

# GASEOUS EMISSIONS DURING AGRICULTURAL BIOMASS COMBUSTION IN A 50 kW MOVING STEP GRATE BOILER

Katarzyna Pałaszynska\*, Marek Juszcak

Poznan University of Technology, Institute of Environmental Engineering,  
Division of Heating, Air Conditioning and Air Protection, Berdychowo 4, 60-965 Poznań, Poland

Results of the study examining carbon monoxide and nitric oxide concentrations while burning different types of agricultural biomass: coffee husk pellets alone or in combination with wheat straw pellets and cherry stones, sewage sludge pellets, corn stover briquettes and a mixture of rye straw briquettes and miscanthus briquettes were presented. The combustion was performed in a 50 kW boiler type Biowarmer with a cast-iron moving step grate. The temperature in the combustion chamber did not exceed 800 °C. For all biomass types, only brittle slag was generated in the furnace, which was easily broken by a reciprocating movement of the grate. Carbon monoxide concentration in the flue gas except for the case of sewage sludge pellet firing did not exceed the permitted value of 3000 mg/m<sup>3</sup> and nitric oxide concentration 515 mg/m<sup>3</sup>, both presented for 10% O<sub>2</sub> concentration in the flue gas based in dry gas. Hydrocarbon concentrations for all test runs were close to zero.

**Keywords:** agricultural biomass, boiler, pollutant emission, combustion

## 1. INTRODUCTION

Combustion of agricultural biomass (e.g. cereal straw, corn stover, sunflower husks, coffee husks, etc.), as well as energy crops, such as miscanthus, is more challenging (Hardy et al., 2012; Verma et al. 2009; 2011; 2013) than firing solid fuels, such as wood (Juszcak, 2014; Juszcak, Lossy, 2012) or hard coal. This is due to the fact that ash coming from agricultural biomass sinters at low temperatures, often below 850 °C, resulting in slag formation (Cioaba et al., 2015; Gible et al., 2008; Yanqing et al., 2016). For example, ash sintering temperature of different biomass types is: wheat straw 840 °C, rape straw 640 °C, sunflower husk pellets 810 °C (Mroczek et al., 2011), rye straw 730 °C, oat straw 770 °C, mustard straw 630 °C, corn stover 650 °C, hemp straw 640 °C, sorghum stalks 760 °C (attempts are being made to grow this energy crop in Poland), tobacco stalks 570 °C (Cichy, 2013), respectively. For hard coal and wood on the other hand, ash sintering temperature is above 1100 °C (Hartmann et al., 2013). Slag formation in the furnace reduces air access to the fuel, thus decreasing the temperature and resulting in an increasing carbon monoxide concentration in flue gases. In order to fire agricultural biomass in grate furnaces with a relatively low carbon monoxide concentration in the flue gas, it is necessary to guarantee that the temperature in the furnace and the combustion chamber exceeds 650 °C (since only above that temperature carbon monoxide and some hydrocarbons are well oxidized) and at the same time below the ash sintering temperature (in case of retort and horizontal-fed furnaces) or the ash softening temperature (in case of moving step grate furnaces).

Some additives that increase ash sintering and softening temperatures, e.g. halloysite, zeolite or kaolinite, can slightly reduce the amount of slag in the furnace and the amount of deposits in the boiler (Kubica et al., 2016; Mroczek et al., 2011).

\* Corresponding author, e-mail: katarzyna.palaszynska@put.poznan.pl

<http://journals.pan.pl/dlibra/journal/98834>

Another solution to this problem is to use a combination of agricultural biomass and wood. This allows firing agricultural biomass in retort and horizontal-feed furnaces of wood pellet boilers while obtaining relatively low emissions (the higher the percentage of wood in the fuel mix the lower the concentration of carbon monoxide in the flue gas). It has to be noted, however, that in this case carbon monoxide emission is considerably higher than in the case of pure wood pellet combustion (Juszcak and Lossy, 2012). Similar conclusions were drawn (Garcia-Cuevas et al., 2011) while using a mixture of olive pomace and grape pomace with oak wood at a ratio of 0, 25, 50, 75, 100% of agricultural biomass, and observing an improvement in the combustion process parameters with the increase of wood in the fuel mixture. It was confirmed by other experiments (Mediavilla et al., 2009), where grape pomace pellets and mixed biomass pellets (pomace and waste cork) in different proportions were fired on a fixed grate of a 17.5 kW boiler. The carbon monoxide concentration achieved during the combustion of grape pomace alone was 9000 mg/m<sup>3</sup>, while with the proportion of 70% by weight of cork it was 1700 mg/m<sup>3</sup> (presented for 10% O<sub>2</sub> concentration in the flue gas), thus it was decreasing with the increasing cork proportion.

Moving step grate furnace is better suited for agricultural biomass combustion than the retort or horizontal-feed furnaces, because slag is eliminated by a reciprocating movement of the pushing-bars. Nonetheless, the temperature in the furnace should not exceed the so called “ash softening temperature” (which is higher than the ash sintering temperature), as this is when slag gets soft, sticks to the grate and cannot be effectively eliminated from the moving step grate furnace. Good applicability of the moving step grate furnace for agricultural biomass combustion was confirmed (Mediavilla et al., 2011) while firing oat straw, wheat straw and triticale straw in a 500 kW boiler. The respective carbon monoxide concentration values measured in the flue gas were as follows: 1390, 1700, 700 mg/m<sup>3</sup> presented for 10% O<sub>2</sub> concentration in the flue gas based in dry gas, which for agricultural biomass combustion is a good result. The emissions are linked to the nominal thermal heat output. Good applicability of moving step grates was also indicated by other researchers (Schonnenbeck et al., 2016), who fired pellets made of grape waste mixed with wood or miscanthus in different weight proportions (25, 33 and 50% of grape waste). Carbon monoxide concentration for firing grape waste alone was very high and exceeded 36 000 mg/m<sup>3</sup> (presented for 10% O<sub>2</sub> concentration in the flue gas). After adding wood to grape waste in the proportion of 1:1, this value decreased to approx. 13 500 mg/m<sup>3</sup> (presented for 10% O<sub>2</sub> concentration in the flue gas). The lowest concentration was observed for mixtures of grape waste with miscanthus (Miscanthus/Grape): M/G: 67/33 500 mg/m<sup>3</sup> and M/G 75/25 approx. 300 mg/m<sup>3</sup> (presented for 10% O<sub>2</sub> concentration in the flue gas). The values of the sintering and softening temperatures may differ considerably for the same type of agricultural biomass, depending on the ash chemical composition (EN 14961-1, 2010; Hartge et al., 2000; Wopienka et al., 2011), which is greatly variable and related to the plant species, cultivation method, soil type, etc. (Vassiliev et al., 2013a; 2013b). The tendency to generate slag was determined by studies and a respective formula was established (Pronobis, 2005). In this formula, the weight percentage in ash of the following components has been taken into account: Fe<sub>2</sub>O<sub>3</sub>, CaO, MgO, K<sub>2</sub>O, Na<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>. Just to give an example, for some agricultural biomass types the ash softening temperatures are as follows: rye straw 1002 °C, wheat straw 998 °C, barley straw 980 °C (Hartmann et al., 2012).

