Chemical and Process Engineering 2018, 39 (1), 3–14
DOI: 10.24425/119095

EXPERIMENTAL AND THEORETICAL MODELING OF WASTE COMBUSTION IN A CHAMBER WITH A MOVING GRATE

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The work contains a description of a developed experimental and theoretical method of modeling of solid waste combustion in a device equipped with a moving grate and capability to optimize the work of waste incineration plant. Implementation of this issue was based on results of experimental studies made on a laboratory scale boiler. This was possible by defining and testing indicators of quantitative assessment of combustion such as: reaction front rate, ignition rate, the rate of combusted mass loss and the heat release rate. These indicators as measurable "criteria indicators" allow transfer of parameters from a laboratory-scale unit, working in the transient regime into an industrial full scale grate device working continuously in stable determined conditions. This allows for wide optimization possibilities in the operation of a waste incineration plant, in particular the combustion chamber, equipped with a moving grate system.

Keywords: waste, combustion, physicochemical properties, emission of gas combustion products, quantitative evaluation indicators

1. INTRODUCTION

Waste incineration is a complex process due to a high number of phenomena that occur in the combustion chamber. In order to limit the negative impact on the environment there is a need to optimize the combustion process by the selection of appropriate equipment for its implementation and process parameters and materials (e.g. the fragmentation of waste, pre-drying, etc.) (Czop, 2014; Kajda-Szcześniak and Jaworski, 2016; Kajda-Szcześniak and Nowak, 2014; Levenspiel, 1999; Lin and Ma, 2012; Scholz et al., 2001; Xia et al., 2014).

The basis to seek opportunities for experimental-theoretical modeling and optimization of the combustion process of solid waste in combustion chambers equipped with moving grates is the use of laboratory-scale tests and their further transfer to a full-scale device, supporting and optimizing the process of operating a waste incineration plant (Jaworski, 2012; Yin et al., 2008).

Figure 1 shows a scheme of possible implementation of results of optimization model presented in the manuscript.

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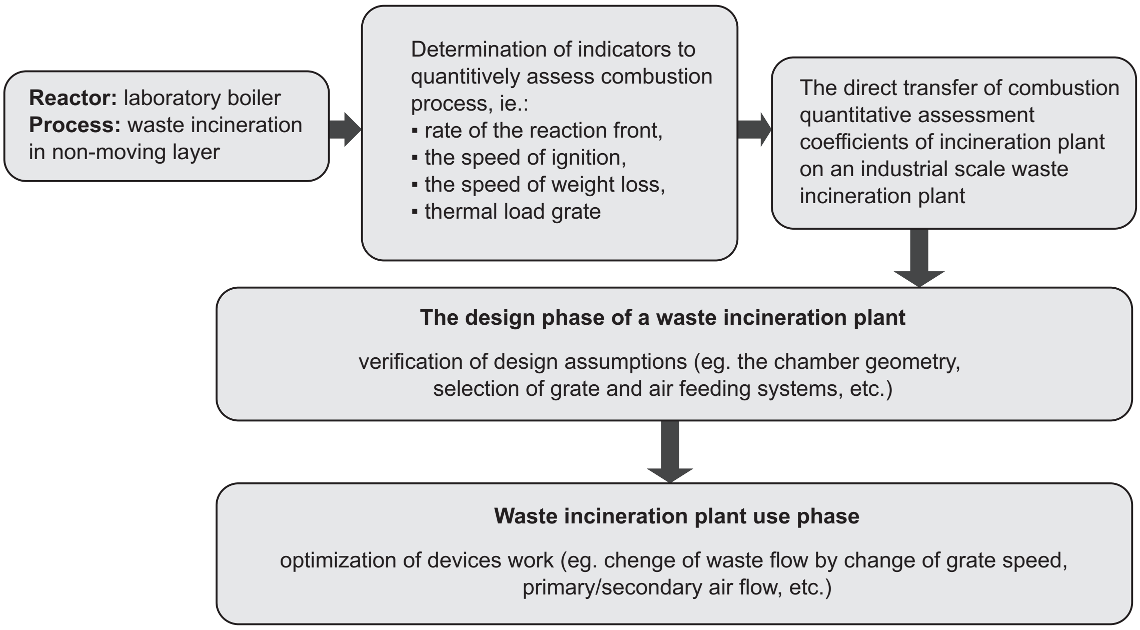

Fig. 1. Potential for application of the results of experimental tests conducted in the laboratory-scale furnace in the experimental-theoretical modeling of the process of solid waste combustion in a commercial-scale moving grate plant (Jaworski, 2012)

1.1. Transfer of physicochemical transformations from the laboratory scale boiler to an industrial scale

It can be assumed that the processes occurring in the plant in the grate zones, i.e. heating, drying, devolatilization and combustion are similar to processes in a laboratory furnace adapted to stationary combustion of waste (Fig. 2). Dynamic, unsteady and intermittent combustion process in a stationary level in the laboratory furnace should be linked with stationary and continuous process encountered in the actual incineration plants. This link occurs through a condition of equal durations of processes correlated by the length of the grate and its speed (transport of waste material) (Jaworski, 2012; Liang and Ma, 2010; Yang et al., 2004).

