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COMBUSTION OF SOLID RECOVERED FUELS MADE FROM POST-CONSUMER WOOD WASTE IN A POWER INSTALLATION OF LOW POWER

The aim of the work was to identify the influence of chosen waste wood materials of assumed technical properties on the change of the course of basic parameters of their combustion process. To achieve the set aim, fuel mixtures of industrial and post-consumer wood waste were prepared. In the research the assessment of prepared solid recovered fuels was made and tests of their combustion in a laboratory heating installation of low power were conducted. The positive results of tests let us hope that previously used wood fuels originating from forest may be substituted with solid recovered fuels produced from wood waste.

Keywords: wood waste, solid recovered fuels, waste managements, thermal conversion of waste with energy recovery, emissions of gaseous products of combustion

Introduction

In economic practice there are many types of wood waste of very diverse properties. The waste is created during harvesting of wood raw material, its processing, and in households, e.g. worn-out and useless wood items. In recent period the last named type of waste has been attracting ever greater interest of people and institutions dealing with waste management. Relatively large overall dimensions of post-consumer products, application of many materials in their production and often unknown origin of those materials make this type of waste a huge problem for municipal service. Research conducted in the Wood Technology Institute in Poznan showed that only in 2002 around $5 \cdot 10^6$ m³ of various types of post-consumer wood materials were produced in Poland [Ratajczak et al. 2003]. However, only insignificant part of it was deposited at municipal landfills. In the

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case of Poznan agglomeration this part amounted to as little as 2 400 Mg (approximately 6%¹ in 2008. Choosing a rational way of utilisation of this waste, one should take into account the quantity of different types of ballast substances in wood material.

One of the right lines of management of those materials is combustion of the so-called solid recovered fuels produced from them [Cichy 2007]. According to the definition presented in a technical specification [CEN/TS 15357:2006] the name of solid recovered fuels encompasses materials intended for combustion and produced from waste, different from hazardous, with a view of using them for energy recovery in suitable installations, whilst those materials fulfil requirements of CEN/TS 15359. The literature proposes a series of different names for that type of materials such as alternative fuels, fuels from waste [Wandrasz, Nadziakiewicz 1997, 1999, 2001; Wandrasz, Pikoń 2003, 2005, 2007] or formed fuels [Wandrasz, Wandrasz 2006]. However, in the authors' opinion terminology introduced by the European Committee for Standardization (CEN) seems to be the most universal. According to that terminology initial preparation of wood waste consisting in mixing of its various types in set proportions may be called production of fuels, and fuel materials obtained in this way may be called solid recovered fuels (acc. to CEN/TS 15357:2006). The share of wood in those fuels may be as high as 90%, which allows considering those materials biomass [Rozporządzenie... 2005, 2008] like it is abroad [Głowacki, Cichy 2007].

When the demand for solid biofuels is increasing (which also is connected with the international commitments of Poland), manufacture of a new type of fuel materials produced from wood waste is an especially desired activity [Cichy 2007]. However, the available literature lacks information on behaviour of such fuels during power combustion [Ściażko, Zuwała 2007; Rybak 2006; Wandrasz, Nadziakiewicz 1997, 1999, 2001; Wandrasz, Pikoń 2003, 2005, 2007, Wandrasz, Wandrasz 2006]. Therefore, it is necessary to conduct deepened research aimed at identification of phenomena occurring in real hearth that may have a significant influence on both the very process of combustion of solid recovered fuels made from wood waste and creation of products of their combustion that are dangerous to the environment. The issue is of special importance in the present legal situation when that waste should be processed before it is deposited at landfills. Previous experience indicates the possibility of burdening wood waste with different types of chemical preparations. In this case the process of production of recovered fuels should consist in such selection of their parameters so as to obtain as a result a solid combustible substance that may be used in power installations.

¹ Source: Information obtained from the Waste Management Plant in Poznan.

It seems that due to relatively low supply of wood on the domestic market and legal restrictions on the use of forest wood in the power industry the increased demand for biomass fuels may not be satisfied [Rozporządzenie... 2008]. Discovery of a renewable energy carrier that would be an alternative to wood could be at least a partial solution to that acute problem. However, it seems necessary to correctly define parameters of production process of such type of fuels in terms of their combustion properties, and especially limitation of possibilities of creation of adverse combustion products.

Aim and scope of research

The aim of the research was to identify the influence of essential properties of chosen chemically contaminated wood materials on changes in the course of basic parameters of their combustion process.

To achieve the set goal and on the basis of previous experiments [Cichy, Wróblewska 2003; Cichy 2007] tests consisting in energy processing of recovered fuels produced from wood waste were planned. Three types of post-consumer waste materials were used in the tests:

- post-consumer furniture,
- worn-out exterior builder's carpentry and joinery elements (exterior door),
- worn-out telecommunications poles,
- industrial waste – sawmill softwood sawdust.

The selected materials were subjected to the following laboratory analyses so as to evaluate their fuel properties and possible hazards during combustion:

- determination of moisture and ash content,
- determination of content of the so-called “volatile components”,
- determination of heat of combustion and calculation of calorific value,
- determination of content of basic elements (C, H, N, S).

In the body of research tests at testing station consisting of low power boiler adjusted to wood combustion were conducted. Combustion experiments were carried out in the laboratory boiler room consisting of:

- boiler of power of 20 kW intended for combustion of wood and other solid fuels,
- heat accumulator,
- heat exchanger,
- central heating circulating pumps,
- heat gauge,
- exhaust discharging installation with chimney.

During tests, conducted maintaining optimum parameters of the boiler's performance, temperatures inside the test hearth and the boiler's heat efficiency

were controlled. The composition of released combustion gases was the observed factor.

Research methodology

Four types of wood waste were obtained for tests, of which three were post-consumer waste and one was industrial waste:

- telecommunications poles obtained from a telecommunications company. The poles originated from telecommunications network systems set up in the period 1930÷1960 and traces of mechanical wear were visible. In almost 90% the poles were preserved with an oily agent – impregnation oil (creosote oil),
- exterior doors originated from a building set up some 45 years ago. The body of the doors consisted of door leaf panels made of furniture panel. Due to the age of the doors, it should be assumed that furniture panels were manufactured using classical glues made from natural raw materials, i.e. casein or gluten. Throughout the whole period of exploitation tested elements were exposed to atmospheric factors. Traces of wood-decaying fungi were visible on the obtained samples as well as trace quantities of paints (enamel paints); therefore, characteristics of this waste were similar to those of natural wood,
- post-consumer furniture manufactured at the turn of 1970s and 1980s. It is typical box furniture made of particleboards, plywood or fibreboard (around 80%) and solid wood (around 20%). The external surfaces of particleboards were covered with paper foil, whilst solid elements and plywood or fibreboards were finished with layers of paints or lacquers,
- sawmill softwood sawdust was obtained from a WITAR Company sawmill in Porążyn.

To conduct the planned tests of combustion processes, the obtained waste wooden elements were reduced to the form of small chips. Chipping was carried out using mechanical disintegrator used in the technology of production of fuel briquettes from biomass. Approximately 100 kg of each type of raw material was prepared. Chipped material was packed into sacks and stored in a dry store-room until the tests started. This way a similar level of moisture content of the analysed material was achieved.

Recovered biofuel production process consisted in preparation of appropriate mixtures of waste differing in chemical composition. Selected wood materials were mixed with each other in proportions given in table 1. The authors were especially interested to know the influence of the share of ballast substances (like binding, finishing, and preservative substances) on the amount of emission of gaseous products of combustion that have the influence on possible hazards to the environment. The use of a 1-percent share of chemically burdened waste in

the formed fuel stemmed from legal regulations effective in Poland that allow combustion of waste other than hazardous in the amount not exceeding 1% mixed with conventional fuel in typical power installations [Rozporządzenie... 2005].

Table 1. The share of particular types of waste in produced recovered fuels
Tabela 1. Udział poszczególnych rodzajów odpadów w wytworzonych paliwach wtórnych

No. <i>L.p.</i>	Post-consumer furniture <i>Meble użytkowe</i>	Softwood sawdust <i>Trociny iglaste</i>	No. <i>L.p.</i>	Telecommunica- tions poles <i>Słupy teletechniczne</i>	Exterior doors <i>Drzwi zewnętrzne</i>
	[%]			[%]	
1.	50	50	6.	50	50
2.	25	75	7.	25	75
3.	15	85	8.	15	85
4.	5	95	9.	5	95
5.	1	99	10.	1	99

Samples for laboratory analyses were taken from the prepared recovered wood fuels. Sampled material was reduced using a laboratory mill of Pulverisette 14 type and a laboratory mill of Pulverisette 15 type by Fritsch. Next, in order to characterise the obtained material in detail, the following characteristics were determined:

- elementary composition in the scope of content of carbon, hydrogen, nitrogen, and sulphur using an analyser of EA 1108 type by Carlo Erba Instruments. The scale of the analyser was 0.01÷100%. Analysed samples were dried in the temperature of 60°C until they reached constant mass. Sulphanilic acid was used as an external standard,
- basic fuel properties that were determined using appropriate procedures developed for the assessment of municipal waste properties:
 - moisture content (PN-Z-15008-02:1993),
 - ash content (PN-Z-15008-03:1993),
 - content of the so-called “volatile components” (PN-G-04516:1981),
 - calorific value (PN-Z-15008-04:1993),
- calorific value of fuel mixtures (solid recovered fuels) that was calculated based on proposals of Wandrasz and Wandrasz [2006] acc. to the following formulas:

$$W_d = u_1 \cdot (W_d)_{11} + u_2 \cdot (W_d)_{12} + \dots + u_n \cdot (W_d)_{1n} \quad [\text{J/g}] \quad (1)$$

and

$$\sum_i u_i = 1 \quad (2)$$

where:

W_d	– mixture calorific value	[J/g]
$(W_d)_{1..n}$	– n component calorific value	[J/g]
$u_1 \dots u_n$	– mass share of components 1... n .	

Combustion experiments in a quarter-technical scale were conducted according to an own procedure developed on the basis of previous research [Cichy 2004, 2007]. Prepared samples of fuels were combusted at a test station consisting of a set of devices making up a laboratory boiler room. The main element of the station is a central heating boiler with water curtain of Futura Bio 25 type with thermal efficiency of 25 kW produced by CHT – Cichewicz. The boiler is intended for combustion of crumbled wood biomass. Technical characteristic of the laboratory boiler room devices is presented in table 2.

Table 2. Technical parameters of the boiler installed at the test station intended for investigation of processes of combustion of solid recovered fuels made of wood waste

Tabela 2. Parametry techniczne kotła wchodzącego w skład stanowiska badawczego przeznaczonego do badań procesów spalania stałych paliw wtórnych wytworzonych z odpadów drzewnych

No. <i>Lp.</i>	Parameter <i>Parametr</i>	Unit <i>Jednostka</i>	Futura Bio 25 boiler <i>Urządzenie kotłowe Futura Bio 25</i>
1.	Nominal thermal power <i>Nominalna moc cieplna</i>	kW	25
2.	Water maximum temperature <i>Maksymalna temperatura wody</i>	°C	95
3.	Water capacity <i>Pojemność wodna</i>	dm ³	105
4.	Fuel consumption (nominal) <i>Zużycie paliwa (nominalne)</i>	kg/h	2÷5
5.	Fuel bunker capacity <i>Pojemność zasobnika paliwa</i>	dm ³	500
6.	Combustion chamber capacity <i>Pojemność komory spalania</i>	dm ³	–
7.	Permissible working pressure <i>Dopuszczalne ciśnienie robocze</i>	bar	2
8.	Exhaust temperature <i>Temperatura spalin</i>	°C	> 120
9.	Boiler's efficiency <i>Sprawność urządzenia</i>	%	79÷83

Exhaust from both boilers is passed through an exhaust collector to a chimney of height of around 6 meters and diameter of 250 mm. The heat generated during combustion of analysed materials is collected in a buffer accumulator of capacity of 3000 dm³. Measurement ferrules for measuring composition of combustion gases and exhaust temperature were installed in the exhaust collector. Circulation of heating medium (water) in the installation was forced thanks to the use of two pumps installed in a pipeline feeding a heat distributor. Reception of generated heat was assured by an air heater. The heating medium circulation installation was fitted with a vane water meter with sensors that were connected to a calorimeter, thus made it possible to take energy measurements.