The aim of the study was to determine if the moving step grate is suitable for firing the analysed types of agricultural biomass.

## 2. MATERIALS AND METHODS

### 2.1. Experimental set-up

For experimental purposes, a 50 kW boiler type Biowarmer manufactured by CWD Cichewicz and equipped with a cast-iron moving step grate (Fig. 1) was used. This particular boiler was chosen considering its relatively big combustion chamber and a considerable water capacity of 190 l. The reciprocating movement of the furnace allows brittle slag destruction. The speed of the pushing-bars is adjustable. Briquettes

or pellets are supplied from the fuel container (Figs. 1, 2) by a screw conveyor (Fig. 2) to the intermediate boiler hopper, from which they are further transported by a second screw conveyor (fuel dispenser constituting part of the furnace) and are pushed onto the moving step grate (Fig. 2).

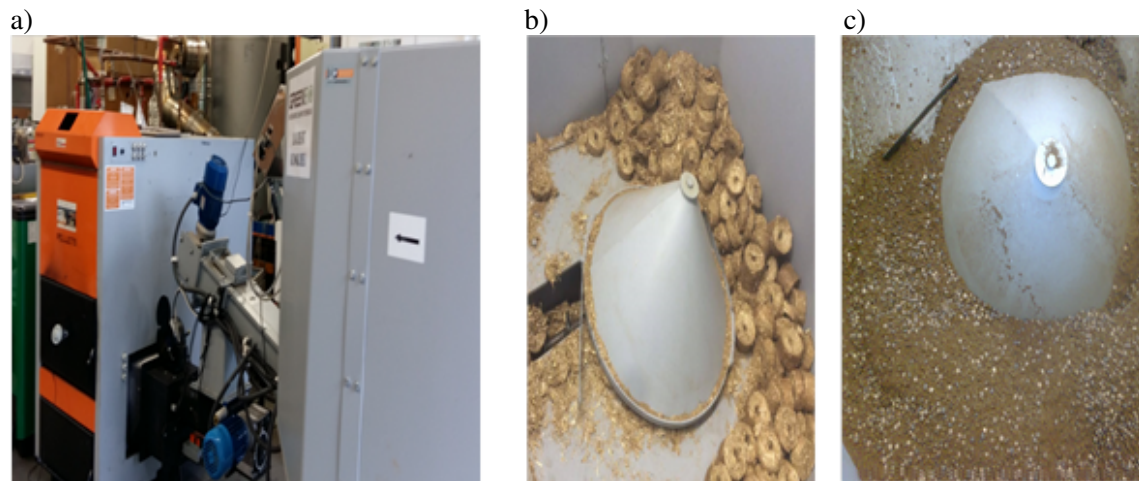


Fig. 1. 50 kW water boiler Biowarmer with a cast-iron moving step grate: a) boiler view, b) view of the fuel container with corn stover briquettes, c) view of the fuel container with coffee husk pellet and cherry stone mixture

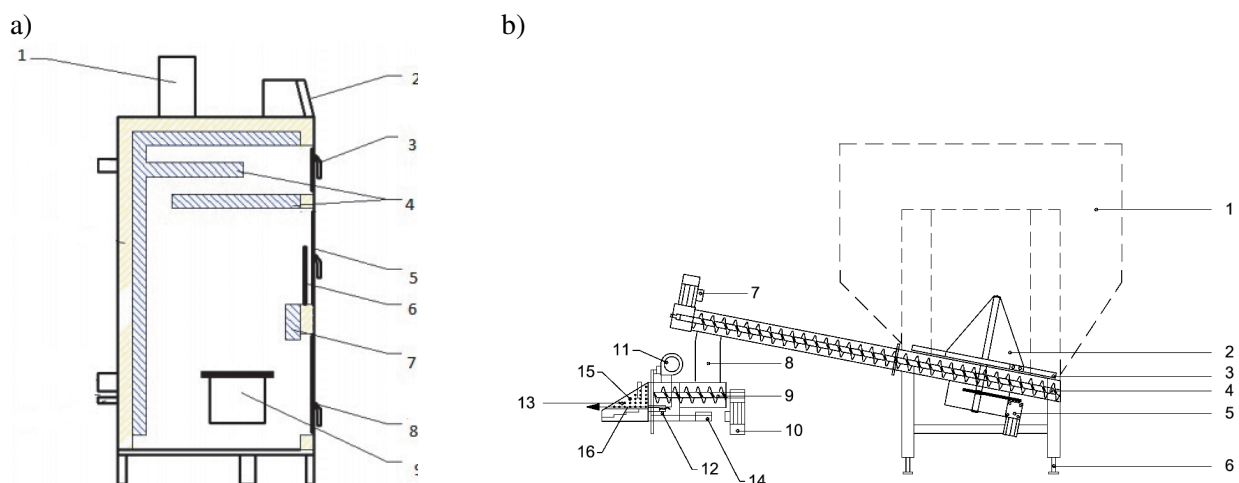


Fig. 2. a) Schematic layout of the boiler: 1. Boiler flue; 2. Boiler controller; 3. Cleaning door; 4. Water jacket / heat exchanger; 5. Loading door; 6. Internal grate door; 7. Water grate; 8. Ash pan door; 9. Torch; b) Schematic layout of the agricultural biomass container, the screw conveyors and the furnace: 1. Fuel container; 2. Fuel mixer; 3. Fuel mixer spades; 4. Screw conveyor; 5. Fuel mixer drive; 6. Regulated container support; 7. Screw conveyor drive; 8. Intermediate hopper; 9. Furnace fuel dispenser; 10. Furnace fuel dispenser drive; 11. Fan; 12. Fuel ignition; 13. Cast-iron moving step grate furnace; 14. Pushing bar drive; 15. Secondary air; 16. Primary air; (Cichewicz, 2015)