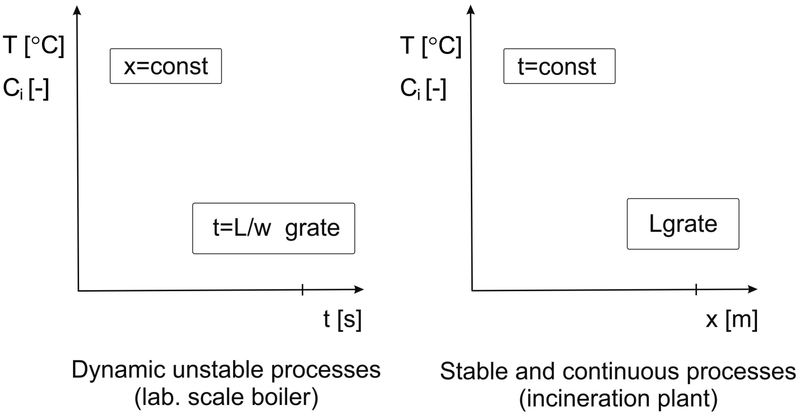

Fig. 2. Scaling up the physicochemical transformations from the laboratory-scale furnace onto the commercial continuous-operation plant (Jaworski, 2012)

For a laboratory furnace with a non-moving layer timeline of gas release (conversion of waste as solid fuel to gas phase) and the weight loss is very similar to a process carried out in a full scale incineration plant as a function of the residence time of the waste material taking into account the location and the specificity of combustion zones on the grate (Jaworski, 2012). Bleckwehl et al. (2004, 2005a, 2005b) and Jaworski (2008) demonstrated and verified quantitative and qualitative device similarities of real devices and model calculations (Fig. 3). The difference in the shape of curves is due to a higher intensity of mass transfer processes in the combusted layer on the grate of a industrial device caused by the mixing movement (intensive mixing) of grate relative to the stationary parts of the waste in a laboratory boiler.

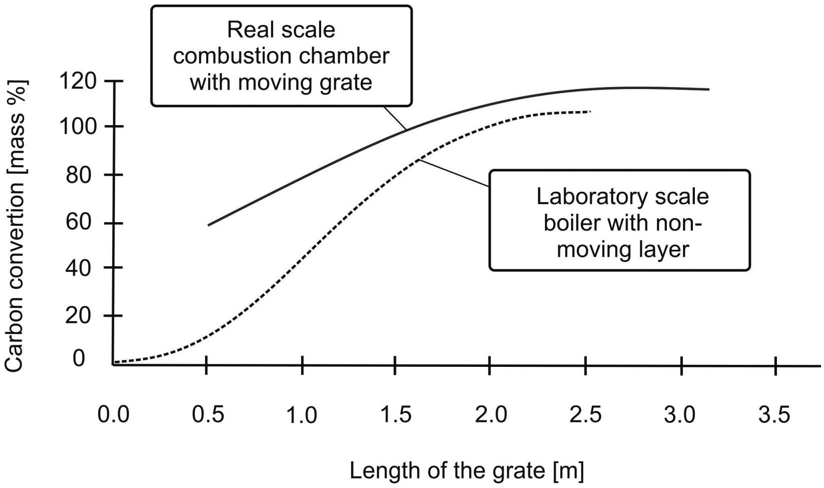

Fig. 3. Comparison of the conversion of carbon element mass in the laboratory-scale fixed bed furnace to the actual continuous-operation plant with a moving poking grate (Bleckwehl et al., 2004; Bleckwehl et al., 2005a, 2005b; Kolb et al., 2003)

The quantitative assessment indicators determined in the laboratory scale device (combustion in a fixed layer) can be used in the analysis of the combustion process taking place on the moving grate of the actual waste incineration plant. The above has been proven by research on the degree of conversion of carbon contained in the waste material analysis carried out in both scales – Fig. 3. A slightly higher degree of conversion of carbon in the real scale device is caused by more effective air supply (oxygen as an oxidant) to the grains of the waste material being combusted. This is the result of combing and mixing function of the grate (grate: cylindrical or sliding grate) as well as different average residual time of waste material on grates (so-called RCP). This slight difference in the degree of carbon conversion determined in the laboratory scale can be compensated by the correction of the above-mentioned indicators taking into account the additional mixing effect and RCP on the real grate. Currently the thermal process waste management market is developing at a fast pace. More than 1 mln of waste is actually combusted in Poland (about 10% of the whole volume of municipal solid waste generated annually in Poland). Therefore, methods for optimizing the waste incineration process in IPTOK are needed and should be developed. The proposed method allows to significantly reduce the costs of testing the quantitative assessment of the solid waste incineration process in these installations.