The body of the study was research on combustion process of the prepared recovered wood fuels. The main aim of the research was to measure emission of combustion gases produced during that process. The analysis of combustion gases was carried out using an exhaust analyser of Lancom Series II type by Land Combustion. Parameters and scale of that device are shown in table 3. During combustion process measurements of temperatures inside the test hearth were taken as well using temperature sensors (of NiCrSi-NiSi type) and digital temperature gauge of DT 16 type by Metrol. Temperature was measured every 2 minutes and analysis of composition of combustion gases was being carried out at the same time. Apart from the above-mentioned measurements, thermal effects of the process in the laboratory central heating installation were recorded.

Table 3. Measurement scale and basic parameters of exhaust analyser of Lancom Series II type

Tabela 3. Zakres pomiarowy i podstawowe parametry analizatora spalin Lancom Series II

Measured parameter <i>Mierzony parametr</i>	Unit <i>Jednostka</i>	Measurement scale <i>Zakres pomiarowy</i>	Accuracy <i>Dokładność</i>	Resolution <i>Rozdzielczość</i>
O ₂	%	0 ... 25	± 1%	± 0,1
CO _{wysoki/high}	ppm	0 ... 40.000	± 2%	± 100
NO	ppm	0 ... 2.000	± 2%	± 1
NO ₂	ppm	0 ... 100	± 2%	± 1
SO ₂	ppm	0 ... 2.000	± 2%	± 1
C _x H _y	ppm	0 ... 50.000	± 2%	± 100
CO ₂	%	0 ... 25	± 2 %	± 0,1
NO _x	ppm			
Combustion efficiency <i>Sprawność spalania</i>	%			
Air surplus coefficient <i>Współczynnik nadmiaru powietrza</i>	–			

Those measurements were taken using an electronic calorimeter of CE 3 type, by PoWoGaz S.A., that allows readings such as: heating medium energy (GJ), temperatures of feed and return ($^{\circ}\text{C}$), momentary power (kW), momentary flow of the heating factor (m^3/h). The measurement procedure consisted of the following elements:

- setting fuel in the hearth alight and combustion of fuel under the boiler until optimum combustion process parameters are reached,
- period of reaching stable conditions of the process (3 hours),
- stabilisation of the process with assumed working conditions (around 1 hour),
- analysis of combustion process:
 - measurement of temperatures inside the hearth,
 - measurement of concentration of gaseous combustion products,
 - measurement of combustion parameters,
 - measurement of energy parameters of the process,
- extinguishing the hearth,
- preparation of the station for next analyses.

Tests were carried out using an operating installation and keeping heat power close to 75% of the nominal power. The operators saw to it that during the whole measurement period there was no significant fluctuation in an average value of parameters. Obtained results of chimney emission were converted into normal conditions and into 11-percent content of oxygen [PN-ISO 8756:2000], whilst NO_x concentration was given after conversion into nitrogen dioxide (NO_2).

Test results

Basic properties of tested recovered fuels

Table 4 presents results of determinations of elementary composition of the initial waste materials. As it follows from the presented data, the content of carbon in tested materials was changing in the range from 48.43% (post-consumer furniture) to 52.99% (telecommunications poles). The content of hydrogen was running similarly: from 6.80% in post-consumer furniture to 7.05% in telecommunications poles. Such state of affairs resulted from specific chemical composition of evaluated materials, and mainly from the nature of ballast substances: in the case of telecommunications poles the substance was impregnation oil (creosote oil) that is a mixture of hydrocarbons – products of dry distillation of hard coal; in the case of post-consumer furniture the substance was amine resins used as binding agents (glues) and finishing agents (components of artificial veneers). Significant differences were noted also when nitrogen content

was evaluated. In accordance with expectations, the highest amounts of that element were found in furniture (3.19%), which resulted from a considerable share of particleboards and plywood in the total mass of that waste. In the other materials the level of nitrogen content was similar to the level found in natural wood (0.09÷0.21%). In none of the analysed samples any share of sulphur was found (within the limits of the method determinability). The differences in oxygen content in tested materials mainly resulted from their burdening with ballast substances and so the lowest content of that element was found in telecommunications poles (39.36%), and the highest in softwood sawdust (41.87%). From the above comparison also it follows that chemical composition of samples obtained from exterior doors was similar to the composition of natural, “pure” wood (C – 49.72%, H – 6.98%, N – 0.21%, and O – 41.18%). The above-described raw materials served for preparation of fuel mixtures (production of solid recovered fuels from wood waste). The purpose of the authors was to prepare mixtures in which contaminated materials (post-consumer furniture, and telecommunications poles) would be “diluted” with pure materials or materials of low content of chemical contaminants (sawdust, post-consumer door). Table 5 presents basic elementary composition of those mixtures. Obtained fuel mixtures (solid recovered fuels from wood waste) were subjected to further tests.

Table 4. Content of basic elements in the initial waste materials used in the tests
Tabela 4. Zawartość podstawowych pierwiastków w wyjściowych materiałach odpadowych wykorzystanych w doświadczeniach

Name of the sample <i>Nazwa próbki</i>	Element content <i>Zawartość pierwiastka</i>				
	Carbon <i>Węgiel</i>	Hydrogen <i>Wodór</i>	Nitrogen <i>Azot</i>	Sulphur <i>Siarka</i>	Oxygen ^{*)} <i>Tlen^{*)}</i>
	[%]				
Post-consumer furniture <i>Meble użytkowe</i>	48.43	6.80	3.19	n.d. <i>n.w.</i>	40.30
Post-consumer doors <i>Drzwi użytkowe</i>	49.72	6.98	0.21	n.d. <i>n.w.</i>	41.18
Telecommunications poles <i>Słupy teletechniczne</i>	52.99	7.05	0.19	n.d. <i>n.w.</i>	39.36
Softwood sawdust <i>Trociny iglaste</i>	50.45	6.87	0.09	n.d. <i>n.w.</i>	41.87

^{*)} value determined by calculation

^{*)} *wartość wyznaczona z obliczeń*

n. d. – not detected

n.w. – *nie wykryto*

Table 5. Content of basic elements in fuel mixtures prepared for tests
Tabela 5. Zawartość podstawowych pierwiastków w mieszankach paliwowych przygotowanych do badań

Type of waste – mixture composition Rodzaj odpadów – skład mieszanki		Element content Zawartość pierwiastka				
		Carbon Węgiel	Hydrogen Wodór	Nitrogen Azot	Sulphur Siarka	Oxygen Tlen
[%]						
Post-consumer furniture Meble użytkowe	Softwood sawdust Trociny iglaste					
50	50	49.44	6.84	1.64	n.d. n.w.	41.09
25	75	49.95	6.85	0.87	n.d. n.w.	41.48
15	85	50.15	6.86	0.56	n.d. n.w.	41.63
5	95	50.35	6.87	0.25	n.d. n.w.	41.79
1	99	50.43	6.87	0.12	n.d. n.w.	41.85
Telecommunications poles Słupy teletechniczne	Post-consumer doors Drzwi użytkowe					
50	50	51.36	7.02	0.20	n.d. n.w.	40.27
25	75	50.54	7.00	0.21	n.d. n.w.	40.73
15	85	50.21	6.99	0.21	n.d. n.w.	40.91
5	95	49.88	6.98	0.21	n.d. n.w.	41.09
1	99	49.75	6.98	0.21	n.d. n.w.	41.16

n.d. – not detected

n.w. – nie wykryto

Table 6 shows results of determinations of basic fuel properties of the initial wood materials. From presented data it follows that tested waste materials were characterised by low moisture content (6.79÷10.18%) and high content of volatile components (78.61÷84.98%). Evaluated fuels were also characterised by diverse ash content – relatively low for sawmill sawdust and telecommunica-

tions poles (0.72 and 0.39%, respectively) and little higher for post-consumer furniture and post-consumer doors (1.24 and 1.87%, respectively). A relatively high burdening of evaluated materials with ballast substances accounts for such state of affairs (sand in sawdust and telecommunications poles, mineral pigments in veneers of post-consumer furniture, remains of fittings and nails in remnants of post-consumer doors).

Table 6. Basic fuel properties of the initial waste materials

Tabela 6. Podstawowe właściwości paliwowe wyjściowych materiałów odpadowych

Type of waste <i>Rodzaj odpadów</i>	Determination type <i>Rodzaj oznaczenia</i>		
	Moisture content <i>Wilgotność</i>	Ash <i>Popiół</i>	Volatile components <i>Części lotne</i>
[%]			
Post-consumer furniture <i>Meble użytkowe</i>	6.79	1.24	78.61
Post-consumer doors <i>Drzwi użytkowe</i>	8.51	1.87	80.49
Telecommunications poles <i>Słupy teletechniczne</i>	10.18	0.39	84.98
Sawmill sawdust <i>Trociny tartaczne</i>	9.16	0.72	82.85

Table 7 presents results of determinations of moisture content and ash for prepared fuel mixtures. In accordance with expectations, obtained results are resultants of initial parameters of waste materials. Table 8 compares results of determinations of heat of combustion and calculations of calorific value in analytical state, on “as received” basis, and on “dry and ash-free” basis for the initial wood materials. Chemical contaminants in analysed samples of post-consumer wood did not have any radical influence on calorific value of burnt materials. The heat of combustion fluctuated around 19.5 MJ/kg (19.264÷19.703 MJ/kg), and only in the case of waste telecommunications poles this value was higher (21.569 MJ/kg), which was undoubtedly a result of the content of creosote oil characterised by high calorific value. Because most of evaluated waste was characterised by relatively low moisture content, calorific value calculated for working state was changing insignificantly from 17.685 to 18.076 MJ/kg, and in the case of telecommunications poles it was 19.861 MJ/kg. Having taken into account moisture content and ash content in burnt materials, higher diversity of calorific value was observed. Calorific value calculated on “dry and ash-free” basis was changing in the range from 18.808 to 19.455 MJ/kg (for telecommunications poles calorific value was 21.675 MJ/kg).