The speed of both conveyors is constant and fixed by the boiler manufacturer. Fuel supply to the furnace is not continuous but cyclical, i.e. within the cycle the operation/stand-by time is set so that the desired fuel stream value is obtained depending on the boiler heat output set by the user. Combustion air is supplied by a fan (Fig. 2). Fan capacity is set manually by the user for the desired boiler heat output in order to achieve the lowest possible value of carbon monoxide concentration in the flue gas. Combustion air stream rate is the same during the phase of fuel supply to the furnace and the stand-by period. This means that the combustion intensity is variable throughout the fuel supply/stand-by cycle and therefore also the temperature and oxygen concentration in the combustion chamber is subjected to cyclical fluctuations. The boiler is not equipped with a flue-gas extractor fan. Primary air flows along the longitudinal axis of the furnace and secondary air reaches the furnace through holes in its lateral walls (Fig. 2b).

The boiler is located in a full scale heat station connected to district heating network, heat transfer unit, heat receivers: radiators and water heat storages. The experimental set-up described above belongs to the Poznan University of Technology, Institute of Environmental Engineering.

## 2.2. Material

The study was performed using pellets made from: sewage sludge, coffee husks, wheat straw; briquettes made from: corn stover, rye straw, miscanthus; as well as cherry stones (Fig. 3). The cylindrical briquettes with a diameter of 80 mm and height mostly 100 mm were made in a briquetting press type Biomasser manufactured by Asket (Fig. 4).



Fig. 3. Biomass types used in the study: a) wheat straw pellets, b) cherry stones, c) coffee husk pellets, d) sewage sludge pellets

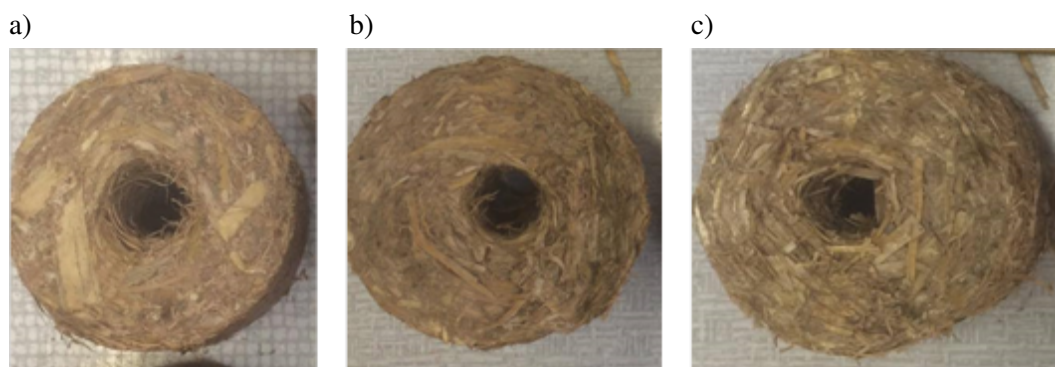


Fig. 4. Biomass in form of briquettes used in the study: a) corn stover, b) miscanthus, c) rye straw



The ultimate analysis of the biomass used for the study purposes was presented in Table 1. 10 measurements were performed for humidity and lower heating value.

Table 1. Biomass ultimate analysis

Biomass type / measured parameters	C	H	N	S	Ash	Relative humidity		Lower heating value*	
Unit	%	%	%	%	%	%		MJ/kg	
CORN STOVER	47.09	5.4	0.81	0.12	4.1	16	min = 14.4 max = 17.7 Δ = 1.5	15.8	min = 14.22 max = 18.2 Δ = 1.4
RYE STRAW	42.54	6.12	0.69	0.1	4.8	17	min = 14.96 max = 19.5 Δ = 1.96	15.1	min = 13.9 max = 17.2 Δ = 1.5
SEWAGE SLUDGE	50.1	7.2	5.9	2.12	6.2	9	min = 8.55 max = 9.8 Δ = 1.8	14.8	min = 13.5 max = 16.6 Δ = 1.8
MISCANTHUS	48.15	6.09	0.23	0	3.9	13	min = 11 max = 14.3 Δ = 1.6	16.1	min = 13.7 max = 17.7 Δ = 1.55
CHERRY STONES	51.58	6.45	1.4	nd**	3.5	5	min = 4.3 max = 5.5 Δ = 1.7	19.3	min = 16.4 max = 21.2 Δ = 1.7
COFFEE HUSKS	49.4	6.1	0.81	0.07	2.8	9	min = 8.1 max = 9.9 Δ = 1.8	17.2	min = 15.5 max = 18.7 Δ = 1.7
WHEAT STRAW	48.3	5.8	0.7	nd**	5.7	6	min = 5.4 max = 6.6 Δ = 1.7	18.5	min = 15.5 max = 20.3 Δ = 1.8

\* determined according to PN-81/G-04513, 1981; \*\* nd – not detected

### 2.3. Experimental procedure

The aim of study was to compare the values of carbon monoxide concentration in the flue gas during pellet and briquettes combustion (Table 2) for the maximum heat output and the heat output reduced by about

Table 2. Scope of study

PELLETS	1) sewage sludge
	2) coffee husks and wheat straw <i>in a weight ratio of 50 : 50 [%]</i>
	3) coffee husks and wheat straw <i>in a weight ratio of 60 : 40 [%]</i>
	4) coffee husks and cherry stones <i>in a weight ratio of 70 : 30 [%]</i>
	5) coffee husks and cherry stones <i>in a weight ratio of 80 : 20 [%]</i>
	6) coffee husks and cherry stones <i>in a weight ratio of 90 : 10 [%]</i>
	7) coffee husks 100 [%]
BRIQUETTES	8) corn stover
	9) rye straw and miscanthus straw <i>in a weight ratio of 50 : 50 [%]</i>

half. Different fuel mixtures in different weight ratios were used in order to establish the best possible conditions for different biomass types. Each test run lasted for approx. 10 hours. For a certain test run fuel supply was cyclical but air stream remained unchanged.

