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ANALYSIS OF THE PROCESS OF COMBUSTION OF POST-CONSUMER WOOD USING QUANTITATIVE ASSESSMENT INDICATORS

The paper presents an analysis of the fuel and emission properties of selected types of post-consumer wood. The tested materials include flooring, wood door frames, and used furniture, as well as wood as a material for comparison. In addition, through the results of tests carried out in the laboratory, the paper presents possibilities related to the optimization of waste combustion plants equipped with combustion chambers with mobile grates. For this purpose, indicators of quantitative assessment were determined, i.e. the reaction rate, the fire point, mass loss during combustion, and the heat load of the grate.

Keywords: post-consumer wood, fuel properties, combustion, emission of gas combustion products, quantitative assessment indicators of waste combustion

Introduction

Together with a growing consumption of furniture and home decoration products in Poland, a growth in the amount of wood and wooden board waste has been observed. Problems with the proper management of post-consumer wood waste result among other things from its large dispersion and its variety in respect of amount and form [Cichy and Wróblewska 2003; Ratajczak and Szostak 2003; Danecki 2007]. Post-consumer wood waste includes packaging wood, pallets, wood processing waste, furniture, floors and door frames, and wooden construction elements. Due to the large variety of post-consumer wood waste, knowledge of chemical contamination is necessary. Substances most frequently used to treat wood include urea-formaldehyde, melamine-formaldehyde and phenol-formaldehyde resins, other glues, paraffin waxes, varnishes, veneers, foils and wood preservatives [Roffael et al. 2005; Nicewicz 2006; Danecki 2007; Wasilewski and Hrycko 2010]. Knowledge of which chemicals have been applied would make it possible to sort waste into groups and to suggest which is the best waste management method – recycling, thermal utilization or deposit [Danecki 2007; Cichy and Pawłowski 2009, 2010; Cichy

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2012; Nicewicz et al. 2012; Klimczewski and Nicewicz 2013; Wan et al. 2014]. This is an important issue, because in Poland an increase of 4% in the demand for wood and wood-like products has been observed. At the same time, a decrease in wood resources has been accompanied by an increase in wood and wood-like waste [3spare: reading on 29.05.2015]. It is estimated that the supply of post-consumer wood which comes only from the replacement of furniture and interior furnishings amounts to approximately 1.44-1.68 Mio m³ per year. On the basis of European indicators of the post-consumer wood market, it may be assumed that with the acquisition in 2005 of 29.7 Mio m³ of wood from forests, the amount of post-consumer wood for reuse in the period of one year would reach 2.8 Mio m³ and 5.7 Mio m³ for energy use [Danecki 2007]. The appropriate management of such wood waste could significantly contribute to a limitation of forest logging, a decrease in the amount of waste directed to landfills, and the recovery of energy and raw materials [3spare: reading on 29.05.2015].

One method for recovering energy from biomass and wood waste is combustion or co-combustion with traditional fuel. The combustion process seems to be simple. However, in reality, it is a complex process due to a number of physical and chemical phenomena taking place during combustion. The combustion of waste in industrial plants has been carried out for nearly 100 years. The characteristics of this process are totally different from those in the combustion of conventional fuels, such as coal or lignite. These differences are caused by the heterogenic content of waste, the large graining variety (different fractions) and regional and seasonal variations in the physiochemical properties of the waste. The combustion of waste is characterized by an unspecified and non-homogeneous process, as well as by the generation of detrimental substances. The possible, detrimental consequences of this process consist of slag formation, as well as the corrosion and erosion of the combustion device. Hence, it is necessary to assure constant optimization of the waste combustion plant operation [Marutzky and Schriever 1986; Nussbaumer 2003; Jaworski 2005, 2007; Cichy 2012; Nadziakiewicz et. al. 2012; Czop 2014; Kajda-Szcześniak and Nowak 2014].

Due to the above, this article deals with the issues related to the optimization of the combustion process, the goal of which is to decrease the risk of detrimental impact on the natural environment. Tests were carried out in the laboratory and they were pertained to a real combustion plant with application of quantitative assessment indicators.

Indicators of quantitative evaluation of waste combustion

The replacement of classic fuels with fuels based on wood waste allows, on the one hand, a reduction in CO₂ emissions (especially in respect of biodegradable mass, for example biomass) and, on the other, helps to avoid the deposition of natural fuels, following the rules of sustainable development. For the thermal

disposal of fuels produced from wood waste in incineration or heat plants operating with coal and biomass, etc, it is necessary to define and determine certain characteristic indicators in order to evaluate the combustion process. These indicators should serve as a basis for a comparison between waste fuels and with classic fuels. In addition, perhaps more importantly, they could serve as some sort of “criteria numbers” allowing the transfer of values from the laboratory device, which works on an irregular basis, to the actual industrial device, which works constantly with determined parameters and is equipped with grated firing. It would provide many opportunities for the optimization of exploitation parameters of incineration plants, especially plants equipped with a mobile grate. The following indicators of the quantitative evaluation of the combustion of fuels have been proposed: reaction rate, ignition rate, combustion mass loss and heat load on the grate [Jaworski 2012].