Table 7. Basic fuel properties of recovered fuels made of wood waste**Tabela 7. Podstawowe właściwości paliwowe paliw wtórnych wytworzonych z odpadów drzewnych**

Type of waste – mixture composition <i>Rodzaj odpadów – skład mieszanki</i>		Determination type <i>Rodzaj oznaczenia</i>	
		Moisture content <i>Wilgotność</i>	Ash <i>Popiół</i>
[%]			
Post-consumer furniture <i>Meble użytkowe</i>	Sawmill sawdust <i>Trociny tartaczne</i>		
50	50	7.98	0.98
25	75	8.57	0.85
15	85	8.80	0.80
5	95	9.04	0.75
1	99	9.14	0.73
Telecommunications poles <i>Słupy teletechniczne</i>	Post-consumer doors <i>Drzwi użytkowe</i>		
50	50	9.35	1.13
25	75	8.93	1.50
15	85	8.76	1.65
5	95	8.59	1.80
1	99	8.53	1.86

Table 8. Basic fuel properties of the initial waste materials**Tabela 8. Podstawowe właściwości paliwowe wyjściowych materiałów odpadowych**

Type of waste <i>Rodzaj odpadów</i>	Determination type <i>Rodzaj oznaczenia</i>			
	Heat of combustion <i>Ciepło spalania</i>	Calorific value <i>Wartość opałowa</i>		
		in analytical state <i>w stanie analitycznym</i>	“as received” basis <i>w stanie roboczym</i>	dry and ash-free basis <i>w stanie suchym i bezpopiołowym</i>
		[kJ/kg]		
Post-consumer furniture <i>Meble użytkowe</i>	19 264	17 685	17 070	18 808
Post-consumer doors <i>Drzwi użytkowe</i>	19 412	17 746	17 167	19 447
Telecommunications poles <i>Słupy teletechniczne</i>	21 569	19 861	19 078	21 675
Sawmill sawdust <i>Trociny tartaczne</i>	19 703	18 076	17 223	19 455

Table 9. Calorific value of recovered fuels made of wood waste**Tabela 9. Wartość opalowa paliw wtórnych przygotowanych z odpadów drzewnych**

Type of waste – mixture composition <i>Rodzaj odpadów – skład mieszanki</i>		Calorific value in working state <i>Wartość opalowa w stanie roboczym</i>
[%]		[kJ/kg]
Post-consumer furniture <i>Meble użytkowe</i>	Sawmill sawdust <i>Trociny tartaczne</i>	
50	50	17 147
25	75	17 185
15	85	17 200
5	95	17 215
1	99	17 221
Telecommunications poles <i>Słupy teletechniczne</i>	Post-consumer doors <i>Drzwi użytkowe</i>	
50	50	18 123
25	75	17 645
15	85	17 454
5	95	17 263
1	99	17 186

Table 9 presents numerical data on calorific value for every of prepared fuel mixtures. In accordance with expectations, only insignificant changes of that parameter (up to 74 kJ/kg) were observed in the case of mixtures of sawdust and furniture, whilst in the case of mixtures of post-consumer doors and telecommunications poles the difference between extreme values was over 900 kJ/kg, which stemmed from high diversity of that parameter for the initial materials (17.167 MJ/kg and 19.078 MJ/kg, relatively). From the above comparisons of fuel properties and basic chemical composition of raw materials prepared for tests it unambiguously follows that evaluated materials are characterised by very good properties which make it possible to use those materials as biomass fuels, i.e. solid recovered fuels from wood waste.

Experiments of combustion of tested wood materials

The actual tests were preceded with initial experiments in which combustion conditions optimal for a given type of fuel were determined. The determined parameters of combustion process are: fuel granulation, amount of air dosed, and amount of fuel dosed. After the parameters of boiler operation were standardised, a measured out amount of tested fuel was added to a bunker and at the same time recording of the following measured parameters was started:

- the amount of emission of gaseous combustion products to the atmosphere (CO, CO₂, NO, NO₂, C_xH_y, O₂),
- combustion process efficiency,
- air surplus coefficient.

Simultaneously the following thermal parameters, produced during operation of the laboratory boiler system, were recorded:

- unit amount of heat generated by the system,
- total amount of heat generated by the system during combustion of a defined amount of tested fuel.

Combustion of fuels formed from sawdust and post-consumer furniture

Fig. 1÷10 present compared data on fuels obtained from waste of pure wood (softwood sawdust) and composite wood products (post-consumer furniture). Figure 1 shows changes of air surplus coefficient during combustion of analysed fuel mixtures. As it follows from the compared data, combustion parameters (the amount of fuel and air dosed into the hearth chamber) for all types of tested recovered fuels were set in such way so as to have the air surplus coefficient λ fluctuate between 2.00 and 4.00. In few cases an aberration from that rule was observed. That was caused by some heterogeneity of the size of burnt particles, i.e. the fuel contained both fine wood particles of size close to microchips from particleboards and much bigger particles of shape similar to chips used in OSB technology. Such state of affairs caused the situation when the capacity of fuel fed into the hearth was the same at any time of analysed process, but the mass of the fuel portion was different (various fed mass). It cannot be ascertained that composition of fuel mixture (the share of post-consumer furniture in burnt fuel) directly influenced the value of calculated air surplus coefficient.

Fig. 2 presents changes in exhaust temperature measured in flue during combustion of analysed fuel mixtures. During the measurements temperature was changing in the range 100÷400°C and most often it ranged from 250 to 350°C. As regards the value of air surplus coefficient λ , it may be said that the value of coefficient λ drops as temperature of combustion gases rises and contrarily: a drop in exhaust temperature is observed as an increase in air surplus coefficient. Like in the former case, it cannot be ascertained that composition of analysed formed fuels directly influenced the height of temperatures measured in the flue. Fig. 3 and 4 present changes in temperatures inside the test hearth. Combustion of fuel in the boiler used in tests is carried out in the so-called trough hearth made of ceramic materials and fitted with suitable air delivering nozzles. Fuel is fed to the trough hearth using a worm conveyor. Temperature sensors showing changes inside the hearth are installed at the beginning and end of the trough hearth. In the first part of the trough hearth biomass fuel is subjected to initial thermal processing. As a result of this processing water contained in the fuel is evaporated and then the so-called volatile components are

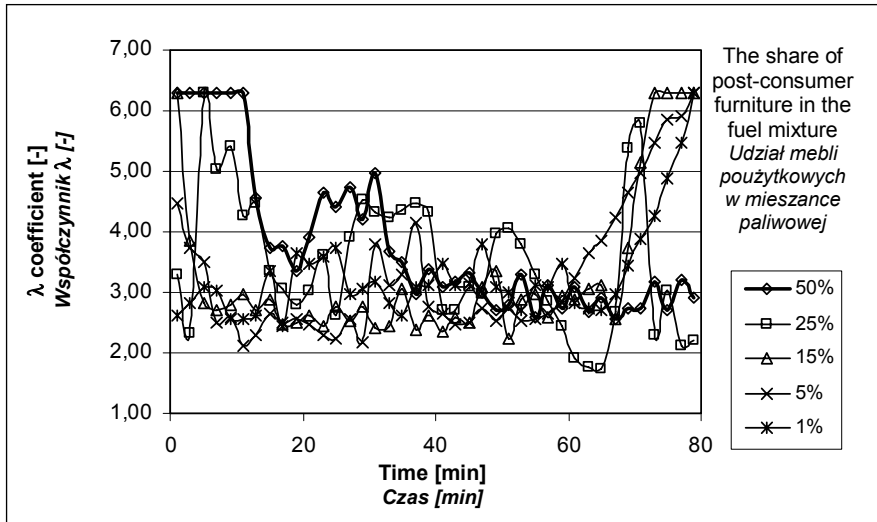


Fig. 1. The value of air surplus coefficient during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 1. Wielkość współczynnika nadmiaru powietrza w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

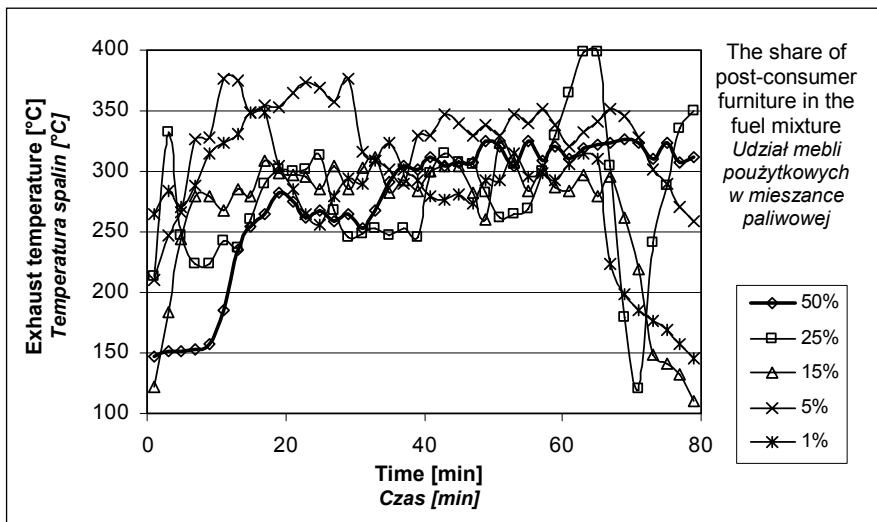


Fig. 2. Changes in temperatures of combustion gases during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 2. Zmiany temperatur gazów spalinowych w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

degassed. Those are endothermic changes, and changes in the second part of the trough hearth are the source of heat necessary for endothermic changes to happen. This is the place where actual oxidisation of earlier released volatile components happens as well as burning out of produced carbonisate. Those changes are exothermic.

Fig. 3 shows data from the first measurement point located in the place where fuel is introduced into the hearth. Presented data shows that temperature in that place oscillated around 450°C and ranged from 300°C to 650°C. Insignificant deviations in the initial and final period of experiments most probably were caused by observed heterogeneity of fuel, and thus smaller combustion mass delivered to the hearth grill in the analysed moment. Much higher temperatures (approximately 800°C) in the first measurement point observed when fuel with a 15-percent share of post-consumer furniture was burnt presumably were caused by the fact that the front of burnt fuel was moved towards the bunker. It does not seem that that action had a significant influence on the course of the process of combustion of evaluated fuel mixture. The course of combustion process also does not indicate that chemical composition of assessed fuel mixtures had a significant influence on diversity of temperatures recorded in that measurement point. Observed changes resulted from the nature of operation of the controller supervising work of the fuel feeder. Fig. 4 presents changes of temperatures recorded in the second (2) measurement point of the hearth. As it follows from presented data, recorded temperatures were changing within the range from 400 to 800°C. Observed deviations from those values were caused by cyclic operation of fuel feeder, like it was in the case of the first (1) measurement point. It does not seem that composition of fuel mixture delivered to the hearth grill had a significant influence on the value of temperature recorded in this point (2). Dynamic changes were observed in the trough hearth and on the hearth grill. Portions of fuel delivered to the trough hearth by the worm conveyor underwent previously described physical and chemical changes. Turning on of the feeder resulted in delivery of a new portion of fuel to the trough hearth. This fuel falls on already burning wood particles and produced incandescing carbonisate. As a result the new portion of fuel was moved and mixed with burning particles. The effect of those actions was a cyclic drop of temperature. After few minutes temperature rose rapidly, which was an effect of the new portion of fuel being set alight. Described course of combustion process is a result of simple constructional solutions applied in the power device of low power intended for combustion of solid biofuels.