Transfer phenomena of physicochemical transformations from the laboratory scale boiler by indicators of quantitative combustion of fuel (waste) to an industrial device equipped with a moving grate operating continuously deliver important information about the combustion process and allow to adjust to some extent the optimization of the combustion process in a real device. This could reduce potential costs of studying the combustion process in real scale devices. This mainly concerns the study of different fuels (waste) on a laboratory scale and determining of quantitative assessment indicators as well as dispersion coefficients, and then matching them on the basis of the optimal operating parameters of grate system in waste incinerator plant (Jaworski, 2012; Yang et al., 2004).

Replacement of conventional fuels with fuels obtained from waste provides on one hand CO_2 emission reduction (especially due to biodegradable fraction – like biomass – combustion), and on the other hand protection of natural resources according to the principles of sustainable development (circular economy). In order to accomplish processes of thermal utilization of fuel from waste in a safe manner in incineration plants, it is essential to define some specific indicators that would determine the combustion process. These indicators should provide a comparison of different fuels. They should serve as a specific measurable "criteria indicators" to make possible scaling up the results from laboratory-scale to the actual full scale. This allows wide possibilities for optimization of the operation of the waste incineration plant, in particular the combustion chamber, equipped with a movable grid system. The following indicators are defined below for the quantitative evaluation of combustion: the reaction front rate, the ignition rate, mass loss and grate heat release rate (Jaworski, 2012).

The reaction front rate or flame front in the fuel layer on the grate can be determined as a point in which the derivative (1),

$$\frac{\Delta\vartheta}{\Delta t} \rightarrow \left(\frac{\Delta\vartheta}{\Delta t}\right)_{\max} \tag{1}$$

achieves its maximum value. The advance of this reaction front (u_{FR}) determines its moving rate which can be defined as (2):

$$u_{FR} = \frac{dx_{FR}}{dt} \tag{2}$$

The ignition rate (SZ) determines the fuel flow per unit of time, which undergoes ignition per unit area. The ignition rate is determined by Equation (3):

$$\mathrm{SZ} = u_{FR} \times \rho_n \tag{3}$$

This ratio could be used to specify parameters in industrial grate devices. In the case of fast ignition fuels one should increase the mass flow per unit area in order to secure the flame reaction. However, in the case of slow ignition fuels, mass flow must be reduced or the air must be pre-heated in order to speed up the fuel drying process (Jaworski, 2012).

The rate of mass loss (SUM) determines the mass loss over time and per unit area of the grate. The rate of mass loss is described by Equation (4):

$$SUM = \frac{\Delta m_{\text{fuel}}}{A_R} \tag{4}$$

This ratio makes it possible to calculate the length of the combustion zone in industrial devices at a known mass flow rate of fuel and the area of the grate. The indicator shows the relationship between mass ignition and actual fuel loss. In the case of a fuel which has an ignition rate point of much higher value than the rate of mass loss, there is a danger of retention of unburned fuel at the end of the grate (Jaworski, 2012).

The grate heat release rate (OCR) provides data on how much energy from the fuel is released through oxidation in time and in a specific area of the grid.

$$OCR = SUM \times W_d \tag{5}$$

The grate heat release rate is an important issue for operation of grid in waste incineration devices. Observation of the indicator of the heat load of the grate prompts technical service staff to react in case of grate overload (Jaworski, 2012).

2. EXPERIMENT (MATERIALS AND METHODS)

Research of the combustion processes in the grid furnace was conducted for the following types of waste:

- W-1 – printed paper,
- W-2 – softwood,
- W-3 – a mixture of paper (W-1) and wood (W-2), a mixing ratio of 40% W-1 and 60% W-2,
- W-4 – post-consumer furniture, box furniture based on wood derived slabs with a high-gloss front. The exploitation time of the furniture was approximately 30 years.

The study shows the results of technical and elemental analysis for waste W-4, while results for waste W-1, W-2, W-3 are taken from the literature (Kaltschmitt and Hartmann, 2001; Wandrasz and Wandrasz, 2006). All the tests were performed in accordance with the valid standards.

The test stand consisted of a chamber kiln type FCF 30 RP, of the output of 5 kW – Fig. 4.