Temperature sensors were placed at the height of the layer which was the subject of the process of combustion on the grate, in order to determine the maximum increase in temperature:

$$\frac{\Delta \vartheta}{\Delta t} = \left(\frac{\Delta \vartheta}{\Delta t} \right)_{\max} \quad (1)$$

in each thermo-element of the fuel layer indicating the location of the area of reaction or flame. Such a reaction in the fuel deposit is described as the reaction rate and marked as:

$$u_{FR} = \frac{dx_{FR}}{dt} \left[\frac{\text{m}}{\text{s}} \right] \quad (2)$$

where: x_{FR} – location of the front of reaction, [m].

The velocity of ignition (SZ) indicates the mass stream of fuel per unit time, which undergoes ignition per unit area.

$$SZ = u_{FR} \cdot \rho_n \left[\frac{\text{kg}}{\text{m}^2 \text{ s}} \right] \quad (3)$$

ρ_n – bulk density, [kg/m³].

This indicator describes the combustion parameters in grated industrial devices. For fuels with greater ignition velocity, the mass flux per area unit should be increased in order to maintain the combustion process. For fuels with lower ignition velocity, the mass flux should be decreased or the air should be heated for faster drying [Jaworski 2012].

Mass loss rate (SUM) is determined by the mass loss in time and per unit area of the grate

$$\text{SUM} = \frac{\Delta m_{\text{fuel}}}{A_R} \left[\frac{\text{kg}}{\text{m}^2 \text{ s}} \right] \quad (4)$$

A_R – area of the grate, [m²].

With this indicator, the length of the combustion zone in industrial devices can be calculated, if the stream of fuel and the area of the grate are known. This indicator describes the relationship between the ignition velocity and the related real fuel mass loss. For fuels with a much faster ignition than the value of the mass loss rate, there is the risk that the unburned fuel would be moved to the end of the grate.

The heat load of the grate (*OCR*) indicates how much of the energy from the fuel will be released during its oxidation in a given period of time and on a given area of the grate (it may determine the way of cooling) [Jaworski 2012].

$$OCR = \text{SUM} \cdot W_d \left[\frac{\text{kW}}{\text{m}^2} \right] \quad (5)$$

W_d – lower calorific value of the fuel, [kJ/kg].

Observation of the indicator of the heat load of the grate prompts technical service staff to react in case of grate overload.

Investigated materials and test methods

Scope of the research

The paper presents an analysis of the physicochemical properties of selected post-consumer wood waste. The goal of the analysis was to determine specific fuel properties, such as moisture, ash content, content of volatile components, flash point, calorific value and elemental composition (C, H, O, N, S, Cl).

In addition, possibilities for the optimization of the exploitation parameters of industrial devices equipped with a mobile grate are presented. This is estimated through the results of tests carried out in the laboratory. For this purpose, previously defined indicators of the quantitative evaluation of waste combustion were determined, i.e. the reaction rate, ignition rate, loss of combusted mass and heat load on the grate.

Material for tests

The tests covered the following types of post-consumer wood:

- O-I – post-consumer furniture, box furniture based on wood derived slabs with a matt front. The exploitation time of the furniture was approximately 40 years.
- O-II – mixed floor panels of wear ratings AC3, AC4 and AC5 in the proportions 1:1:1,
- O-III – mixed door frames, in the proportions 1:1 (a door wing made of MDF, covered with veneer on the outer side, mixed with a door wing made of MDF frame, filled with honeycomb shaped cardboard, covered with varnish on the outer side),
- O-IV – wood from coniferous trees.

The wooden materials used for the tests were crushed using a Trymer T45,5SW mill equipped with a mesh measuring $\varnothing 14$ mm in diameter.

Physicochemical properties

The moisture content was determined according to the standard PN-Z-15008-02:1993 by drying method at a temperature of 105°C. The ash content was determined according to standard PN-Z-15008-03:1993, and the content of volatile matter was determined in compliance with standard PN-G-04516:1998. The ignition temperature was determined in accordance with standard PN-EN ISO 2592:2008 using a Cleveland open-cup tester. The heat of combustion was determined following the procedure described in PN-ISO 1928:2002.

The carbon and hydrogen content was determined according to standard PN-Z-15008-05:1993. It consisted of the total combustion of a sample in a stream of oxygen, and determination of the mass, water and carbon dioxide content in the flue gas.

The nitrogen content was determined by Kjeldahl method, according to standard PN-G-04523:1992.

The sulphur content was determined using the Eschka method, on the basis of the standard PN-ISO 334:1997. The chloride content was determined by the Mohr method using an Eschka mixture in compliance with standard PN-ISO 587:2000.

Experimental stand

A schematic diagram of the testing stand used is presented in figure 1.

The stand consisted of an FCF 30 RP chamber furnace with 5 kW power, according to the DTR (operation and maintenance manual). The furnace was equipped with a specially designed grate with equipment for measuring the parameters inside the layer of combusted waste. Furthermore, the post was equipped with an exhaust analyzer allowing the measurement of the composition of the exhaust gas. It also had a weighbridge which registered the mass loss of waste during the combustion process.

