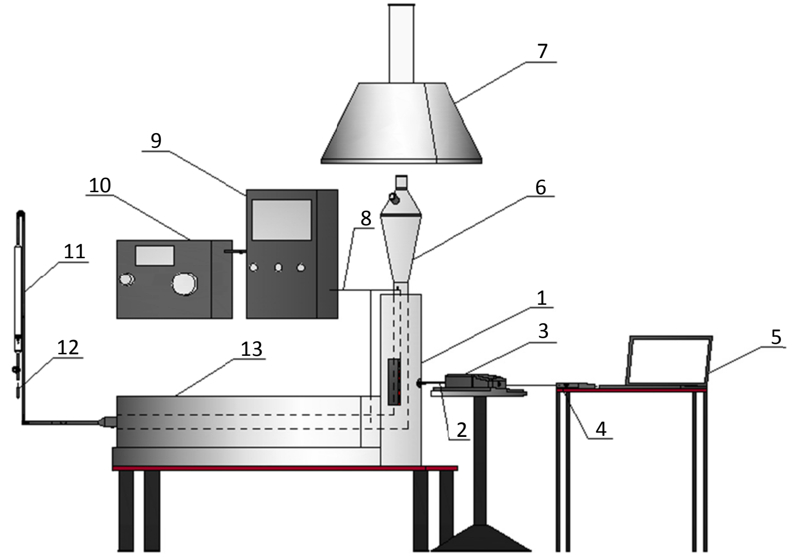


Fig. 6. Diagram of the test stand: 1 – combustion chamber, 2 – PtRh10 thermocouples, 3 – electronic scales, 4 – measurement card, 5 – computer, 6 – expansion chamber, 7 – flue gas exhaust, 8 – NiCr-Ni thermocouple (to measure temperature in the combustion chamber), 9 – microprocessor temperature controllers, 10 – power controller, 11 – float flow meter, 12 – control valves, 13 – ceramic block

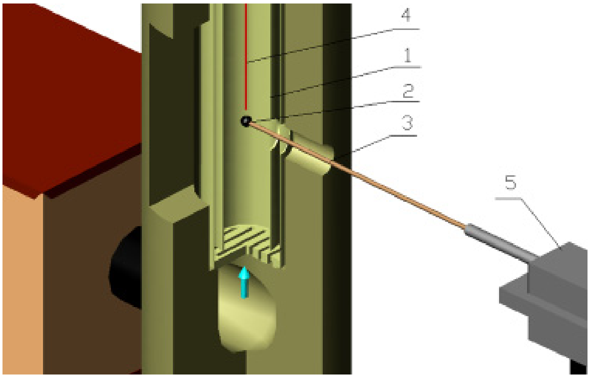


Fig. 7. Diagram of the measurement system: 1 – test chamber, 2 – fuel sample, 3 – PtRh10 thermocouples, 4 – NiCr-Ni thermocouple, 5 – scales

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 (4) connected to a computer (5).

An interesting element of the study was to conduct experiments of fuel combustion in the combustion chamber – without the air flow (Fig. 8). The combustion chamber 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.

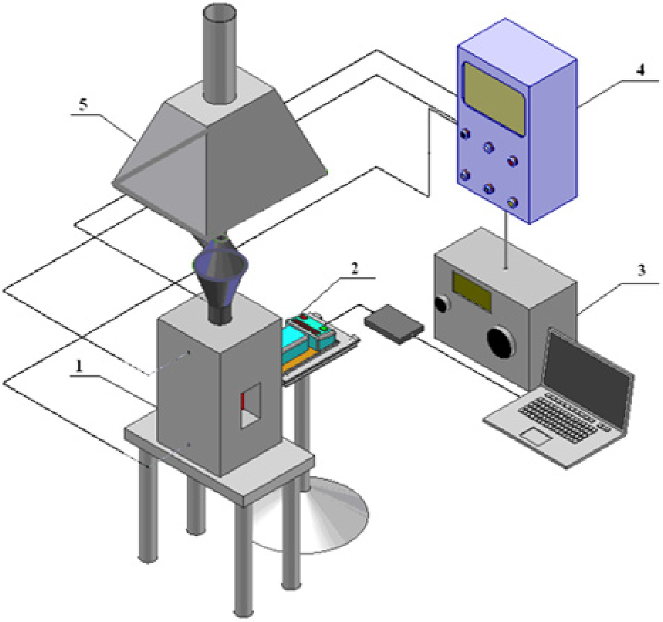


Fig. 8. Diagram of combustion chamber for slurry fuel samples (no air intake): 1 – combustion chamber, 2 – measuring system, 3 – power controller, 4 – temperature control system, 5 – flue gas exhaust

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 samples were formed by polishing fuel fragments to obtain a spherical form. Grinding grain 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 grinding grain dust by grinding and sieving the fuel through a sieve (below 100 mm). The size of fuel samples depended on the nature of tests and the research plan design – in case of the rotary-uniform design.