Changes of temperature of circulating water measured by a sensor installed in the boiler of the test installation are presented in fig. 5. Compared data shows that the temperature increase connected with energy delivered to the system was quite regular. Tests of most of analysed samples of fuels were started when the temperature of water in the boiler fluctuated between 42 and 52°C. Only in the

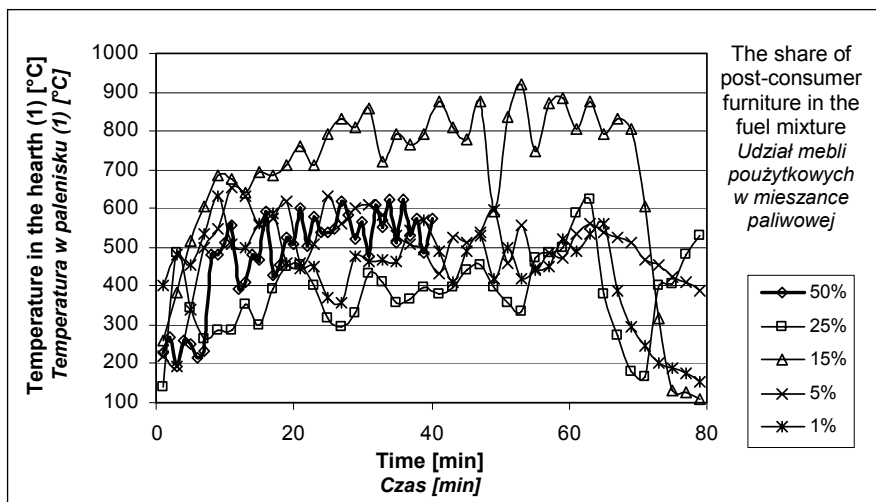


Fig. 3. The course of changes in temperatures recorded in the first measurement point of the hearth during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 3. Przebieg zmian temperatur rejestrowanych w pierwszym punkcie pomiarowym paleniska przy spalaniu mieszanek paliwowych trociny iglaste – meble użytkowe

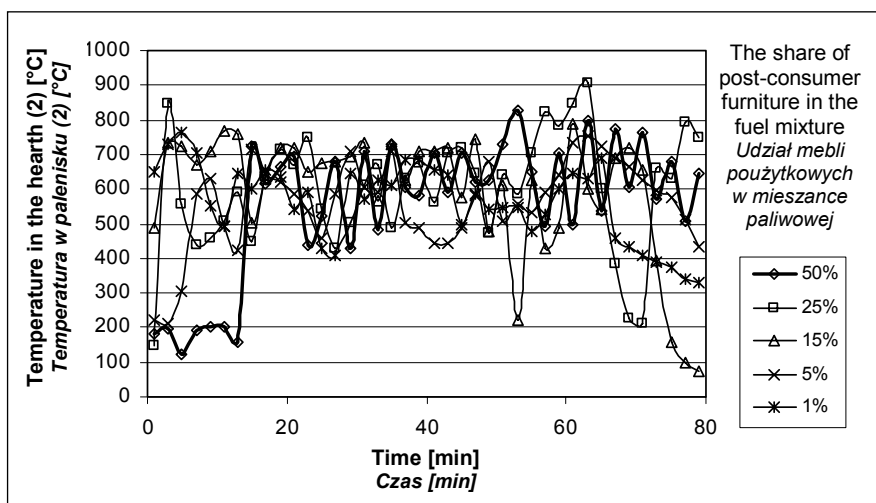


Fig. 4. The course of changes in temperatures recorded in the second measurement point of the hearth during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 4. Przebieg zmian temperatur rejestrowanych w drugim punkcie pomiarowym paleniska przy spalaniu mieszanek paliwowych trociny iglaste – meble użytkowe

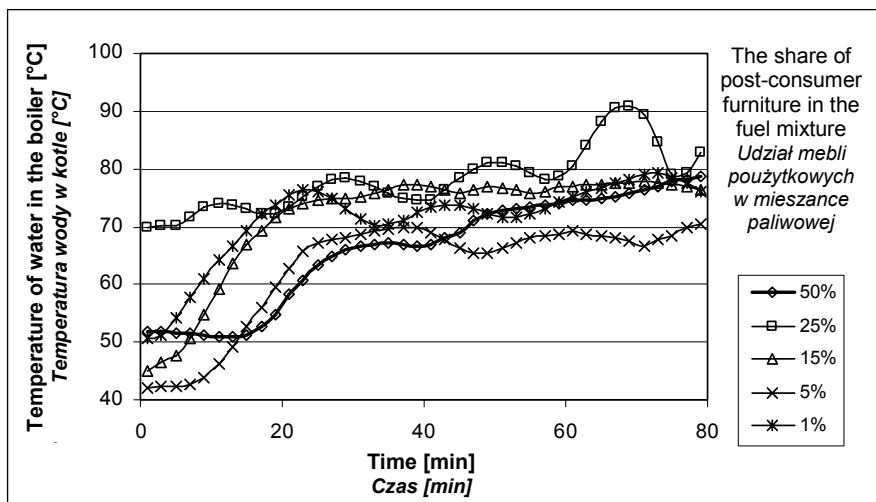


Fig. 5. Changes in the temperature of boiler water recorded in the boiler during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 5. Zmiany temperatury wody kotłowej rejestrowane w kotłach w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

case of fuel with a 25-percent share of post-consumer furniture it was necessary to start measurements when the temperature reached 70°C, which was the reason why in the final period of measurements the temperature in the boiler was higher than 90°C. Large inertia of the system, i.e. steel boiler and heating medium (water), allowed for much levelling of temperature curves in relation to temperatures measured inside the hearth that were changing in the range of around 200°C. It cannot be said that composition of fuel mixtures directly influenced changes of water temperatures measured inside the boiler.

Much greater fluctuations were recorded during evaluation of changes of boiler's momentary power during tests of combustion of fuel mixtures consisting of softwood sawdust and post-consumer furniture. The changes are presented in fig. 6. Compared data shows that at the beginning of tests thermal power of the boiler installation was changing in the range from 1.5 to 4.5 kW. After around 30 minutes the system reached the power ranging from 9.5 to 11.0 kW, which was approximately 50% of the nominal power of the boiler. Undoubtedly, high changeability of this parameter was influenced by changes in the flow of combustion mass in the trough hearth recorded as changes of temperatures inside the hearth (fig. 3 and 4). Presented data does not justify a statement that composition of fuel mixtures influenced the value of momentary power in the thermal system on which tests were conducted.

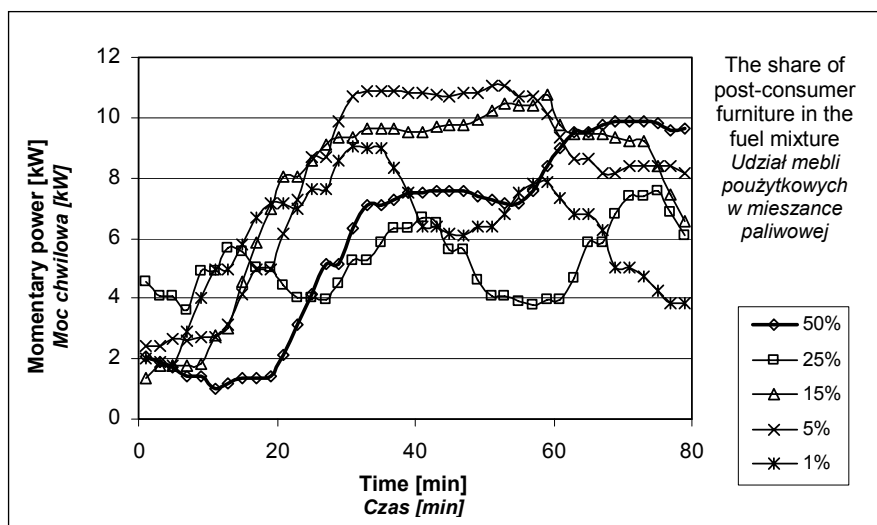


Fig. 6. Changes in momentary power of the boiler installation recorded during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 6. Zmiany mocy chwilowej instalacji kotłowej rejestrowane w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

Next chart (fig. 7) presents values of energy generated by the thermal installation during tests of combustion of prepared fuel mixtures. As it follows from presented data, similar amounts of energy ranging from 43 to 53 MJ were obtained during combustion of the same mass of fuel in similar thermal conditions of combustion process. Observed differences in the value of generated energy mainly resulted from unequal course of combustion process, heterogeneity of fuel, and cyclic operation of the controller supervising delivery of fuel to the hearth. Neither any significant differences in calorific values of evaluated fuel mixtures ($17.15 \div 17.22$ MJ/kg), nor any influence of chemical composition of those mixtures on the amount of energy produced by the measured system were noted.

Fig. 8÷10 present the amount of emission of gaseous products of the process during tests of combustion of analysed fuel mixtures (formed fuels) made from softwood sawdust and post-consumer furniture. Fig. 8 demonstrates changes in the amount of emission of carbon oxide during combustion of fuel mixtures consisting of sawdust and post-consumer furniture. From presented data it follows that the amount of emitted CO decreased as temperature in the hearth rose, and so in the initial period of the hearth work (when the fire kindled) the emission amount was around 9 g/m^3 , and in the final period it dropped to around 2 g/m^3 . It seems that the main factor that influenced the amount of emission of

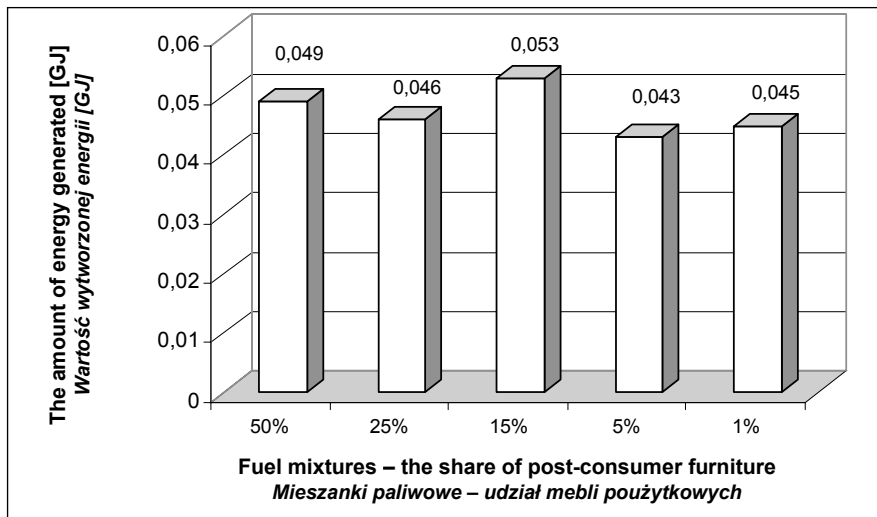


Fig. 7. The value of thermal energy generated in the boiler installation during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture
Rys. 7. Wartość wytworzonej energii cieplnej w instalacji kotłowej w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

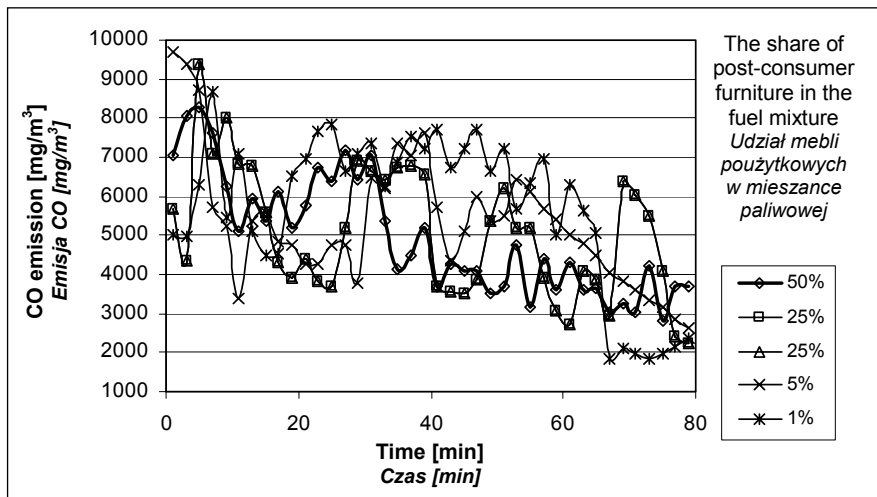


Fig. 8. Carbon oxide emission converted into 11% O₂ during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture
Rys. 8. Emisja tlenku węgla w przeliczeniu na 11% O₂ w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

that gas temperature reached in a given moment in the hearth. A low value of that parameter, i.e. approximately 200÷400°C, caused a situation when effectiveness of oxidisation of volatile components produced in the hearth was relatively low. An increase in temperature to the level of 600÷900°C was the reason why significant part of produced gases was burnt. The increase of temperature in the hearth was caused by released energy coming from combustion of carbon oxide. Despite some differentiation between curves of CO content in exhaust in relation to composition of fuel mixture, it cannot be unambiguously said that the share of contamination in burnt fuel directly influenced the amount of carbon oxide emission.

Fig. 9 depicts the content of carbon dioxide in combustion gases during combustion of analysed fuel mixtures. As it follows from presented data, the amount of CO₂ emission during tests of combustion was fluctuating between around 2 to 9%. The high content of carbon dioxide in exhaust (approximately 9÷10%) proved correct course of combustion process. As a result of it an increase in temperature inside the hearth was recorded (fig. 3 and fig. 4) as well as a reduction in carbon oxide emission (fig. 8). Like in the case of curves illustrating changes in the amount of carbon oxide emission, despite differences, it is hard to unambiguously ascertain that the share of contamination in burnt fuel mixtures influenced the content of carbon dioxide found in exhaust.