Determination of the content of exhaust gases

For the measurement of exhaust fumes, the Madur GA-40Tplus portable analyzer was used. The analyzer enabled an analysis of the concentration of six gases (O_2 , CO_2 , CO , NO_x , SO_2). Additional measurements during combustion process

Temperature measurements inside the layer of the combusted post-consumer wood waste were taken with the use of three thermocouples, placed in the body of the working grate at layer height. The first thermocouple was placed at a height of 50 mm from the bottom of the grate, the second at 150 mm, and the third at 250 mm. The distance between the thermocouples was 100 mm. The

temperatures were recorded using an electrical measuring device with a testing interval of 1 minute.

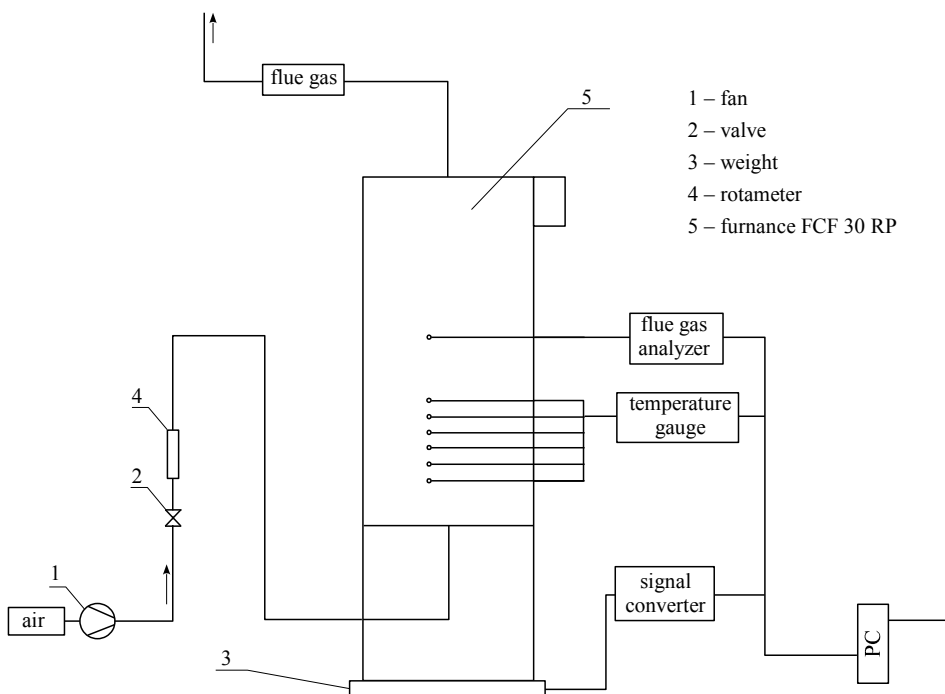


Fig. 1. Schematic of the testing stand for assessment of the fuel combustion process [Jaworski 2012]

Testing process

Tests of the combustion process within the layer were carried out in devices in a laboratory scale. The tests were performed according to the following scheme:

- a. preliminary tests, which consisted of:
 - preparation of fuel for combustion, determination of the mass of combusted waste,
 - determination of the bulk density of the layer of combusted waste,
 - determination of the area of the grate,
 - determination of the parameters of the combustion process, i.e. temperature, process time, amount of air supplied to the combustion chamber,
 - necessary preliminary calculations of the combustion process in order to determine the stream of air for the assumed process time and the coefficient of the surplus air,
- b. actual tests covered:
 - attainment of the process temperature within a range of 850-900°C, accounting for 20 minutes of furnace relief at 350°C,

- activation of the primary air fan; setting primary air stream with a rotameter within a range of 18-19 m³/h,
- removal of the dummy grate and placing of the working grate with the waste in the furnace,
- measurement of temperatures inside the layer of combusted waste,
- measurement of the concentration of exhaust fumes,
- measurement of the mass loss of the combusted waste,
- constant measurement of the time which enabled measurement of the parameters at the same time,
- the test was terminated by disconnecting the furnace from the power supply, disconnecting the measuring devices, disconnecting the air fan, removal of the working grate from the furnace, and placing the dummy grate in the furnace.

Results and discussion

Physicochemical properties of tested waste

The results of the physicochemical analysis of the selected post-consumer wood waste are shown in table 1.

Table 1. Physicochemical properties of tested waste

Property	Unit	O-I	O-II	O-III	O-IV [Kaltschmitt and Hartmann 2001]
Moisture content	%	7.03	5.08	6.36	–
Ash, A ^d	%	0.88	1.02	0.73	0.60
Volatile components, V ^d	%	77.60	79.03	79.29	82.90
Flash point	°C	187.00	201.50	219.00	–
Heat of combustion, W _g ^d	MJ/kg	22.07	20.16	16.29	20.20
Calorific value, W _d ^d	MJ/kg	20.95	19.22	15.40	18.80
Carbon, C ^d	%	51.51	51.24	51.22	49.80
Hydrogen, H ^d	%	5.00	4.40	4.22	6.30
Oxygen, O ^d	%	35.29	29.55	33.75	43.20
Nitrogen, N ^d	%	6.88	13.23	9.59	0.13
Sulphur, S ^d	%	0.26	0.19	0.28	0.02
Chloride, Cl ^d	%	0.18	0.36	0.22	0.01

– No data

– The oxygen content was determined by calculation

The results show that the tested post-consumer wood waste O-I – O-III were similar regarding their physicochemical properties. The moisture content of all the tested waste was low and fell within the range, from 5.08% for waste O-II to 7.03% for waste O-I. All the tested waste had very low ash content, not exceeding 1.02%. Analysis of the fly ash content showed slight differences between the waste O-I, O-II and O-III. The content of volatile components in the tested waste ranged from 77.60% to 79.29%.