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; Pelka, 2013).

Table 2 presents an analysis of fuel used in studies discussed herein.

TABLE 2

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 combustible sulphur**	**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_c^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	1.04
Hard coal	2.66	30.90	2.36	31198	79.53	4.33	1.27	9.75	0.10	0.31
Anthracite 42	1.50	3.00	2.50	39350	93.00	1.70	–	1.01	–	0.23
Grinding grain	8.45	70.53	4.55	15825	40.90	6.07	2.73	37.30	–	0.18
Sewage sludge	4.94	51.44	36.44	12574	30.77	3.92	4.26	18.23	–	1.44

5. Experimental studies

An important element of the research was determining the impact of various process parameters on the process of combustion of sewage sludge in the air stream. Due to the need to obtain a correlation between process parameters deciding about the fuel combustion process, it was necessary to carry out tests in accordance with a relevant plan. After becoming familiar and analysing designs used in experiments (Polanski R., 1984) it was found that the most appropriate design to carry out the experiments in question was the rotary-uniform design. Characteristics of the design is shown in Table 3. The following process parameters were applied:

x_1 – temperature in combustion chamber t_{ot}, °C,
x_2 – speed of air intake w, m/s (calculated into temperature conditions),
x_3 – fuel diameter, d, mm,

Range of input values specified in tables 4 and 5. Measurement in each design was repeated three times.

TABLE 3

Characteristic of the rotary-uniform design depending on number of input values

i	3
α_{rot}	1.682
n_k	8
n_α	6
n_0	6
N	20

where:

i — number of input parameters (values),

a_{rot} — star shoulder value,

n_k — number of systems constituting kernel of schedule,

n_α — number of systems, based on which star points are formed,

n_0 — number of systems in the centre of schedule,

N — the total number of systems in the rotary design.

TABLE 4

Values of input data

$\boldsymbol{x_k}$	$\boldsymbol{x_{k\,\mathrm{min}} \div x_{k\,\mathrm{max}}}$	$\boldsymbol{x_k}$				
		$-\alpha$	**–1**	**0**	**+1**	**$+\alpha$**
x_1	800÷900	800	825	850	875	900
x_2	3÷6	3	3.6	4.5	5.4	6
x_3	6÷12	6	7.2	9	10.8	12

when: $\bar{x}_1 = 850$; $\bar{x}_2 = 4.5$; $\bar{x}_3 = 9$.

TABLE 5

Fuel combustion study programme

u	$\boldsymbol{x_k}$		
	$\boldsymbol{x_1}$	$\boldsymbol{x_2}$	$\boldsymbol{x_3}$
1	820	3.6	7.2
2	880	3.6	7.2
3	820	5.4	7.2
4	880	5.4	7.2
5	820	3.6	10.8
6	880	3.6	10.8
7	820	5.4	10.8
8	880	5.4	10.8
9	800	4.5	9
10	900	4.5	9
11	850	3	9
12	850	6	9
13	850	4.5	6
14	850	4.5	12
15	850	4.5	9

16	850	4.5	9
17	850	4.5	9
18	850	4.5	9
19	850	4.5	9
20	850	4.5	9

Statistical analysis of measurements results was made on the basis of work by (Polanski, 1984). The aim of the analysis was selection of a regression function most adequate to the measurement results. It was found that the most representative function approximating the results of measurements is a polynomial of the second degree with first-order interaction in the following form:

$$\begin{aligned}\breve{z} = b_0 + b_{01}\cdot\hat{x}_1 + b_{02}\cdot\hat{x}_2 + b_{03}\cdot\hat{x}_3 + b_{11}\cdot\hat{x}_1^{\,2} + b_{22}\cdot\hat{x}_2^{\,2} + b_{33}\cdot\hat{x}_3^{\,2} \\ + b_{12}\cdot\hat{x}_1\cdot\hat{x}_2 + b_{13}\cdot\hat{x}_1\cdot\hat{x}_3 + b_{23}\cdot\hat{x}_2\cdot\hat{x}_3\end{aligned} \tag{1}$$

where:

$\breve{z}$ — approximated output value calculated from the function of the subject of the study for this measurement,

b_0, b_k, b_{kk}, b_{qk} — approximating polynomial coefficients,

the following normalization relations were used:

$$\hat{x}_k = \frac{2\alpha_{rot}\left(x_k - \overline{x}_k\right)}{x_{k\max} - x_{k\min}} \tag{2}$$

The values of the regression coefficients are presented in Table 6.