Fig. 4. Photo of the testing stand
(fot. M. Kajda-Szcześniak)

The furnace is equipped with a specially designed grate with accessories enabling measurement of temperature inside the layers of incinerated waste. Three thermocouples were placed in the body of the working grate along the layer height in the following way: the first thermocouple (T0) at a height of 50 mm from the bottom grate, the second (T1) at a height of 150 mm, and the third one (T2) at a height of 250 mm. The spacing between the thermocouples was 100 mm. The temperatures were recorded using an electrical measuring device with a testing interval of 1 minute. 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.

Tests were accomplished in two stages. During the first stage the mass of incinerated waste and waste bulk density were determined. Subsequently, the combustion process parameters, such as temperature, process time, the amount of air supplied to the combustion chamber and the calculated area of the grate. These values were essential for the assesment of the combustion process in order to select the airflow to the assumed process time and the excess air ratio. The second stage involved reaching the process temperature of 850°C, taking into account the 20 minute relaxation of the oven at 350°C, the incorporation of a fan of primary air and setting the primary air stream through a rotameter to a desired value, removal of a dummy grid and placing a work grate with the waste in the furnace, measuring the temperature inside the layer, measuring the concentration of exhaust gases (CO_2, CO, SO_2 O_2, NO_x), the mass loss during incineration. The research was conducted for various combinations of materials, such as the type of waste, as well as process parameter combinations like time and excess air ratio.

3. RESULTS AND DISCUSSION

The results of tests for determining the properties of the selected waste fuel and elementary composition of the burning material are listed in Table 1. It has been found that the wastes W-1 – W-4 are characterized by good fuel properties having low moisture content of less than 10%, low ash content below 1.07% and high volatile matter content, equal to 80.43% for the waste W-4 and up to 89.12% for the waste W-1. It was also found that the tested wastes have good calorific value ranging from 17.92 MJ/kg for waste W-1 to 21.82 MJ/kg for the waste W-4, respectively.

Table 1. Properties of waste

Property	W-1[a]	W-2[b]	W-3	W-4
Proximate analysis				
W [%]	5.83	9.11	7.80	7.56
Combustible [%]	98.93	99.40	99.21	99.27
Ash, A^d [%]	1.07	0.60	0.79	0.73
Volatile matter, V^d [%]	89.12	82.90	85.39	80.43
Calorific value, Q_d^d [MJ/kg]	17.92	18.80	18.45	21.82
Ultimate analysis (a dry basis) [%]				
C^d	44.90	49.80	47.84	42.60
H^d	6.08	6.30	6.21	3.55
O^d	47.84	43.20	45.06	41.71
N^d	0.00	0.13	0.08	10.81
S^d	0.11	0.015	0.05	0.21
Cl^d	0.00	0.005	0.003	0.39

[a] Wandrasz and Wandrasz (2006); [b] Kaltschmitt and Hartmann (2001)

Analysis revealed many similarities in elementary composition for the waste W-1, W-2 and W-3. Differences occur in the case of the waste W-4. This waste is loaded with chemical compounds in the form of adhesive resins like urea-formaldehyde (Cichy and Pawłowski, 2009; Kajda-Szcześniak and Jaworski, 2016). Resins used in the production are characterized by high nitrogen content, recorded at 10.81%. The sulphur content for waste W-4 equaled 0.21% and chloride content equaled 0.39%.

Table 2 presents the results of research on determination of quantitative indicators used to assess the incineration of waste i.e. reaction front rate, ignition rate, the rate of mass loss and grate heat release rate. The obtained ratios can be used for designing combustion devices in an industrial scale. It was noted that the waste W-4 was characterized by the lowest reaction front rate because of chemical contamination. The determined ignition rate is several times higher than the rate of mass loss for each of the analyzed waste. That is why there is a danger for retention of unburned waste at the end of the grate. Waste W-4 is characterized by the highest calorific value of all the wastes, so that this results in a maximum grate heat release rate, which may require additional cooling of the grate.

Table 2. Quantitative evaluation indicators for the combustion of wastete

Type of waste	Process tempe-rature, T [°C]	Combu-stion time, t_1 [s]	Coeffi-cient of surplus air, λ	Bulk density, ρ_n [kg/m^3]	Reac-tion rate, u_{FR} [m/s]	Ignition rate, SZ [kg/m^{2}s]	Mass loss rate, SUM [kg/m^{2}s]	Heat load on grate, OCR [kW/m^2]
W-1	850	900	4.78	36	0.0010	0.0360	0.0139	234.59
W-2	850	1500	2.10	170	0.0005	0.0850	0.0292	498.46
W-3	850	1200	1.93	108	0.0007	0.0756	0.0182	309.98
W-4	850	2460	2.97	310	0.0002	0.0553	0.0305	614.94

Figures 5–8 illustrate temperature changes within the layer of incinerated waste on the grid with time. All three measurement points were located at the height of 50 mm (T0), 150 mm (T1) and 250 mm (T2) from the bottom of the grate. It was noted that along the height of the layer at the initial stage of the process the temperature was rising to its maximum value. This marked the transition of the reaction front through the measuring points.