One of the most important parameters was the calorific value calculated on the basis of the determined combustion heat, hydrogen content and moisture content. It was noted that waste O-I had the highest calorific value equalling 20.95 MJ/kg. For the other waste, the calorific value was lower and amounted to 19.22 MJ/kg for waste O-II and 15.40 MJ/kg for waste O-III. The marked flash point fell within a range of 187°C for waste O-I to 219°C for waste O-III.

The analysis concerning a determination of the content of chemical elements proved that the basic elements which formed part of the selected waste from the wood-based panels were C, H, O and N. The carbon content of the tested waste (O-I - O-III) was equal 51%. The content of hydrogen in the tested waste was below 5%. On the basis of the executed tests, a high content of nitrogen was identified in all the analyzed waste. This value was the lowest for waste O-I at 6.88% and the highest for waste O-II at 13.23%. The nitrogen content may have resulted from the existence of urea- and melamine-based resins, lacquers and coatings, as Wandrasz and Wandrasz [2006] found that the content of nitrogen in urea-formaldehyde resins amounts to 37%, and in melamine-formaldehyde resins it reaches 48%. According to Cichy [2012], the content of nitrogen in post-consumed timber from Polish manufactured products falls within a range of 1.5% to 7%, while for urea-resin bonded plywood this value is approximately 8%.

The sulphur content of the tested waste was at a low level, below 0.28%. The recorded chloride content ranged from 0.18% to 0.36%. The waste assortments from the wood-based panels had similar properties to wood O-IV. An exception from this finding was the nitrogen content. The wood also had a lower content of sulphur and chloride.

Emission properties of tested waste

The results of the measurements are presented in figures 2-5. The emissions from the combustion of wood-derived waste were compared to the results of the combustion of pure wood.

During the combustion process, an increased emission of nitrogen oxides for waste O-I, O-II and O-III was recorded. This was due to the application of adhesive resins at the production stage of the wood-derived products, which generated a high nitrogen content in the elemental composition. The results confirm that waste of this type should be burned in devices with a properly selected exhaust purification system, which will bring advantages in terms of the environment and energy. In figure 2 it can be seen very clearly, and also in figures 3 and 4, a sufficiently elongated afterburning stage (extended process time) which is shown in the slow decrease in CO₂ concentrations until the values approach zero. The reason was the extended presence of solid combustible particles in the combusted layer of waste, which came from more complex resins and resins which were more difficult to decompose – a component of the tested waste.

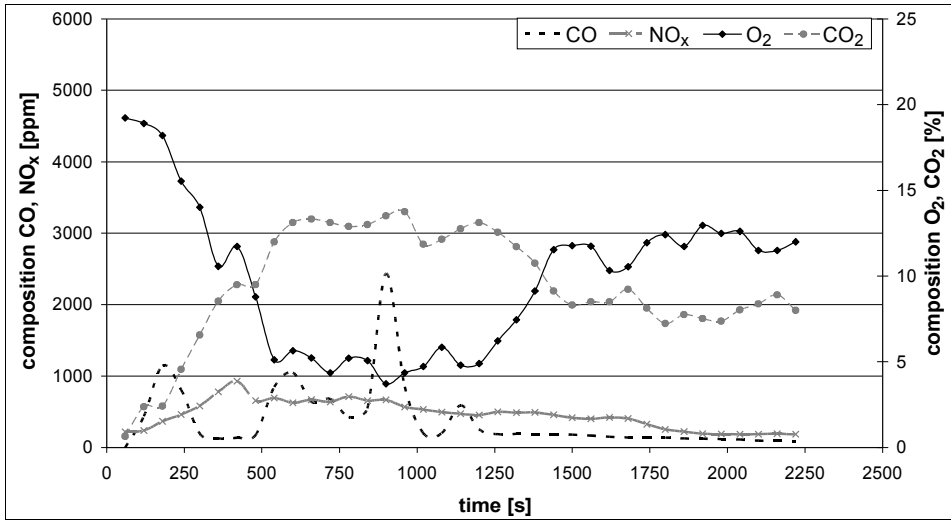


Fig. 2. Change in composition of exhaust gases during the combustion process of waste O-I

