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Mathematical Description of Combustion Process of Selected Groups of Waste

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1. Introduction

Industrial development and progress of civilization is a serious threat to the natural environment. Currently, the most important problem is the protection of the environment. Every year, around the world a continuous increase in the number of waste from various sectors of the economy and industry is observed. In many cases they are landfilled [9, 10].

Important place among industrial waste occupy plastic waste, waste tyres and waste from paint and lacquer industry [4, 9].

Utilization of these wastes has become a great problem, both because of their great amounts, as well as because of their landfilling because they often contain materials very harmful for the environment.

The most popular method of utilization of waste is incineration. That process allows on one hand to get rid of large quantities of waste from landfills, giving some energy at the same time, but on the other hand, it is a serious threat for the environment because of toxic substances emitted into the environment. The most noxious byproducts of combustion are: CO, SO_2, NO_x [1, 5, 6].

Results obtained during laboratory investigations of process of thermal destruction of different groups of waste (municipal and industrial) are presented in this paper. Finally, on the basis of results from individual stages of laboratory investigations, a mathematical and empirical description – criterion determining the parametric conditions of incineration of selected waste groups – in relation to main pollutants in flow gases together with the range of applicability of determined approximation equations has been developed. Applicability of the equations was determined for individual parameters in the ranges of their values presented in the research methodology.

2. Research methodology

During investigations of combustion process, described in this paper, following waste were used:

- waste paints,
- waste tyres,
- waste plastics (polyethylene terephthalate PET) – a representative of polyesters, polyvinylchloride PVC – representative of vinyl polymers, polypropylene PP – a representative of polyolefins,
- sewage sludge (from Jamno Sewage Treatment Plant, which is an object operated by "Koszalin Water Supply and Sewage System" Company Ltd.

The results of the technical analysis of materials used in the investigations are presented in Table 1.

Investigations of incineration process were carried out in the experimental stand, which consists of: pipe furnace PRC 20 HM and combustion gas analyser MADUR GA-21 *plus*. PRC 20 HM is laboratory monozonal pipe furnace with horizontal heating which maximum temperature of continuous work is 1473K. The incineration process was carried out in the atmosphere of air, which was introduced by a small diaphragmatic pump, through a rotameter, which measures flow rate. Stream of flue gases from furnace reactor was analysed using combustion gas analyser MADUR GA-21 plus. The analyser is a versatile device, which measures concentration of gases with electrochemical and infrared sensors. In order to facilitate orientation and make possible comparing the results all concentrations of pollutants in the combustion gases ware calculated for standard terms of combustion at 11% of O_2 content in exhaust gases. Flow rates of air into the furnace chamber an combustion gases from the furnace were measured with ROS-06 flowmeters. Their range is 0.5÷8.5 of $dm^3 \cdot min^{-1}$.

Table 1. Results of technical analysis of materials used in investigations
Tabela 1. Zestawienie zbiorcze wyników analizy technicznej materiałów wykorzystanych do badań

Granular size, mm	Water content W^a, %	Ash content A^a, %	Volatiles content V^a, %	Calorific value Q^a_s, MJ/kg
Sewage sludge (in the dry state)				
0,125÷1,25	10,6	32,3	54,3	13,57
Waste paint				
0,35÷1,25	0,8	7,8	18,0	24,91
Waste tyres				
0,35÷1,25	6,3	12,3	58,2	31,84
Polyethylene terephthalate PET				
1,0÷2,0	0,3	2,6	42,6	23,11
Polyvinylchloride PVC				
0,35÷1,25	0,2	5,3	49,7	25,76
Polypropylene PP				
0,5÷2,0	0,8	3,1	58,4	42,02

In the studies of incineration process of materials presented in Table 1, independent parameters (variables) were:
T – temperature in the furnace combustion zone, K, – this parameter was changed in the range: 873.15÷1443.15K, increasing it 100K each time,

while the limit value for the temperature was 1443.15 K, which is the maximum that could be obtained in the combustion zone,
λ – excess air coefficient – parameter defined as the ratio of the amount of air supplied for combustion and the amount of air theoretically required for combustion, value of this parameter was changed in the range 1.3÷2.0,
m – mass index of the material, $kg \cdot m^{-3}$ – parameter defining the amount of the sample of tested fed into the furnace in relation to the volume of the incineration chamber of the furnace; values for this parameter were: 1.2, 2.4 and 3.6 $kg \cdot m^{-3}$.