Later a decrease of temperature in the measuring point was observed. This means that the waste layer burnt out. In the final phase of the process in all three measurement points, the temperatures were similar. This indicates the end of the combustion process. Figures 5–8 show the course of the reaction front for the analyzed waste. It was found that the reaction front for the wastes W-1 and W-3 is faster and has a more dynamic character. The knowledge of the course of the reaction front allows the determination of the ignition rate indicator, which could be applied to specify parameters in grate industrial applications.

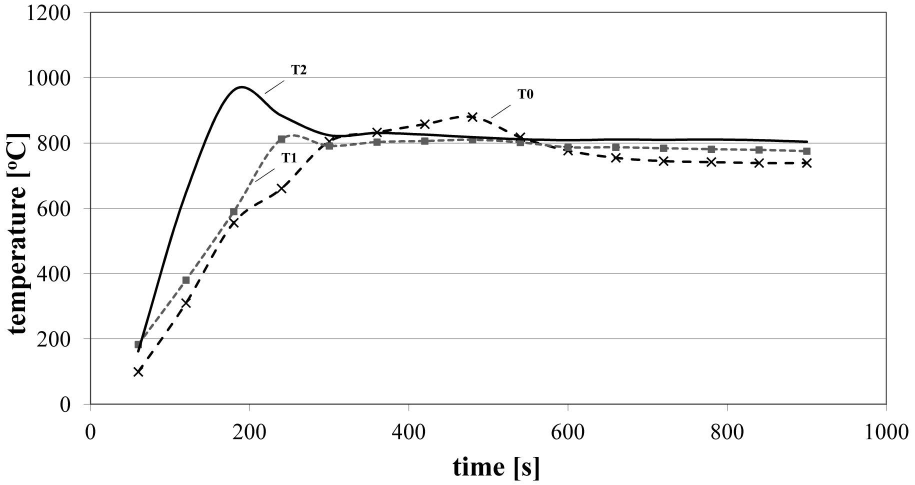

Fig. 5. Distribution of temperature of solid and gas phases in the combusted layer of the waste type W-1 with the time of the combustion process for the temperature of 850°C

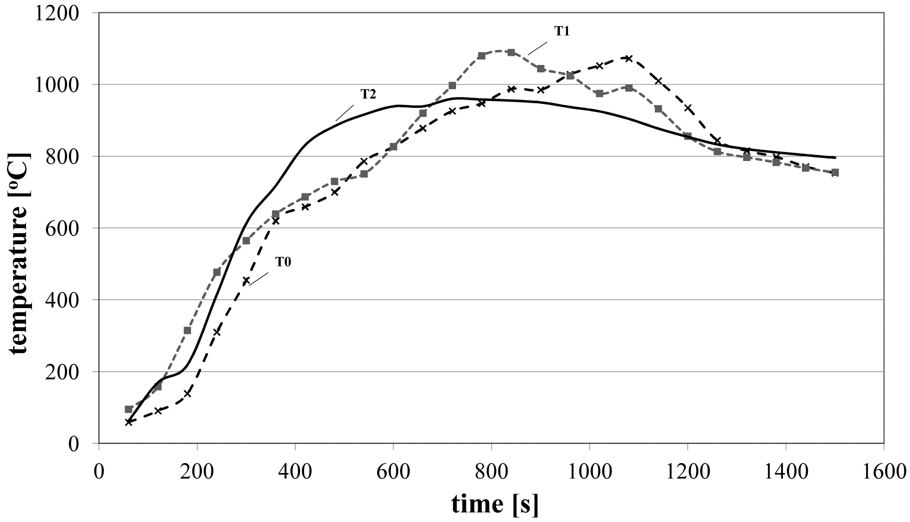

Fig. 6. Distribution of temperature of solid and gas phases in the combusted layer of the waste type W-2 with the time of the combustion process for the temperature of 850°C