TABLE 6

Values of approximation coefficients

Coefficient	**Value of coefficient**
b_0	1.541
b_{01}	0.072
b_{02}	0.045
b_{03}	0.407
b_{11}	-0.009
b_{22}	-0.02
b_{33}	0.042
b_{12}	0.02
b_{13}	0.007
b_{23}	0.032

Based on the regression equation (1) the mass rate of fuel combustion in various conditions of the combustion process carried out in a stream of air was indicated. Figures 9-23 are sample graphs prepared as a function of variation of two parameters of the process (at a constant average value $\overline{x}$ of the other three input values).

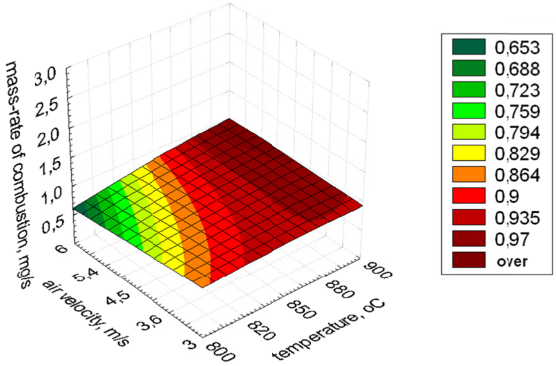


Fig. 9. Influence of temperature changes in the combustion chamber and the velocity of the air flow on the mass rate of sewage sludge combustion; *d* = 6 mm

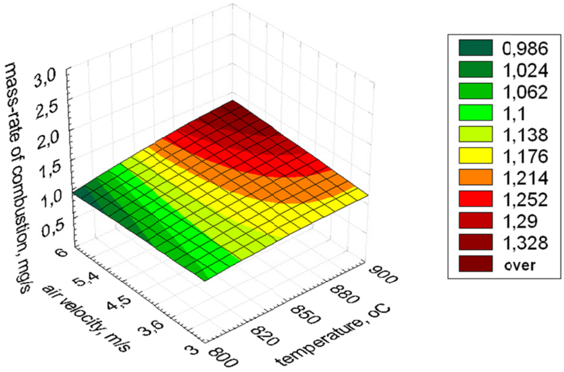


Fig. 10. Influence of temperature changes in the combustion chamber and the velocity of the air flow on the mass rate of sewage sludge combustion; *d* = 7.2 mm

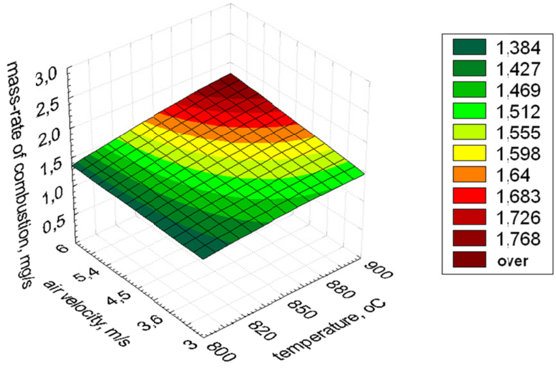


Fig. 11. Influence of temperature changes in the combustion chamber and the velocity of the air flow on the mass rate of sewage sludge combustion; *d* = 9 mm

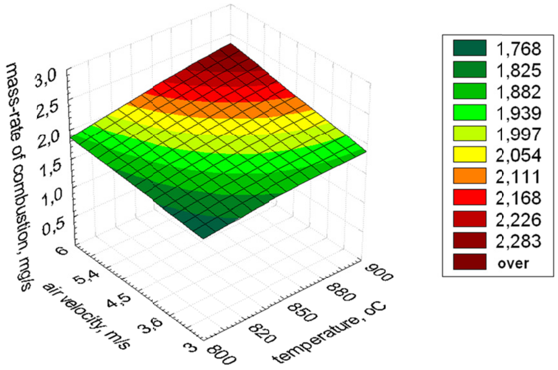


Fig. 12. Influence of temperature changes in the combustion chamber and the velocity of the air flow on the mass rate of sewage sludge combustion; *d* = 10.8 mm