In the first series of investigations of the combustion process, parameter *T* was assumed as an independent variable parameter, and coefficient $\lambda = 1.8$ and index $m = 1.2\ kg \cdot m^{-3}$ were assumed as independent parameters at a constant level.

In the next stage of the investigations, independent parameters at a constant level were: $T = 1273.15K$ and $m = 1.2\ kg \cdot m^{-3}$ and λ coefficient was an independent variable parameter.

In the third stage of investigations on the combustion process, independent parameters at a constant level were: $T = 1273.15K$ and $\lambda = 1.8$. In this stage index *m* was a variable.

In all stages of investigations, dependent variable parameters were concentration of following flue gases: c_{SO2}, c_{NOx}, c_{CO}.

3. Approximation with central point method

Analysis of relations between independent variable parameters and dependent variable parameter was conducted using central point method, developed by Prof. Tadeusz Piecuch. This method was applied by Prof. Tadeusz Piecuch for the first time in his habilitation dissertation in 1975. This method has been described in detail in J. Piekarski dissertation [7], as well as in T. Dąbrowski [2] and B. Juraszka [3] dissertations supervised by Prof. Tadeusz Piecuch. Prof. A.M. Anielak developed central point method to approximation against line and used it in her dissertation (Silesian University of Technology, 1982).

It is a method where computational problem to be solved is to match the curve, which is a graphical representation of sought function, to a set of points. Functional relations between the variables are pre-determined by the approximation method of least squares.

The resulting function from the first stage of approximation, according to this method, is one of the following forms:

exponential function $y(x_1) = a + \exp(b + c \cdot x_1)$, (2.1)

logarithmic function $y(x_1) = a + b \cdot \log(c + x_1)$, (2.2)

polynomial function $y(x_1) = \sum_{i=0}^{n} a_i \cdot x_1^i$, (2.3)

function of straight $y(x_1) = a + b \cdot x_1$. (2.4)

where:
$y(x_1)$ – output parameter dependent on the first stage of approximation,
a, b, c, a_i – coefficients of approximation function,
x_1 – independent input parameter.

Then, assuming the coordinates of the central point of approximation $C(x_{1c},y_{1c})$, constant on the first stage of approximation for this point is calculated:

$$C^{x1} = y(x_{1C}) \quad (2.5)$$

where:
C^{x1} – value of the constant of the approximation on the first stage of approximation,
x_{1C} – independent input value of x_1 in the central point.

In the second stage of approximation, equation is determined as described previously, however assuming the coordinates of the approximation central point $C(x_{2c},y_{2c})$, constant on the second stage of approximation for this point is calculated:

$$C^{x1x2} = y(x_{1C}, x_{2C}) \quad (2.6)$$

where:
C^{x1x2} – value of the constant of the approximation on the second stage of approximation,
x_{1C} – independent input value of x_1 in the central point,
x_{2C} – independent input value of x_2 in the central point.

The general equation on the first and the second stage of approximation is as follows:

$$y = y(x_1) + y(x_2) - C^{x1} \qquad (2.7)$$

where:
$y(x_1)$ – equation on the first stage of approximation,
$y(x_2)$ – equation on the second stage of approximation,
C^{x1} – value of the constant of the approximation on the first stage of approximation,

The equation after the third stage of approximation is obtained by analogy, while assuming the coordinates of the approximation central point $C(x_{3c},y_{3c})$, the constant on the third stage of approximation for this point is calculated:

$$C^{x1x2x3} = y(x_{1C}, x_{2C}, x_{3C}) \qquad (2.8)$$

where:
C^{x1x2x3} – value of the constant of the approximation on the third stage of approximation,
x_{1C} – independent input value of x_1 in the central point,
x_{2C} – independent input value of x_2 in the central point,
x_{3C} – independent input value of x_3 in the central point.

The general equation after the first, the second and the third stage of approximation is as follows:

$$y = y(x_1) + y(x_2) + y(x_3) - (C^{x1} + C^{x1x2}) \qquad (2.9)$$

where:
$y(x_1)$ – equation on the first stage of approximation,
$y(x_2)$ – equation on the second stage of approximation,
$y(x_3)$ – equation on the third stage of approximation,
C^{x1} – value of the constant of the approximation on the first stage of approximation,
C^{x1x2} – value of the constant of the approximation on the second stage of approximation.