#### 2.4. Measuring equipment and methods

Concentrations of oxygen, carbon monoxide, nitric oxide, nitrogen dioxide and hydrocarbons (transformed to methane) in the flue gas downstream the boiler were measured using Vario Plus flue gas analyser (MRU brand). Oxygen, nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) concentrations were measured with electrochemical cells, while carbon monoxide and hydrocarbon concentrations using the infrared procedure. NO<sub>x</sub> concentration was calculated with the gas analyser by summing up the concentration of NO (transformed to NO<sub>2</sub>) and NO<sub>2</sub>. The flue gas analyser also measured the flue gas temperature downstream the boiler and calculated the air excess ratio. Heat received by the boiler water and boiler heat output were measured with Kamstrup ultrasonic heat meter. The temperature in the combustion chamber presented in Table 3 was measured approx. 0.2 m above the grate with a thermocouple PtRhPt that was radiation shielded in order to reduce the negative effect of radiation (the view of the combustion chamber was presented in Fig. 5). Occasionally, after withdrawing the thermocouple, temperature in the flame was measured by introducing a pyrometer through the same orifice. The boiler heat efficiency was calculated as heat transferred to the boiler water divided by fuel mass multiplied by fuel lower heating value. All the measured parameters were recorded continuously and transferred in real time to computer memory, where they were registered every 3 seconds for averaged value calculation. Fuel mass was determined with a Sartorius lab balance prior to each test run, before loading the fuel to the fuel container. Fuel moisture content was determined with the weighing method using a dryer, and the higher heating value, as well as lower heating value, by the bomb calorimetric method (PN-81/G-04513, 1981).



Fig. 5. Thermocouple's position in the boiler combustion chamber

### 3. RESULTS

The results obtained during the measurements performed in the heat station while firing different fuel types are presented in Table 3 below. The slag generated in the furnace and the deposits observed in the combustion chamber and on the heat exchanging surfaces were shown in Fig. 6 and 7, respectively.

Table 3. Comparison of mean parameter values obtained while firing biomass in a 50 kW boiler type Biowarmer with a cast-iron step moving grate

Mean values	O <sub>2</sub>	Air excess ratio	Temp. in the combustion chamber	Boiler heat output	Boiler heat efficiency	CO conc.	NO conc.	NO <sub>x</sub> conc.
	%	–	[°C]	kW	%	[mg/m <sup>3</sup> ] (10% O <sub>2</sub> )		
Sewage sludge	9.2	1.8	585	42	73	6938	512	785
50% coffee husks + 50% wheat straw mix.	8.7	1.7	783	48	71	1967	318	487
60% coffee husks + 40% wheat straw mix.	11.7	2.3	694	36	68	2579	365	560
70% coffee husks + 30% cherry stones mix.	10.1	1.9	744	45	70	2541	412	632
80% coffee husks + 20% cherry stones mix.	8.7	1.7	820	50	69	2001	395	605
90% coffee husks + 10% cherry stones mix.	8.7	1.7	787	49	71	1967	318	487
100% coffee husks	9.7	1.9	784	47	69	2760	484	742
Corn stover**	9.1	1.8	242	51	69	817	264	404
Corn stover*	11.2	2.1	235	24	67	1364	280	429
Corn stover and miscanthus**	8.4	1.7	267	53	66	586	224	343
Corn stover and miscanthus*	12.9	2.6	251	25	62	691	173	265

\* determined according to PN-81/G-04513, 1981; \*\* nd – not detected

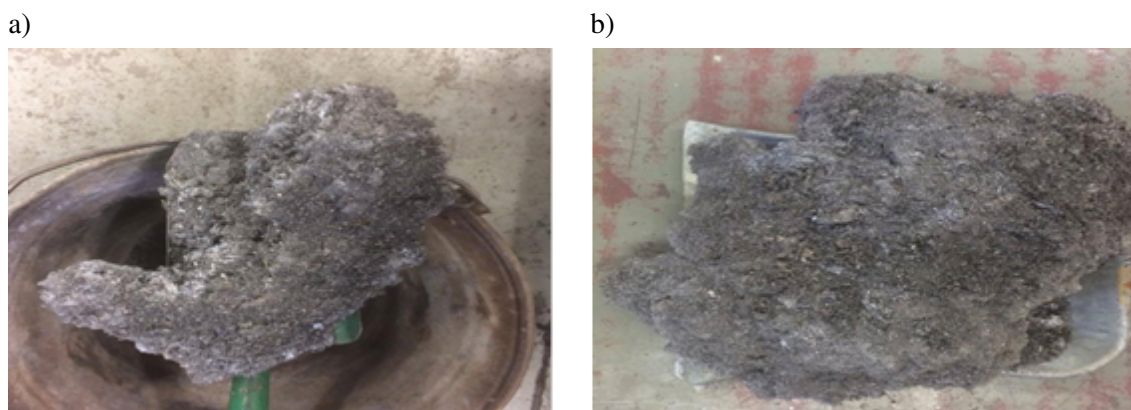


Fig. 6. Slag generated after firing: a) corn stover briquettes, b) rye and miscanthus briquettes mixture

The measurements of temperature made with the pyrometer and with the thermocouple showed that the temperature in the combustion chamber was approx. 50–100 °C lower than the temperature in the flame. Fig. 8 shows the correlation between the temperature in the combustion chamber and the oxygen concentration, whereas Fig. 9 the correlation between nitric oxide concentration and carbon monoxide concentration. Fig. 10 on the other hand compares the concentration of carbon monoxide and nitric oxide in correlation with the temperature and oxygen concentration in the combustion chamber for two different fuel types: coffee husk pellets and a mixture of coffee husk pellets and cherry stones (a proportion of 20% cherry stones by weight).