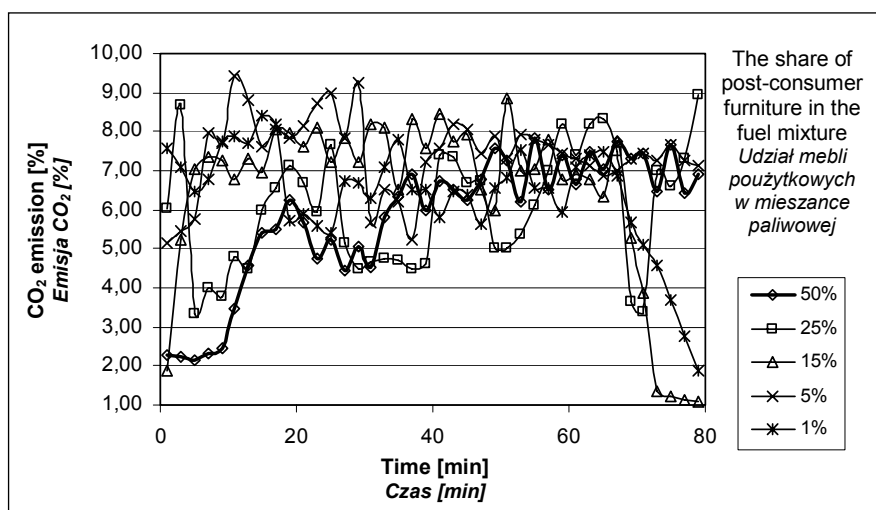


Fig. 9. Carbon dioxide emission during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 9. Emisja ditlenku węgla w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

Changes in the emission of nitrogen oxides (NO_x) during combustion of analysed fuel mixtures are illustrated in fig. 10. To present this process in a reliable way, results of nitrogen oxide (NO) emission and nitrogen dioxide (NO_2) emission obtained during measurements were converted into nitrogen dioxide (NO_2) in accordance with applicable procedures. Next, the obtained data was converted into 11-percent content of O_2 in combustion gases. From presented data (fig. 10) it stems that the level of NO_x emission was closely connected with composition of fuel mixtures, and especially with the share of post-consumer furniture in them. The content of nitrogen in evaluated mixtures was ranging from 0.12% in fuel with 1-percent share of post-consumer furniture to 1.64% in fuel with 50-percent content of furniture waste (table 5). According to expectations, the highest level of NO_x emission was observed in the case of exhaust produced during combustion of fuel containing 50% of post-consumer furniture. Obtained data oscillated around the value of 1080 mg of NO_x in 1 m^3 of combustion gases. In the case of the other mixtures levels of the emission of nitrogen oxides were, respectively: 25% of post-consumer furniture – 600 mg/m^3 , 15% – 350 mg/m^3 , 5% – 290 mg/m^3 , and 1% – 200 mg/m^3 .

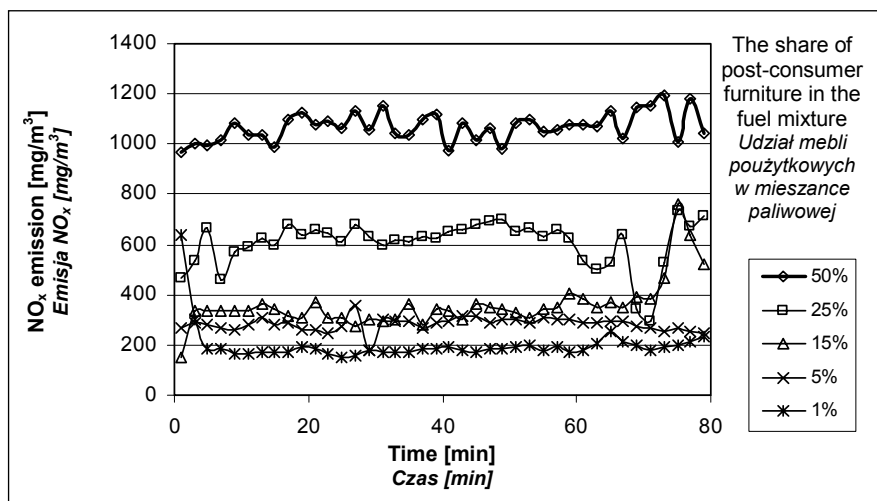


Fig. 10. Emission of nitrogen oxides converted into NO_2 with reference to 11% O_2 during combustion of fuel mixtures made from softwood sawdust and post-consumer furniture

Rys. 10. Emisja tlenków azotu w przeliczeniu na NO_2 w odniesieniu do 11% O_2 w trakcie spalania mieszanek paliwowych trociny iglaste – meble użytkowe

Considerable fluctuations in the values of NO_x emission, noticeable especially at the beginning and at the end of measurement cycle, resulted from conversion of relatively low emission values into 11% O_2 when the content of gaseous products in exhaust is low (O_2 content close to 20.9%). Unequal course of combustion process showed the phenomenon described in former studies [Cichy 2004], i.e. reactions of oxidisation and reduction with carbon oxide and nitrogen oxides. On the one hand, a result of that process is reduction of created fuel nitrogen oxides and on the other hand, oxidisation of a product of incomplete combustion of organic fuel, i.e. CO. It stems from the above that limitation of the emission of nitrogen oxides using primary methods (gradation of dosing of air into hearth) is possible also in low power hearths of much simplified construction.

During experiments of combustion of fuel mixtures consisting of sawmill sawdust and post-consumer furniture no presence of hydrocarbons in exhaust above the determinability level of the applied analytical method, i.e. around 0.01%, was observed. However, a conclusion that no light hydrocarbons are present in exhaust when such type of fuel mixtures is burnt should not be drawn from the above. That situation indicates only that combustion is relatively high efficient and introduction of an additional combustion level probably would make it possible to burn out produced carbon oxide and make the process even more efficient.

Combustion of solid recovered fuels from waste post-consumer doors and worn-out telecommunications poles

In the second part of research tests of combustion of fuels mixtures made of crumbled telecommunications poles and crumbled wooden elements of exterior doors were carried out. Post-consumer exterior wooden doors were made of furniture panels and solid wood elements. In connection with the above, those materials were considered composite wood products. Crumbled elements of telecommunications poles were an addition of waste materials containing hazardous substances. Such actions are substantiated by provisions of the Act on waste (2001)² and the Regulation of the Minister of the Environment on standards of emission from installations [2005].

The process of combustion of fuel mixtures containing post-consumer doors and telecommunications poles was carried out keeping parameters of operation of the boiler's devices the same as in the case of the mixtures consisting of sawmill sawdust and post-consumer furniture. Results of measurements made during combustion experiments are illustrated in charts (fig. 11÷21).

² The Act of 27 April 2001 on waste – article 11(2) “It is allowed to mix hazardous waste of different types and hazardous waste with waste other than hazardous with a view to improving safety of recovery processes or neutralising waste created as a result of mixing, if those processes will not result in increasing danger to human life and health or the environment”.

Changes in air surplus coefficient λ that characterises the course of combustion process in boiler are presented in fig. 11. Compared results show that in the main combustion process the value of coefficient λ changed within the range 2.0÷3.5. Essential aberrations from those values were recorded in the initial and final period of measurement cycle. Such state of affairs was connected with uneven filling of the hearth that was observed at the beginning of measurement period when fuel was delivered to the hearth in smaller portions, as well as at the end of the period when the worm conveyor was not anymore fully filled with fuel. Some inconvenience that had a bearing on coefficient λ increase was heterogeneity of granulation of burnt fuels. The content of too big particles in overall mass of fuel caused a situation when the portion of fuel dosed to the hearth contained less mass of combustible substances. However, no significant influence of composition of fuel mixtures on the value of air surplus coefficient during analysed measurement cycles was noted.

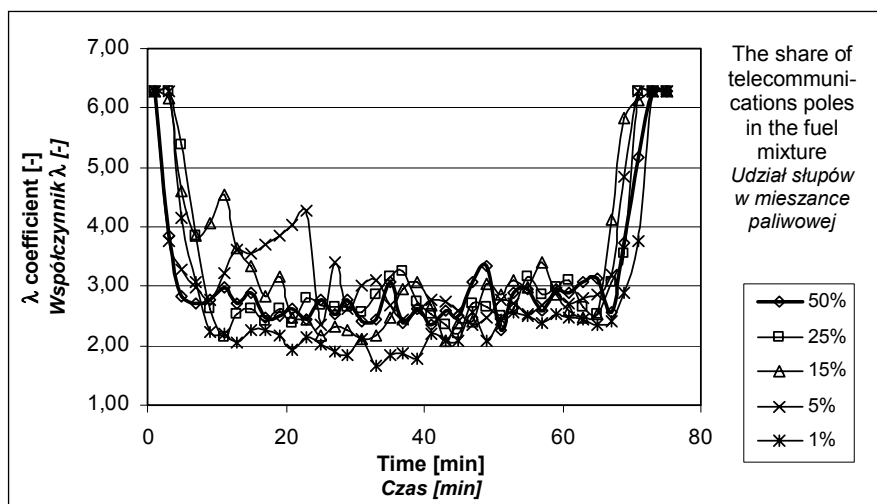


Fig. 11. The value of air surplus coefficient during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 11. Wielkość współczynnika nadmiaru powietrza w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

Fig. 12 presents changes in temperature of combustion gases that occur during combustion of fuel mixtures containing telecommunications poles and post-consumer doors. As it follows from compared data, exhaust temperature in the main measurement period fluctuated between around 270°C and around 400°C. Like in the case of coefficient λ , lower exhaust temperatures were recorded at the beginning and at the end of measurement cycle, which resulted from

the necessity of heating up the boiler installation (beginning of the cycle) and reduction of fuel portions delivered to the hearth grill (end of measurement cycle). Despite some differentiation, the influence of composition of fuel mixtures on exhaust temperature in analysed measurement cycles cannot be ascertained unambiguously.

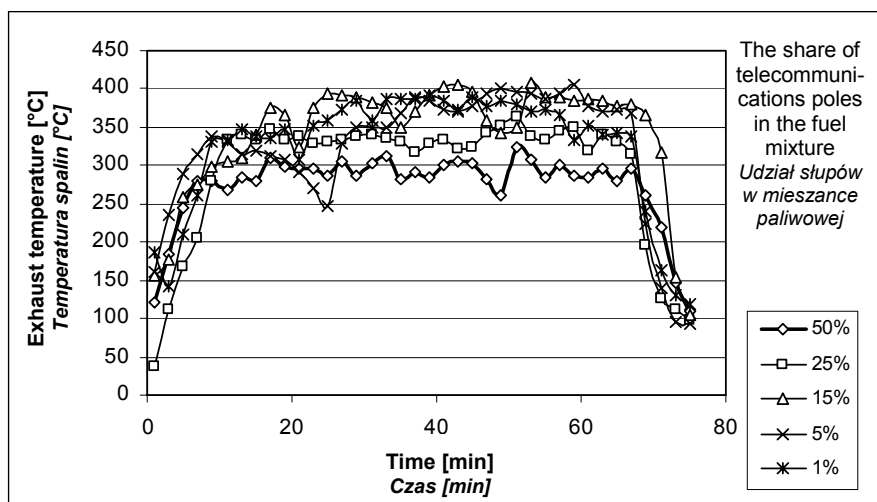


Fig. 12. Changes in temperatures of combustion gases during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 12. Zmiany temperatur gazów spalinowych w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

Fig. 13 illustrates changes of temperatures inside the hearth that are recorded in the first measurement point. Presented data shows that in the body of the measurement cycle temperature in measurement point no. 1 changed within the range from around 550°C to around 900°C. Most probably observed changes resulted from changing geometry of burning fuel whose prism on the grill grows when the feeder is on, pours down due to gravitation, and dwindles due to combustion. As a result, recorded temperature of flame changes as well. Like in the case of the exhaust temperature, in the initial period an increase in temperature from approximately 180°C to a maximum temperature was observed. This was a result of gradual heating up of the boiler's system. A decrease in temperatures in the final period of the cycle was caused by gradual reduction of fuel portions delivered to the hearth grill. It cannot be ascertained unambiguously that composition of fuel mixtures significantly influenced values of temperatures recorded in point 1.