Finally, equation after the subsequent stages of approximation are obtained by analogy.

After the full series of research, according to central point method, a certain abstract mathematical space of bunch of curves is obtained:

$$y = \sum_{i=1}^{n} y_n - \sum_{i=1}^{n-1} C^n \qquad (2.10)$$

where:
y_n – approximated polynomial on the nth stage of approximation,
C^n – value of the constant of the approximation on the nth stage of approximation,
x_1, x_2, x_n – independent variables.

A characteristic feature of this method is that all the curves always run through a single central point and are limited by ranges in which different independent variables were presented. Individual curves make up certain spaces, in which obtained equations are accurate enough [2, 3, 7].

Relations between independent variable parameters and dependent variable parameter were calculated using nonlinear method of least squares: algorithm of Levenberg-Marquardt, in STATISTICA 8.0. Regression coefficient for equations was not lower than R = 0.98, at confidence level: 95.0% (α = 0.05).

4. Results

Results of investigations on the influence of temperature in the combustion zone in the furnace on concentration of SO_2 in the combustion process of sewage sludge are shown in Figure 1. The graph in Figure 1 is approximated by the following equation:

$$c_{SO2}(T) = a + b \cdot T \qquad (3.1)$$

where:
a, b – coefficients of approximation function.

Approximated equation on the first stage is as follows:

$$c_{SO2}(T) = -402.2 + 0.6 \cdot T \qquad (3.2)$$

while value of the constant of the approximation for central point $C^T = c_{SO2}(1273.15)$ is $C^T = 393.6$.

Results of the research on the influence of excess air coefficient λ on concentration of SO_2 in the combustion process of sewage sludge are also shown in Figure 1. The graph in Figure 1 is approximated by the following equation:

$$c_{SO2}(\lambda) = a + b \cdot \lambda \qquad (3.3)$$

The equation (3.3) on the second stage of approximation is as follows:

$$c_{SO2}(\lambda) = 511.2 - 82.2 \cdot \lambda \qquad (3.4)$$

The general equation on the first and the second stage of approximation is as follows:

$$c_{SO2}(T,\lambda) = c_{SO2}(T) + c_{SO2}(\lambda) - C^T \qquad (3.5)$$

The full function notation of this equation including values of constant coefficients at the independent variables, is as follows:

$$c_{SO2}(T,\lambda) = 0{,}6 \cdot T - 82{,}2 \cdot \lambda - 284{,}6 \qquad (3.6)$$

while value of the constant of the approximation for central point $C^{T\lambda} = c_{SO2}(1273.15;1.8)$ is $C^{T\lambda} = 363.2$.

Results of the investigations on the influence of mass index of the material *m* on concentration of SO_2 in the combustion process of sewage sludge are shown in Figure 1. The graph in Figure 1 is approximated by the following equation:

$$c_{SO2}(m) = a + b \cdot m \qquad (3.7)$$

which on the third stage of approximation is as follows:

$$c_{SO2}(m) = 79.2 + 250.0 \cdot m \qquad (3.8)$$

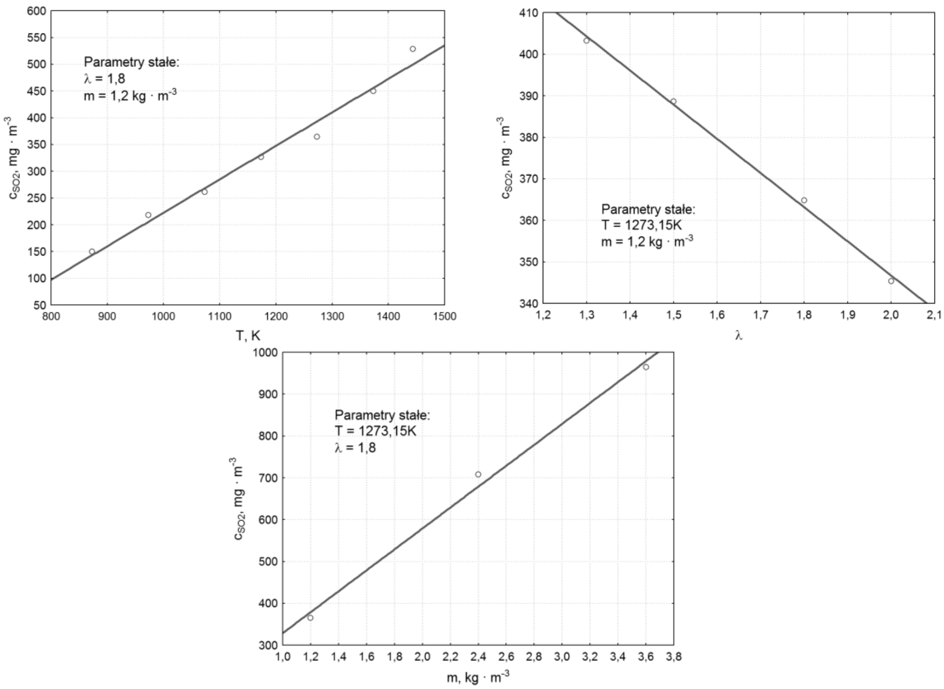

Fig. 1. Influence of temperature in the combustion zone in the furnace *T*, excess air coefficient *λ* and mass index of the material *m* on concentration of SO_2 in the combustion process of sewage sludge
Rys. 1. Wpływ temperatury w strefie spalania *T*, współczynnika nadmiaru powietrza *λ* oraz wskaźnika masy materiału *m* na stężenie tlenku siarki(IV) w procesie spalania osadów ściekowych

The final approximated equation after the first, the second and the third stage, of influence of *T*, *λ* and *m* parameters on the concentration of SO_2 in the combustion process of sewage sludge is as follows:

$$c_{SO2}(T,\lambda,m) = c_{SO2}(T) + c_{SO2}(\lambda) + c_{SO2}(m) - (C^{T} + C^{T\lambda}) \qquad (3.9)$$

The full function notation of this equation including values of constant coefficients at the independent variables, is as follows:

$$c_{SO2}(T,\lambda,m) = 0.6 \cdot T - 82.2 \cdot \lambda + 250.0 \cdot m - 568.5 \qquad (3.10)$$

Results of the research on the influence of temperature in the combustion zone in the furnace *T*, excess air coefficient λ and mass index of the material *m* on concentration of NO_x in the combustion process of sewage sludge are presented in Figure 2.

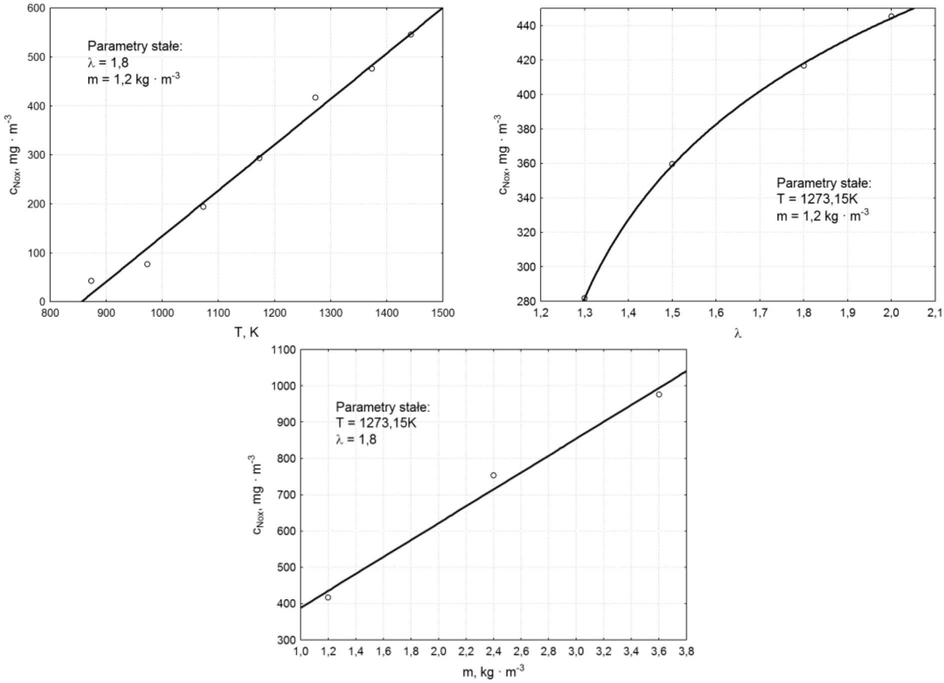

Fig. 2. Influence of temperature in the combustion zone in the furnace *T*, excess air coefficient λ and mass index of the material *m* on concentration of NO_x in the combustion process of sewage sludge