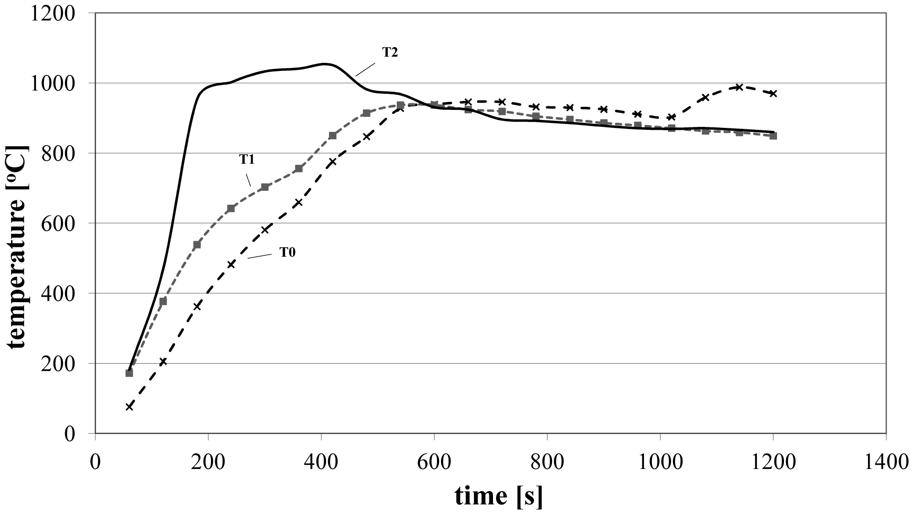

Fig. 7. Distribution of temperature of solid and gas phases in the combusted layer of the waste type W-3 with the time of the combustion process for the temperature of 850°C

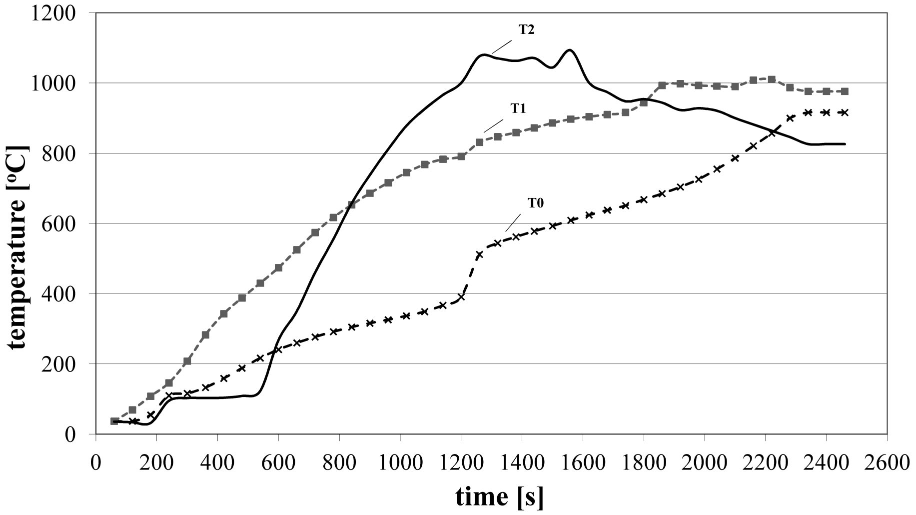

Fig. 8. Distribution of temperature of solid and gas phases in the combusted layer of the waste type W-4 with the time of the combustion process for the temperature of 850°C

Figure 9 shows how during the combustion process the mass of waste changes. It is evident that the layers of waste have different time of burning out. The shortest time for the waste layer to be burned out was observed for W-1, while the longest one for waste W-4. This is due to the presence of adhesive resins in that waste. A feature common for all the tested waste types is the greatest mass loss during the first phase of the combustion process.

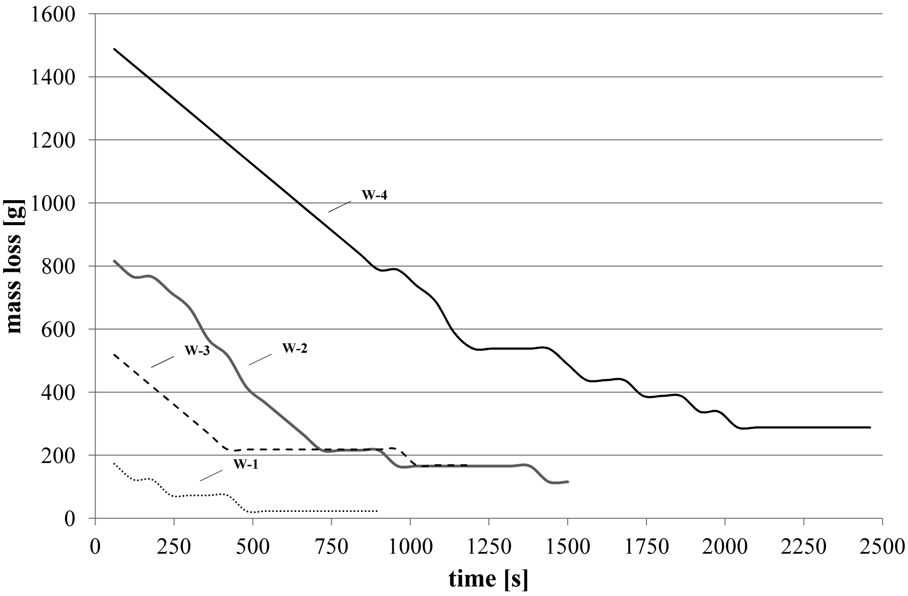

Fig. 9. Mass loss of the combusted layer of the waste W-1 – W-4 during combustion, at 850°C

Figs. 10–13 show that the incineration processes for W-1, W-2 and W-3 are of similar character.