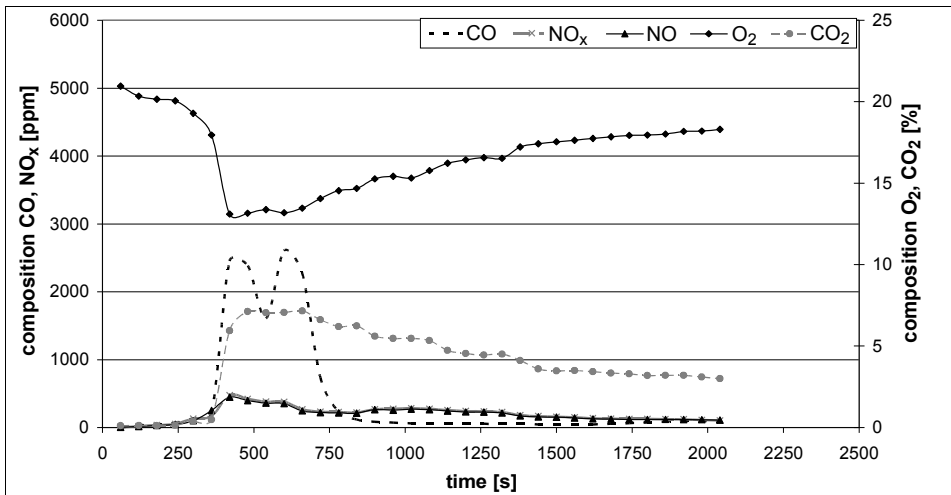


Fig. 3. Change in composition of exhaust gases during the combustion process of waste type O-II

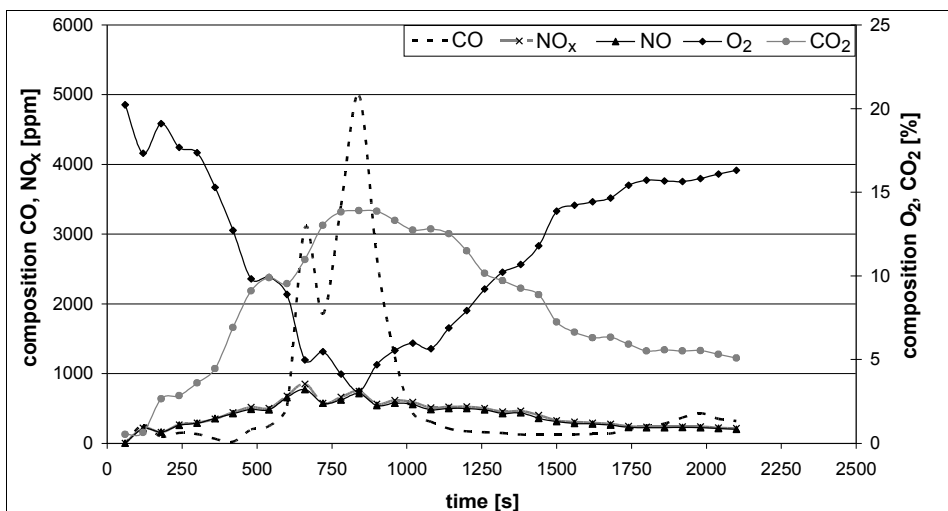


Fig. 4. Change in composition of exhaust gases during the combustion of waste type O-III

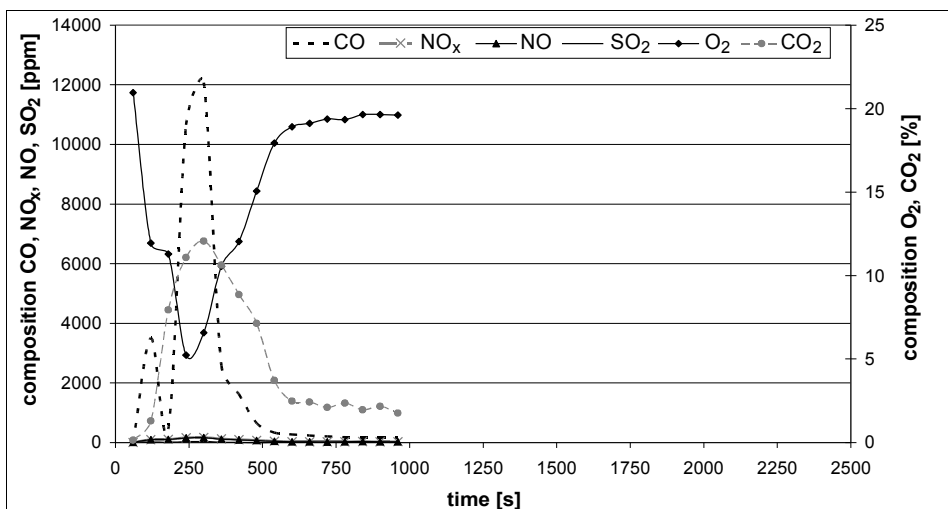


Fig. 5. Change in composition of exhaust gases during the combustion of waste type O-IV

Distribution of temperatures in solid and gas phases in the combusted waste layer

The tests of the distribution of temperatures in solid and gas phases in the combusted waste layer on the grate are shown in figures 6-9. The measurements were taken at three given heights – 50 mm from the bottom of the grate, 150 mm and 250 mm.