Rys. 2. Wpływ temperatury w strefie spalania *T*, współczynnika nadmiaru powietrza λ oraz wskaźnika masy materiału *m* na stężenie tlenków azotu w procesie spalania osadów ściekowych

The final equation after next stages of approximation, influence of *T*, λ and *m* parameters on the concentration of NO_x in the combustion process of sewage sludge is as follows:

$$c_{NOx}(T,\lambda,m) = 0,9 \cdot T + 100,7 \cdot \ln(-1,1 + \lambda) + 232,8 \cdot m - 1014,1 \qquad (3.11)$$

Results of the investigations on the influence of *T*, *λ* and *m* parameters on concentration of CO in the combustion process of sewage sludge are presented in Figure 3. The final equation is as follows:

$$c_{CO}(T,\lambda,m) = \exp(15,8 - T) - 10,9 \cdot \lambda + \exp(-0,1 + 0,7 \cdot m) - 81,2 \quad (3.12)$$

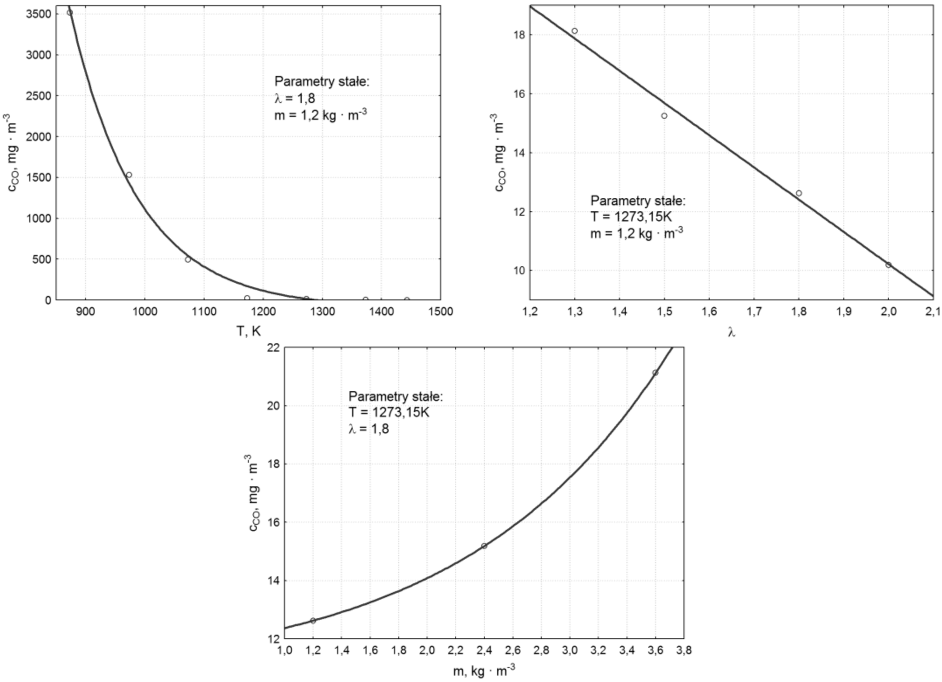

Fig. 3. Influence of temperature in the combustion zone in the furnace *T*, excess air coefficient *λ* and mass index of the material *m* on concentration of CO in the combustion process of sewage sludge

Rys. 3. Wpływ temperatury w strefie spalania *T*, współczynnika nadmiaru powietrza *λ* oraz wskaźnika masy materiału *m* na stężenie tlenku węgla(II) w procesie spalania osadów ściekowych

All equations describing influence of *T*, *λ* and *m* parameters on the concentration of measured gases after in combustion process of the investigated waste materials were obtained using method described above.