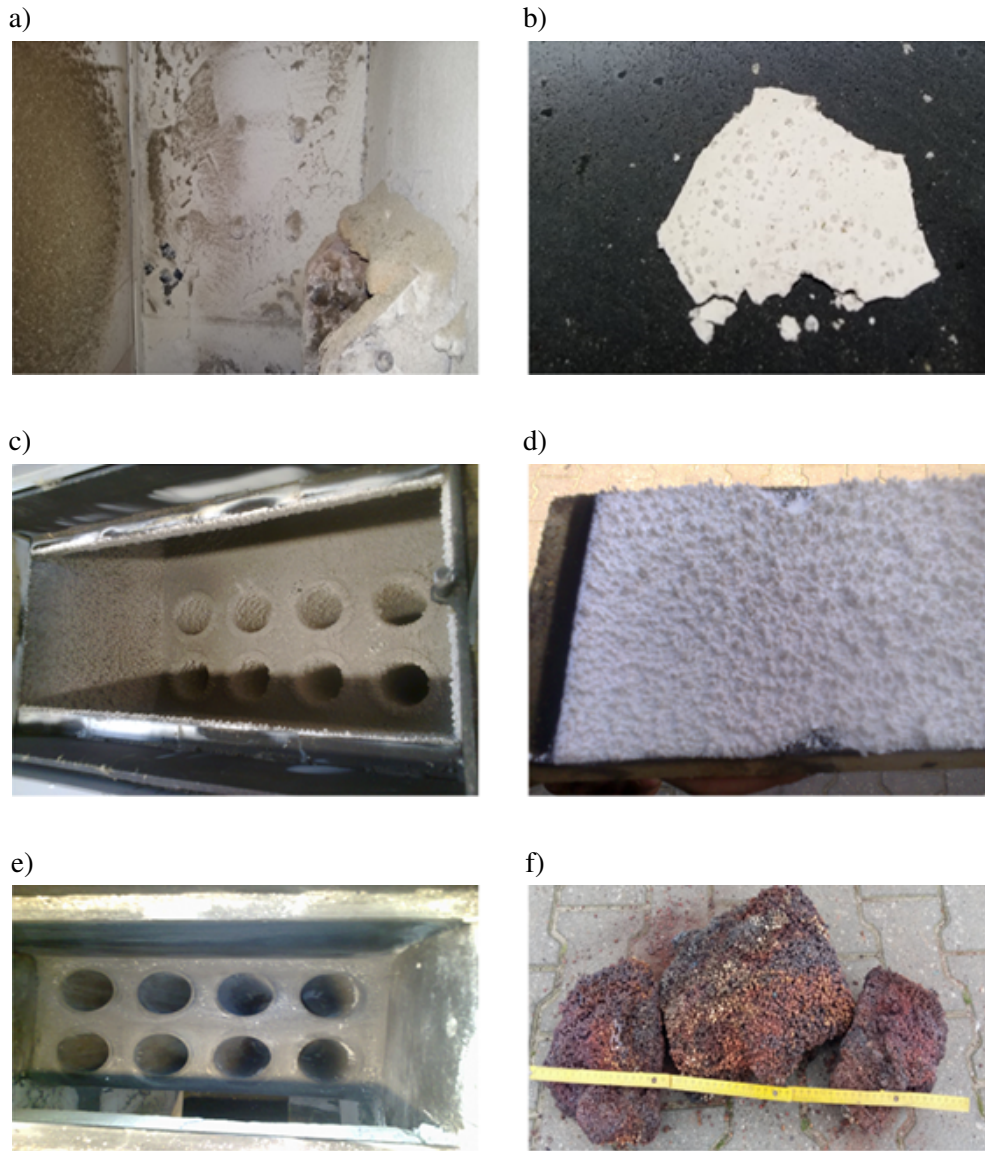


Fig. 7. Deposits after burning coffee husk pellets: a) in the combustion chamber, b) brittle deposit layer extracted from the combustion chamber; deposits after 40 hours of burning coffee husk pellets, also in combination with cherry stones: c) fire tubes, d) fire tube chamber cover, e) fire tubes after cleaning: no deposits, f) slag from sewage sludge pellets

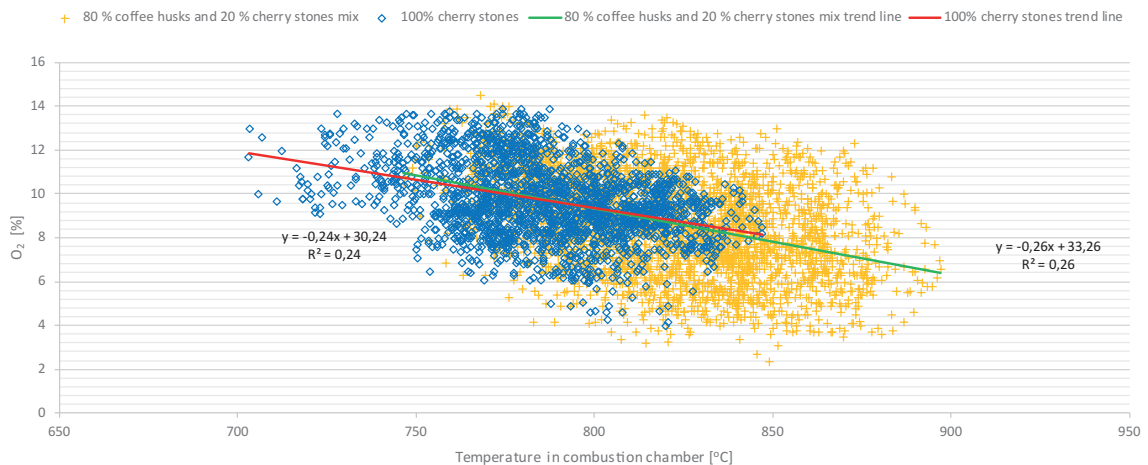


Fig. 8. Correlation between temperature in the combustion chamber and oxygen concentration in the flue gas



Gaseous emissions during agricultural biomass combustion in a 50 kW moving step grate boiler