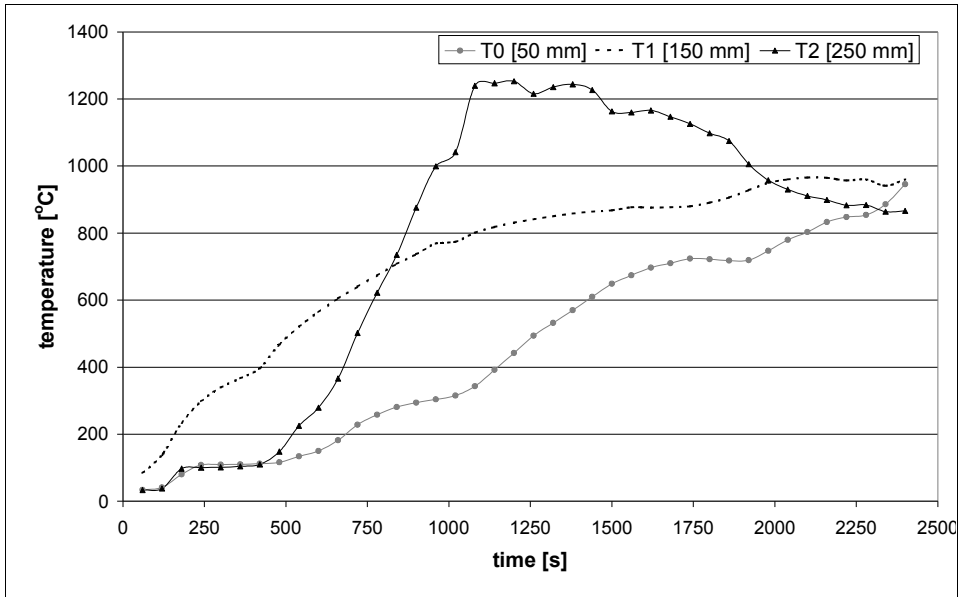


Fig. 6. Distribution of temperatures in solid and gas phases in the combusted layer of waste type O-I during the combustion process at a temperature of 850°C.

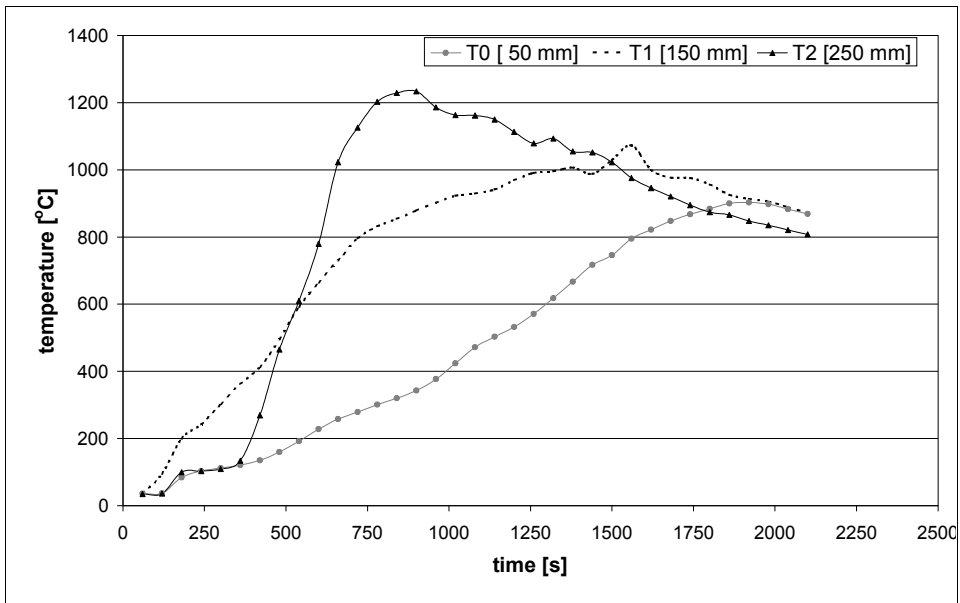


Fig. 7. Distribution of the temperature in solid and gas phases in the combusted layer of waste O-II during the combustion process at a temperature of 850°C

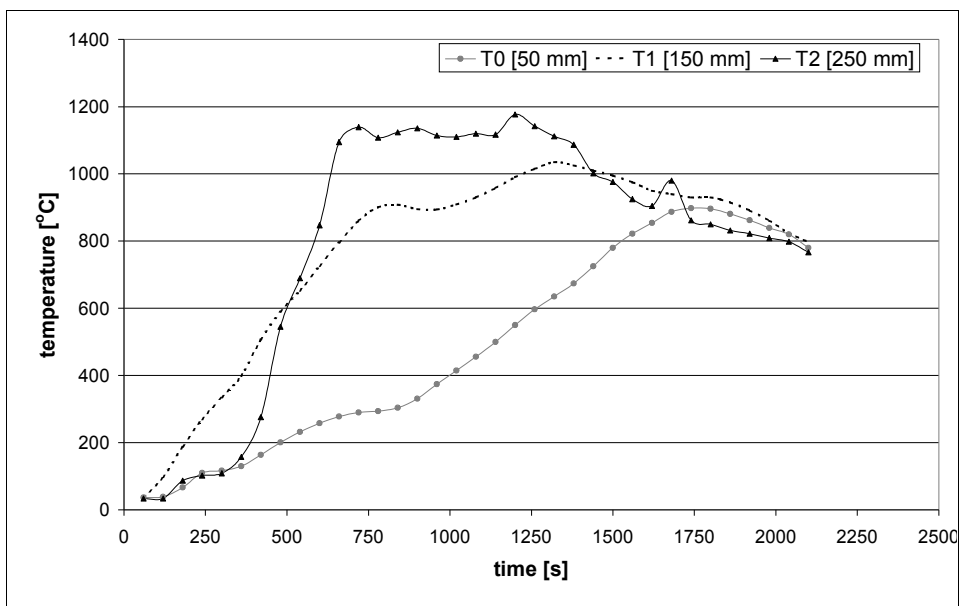


Fig. 8. Distribution of the temperature in solid and gas phases in the combusted layer of waste O-III during the combustion process at a temperature of 850°C