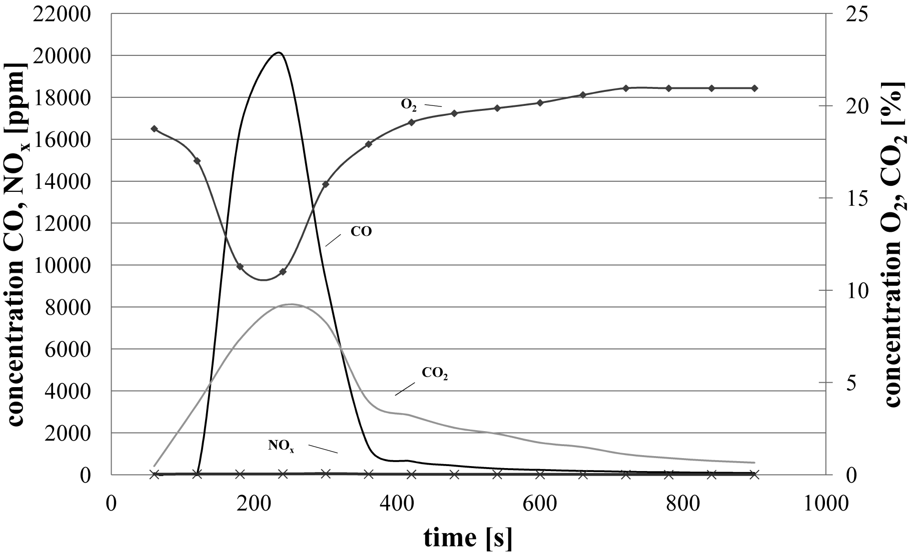

Fig. 10. Changes of concentration of exhaust gases during the combustion process of the waste W-1

A different process was noted for the waste W-4 (Fig. 13). A prolonged combustion process as evidenced by the slower process of returning CO_2 concentration to a value close to zero has been observed. This is due to the presence in the layer of waste chemicals acting as a binder and in addition due to multi-phase (shifted in time) combustion of components of the substances and products of their decomposition (char). Moreover, the high content of nitrogen results in increased emissions of nitrogen oxides from combustion of the waste W-4 compared to other wastes.

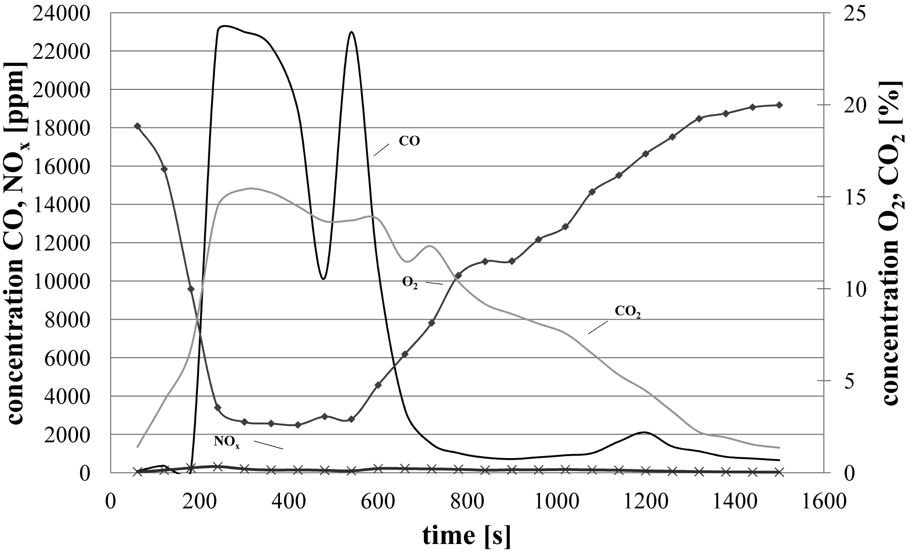

Fig. 11. Changes in concentration of exhaust gases during the combustion process of the waste W-2