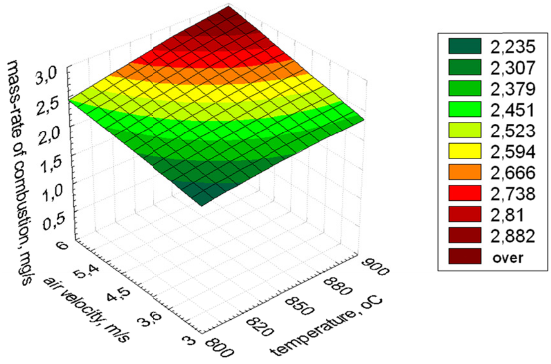


Fig. 13. Influence of temperature changes in the combustion chamber and the velocity of the air flow on the mass rate of sewage sludge combustion; *d* = 12 mm

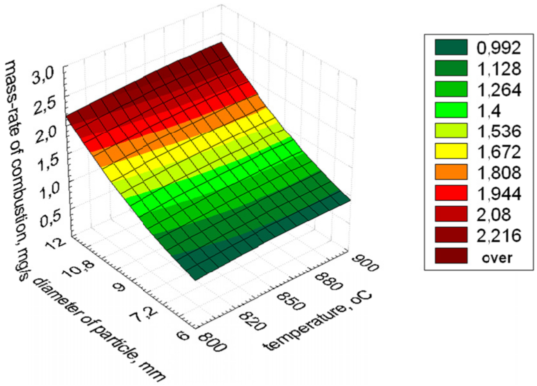


Fig. 14. Influence of temperature changes in the combustion chamber and the diameter of fuel on the mass rate of sewage sludge combustion; *v* = 3 m/s

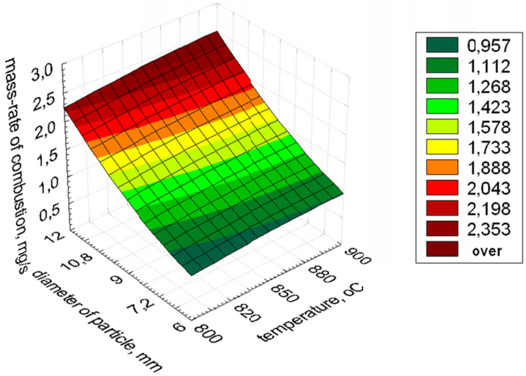


Fig. 15. Influence of temperature changes in the combustion chamber and the diameter of fuel on the mass rate of sewage sludge combustion; $v = 3.6$ m/s

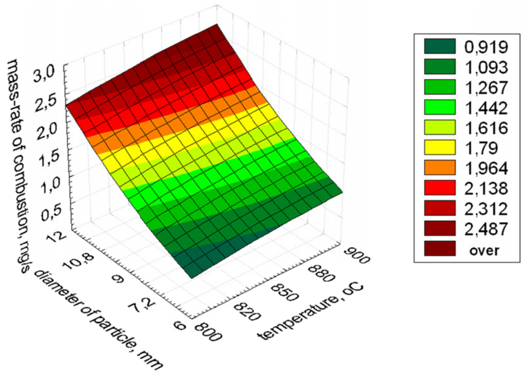


Fig. 16. Influence of temperature changes in the combustion chamber and the diameter of fuel on the mass rate of sewage sludge combustion; $v = 4.5$ m/s

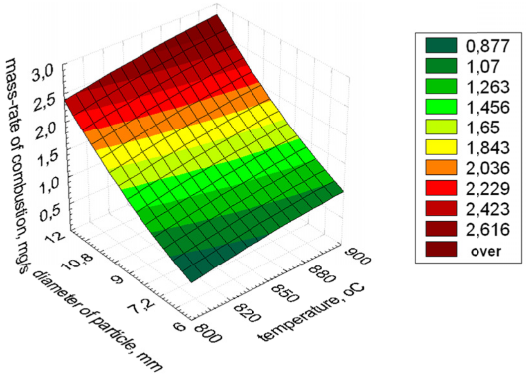


Fig. 17. Influence of temperature changes in the combustion chamber and the diameter of fuel on the mass rate of sewage sludge combustion; $v = 5.4$ m/s