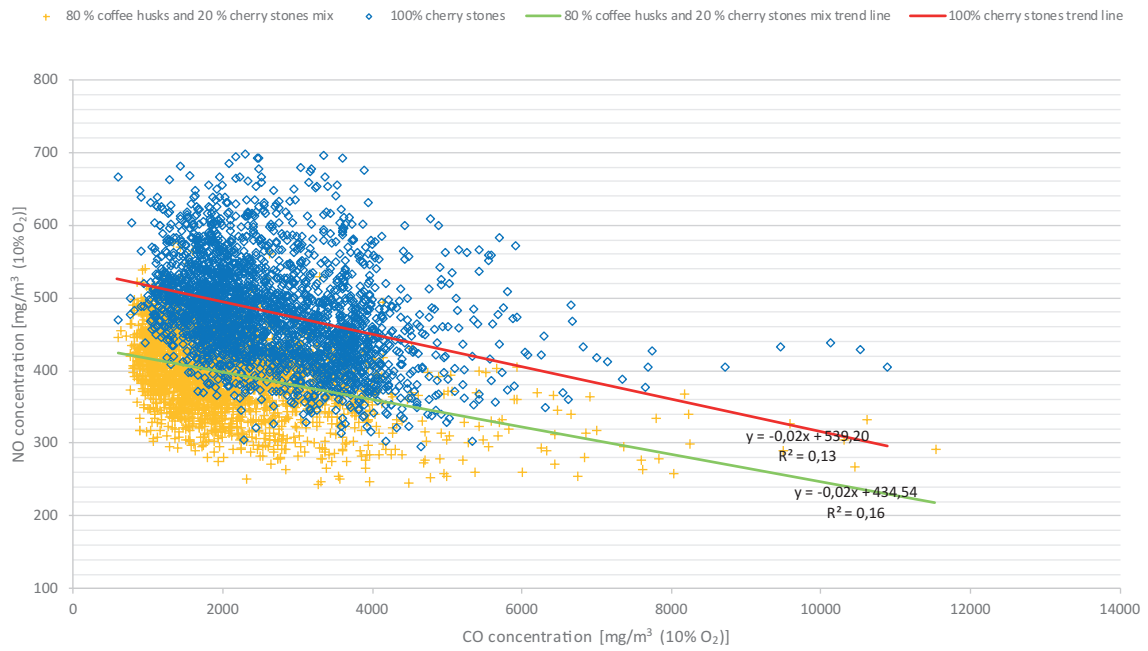


Fig. 9. Nitric oxide concentration versus carbon monoxide concentration

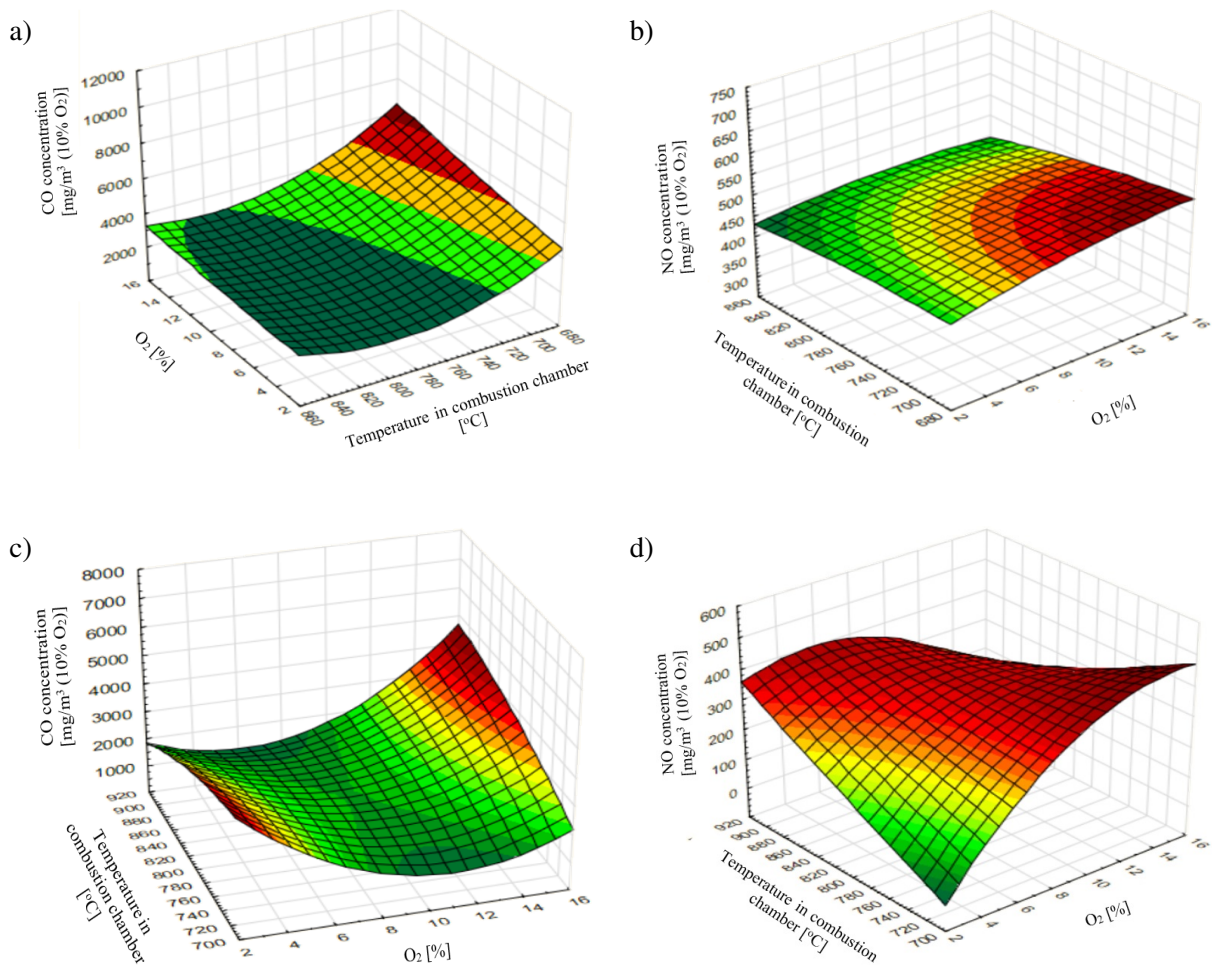


Fig. 10. Diagram showing the variation of pollutant concentrations: a) CO versus temperature in the combustion chamber and oxygen concentration (100% coffee husks), b) NO versus temperature in the combustion chamber and oxygen concentration (100% coffee husks), c) CO versus temperature in the combustion chamber and oxygen concentration (80% coffee husks 20% cherry stones), d) NO versus temperature in the combustion chamber and oxygen concentration (80% coffee husks 20% cherry stones)

#### 4. DISCUSSION

The furnace performance was proper during the firing of all fuel types. There was no need of manual periodical slag elimination from the furnace. For all types of fuel only brittle porous slag was generated (Fig. 6), which was easily disintegrated by a reciprocating movement of the grate pushing-bars and subsequently eliminated out of the furnace. This means that the temperature in the furnace was maintained above the ash sintering temperature and below the ash softening temperature. At the same time, a considerable amount of brittle deposits in the combustion chamber and on the heat exchanging surfaces was observed (Fig. 7), which generated a need of cleaning the boiler after 40 hours of its operation. The biggest amount of deposits appeared after burning coffee husk pellets.