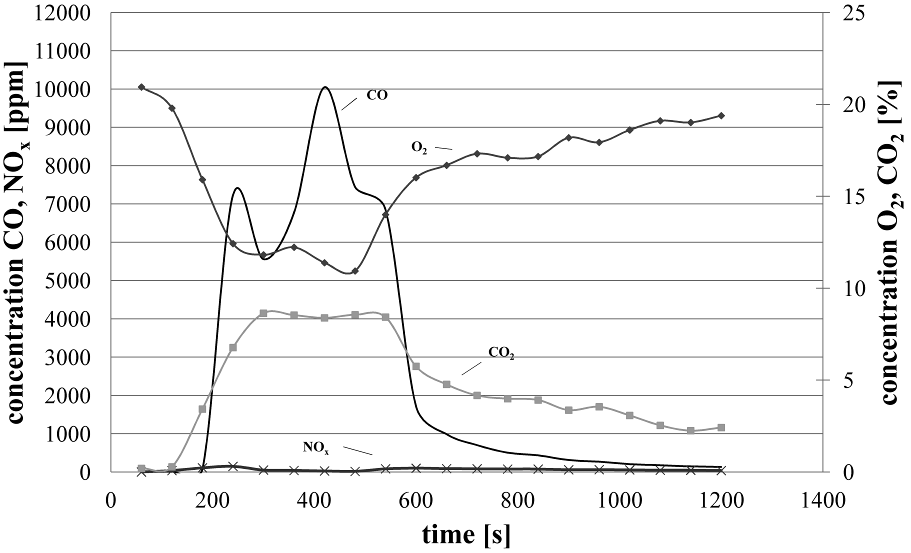

Fig. 12. Changes in concentration of exhaust gases during the combustion process of the waste W-3

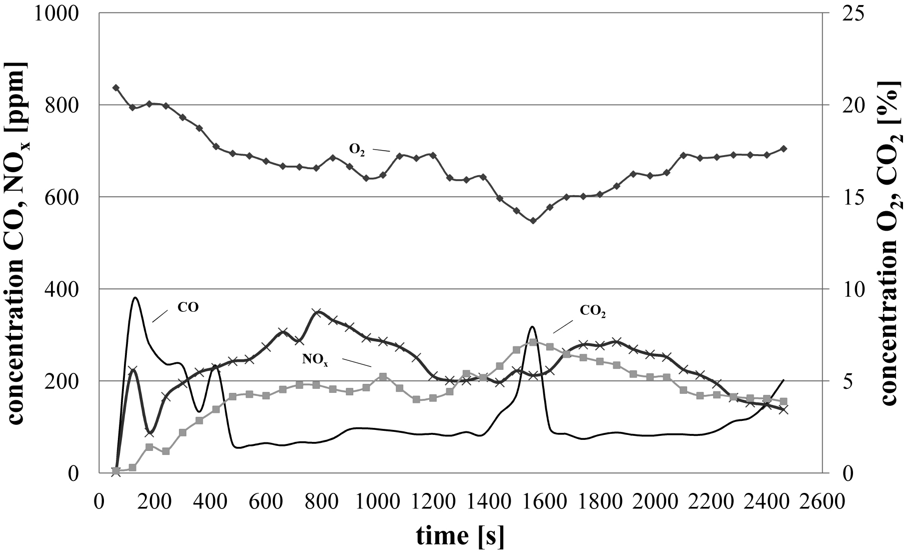

Fig. 13. Changes in concentration of exhaust gases during the combustion process of the waste W-4

4. CONCLUSIONS

The analysis presented above provides important information for designing and operating. This applies to the selection of the appropriate design features such as the type of grate, grate-feed speed (rotation rollers), depending on the type, the angle of the grate, cooling type etc.

It is also possible to formulate operating instructions. For example in the case of fuels with rapid ignition one should increase mass flow rate per unit area to keep combustion going.

In the case of fuels with slow ignition the mass flow rate must be reduced or air must be additionally heated to dry fuel faster. Using the rate of mass loss the full length of combustion zone can be calculated in industrial scale devices.

By comparing this indicator with the ignition rate it is possible to deliver information about the relation between the ignition and the real mass loss of fuel.

For a fuel that has an ignition rate much higher than the rate of mass loss, there is a danger of retention of unburned waste at the end of the grate. The grate heat release rate is an important issue from the grate device operational perspective. Monitoring of this indicator helps to rapidly respond with technical support to any overload. At the stage of designing an incineration plant it provides information whether or not it would be necessary to include a grate cooling system.

SYMBOLS

U_{FR}	reaction front rate, m/s
x_{FR}	location of reaction front, m
t	time of combustion, s
SZ	ignition rate, kg/(m^{2}s)
ρ_n	bulk density, kg/m^3
SUM	the rate of mass loss, kg/(m^{2}s)
A_R	grate area, m^2
Δm_{fuel}	the mass loss over time, kg/s
OCR	grate heat release rate, kW/m^2
W_d	calorific value of the fuel, kJ/kg
x	position of the waste on the grate, m
t	residence time of the waste on the grate, calculated on the basis of residence time distribution (RCP), s
L	length of the grid, m
w	the speed of the waste on the grid, calculated on the basis of the RCP, m/s

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Received 26 September 2016
Received in revised form 27 November 2017
Accepted 19 December 2017