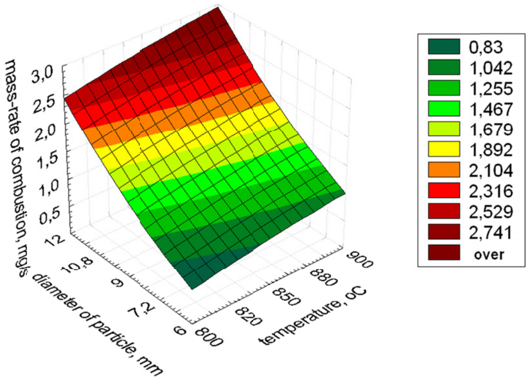


Fig. 18. Influence of temperature changes in the combustion chamber and the diameter of fuel on the mass rate of sewage sludge combustion; $v = 6$ m/s

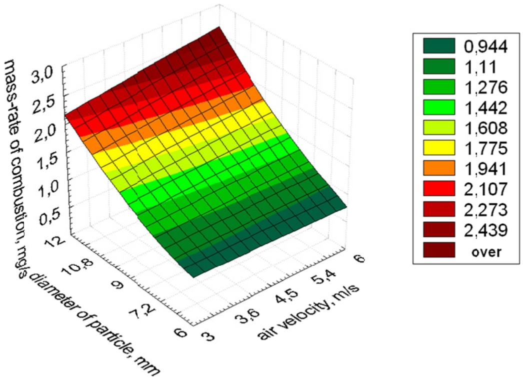


Fig. 19. The impact of changes in air flow velocity and the diameter of fuel on mass combustion rate of sewage sludge, $t = 800$°C

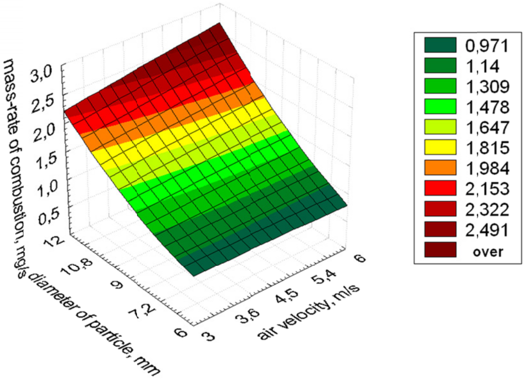


Fig. 20. The impact of changes in air flow velocity and the diameter of fuel on mass combustion rate of sewage sludge, $t = 820$°C

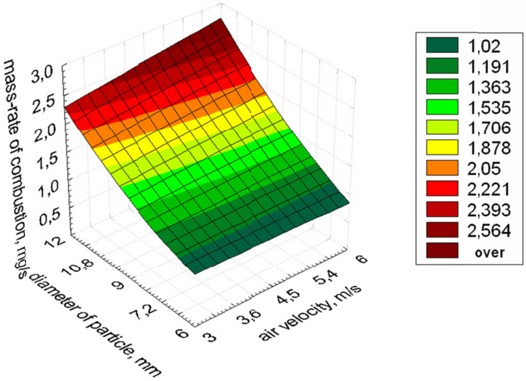


Fig. 21. The impact of changes in air flow velocity and the diameter of fuel on mass combustion rate of sewage sludge, *t* = 850°C

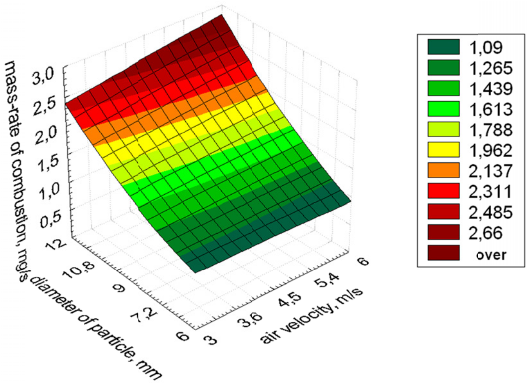


Fig. 22. The impact of changes in air flow velocity and the diameter of fuel on mass combustion rate of sewage sludge, *t* = 880°C

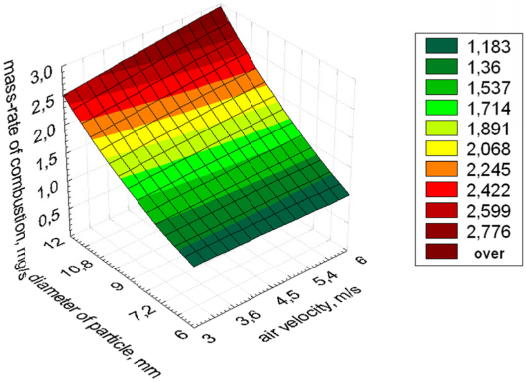


Fig. 23. The impact of changes in air flow velocity and the diameter of fuel on mass combustion rate of sewage sludge, *t* = 900°C