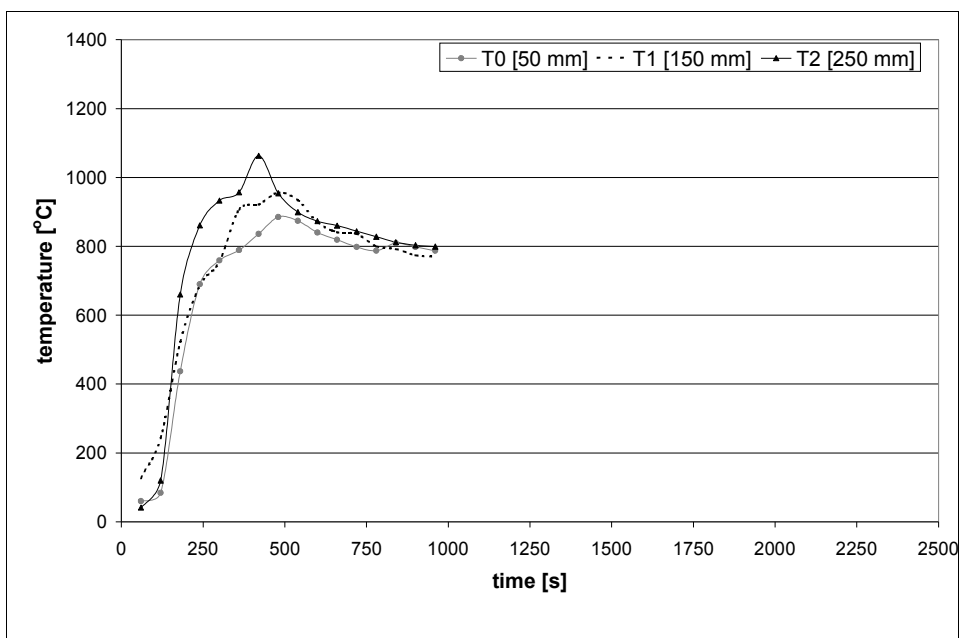


Fig. 9. Distribution of the temperature in solid and gas phases in the combusted layer of waste O-IV during the combustion process at a temperature of 850°C

Initially the temperatures increased over a certain period of time and then decreased, all reaching similar values in the final phase of the combustion process. This phenomenon was caused by the combustion of the waste in the layer. On the basis of the measurements, it was possible to calculate the following indicators: the reaction rate and the ignition rate. In each case, the highest temperature was noted on a thermocouple placed at the highest position in the layer. However, the largest increase in temperature in the initial phase (up to approximately 600°C) was recorded by the middle thermocouple. The most probable explanation for this finding is that this location had the best combustion conditions, i.e. a suitable temperature and an availability of oxygen, whose deficiency in the top layer of the waste suppressed the total and complete combustion process.

Figure 10 shows how the mass of tested waste was reduced during the combustion process.

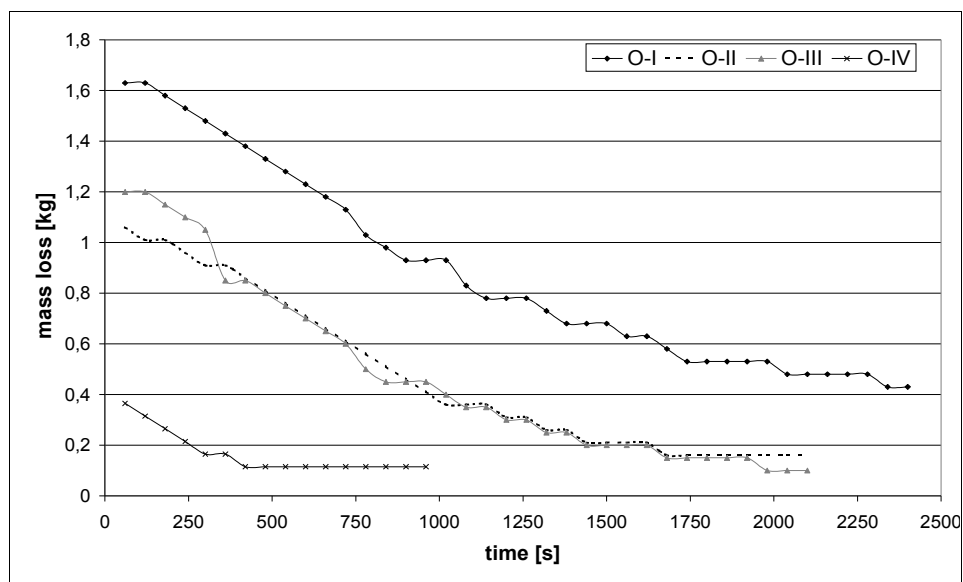


Fig. 10. Mass loss of the combusted layer of waste O-I – O-IV during combustion, at a temperature of 850°C