For all the fuel types, except for sewage sludge pellets, the values of carbon monoxide concentration (Table 3) did not exceed the permitted value of 3000 mg/m<sup>3</sup> (PN-EN 303-5, 2012) and the nitric oxide concentration did not exceed 520 mg/m<sup>3</sup> both presented for 10% O<sub>2</sub> concentration in the flue gas based in dry gas. Only rarely slight punctual incidental hydrocarbon concentrations were detected during the study. The mean values of hydrocarbon concentrations for all test runs are negligible (close to zero) (Table 3).

With a constant combustion air stream and variable fuel stream (cyclical fuel supply) for each test run, the intensity of the combustion process was changing in time. Even during fuel supply periods (for each particular test run), the fuel stream was variable in spite of fixed revolutions of the screw conveyors, because briquettes and pellets form a non-homogeneous mass, making the conveyors grab a slightly different fuel dose with each movement. This also affected the intensity of the combustion process and, as a result, the temperature in the combustion chamber and oxygen concentration was changing. At times when the firing got more intense, the temperature in the furnace and the combustion chamber rose and oxygen concentration slightly decreased (Fig. 8).

In some cases (Fig. 10) that carbon monoxide concentration initially decreases with an increase in oxygen concentration, achieving its minimum at a certain point, then further increases. The lowest the oxygen concentration at which the minimum carbon monoxide concentration value is obtained the better the furnace adapted for burning certain fuel type. For solid fuels, in furnaces well adapted to a certain type of fuel, the minimum carbon monoxide concentration is obtained at the oxygen concentration of approx. 6% (air excess ratio 1.4), in furnaces moderately adapted it is 9–10% (air excess ratio approx. 1.9). The oxygen concentration value at which carbon monoxide concentration is the lowest can be determined experimentally and subsequently combustion air stream can be adjusted.

As far as nitric oxide emissions are concerned, with a relatively constant combustion air stream (for a certain test run) and periodical fuel supply to the furnace, the value of nitric oxide concentration is affected by two opposite factors. The growing temperature in the combustion chamber causes an increase in nitric oxide concentration, whereas at the same time decreasing oxygen concentration results in a reduction in nitric oxide concentration. These correlations considerably influence the shape of nitric oxide surface showed in Fig. 10.

A non-homogeneous fuel stream also brings about the fluctuations in carbon and nitrogen element streams delivered with the fuel to the furnace. This might justify differences in shape of carbon monoxide and nitric oxide surfaces (Fig. 10) and also poor correlation between the analysed values of NO versus CO in Fig. 9. The slightly different shape of the surface in Fig. 10 than expected might result from the fact that carbon monoxide reacts with nitrogen oxide, reducing it to molecular nitrogen (NO<sub>2</sub>) and at the same time oxidising itself to carbon dioxide, according to the reaction:  $\text{CO} + \text{NO} \rightarrow 1/2 \text{N}_2 + \text{CO}_2$  (Marutzky R., 1997). Correlation between nitric oxide concentration and carbon monoxide concentration was also indicated in other studies (Dell'Antonia et al., 2011), while analysing burning barley in a 30 kW heating boiler. In the aforementioned study the same gas analyser as the one applied in this study, i.e. Vario Plus industrial gas analyser was used. The Biowarmer boiler can be used to fire the examined agricultural biomass. However, the combustion process needs to be directly monitored, preferably using a thermocouple located

in combustion chamber and a flue gas analyser for CO concentration control. When in 2020, as predicted, the permitted value for CO<sub>2</sub> concentration in the flue gas gets reduced to 500 mg/m<sup>3</sup> (10% O<sub>2</sub>) based on dry gas, this particular type of boiler will not be eligible any more for burning the agricultural biomass analysed in the study.

## 5. CONCLUSIONS

The Biowarmer boiler with cast-iron moving step grate can be used for burning the tested biomass once an electrostatic precipitator has been installed in it and with constant carbon monoxide concentration control. However, due to a considerable amount of deposits generated in the combustion chamber and on the boiler heat exchanging surfaces and the subsequent need of frequent boiler cleaning, the studied fuel and boiler can be recommended only to users who generate this kind of fuel (agricultural biomass) anyway and need to somehow utilise it.

*I would like to thank the technical workers and students of Poznan University of Technology for their help during the research. This work was carried out as a part of the research project 01/13/DSPB/0810, 01/13/DSPB/0831 sponsored by Poznan University of Technology. The article was translated into English by Małgorzata Juszczak.*