On the basis of Figures 9-23, it was found that:

a) increasing the size of a fuel sample leads to an increase in the fuel mass combustion rate (Fig. 9-13):
   - in the entire speed range of air flow along with increasing temperature, particularly in the high-speed air flow,
   - with the increase of air flow speed in the range of higher temperatures in the combustion chamber.

b) increasing the speed of air flow leads to an increase in the fuel mass combustion rate (Fig. 14-18):
   - in the entire range of temperatures in the combustion chamber along with an increase in diameter of the fuel,
   - in the entire range of diameters of the fuel in question along with an increase in temperature in the combustion chamber.

c) increasing the temperature in the combustion chamber leads to an increase in the fuel mass combustion rate (Fig. 19-23):
   - in the entire range of speed of air flow along with an increase in diameter of the fuel,
   - with the increase of air flow speed in the range of larger diameters of the fuel.

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. It should be noted that ignition of fuel is a complex process and is influenced mainly by fuel properties. If the fuel has a higher reactivity, its ignition occurs faster due to earlier and more intense heat emission. As it is known, the reaction rate is intensified when the heat release increases. High content of biomass and sewage sludge in a fuel blend with coal can, therefore, lead to longer degassing of volatiles and reduction in fuel combustion time. It should be emphasised that in the case of sewage sludge and biomass, degassing and combustion of volatile matter is an important step in the process of combustion. The amount of heat supplied by the process of combustion of volatiles in this type of fuel is much higher than in the case of coal. 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 rate of combustion of carbonating agent of the above-mentioned fuels, which is the longest phase of the combustion, is also greater than in case of carbon.

Analysing wave shapes of fuel temperature (Fig. 24-28), it can be stated that upon introduction of fuel into the combustion chamber in the atmosphere of flowing oxidizing gas, its ignition takes place via the volatiles emitted from the fuel. Visual observation of the process indicates that this moment corresponds to the moment the flame of burning volatile elements becomes visible and recording fuel temperature changes proves that at this point there is an increase in the intensity of fuel heating. 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. Combustion time of volatiles emitted from the fuel was determined from the appearance of flame until it extinguished. What is very instructive is the visual observation of the process of combustion of fuels in the course of the experiments (Fig. 29). This allows for a thorough interpretation of the phenomenon at various stages of combustion (heating, evaporation, devolatilisation and volatile combustion, char combustion).

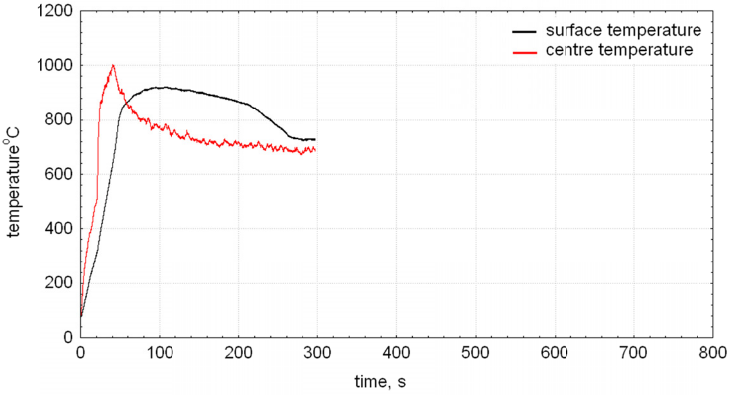


Fig. 24. The course of temperature changes on the surface and inside a sample of sewage sludge

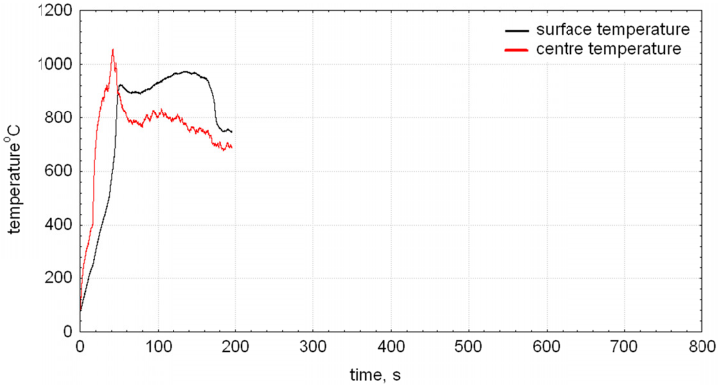


Fig. 25. The course of temperature changes on the surface and inside a sample of biomass