List of equations describing the combustion process of selected waste groups:

Waste paint
$c_{SO2}(T,\lambda,m) = 0{,}04 \cdot T - 5{,}8 \cdot \lambda + 42{,}9 \cdot m - 58{,}1$
$c_{NOx}(T,\lambda,m) = \exp(4{,}1 + 0{,}8 \cdot 10^{-3} \cdot T) + \exp(0{,}8 + 1{,}5 \cdot \lambda) + 28{,}2 \cdot m - 170{,}0$
$c_{CO}(T,\lambda,m) = \exp(16{,}3 - T) - 11{,}6 \cdot \lambda + 4{,}5 \cdot m - 5{,}5$

Waste tyres
$c_{SO2}(T,\lambda,m) = \exp(4{,}7 + T) - 26{,}1 \cdot \lambda + 313{,}4 \cdot m - 470{,}7$
$c_{NOx}(T,\lambda,m) = 107{,}9 \cdot \log(-549{,}3 + T) + 109{,}4 \cdot \lambda + 53{,}4 \cdot m - 451{,}1$
$c_{CO}(T,\lambda,m) = \exp(16{,}2 - T) - 10{,}0 \cdot \lambda + 25{,}1 \cdot \ln(2{,}2 + m) - 38{,}9$

Waste plastics – polyesters
$c_{SO2}(T,\lambda,m) = T - 2615{,}6 \cdot \log(166{,}7 + \lambda) + 78{,}6 \cdot m + 5724{,}5$
$c_{NOx}(T,\lambda,m) = 121{,}7 \cdot \log(0{,}1 + T) + \exp(-1{,}0 + 1{,}8 \cdot \lambda) + 13{,}4 \cdot \log(m) - 328{,}0$
$c_{CO}(T,\lambda,m) = \exp(20{,}3 - T) - 4{,}8 \cdot \lambda + 1204{,}7 \cdot \ln(m) - 211{,}8$

Waste plastics – polyolefins
$c_{SO2}(T,\lambda,m) = T - 17{,}3 \cdot \lambda + 9{,}1 \cdot m + 5{,}8$
$c_{NOx}(T,\lambda,m) = 0{,}1 \cdot T + 72{,}6 \cdot \log(-0{,}5 + \lambda) + 19{,}2 \cdot m - 9{,}9$
$c_{CO}(T,\lambda,m) = \exp(10{,}4 - T) - 17{,}3 \cdot \lambda + 945{,}8 \cdot m - 2638{,}6$

Waste plastics – vinyl polymers
$c_{SO2}(T,\lambda,m) = 154{,}6 \cdot \log(T) - 8{,}8 \cdot \lambda + 191{,}3 \cdot \log(m) - 363{,}3$
$c_{NOx}(T,\lambda,m) = \exp(2{,}2 + T) + 43{,}0 \cdot \log(\lambda) + 11{,}6 \cdot m - 55{,}6$
$c_{CO}(T,\lambda,m) = - 31{,}4 \cdot T + T^2 - 33{,}9 \cdot \lambda + 93{,}6 \cdot m + 22889{,}9$

Sewage sludge
$c_{SO2}(T,\lambda,m) = 0{,}6 \cdot T - 82{,}2 \cdot \lambda + 250{,}0 \cdot m - 568{,}5$
$c_{NOx}(T,\lambda,m) = 0{,}9 \cdot T + 100{,}7 \cdot \ln(-1{,}1 + \lambda) + 232{,}8 \cdot m - 1014{,}1$
$c_{CO}(T,\lambda,m) = \exp(15{,}8 - T) - 10{,}9 \cdot \lambda + \exp(-0{,}1 + 0{,}7 \cdot m) - 81{,}2$

5. Verification of equations

Method of approximation with central point assumes that the investigated independent variable parameters x_1, x_2, x_3, ..., x_n have no interaction with each other, or possible interaction are not significant.

To verify this, after investigations and after determination of final mathematical equations, additional random tests at the freely selected values of each variable should be performed. These variables should be within the ranges of previously investigated changes, selected in such way that these values are associated with the space around a central point of approximation but not in this point – that is the space in which it is assumed that the obtained equation can be used [2, 3, 7]. Verification of statistical hypotheses is used for that purpose, basic type of statistical methods. The accuracy of equations was evaluated by t-studenta test, as the most generally used method for evaluation of differences between the averages in the two groups.

The equations describing individual parameters of the independent variables of investigated combustion processes were verified in the real laboratory conditions. The verification consisted in a seven series of tests in the laboratory for freely selected values of variable parameters that are not the central point values and are within ranges of previous research.

Values of of independent variable parameters, calculated from the analytical and empirical equations and obtained during ;aboratory tests were compared. Example results of statistical analysis are presented in Table 2.

For n – 1 = 6 degrees of freedom and at the significance level $\alpha = 0.05$, the limit value t_α from distribution tables of t-studenta test is $t_{0,05} = 2.447$.