## REFERENCES

- Cichewicz kotły c.o., 2015. Dokumentacja techniczno-ruchowa Instrukcja montażu, obsługi i konserwacji. Available at: [www.cichewicz.pl/pliki-do-pobrania](http://www.cichewicz.pl/pliki-do-pobrania).
- Cichy W., 2013. *Materiały lignocelulozowe jako alternatywne źródło biopaliw stałych*. Wydawnictwo Instytutu Technologii Drewna, Poznań.
- Cioabla E.A., Pop N., Colinoiu D.G., Trif-Tordai G., 2015. An experimental approach to the chemical properties and ash melting behavior in agricultural biomass. *J. Therm. Anal. Calorim.*, 121, 421–427. DOI: 10.1007/s10973-015-4710-1.
- Dell'Antonia D., Gubiani R., Pergher G., 2011. Comparative research of no-food cereals combustion in small heating appliances. *19th European Biomass Conference and Exhibitions*. 6–10 June 2011, Berlin.
- García-Cuevas M.T., Suero S.R., Nogales Delgado S., Montero Puertas I., Arranz Baria J.I., Rojas Moreno C.V., 2011. Effectiveness of blending process as a method for modifying the thermal behaviour and emission of olive and grape pomace during combustion. *19th European Biomass conference and Exhibitions*, 6–10 June 2011, Berlin.
- Gible C., Ohman M., Lindstrom E., Bostrom D., Backman R., Samuelsson R., Burvall J., 2008. Slagging characteristics during residential combustion of biomass pellets. *Energy Fuels*, 22, 3536–3543. DOI: 10.1021/ef8000087x.
- Hardy T., Musialik-Piotrowska A., Ciołek J., Mościcki K., Kordylewski W., 2012. Negative effects of biomass combustion and co-combustion in boilers. *Env. Prot. Eng.*, 1, 25–33.
- Hartge E.U., Ogada T., Saenger M., Siagi Z., Werther J., 2000. Combustion of agricultural residues. *Prog. Energy Combust. Sci.*, 26, 1–27. DOI: 10.1016/S0360-1285(99)00005-2.
- Hartmann H., Reisinger K., Turowski P., Rossmann P., 2013. *Handbuch Bioenergie-Kleinanlagen, Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz*. Fachagentur Nachwachsende Rohstoffe e.v. (FNR), Gülzow-Prutzen.
- Juszczak M., Lossy K., 2012. Pollutant emission from a heat station supplied with agriculture biomass and wood pellet mixture. *Chem. Process Eng.*, 33, 231–242. DOI: 10.2478/v10176-012-00203.
- Juszczak M., 2014. Concentration of carbon monoxide and nitrogen oxides from a 25 kW boiler supplied periodically. *Chem. Process Eng.*, 35, 163–172. DOI: 10.2478/cpe-2014-0012.

- Kubica K., Jewiarz M., Kubica R., Szłęk A., 2016. Straw combustion: Pilot and laboratory studies on straw fired grate boiler. *Energy Fuels*, 30, 4405–4410. DOI: 10.1021/acs.energyfuels.5b02693.
- Marutzky R., *Moderne Feuerungstechnik zur energetischen Verwertung von Holz und Holzabfällen*, Springer-VDI-Verlag GmbH&Co.K.G, Dusseldorf, 1997.
- Mediavilla I., Fernandez M.J., Esteban L.S., 2009. Optimization of pelletisation and combustion in a boiler of 17.5 kWth for vine shoots and industrial cork residue. *Fuel Process. Technol.*, 90, 621–628. DOI: 10.1016/j.fuproc.2008.12.009.
- Mediavilla I., Borjabad E., Ramos R., Fernandez M.J., Carrasco J.E., 2011. Combustion behaviour of oat and triticale straws in comparison with wheat straw. *19th European Biomass Conference and Exhibition*, 6–10 June 2011, Berlin.
- Mroczek K., Kalisz S., Pronobis M., Sołtys J., 2011. The effect of halloysite additive on operation of boilers firing agricultural biomass. *Fuel Process. Technol.*, 92, 845–855. DOI: 10.1016/j.fuproc.2010.11.020.
- Pronobis M., 2005. Evaluation of the influence of biomass co-combustion on boiler furnace slagging by means of fusibility correlations. *Biomass Bioenergy*, 28, 375–383. DOI: 10.1016/j.biombioe.2004.11.003.
- Schonnenbeck C., Trouve G., Valente M., Garra P., Brilhac J.F., 2016. Combustion tests of grape marc in a multi-fuel domestic boiler. *Fuel*, 180, 324–331. DOI: 10.1016/j.fuel.2016.04.034.
- Vassiliev S.V., Baxter D., Andersen L.K., Vassileva C.G., 2013a. An overview of the composition and application of biomass ash. Part 1. Phase-mineral and chemical composition and classification. *Fuel*, 105, 40–76. DOI: 10.1016/j.fuel.2012.09.041.
- Vassiliev S.V., Baxter D., Andersen L.K., Vassileva C.G., 2013b. An overview of the composition and application of biomass ash. Part 2. Potential utilisation, technological and ecological advantages and challenges. *Fuel*, 105, 19–39. DOI: 10.1016/j.fuel.2012.10.001.
- Verma V.K., Brams S., Ruyck I., 2009. Small biomass heating systems: Standards, quality, labeling and market driving factors—An EU outlook. *Biomass Bioenergy*, 33, 1393–1402. DOI: 10.1016/j.biombioe.2009.06.002.
- Verma V.K., Bram S., Delattin F., De Ruyck J., 2013. Real life performance of domestic pellet boiler technologies as a function of operational loads: A case study of Belgium. *Appl. Energy*, 101, 357–362. DOI: 10.1016/j.apenergy.2012.02.017.
- Verma V.K., Bram S., Gautier G., 2011. Performance of domestic pellet boiler as a function of operational loads: Part-2. *Biomass Bioenergy*, 35, 272–279. DOI: 10.1016/j.biombioe.2010.08.043.
- Verma V.K., Bram S., Delattin F., Laha P., Vandendael I., Hubin A., De Ruyck J., 2012. Agro-pellets for domestic heating Boilers: Standard laboratory and real life performance. *Appl. Energy*, 90, 17–23. DOI: 10.1016/j.apenergy.2010.12.079.
- Wopienka E., Carvalho L., Ohman M., Schwabl M., Haslinger W., 2011. Evaluation of ash melting behaviour of solid biomass based on fuel analyses. *19th European Biomass Conference and Exhibition*, 6–10 June 2011, Berlin.
- Yanqing N., Houzhang T., Shi'en H., 2016. Ash-related issues during biomass combustion: Alkali-induced slagging melt-induced slagging(ash fusion), agglomeration, corrosion, ash utilization, and related countermeasures. *Prog. Energy Combust. Sci.*, 52, 1–61. DOI: 10.1016/j.peccs.2015.09.003.
- EN 14961-1, 2010. Solid biofuels-Fuel specification and classes – Part 1: General requirements.
- PN-EN 14961-1, 2010. Biopaliwa stałe. Specyfikacja paliw i klasy. Część 1: Wymagania ogólne.
- PN-81/G-04513, 1981. Paliwa stałe. Oznaczanie ciepła spalania i obliczanie wartości opałowej.
- PN-EN 303-5:2012. Kotły grzewcze – Część 5: Kotły grzewcze na paliwa stałe z ręcznym i automatycznym zasypem paliwa o mocy nominalnej do 500 kW – Terminologia, wymagania, badania i oznakowanie.

Received 27 August 2017

Received in revised form 16 April 2018

Accepted 26 April 2018