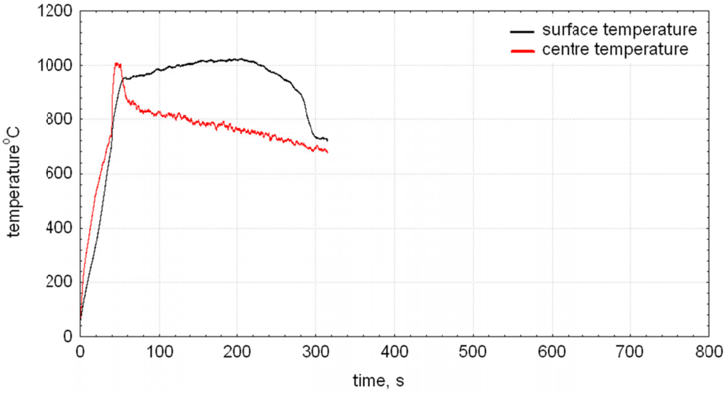


Fig. 26. The course of temperature changes on the surface and inside a sample of brown coal

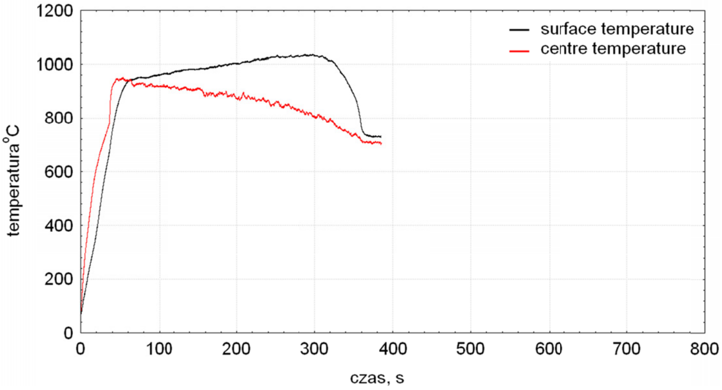


Fig. 27. The course of temperature changes on the surface and inside a sample of hard coal

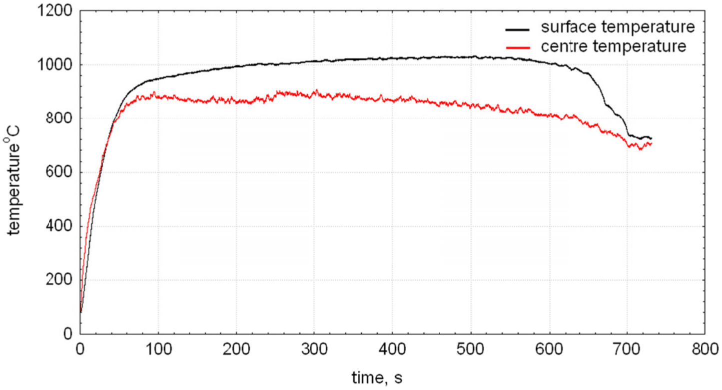


Fig. 28. The course of temperature changes on the surface and inside a sample of anthracite

Simultaneous visualization and 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. Ignition of carbonising agent (degassed fuel) can be observed as the moment when the surface of fuel sample starts glowing. In case of all types of fuel, once the fuel surface temperature reaches its maximum level, a gradual temperature decline is observed, indicating a movement of the combustion front inside the fuel and cooling of the surface by means of ash layer, created in the process of combustion; the layer surrounds the core of the carbonising agent. A rapid decrease in temperature of the agglomerate means that the combustion process finishes. Studies indicated that the high content of volatile matter in the fuel intensifies the initial stages of combustion, distinguished by more intensive reacting of the fuel.