For waste O-I – O-III, the biggest mass losses were noted in the first 16 minutes of the combustion process, but for waste O-IV they were recorded after no more than 5 minutes. At the end of the process, the waste mass stabilized at a steady level, which was evidence of waste burnout. The residue was mineral fractions. Waste O-IV (pure wood without chemical contamination) exhibited, in accordance with the fastest mass loss, the fastest burnout.

Measurement of the mass loss of the waste during combustion together with measurement of the concentration of exhaust fume components provides

important information about termination of combustion. Hence, it helps to determine the best process time.

The tests conducted acted as a basis for a calculation of quantitative evaluation indicators – see table 2.

Table 2. Results of the tests of quantitative evaluation indicators for the combustion of waste

Type of waste	Process temperature T	Combustion time t	Coefficient of surplus air λ	Bulk density ρ_n	Reaction rate u_{FR}	Ignition rate SZ	Mass loss rate SUM	Heat load on grate OCR
	[°C]	[s]	–	[kg/m ³]	[m/s]	[kg/m ² s]	[kg/m ² s]	[kW/m ²]
O-I	850	2400	1.60	340	0.0004	0.143	0.031	603.1
O-II	850	2100	2.07	250	0.0002	0.050	0.033	601.7
O-III	850	2100	2.49	220	0.0005	0.104	0.027	380.6
O-IV	850	960	2.92	76	0.0017	0.127	0.016	277.9

All the tests were conducted with an approximate surplus air coefficient which accounts for the process time in conditions of total and complete combustion. It made it possible to objectively compare all the analyzed post-consumer wood waste and formulate the basic parameters of the process of their combustion in a chamber equipped with a mobile grate. On the basis of the determined indicators of the quantitative evaluation of the waste combustion (tab. 2), the following can be stated:

- waste O-IV had the fastest reaction front rate, which is not a surprise when considering its clean and porous form and lowest bulk density. The lowest value of this parameter was recorded for waste O-II containing the biggest quantity of resins,
- the low value of the reaction front rate in the case of waste O-II also showed the low rate of ignition,
- in all the cases of tested waste, the ignition rate was higher than the mass loss, which may have left residue of the unburned fuel at the end of the grate,
- the very high heat load of the grate in the case of waste O-I and O-II resulted from the very high calorific value of this waste. It may have required the use of additional grate cooling.

Conclusions

Through the ignition rate we may determine parameters in industrial devices with grates, especially under conditions when different fuels are combusted – waste at the same time as in the case of incinerators, or when waste is a participant of the co-combustion process.

In the case of fuels with a high ignition rate, the mass flux per unit area of the grate should be increased in order to maintain the reaction flame. In the case

of fuels with a low ignition rate, the mass flux should be lowered or the air should be heated in order to dry them faster. Through the rate of mass loss the length of the combustion zone in industrial devices can be calculated, provided that the fuel mass flux and the area of the grate are known. This indicator, when compared to the fire point, gives information about the relationship between the mass ignition and real, released fuel mass loss. In the case of fuel which has a much higher fire point than the rate of mass loss, there is a risk that at the end of the grate, parts of the fuel will remain unburned. The heat load on the grate is an important issue from the point of view of exploitation of grated devices for the combustion of waste. Observation of this indicator prompts technical service staff to react to any overloading. At the incinerator design stage it provides information as to whether the grate cooling system, among other measures, needs to be accounted for.

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List of standards

- PN-EN ISO 2592:2008** Oznaczanie temperatury zapłonu w tyglu otwartym metodą Clevelanda (Determination of fire point in open crucible with Cleveland method)
- PN-G-04523:1992** Oznaczanie zawartości azotu metodą Kjeldahla (Determination of nitrogen with the Kjeldahl method)
- PN-G-04516:1998** Oznaczanie zawartości części lotnych metodą wagową (Determination of the content of volatile matter)
- PN-ISO 334:1997** Oznaczanie siarki całkowitej metodą Eschki (Determination of sulphur with the Eschka method)
- PN-ISO 587:2000** Oznaczanie zawartości chloru z zastosowaniem mieszaniny Eschki (Determination of chloride using Eschka mixture)
- PN-ISO 1928:2002** Oznaczanie ciepła spalania metodą spalania w bombie kalometrycznej i obliczanie wartości opałowej (Determining combustion heat with the method of combustion in calorimetric bomb and calculating calorific value).
- PN-Z-15008-02:1993** Oznaczanie wilgotności całkowitej (Determination of moisture content)

PN-Z-15008-03:1993 Oznaczanie zawartości części palnych i niepalnych (Determination of combustible and incombustible elements)

PN-Z-15008-05:1993 Oznaczanie zawartości węgla i wodoru (Determination of carbon and hydrogen)