Comparison of obtained values of test functions t with limit value $t_{0,05}$ allows to notice these values are lower than the limit value. Therefore, with 95% of confidence, equations obtained through analysis of combustion process investigations resuts, are correct and values obtained from them are consistent with the results obtained in laboratory conditions.

Table 2. Example statistical analysis of experimental results obtained in laboratory conditions and using equations calculation in the processes of combustion of selected groups of waste

Tabela 2. Przykładowa analiza statystyczna wyników doświadczeń uzyskanych na podstawie doświadczenia w warunkach rzeczywistych i obliczeń przy pomocy równań w procesie spalania wybranych grup odpadów

Independent parameters			Resulting parameter c_{SO2} Material – sewage sludge							
T, K	λ	m, kg/m^3	Equation	Lab	|d|	$\bar{d}$	Σd^2	s	s^2	test t
923.15	1.4	3.0	643.38	600.60	42.78	12.33	2239.19	195.79	13.99	2.159
1023.15	1.6	1.8	389.42	377.52	11.90					
1123.15	1.9	2.4	577.26	566.28	10.98					
1223.15	1.4	3.0	830.90	820.82	10.08					
1273.15	1.6	1.8	545.69	549.12	3.43					
1323.15	1.9	2.4	702.28	700.70	1.58					
1413.15	1.4	3.0	949.67	955.24	5.57					
Independent parameters			Resulting parameter c_{NOx} Material – waste tyres							
T, K	λ	m, kg/m^3	Equation	Lab	|d|	$\bar{d}$	Σd^2	s	s^2	test t
923.15	1.4	3.0	140.03	106.91	33.12	10.24	1402.37	111.47	10.56	2.375
1023.15	1.6	1.8	108.97	104.86	4.11					
1123.15	1.9	2.4	182.81	172.70	10.11					
1223.15	1.4	3.0	167.66	156.26	11.40					
1273.15	1.6	1.8	128.84	133.64	4.80					
1323.15	1.9	2.4	196.83	193.264	3.57					
1413.15	1.4	3.0	179.31	174.76	4.55					

6. Conclusions

There is a possibility of mathematical description of the combustion process of selected groups of waste and simulation and forecast the obtained results. This mathematical analytical and empirical description may be extended by introduction of new parameters, broadening its usage range, as well as prediction of results in other groups of waste or coal as classical fuel.

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Matematyczny opis procesu spalania wybranych grup odpadów

Streszczenie

W niniejszej pracy przedstawiono wyniki badań pozyskanych w trakcie prowadzenia eksperymentów laboratoryjnych z zakresu termicznej destrukcji różnych grup odpadów (komunalnych i przemysłowych).

Do badań procesu spalania, wyodrębniono następujące odpady:

- odpady farbiarskie,
- odpady gumowe (zużyte opony),
- tworzywa sztuczne (politereftalan etylenu (etylenowy) PET, jako przedstawiciel grupy poliestrów, polichlorek winylu PCW, jako przedstawiciel grupy polimerów winylowych, polipropylen PP, jako przedstawiciel grupy poliolefin),
- osady ściekowe (pobrane z Oczyszczalni Ścieków „Jamno”, która jest obiektem eksploatowanym przez Spółkę z o.o. Miejskie Wodociągi i Kanalizacja w Koszalinie).

Ostatecznie, dysponując określonymi wynikami poszczególnych etapów badań laboratoryjnych, został opracowany opis matematyczno-empiryczny, tworzący kryterium określające warunki parametryczne spalania wybranych grup odpadów w odniesieniu do głównych składników zanieczyszczeń spalin wraz z podaniem zakresu stosowalności wyznaczonych równań aproksymacyjnych.

Analizę związków pomiędzy przyjętymi w badaniach zmiennymi niezależnymi a zmienną zależną dokonano stosując aproksymację metodą punktu centralnego – metodą opracowaną przez prof. Tadeusza Piecucha.

Stosowalność równań tworzących kryterium określono dla poszczególnych parametrów w przedziałach zmian ich wartości, przedstawionych w metodyce badań.

Opis matematyczny empiryczno-analityczny układu może być poszerzany poprzez wprowadzenie nowych parametrów, powiększając zakres jego stosowania, a także umożliwiając prognozowanie wyników w przypadku innych grup odpadów lub węgla kamiennego jako paliwa klasycznego.