The fuel, upon introduction to a high-temperature unit (combustion chamber), slightly changes its size in the subsequent stages of combustion, due to evaporation of water, release of

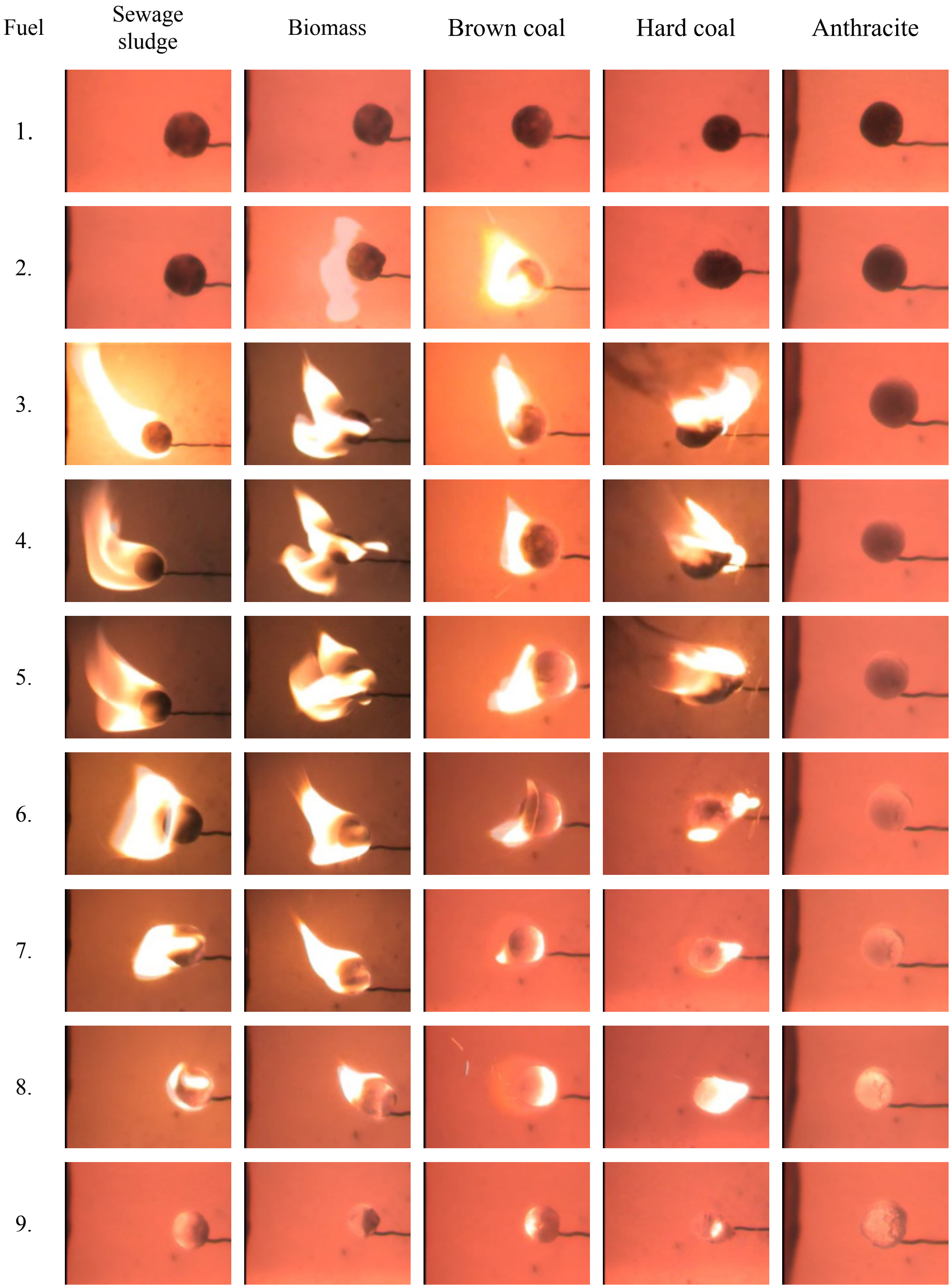


Fig. 29. The visualisation of fuels combustion process

volatiles and after-combustion of solid substances. The degree of initial expansion and contraction of the fuel during the process depends on type of fuel dust and its structure. Fuel formed from anthracite burns slowly and flamelessly, in contrast to fuels having lower content of carbon element.

Studies showed similar behaviour of sewage sludge and brown coal in terms of the combustion process in a stream of air.

6. Conclusions

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

1. The process of combustion of fuel samples formed from sewage sludge, carried out in the air stream at temperature between 800÷900°C, takes place in the kinetic-diffusion area, with a dominance of diffusion factors. Therefore, it depends on the temperature in the combustion chamber, but, first of all, on the speed of air flow and the size of fuel samples.

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

3. The statistical analysis of study results allowed for determining a correlation between parameters deciding about the course of combustion of fuel in the air stream, and for designating approximation functions describing flow of processes.

4. 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.

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