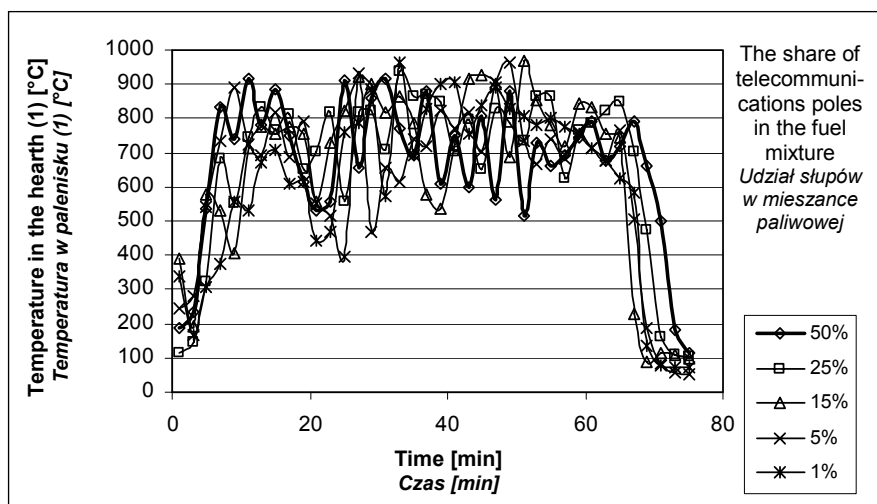


Fig. 13. The course of changes in temperatures recorded in the first measurement point of the hearth during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 13. Przebieg zmian temperatur rejestrowanych w pierwszym punkcie pomiarowym paleniska przy spalaniu mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

Fig. 14 illustrates changes of temperatures inside the hearth and recorded in measurement point no. 2. Values of temperatures measured in that point changed in the main period of the measurement cycle in the range from around 500°C to around 750°C. Like in the case of point 1, a rapid growth of temperature at the beginning of the measurement cycle (till maximum temperature for a given sample was reached) caused by heating up of the cold installation was observed in this case as well. On the other hand, a drop of temperature at the end of the cycle was caused by gradual reduction of fuel portion delivered for combustion, which resulted from gradual emptying of the fuel bunker. Also in this case the influence of composition of fuel mixtures on values of combustion temperatures recorded in this point could not be ascertained unambiguously.

Changes of temperature of circulating water recorded in the boiler during combustion of tested fuel mixtures are compared in fig. 15. Due to inertia of the system, the course of recorded changes was more linear compared to the course of temperatures recorded inside the hearth. Presented data shows that temperature of the heat carrier (water) was changing in the range from approximately 30°C to 80°C. During combustion of each of evaluated mixtures the system reached nominal working parameters after period of time ranging from around 18 to around 30 minutes. It is impossible to ascertain unambiguously that there is an interrelation between composition of fuel mixtures and temperature of boiler water reached during investigated measurement cycles.

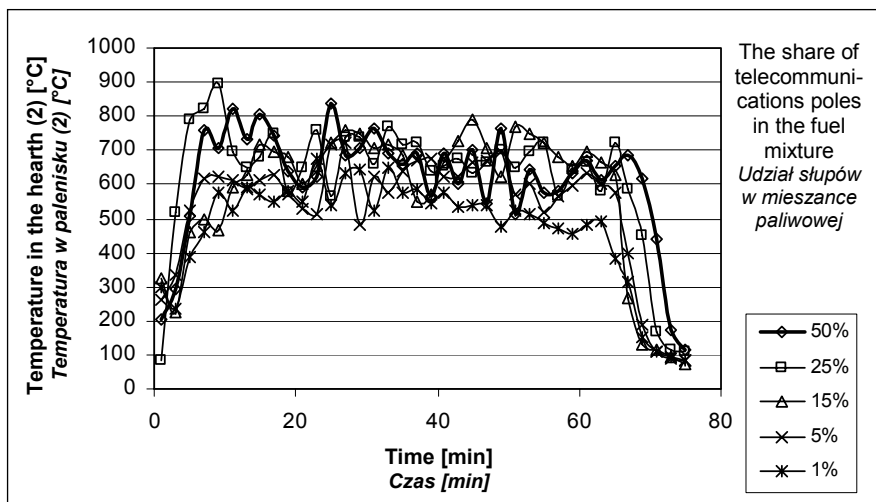


Fig. 14. The course of changes in temperatures recorded in the second measurement point of the hearth during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 14. Przebieg zmian temperatur rejestrowanych w drugim punkcie pomiarowym paleniska przy spalaniu mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

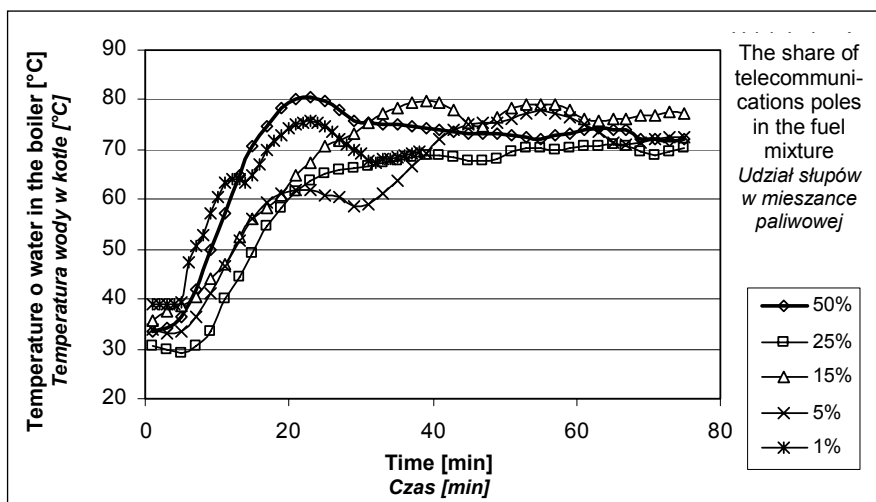


Fig. 15. Changes in the temperature of boiler water recorded in the boiler during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 15. Zmiany temperatury wody kotłowej rejestrowane w kotle w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

Fig. 16 illustrates changes of thermal momentary power of the test boiler installation recorded during tests of fuel mixtures consisting of telecommunications poles and post-consumer doors. An equable course of changes of momentary power indicates correct operation of the boiler and central heating installation co-operating with it. Analysis of compared results shows that from the moment when measurements were started there was a systematic increase in the value of momentary power of the boiler from the level of approximately 1÷4 kW to the level of 11÷16.5 kW. On reaching a maximum power for every measurement cycle, momentary power oscillated around the nominal value, which ranged from around 10 kW to approximately 14 kW. Reaching of an appropriate power level depended on few parameters. One of major parameters was the hearth operation dynamics that was influenced by mass of fuel delivered to the grill in a given moment, which was closely connected with heterogeneous granulation of the fuel mixture. Another important factor was the ability of boiler installation to give off created heat.

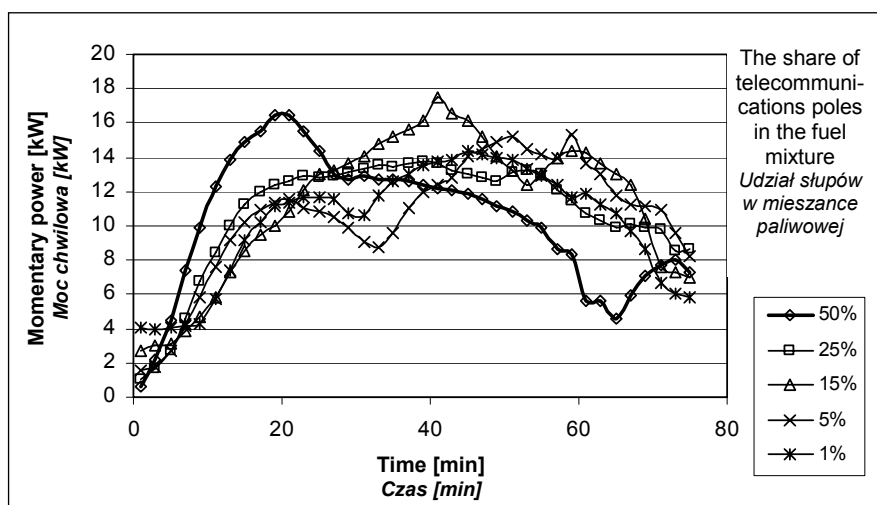


Fig. 16. Changes in momentary power of the boiler installation recorded during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 16. Zmiany mocy chwilowej instalacji kotłowej rejestrowane w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

Next factor recorded during measurements and presented in fig. 17 was the amount of energy generated by the boiler system during combustion of evaluated fuel mixtures. As it follows from the above comparison, values of generated energy differed insignificantly between each other. The difference between

extreme values (mixtures with 50-percent and 1-percent share of telecommunications poles) was 15%. It stems from presented data that calorific value of evaluated fuel decreased as the share of wood impregnated with creosote oil in fuel mixture dropped.

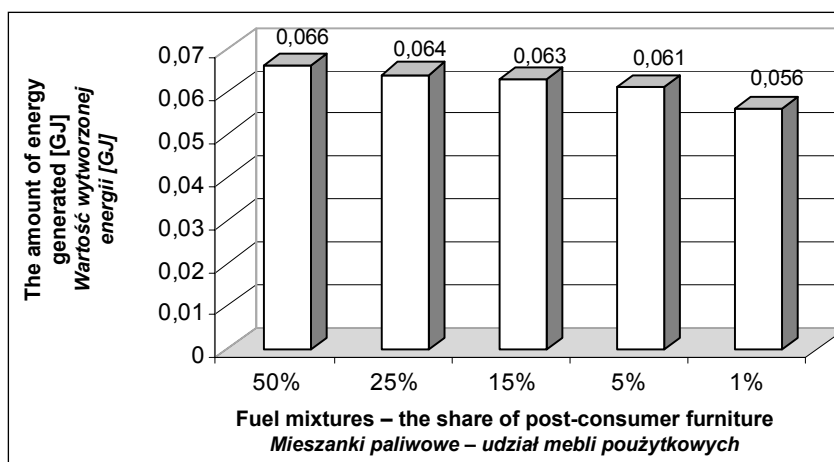


Fig. 17. The value of thermal energy generated in the boiler installation during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 17. Wartość wytworzonej energii cieplnej na instalacji kotłowej w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

Fig. 18 compares results of measurements of carbon oxide emission during combustion of fuels mixture formed from crumbled telecommunications poles and post-consumer doors in conversion into 11-percent content of oxygen in exhaust. Compared data shows that in the case of all analysed samples CO content in exhaust was fluctuating between approximately 1000 and 9000 mg/m³. The highest values of carbon oxide emission during combustion of evaluated fuels were recorded at the beginning and at the end of the test cycle, which was connected with starting and ending of the test cycle. In the body of the test cycle the highest content of carbon oxide in exhaust (3÷4 g/m³) was observed during combustion of mixtures with 50-percent share of telecommunications poles. 25-percent share of impregnated wood in burnt fuel caused reduction of that parameter to the level of approximately 1.7 g/m³. Carbon oxide emission during combustion of the other fuel mixtures was at a similar level and it was around 1.2 g/m³. Analysis of presented results proved that in analysed conditions of combustion process carbon oxide content in combustion gases rose as the share of wood containing creosote oil in burnt fuel increased.

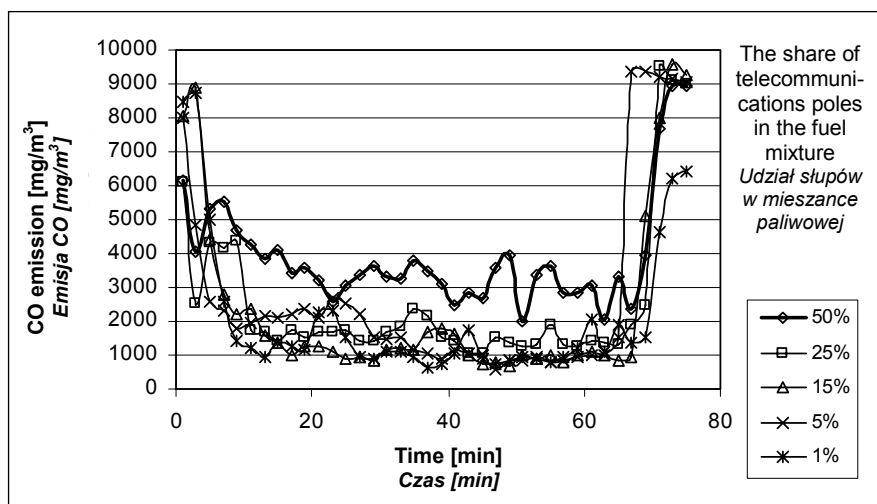


Fig. 18. Carbon oxide emission converted into 11% O_2 during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 18. Emisja tlenku węgla w przeliczeniu na 11% O_2 w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzwi użytkowe

A different situation was observed during analysis of carbon dioxide content in gaseous products of combustion of fuel mixtures containing wood from telecommunications poles and post-consumer doors. This situation is depicted in fig. 19. In this case the highest values of CO_2 (6.5÷10.5%) were observed during combustion of mixtures with the lowest share of impregnated wood (1÷15%). During combustion of the other mixtures (25 and 50% share of pole wood) carbon dioxide emission was at the level of around 6.5÷8.5%. Contrarily to the case of carbon oxide, the beginning and end of the measurement cycle was characterised by the lowest emissions of CO_2 , i.e. from 0.5 to 8.5%. As it follows from former experiments, a well conducted process of combustion of wood materials generates CO_2 emissions at the level from 8% to 12%, thus evaluated fuel mixtures were not completely burnt. It seems that an important reason for such state of affairs was significant content of impregnation oil in burnt fuel, which oil was a mixture of mainly aromatic compounds.

Fig. 20 shows changes in the emission of nitrogen oxides presented as nitrogen dioxide after conversion into 11-percent content of oxygen in exhaust during combustion of tested fuel mixtures consisting of telecommunications poles and post-consumer doors. Presented data shows that the amount of NO_x emission was ranging from around 180 to 400 mg/m^3 . The highest content of nitrogen oxides (average values around 350 mg/m^3) was observed during combustion of fuel mixtures with 50-percent share of crumbled poles. A bit less amounts of

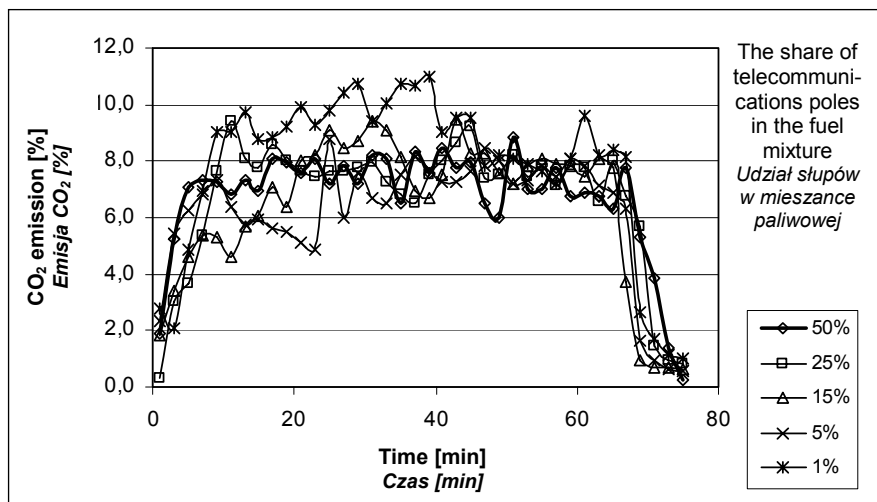


Fig. 19. Carbon dioxide emission during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 19. Emisja dwutlenku węgla w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzewi użytkowe

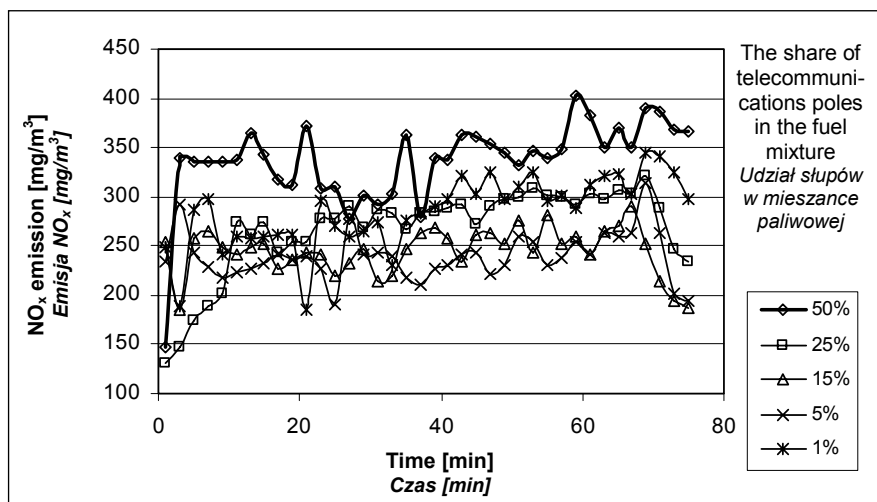


Fig. 20. Emission of nitrogen oxides converted into NO₂ with reference to 11% O₂ during combustion of fuel mixtures made from telecommunications poles and post-consumer doors

Rys. 20. Emisja tlenków azotu w przeliczeniu na NO₂ w odniesieniu do 11% O₂ w trakcie spalania mieszanek paliwowych słupy teletechniczne – drzewi użytkowe

those substances (around 270 mg/m^3 on average) were found in gaseous products of combustion of mixtures containing 25% of telecommunications poles. During combustion of the other mixtures NO_x content ranged from 190 to 330 mg/m^3 . Because evaluated fuel mixtures did not much differ between one another in nitrogen content (table 5), one should think that the source of elevated emissions of those substances was nitrogen contained in atmospheric air delivered to the hearth. As a matter of fact, temperatures recorded in the hearth³ did not exceed 900°C , however, one cannot exclude the possibility that, taking into account relatively high calorific value of evaluated samples ($17.186\div 18.123 \text{ MJ/kg}$) and relatively large capacity of the hearth, in some points of the hearth there could have been temperatures exceeding 1250°C (beyond measurement points), in which thermal nitrogen oxides may be created very dynamically (Marutzky, Seeger 1999). A proof confirming this hypothesis may be the high temperature of exhaust recorded in the flue, i.e. $280\div 400^\circ\text{C}$ (fig. 12), during measurements of combustion of analysed fuel mixtures.

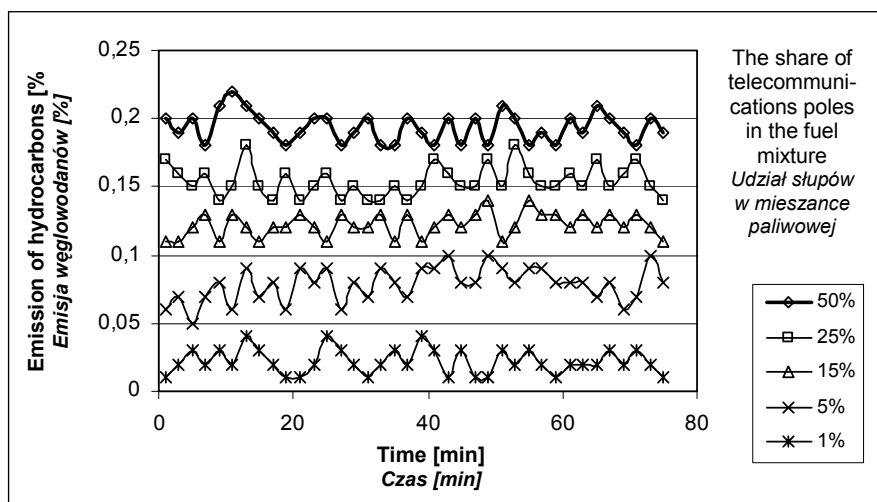


Fig. 21. Emission of hydrocarbons with reference to 11% O_2 during combustion of fuel mixtures made from telecommunications poles and post-consumer doors
Rys. 21. Emisja węglowodorów w odniesieniu do 11% O_2 w trakcie spalania mieszanek paliwowych słupów teletechniczne – drzwi użytkowe

³ Temperatures were recorded in fixed measurement points located in the hearth.

Next picture (fig. 21) presents changes in the emission of light hydrocarbons during combustion of fuel mixtures consisting of telecommunications poles and post-consumer doors. As it follows from data presented in this chart, the amount of C_xH_y emission oscillated around values depending on the share of crumbled pole wood in burnt fuel mixture. During combustion of fuel with 50-percent share of poles the emission of hydrocarbons oscillated around 0.18%. An average value of emission connected with combustion of fuel containing 25% of wood impregnated with creosote was approximately 0.15%. In the case of 15-percent share of crumbled poles in fuel, C_xH_y emission was at the level of 0.12%. 5-percent content of impregnated wood in fuel resulted in the emission of hydrocarbons during combustion of fuel at the level of approximately 0.08%, whilst during combustion of mixture with 1-percent share of telecommunications poles the level of C_xH_y emission was 0.02%. From the above description it stems that combustion of wood containing an additional portion of hydrocarbons in the form of impregnation oil is not complete. Some amounts of not burnt organic compounds together with exhaust are emitted to the atmosphere. Amount of those emissions depends on creosote (impregnation) oil content in burnt fuel mixture and on combustion manner.

Summary

Comparing properties of fuel mixtures obtained by mixing sawmill sawdust with crumbled post-consumer furniture, and crumbled post-consumer doors with telecommunications poles, and also courses of their combustion process, a series of differences and similarities between them was observed. All analysed fuel wood materials were characterised by similar elementary composition as regards the content of carbon, hydrogen, nitrogen, and sulphur, which resulted from over 90% share of natural wood in their overall mass. Significant differences were observed only in nitrogen content in mixtures of post-consumer furniture with sawmill sawdust. In this case the share of post-consumer furniture in the mixture was directly reflected in nitrogen content in evaluated fuel. On comparing fuel properties of prepared recovered fuels from waste, significant differences were noted only for their calorific values. An addition of post-consumer furniture to fuel caused a decrease in calorific value, whilst an addition of telecommunications poles resulted in insignificant increase in calorific value of prepared mixtures. Such situation stemmed from the character of ballast substances contained in the initial fuel components. Impregnation oil (creosote oil) is a mixture of substances of aromatic character, which in the nature of things are characterised by higher heat of combustion, whilst amine glue resins, which are the adhesive of wood particles in wood-based materials, are characterised by lower heat of combustion. As a result, one of the ballast substances (creosote)

raised calorific value of evaluated fuel, whilst the other (amine resins) reduced it.

Differences were noted also when the conditions of combustion process were evaluated. Insignificant discrepancies were observed during combustion of mixtures with the share of wood from poles and post-consumer doors, and post-consumer furniture and sawdust. The first criterion of evaluation was comparison of air surplus coefficient λ for both types of burnt mixtures. For fuels formed with the share of pole wood this coefficient ranged from 2 to 3, whilst during combustion of mixtures containing post-consumer furniture the values of λ were higher and fluctuated between 2.5 and 4.5. Described phenomenon should not be accounted for by higher stoichiometric demand for oxygen, but only by the need for better mixing of fuel with oxidiser and transport of products of partial decomposition and combustion of fuels containing amine resins. This hypothesis may be confirmed by lower content of the so-called "volatile components" in post-consumer furniture waste compared to wood from telecommunications poles.

Relatively high temperatures of exhaust and temperatures recorded in the hearth during combustion of mixtures with the share of telecommunications poles may be explained by their higher calorific values in comparison with fuels containing post-consumer furniture. Those phenomena resulted also in higher energy parameters from combustion tests, i.e. higher energy generated from the same mass of fuels and higher momentary power recorded. The process of combustion of fuels mixtures containing pole wood was more equable compared to post-consumer furniture and, as a result, there was a marked decrease in generated energy as the share of creosote oil in burnt fuel decreased.

Better energy effects obtained during experiments consisting in combustion of mixtures containing telecommunications poles were also reflected in the level of recorded emissions of gaseous products of combustion compared to fuels formed with the share of post-consumer furniture. The level of carbon oxide emission was much lower for fuels containing creosote oil. The situation was similar in the case of evaluation of the content of nitrogen oxides in exhaust. However, in that case the reason for many times higher emission of NO_x was a considerable share of nitrogen in post-consumer furniture waste. This factor was the reason why in the case of mixtures containing 50% of post-consumer furniture recorded emissions were at over three-time higher level than in the case of fuels containing 1% of that waste. A more correct course of the process of combustion of fuels containing pole wood was confirmed by higher content of carbon dioxide in combustion gases. A factor, that may have a considerable influence on evaluation of tested fuels, is the emission of hydrocarbon products of combustion. Substances that were recorded during experiments are a mixture of compounds of which part is classified as hazardous substances. During comparison of products of combustion of fuels with the share of post-consumer

furniture and poles, it was observed that when the former was burnt the emission of hydrocarbons did not exceed determinability level of the applied analytical method, whilst combustion of mixtures containing pole wood was accompanied by higher emissions of C_xH_y that rose as the share of creosote oil in burnt fuels increased. The level of those emissions was quite equal for every type of fuel mixture.

In Poland, effective legal regulations concerning installations intended for combustion of waste order keeping applicable emission standards during processes of thermal conversion of waste with or without recovery of generated energy [Rozporządzenie... 2005]. From among substances named in the Regulation conducted tests took into account carbon oxide, whose permissible content in combustion gases is 100 mg/m^3 , and nitrogen oxides expressed as nitrogen dioxide, whose permissible emission level is 400 mg/m^3 . In accordance with provisions of the Regulation, all analysed substances were converted to 11-percent content of oxygen in exhaust.

Having compared the amount of emission of gaseous products of combustion of fuel mixtures formed with the share of wood from telecommunications poles and post-consumer furniture, it was noted that in the case of carbon oxide the content of analysed gas many-times exceeded the level permitted by the emission standards required for waste combustion installations. During combustion of mixtures of wood from poles and post-consumer doors it was observed that standards were exceeded by 10÷40-times, whilst reduction of impregnated wood share in the mixture resulted in a decrease in carbon oxide content in exhaust. On the other hand, combustion of fuels with the share of post-consumer furniture was accompanied by emissions of CO that exceeded requirements set forth in the Regulation [2005] by 20÷80-times.

The content of nitrogen oxides in exhaust from combustion of evaluated fuels was a little different. During combustion of mixtures with the share of sawdust and post-consumer furniture the emission of NO_x depended on the amount of furniture waste added to formed fuel. A 1÷15-percent content of post-consumer furniture in the mixture had no influence on exceeding the emission standards concerning waste combustion. However, at a 25-percent share of furniture waste in fuel, those standards were exceeded by 1.5-times, and a 50-percent content of furniture waste in fuel resulted in NO_x emissions 2.5 higher than the effective standards. A reason for such state of affairs should be ascribed to processes of oxidisation of nitrogen contained in fuel. Such situation is not encountered in fuel mixtures containing wood from post-consumer doors and telecommunications poles. In this case permissible standards of the emission of nitrogen oxides were not exceeded. However, an increase in the share of creosote oil in burnt fuel caused also an increase in NO_x emission. In that case, however, a reason for creation of higher amounts of nitrogen oxides

presumably was the elevated temperature inside the hearth causing oxidation of nitrogen contained in atmospheric air [Cichy 2004].

The amount of the emission of hydrocarbons was not determined in the emission standards concerning waste conversion installations (Rozporządzenie... 2005); however, the content of hydrocarbons in combustion gases may be determined by correctness of thermo-oxidation processes inside the hearth. When fuels formed with the share of post-consumer furniture were burnt no content of hydrocarbons in exhaust was observed. One should bear in mind, that in this case the determinability level was 100 mg/m^3 . One of the reasons for such state of affairs might have been phenomena of oxidation and reduction which, with much probability, occur inside the hearth between C_xH_y and nitrogen oxides in conditions of oxygen deficiency. On the other hand, during combustion of formed fuels containing pole wood it was observed that the share of hydrocarbons in exhaust increased as creosote content in the fuel rose. However, in this case observed cyclic leaps of C_xH_y concentrations stemmed from the nature of the ballast substance, i.e. creosote oil that is a mixture of hydrocarbons that are products of dry distillation of hard coal. As it follows from presented data, those hydrocarbons in working conditions of the hearth do not undergo full decomposition and oxidation, and in a result they become part of combustion gases emitted to the atmosphere.

Conclusions

Described experiments and follow-on deliberation allow formulation of the following statements and conclusions:

1. During combustion of fuel mixtures produced from post-consumer furniture and sawmill sawdust and from post-consumer doors and wood from telecommunications poles a considerable amount of usable thermal energy is generated. An increase in the share of post-consumer furniture in the mixture has no significant influence on the amount of energy generated (on average 0.050 GJ from mass unit of fuel), whilst an increase in the share of wood from telecommunications poles improves energy effect of combustion process (a growth from 0.056 to 0.066 GJ from mass unit of fuel).
2. Nitrogen, in the form of amine resins, contained in recovered fuels produced from post-consumer furniture directly influenced the amount of the emission of nitrogen oxides during combustion of those fuels in power installations of low power.
3. Combustion at the test station of recovered fuels obtained by mixing post-consumer furniture with sawmill sawdust caused the following effects:
 - 1-percent share of furniture waste in obtained fuel did not cause any repercussions in the form of elevated emissions of nitrogen oxides from the installation (below 200 mg of NO_2/m^3),

- when the content of post-consumer furniture in fuel ranged from 5 to 15% elevated emissions of nitrogen oxides to the atmosphere (around 300 and 350 mg of NO_2/m^3) were observed; however, the emission did not exceed effective emission standards,
 - when the share of post-consumer furniture was at the level of 50% and 25%, emissions of NO_x considerably exceeded the emission standards (around 1100 and 600 mg of NO_2/m^3).
4. No emission of hydrocarbons above the determinability level of the applied analytical method was observed during combustion of recovered fuel mixtures produced from post-consumer furniture and sawmill sawdust, whilst carbon oxide emissions considerably exceeded the emission standards for burnt waste (2000÷8000 mg of CO/m^3).
 5. During combustion, the content of creosote oil in fuel mixtures obtained from crumbled wood from post-consumer doors and telecommunications poles caused emissions of carbon oxide exceeding the emission standards, i.e. 800÷4000 mg of CO/m^3 . The highest emissions of CO were observed in the case of mixtures containing 50-percent share of telecommunications poles.
 6. An average content of light hydrocarbons in combustion gases produced during combustion of recovered fuels produced from wood from telecommunications poles and post-consumer doors increased from around 0.03 to 0.20% as the content of poles in burnt fuel mixture rose. The highest values of the content of light hydrocarbons in combustion gases were observed when the share of pole wood in the mixture was 50 percent.
 7. Emissions of nitrogen oxides recorded for combustion of fuel mixtures produced from post-consumer doors and telecommunications poles did not exceed the emission standards permissible at waste combustion. No influence of mixture composition on the amount of NO_x emission was observed.

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SPALANIE STAŁYCH PALIW WTÓRNYCH WYTWORZONYCH Z POUŻYTKOWYCH ODPADÓW DRZEWNYCH NA INSTALACJI ENERGETYCZNEJ MAŁEJ MOCY

Streszczenie

Przy obróbce mechanicznej materiałów drzewnych powstają znaczne ilości materiałów odpadowych. Przepisy prawa polskiego i europejskiego nakazują utylizację wytworzonych odpadów zgodnie z odpowiednimi procedurami, co generuje dodatkowe koszty. Jednym z kierunków zagospodarowania drzewnych materiałów odpadowych jest odzyskiwanie zawartej w nich energii. Przystosowanie odpadów polegające na przygotowaniu paliw roboczych o odpowiednich właściwościach palnych nazywa się wytwarzaniem paliw, a otrzymane materiały stałymi paliwami wtórnymi. Wytworzone w taki sposób paliwa drzewne można zaliczyć do paliw z biomasy.

Celem pracy było poznanie wpływu zasadniczych właściwości wybranych materiałów drzewnych zanieczyszczonych chemicznie o ustalonych właściwościach technicznych na zmiany przebiegu podstawowych parametrów procesu ich spalania.

Do badań wybrano materiały palne z grupy odpadów poużytkowych. Z wytypowanych odpadów przygotowano mieszanki paliwowe o ściśle określonym składzie ilościowym: 1, 5, 15, 25 i 50% udziału odpadów zanieczyszczonych w ogólnej masie paliwa. Składnikami wytworzonych paliw wtórnych były trociny tartaczne i meble poużytkowe oraz drzwi poużytkowe i słupy teletechniczne. W otrzymanych mieszankach określono podstawowe właściwości paliwowe (wartość opałową, zawartość popiołu, wilgotność) i oznaczono zawartość pierwiastków elementarnych (C, H, N, S). Przygotowane paliwa spalano w laboratoryjnej instalacji kotłowej małej mocy. W trakcie prób rejestrowano parametry pracy kotła, parametry instalacji c.o. oraz wielkość emisji gazowych produktów spalania.

Stwierdzono, że oceniane paliwa cechowały zbliżone właściwości (słupy teletechniczne mają wyższą wartość opałową). Udział zanieczyszczeń w ogólnej masie spalanego paliwa nie wpływał w znaczący sposób na wartości parametrów cieplnych procesu spalania i laboratoryjnej instalacji energetycznej. Różnice stwierdzono przy ocenie wielkości emisji gazowych produktów spalania. W przypadku mieszanek: trociny tartaczne – meble poużytkowe wraz ze wzrostem udziału odpadów meblowych wzrastała emisja tlenków azotu. Nie odnotowano natomiast znaczących różnic w emisji pozostałych składników spalin. Podobną tendencję stwierdzono przy ocenie emisji węglowodorów w trakcie spalania mieszanki paliwowej: drzwi poużytkowe – słupy teletechniczne.

Pozytywne wyniki prac badawczych mogą dać nadzieję na wdrożenie tych produktów do praktyki przemysłowej i zastąpienie części stosowanych dziś w energetyce „czystych” paliw biomasowych stałymi paliwami wtórnymi wytworzonymi z odpadów drzewnych.

Słowa kluczowe: odpady drzewne, stałe paliwa wtórne, gospodarka odpadami, termiczne przekształcanie odpadów z odzyskiem energii, emisje gazowych produktów spalania

