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Heating and emission properties of waste biomass in burner furnace

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Abstract

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Utilization of waste suitable as a fuel for small combustion devices is a very important issue. Therefore, this article analyzes selected waste materials from agriculture and maintenance of municipal vegetation. The pellet samples from composting had very high ash content (22.39 and 36.85% wt.), which resulted in low values of net calorific value (12.66 and 10.24 MJ/kg), but also in bad properties of these samples in high concentration of harmful emission. Other problematic fuel samples were pellets from maintenance of city vegetation and reed canary grass, for which high concentration of carbon monoxide was measured during combustion process. The device used for these experiments is based on burner furnace. Combustion conditions could be improved by more uniform fuel supply to the burner and better control of combustion air. Boiler with advanced combustion control can reach better results during combustion process. Results in this article are valid for tested materials combusted in simple pellet burner with limited ability to control combustion process.

Keywords: pellets; wheat straw; compost; elemental analysis; stoichiometry; carbon monoxide

The issue of energy utilization of waste material is a subject of the International and European policy in the field of waste management. The article responds to constantly increasing requirements for the production and operation of devices for energetic utilization of waste. The use of these materials as a fuel in small combustion plants faces many technical and economic challenges. Stricter legislative requirements will focus more on the quality of used biofuels and operating conditions of combustion devices.

Other authors show good results during wood biomass combustion in small combustion devices (Johansson et al. 2003; Eskilsson et al. 2004). It is vital to know the properties of biofuels, which sufficiently characterize them. For larger combustion devices equipped with gas cleaning and combustion process control, fuel quality is not so critical. It is important to recognize two types of pellet fuel: for industrial and small residential combustion devices (Olsson et al. 2003; Obernbergera, Theka 2004).

The options for reducing emissions of incomplete combustion process include uniform fuel supply, sufficiently high temperature in the combustion chamber and sufficient intake of secondary or tertiary air or choice of optimal moisture of biofuel. The main fuel parameters (net calorific value, water content and energy density etc.) affect design of the combustion device and its control in many ways. For example, water content in biomass has an influence on adiabatic temperature of combus-

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tion chamber and on combustion conditions and the amount of produced flue gas (Johansson et al. 2003; Malaťák, Bradna 2014).

Due to the limitations identified during combustion process of selected energy crops and efforts to minimize the level of nitrogen oxides emissions, considerable demands are placed on the system design of combustion air intake, on the temperature control grid, but also on the amount of nitrogen in the fuel. Diaz-Ramirez et al. (2014) showed the behavior of three energy crops during combustion, mainly the influence of nitrogen in the fuel to nitrogen oxides emissions. Wei et al. (2012) determined dependence of carbon oxides emissions concentrations on the amount of combustion air.

Another important factor that influences formation of emissions is also the way of combustion process control (optimal amount of combustion air). Results of Žandeckis et al. (2013) show that even small changes in the way combustion air is injected into the combustion chamber can significantly influence the combustion process. Even in the small combustion devices designed mainly for wood biomass, reduction of combustion air is effective and it can lead to a significant reduction in nitrogen oxides, particularly with biomass fuels that contain relatively high proportion of nitrogen in dry mass (Liu et al. 2013).

The aim of the authors is to define mass flows, emission factors and solid particles characteristics depending on the combustion device used for agricultural raw materials and waste biomass from maintenance of city vegetation. The aim of the measurements is to make elemental and stoichiometric analysis of selected waste biomass samples and thus to compare obtained values with the requirements for pellets of the Czech Ministry of Environment. The next step is to determine emission concentrations of carbon monoxide, nitrogen oxides and flue gas temperatures depending on the amount of combustion air in burner combustion device. Authors of this article wanted to find most important features and aspects of chosen samples for energy use in the used small combustion device. This combustion device is based on the burner furnace with nominal power 18 kW and fuel consumption 4.9 kg/h. The resulting values are graphically shown as a function of the measured parameters against the excess air coefficient. Regression analysis was used for statistical evaluation of results. Eventually, the problematic aspects of thermal use of selected solid biomass samples are specified in the conclusion of this article.

MATERIAL AND METHODS

Biomass from agriculture and maintenance of city vegetation from the Central Bohemia Region of the Czech Republic was used for the research work. Such energetically exploitable biomass usually cannot be used in small combustion devices directly, but it must be modified into a suitable shape and size. For the case of our measurements biomass was processed in the form of pellets of diameter 6 mm. The fuel weight was measured at the beginning of each experiment, prior to putting into the hopper of the combustion device. The weight of each pellet sample was always 15 kg, the entire measurement time lasted for 3 hours. Due to different characteristics of each sample (moisture, specific weight etc.) the amount of pellets varied by 5%.

The composition of biomass samples:

(1) wheat straw,
(2) I. reed canary grass,
(3) II. reed canary grass,
(4) park shrubs from maintenance of city vegetation,
(5) oak and beech in ratio 1:1,
(6) oak, beech and acacia in ratio 1:1:1,
(7) compost from maintenance of city vegetation, and spruce sawdust in ratio 1:1,
(8) oversize chips from composting process.

Elemental analysis of samples is the primary objective of this research work. Elemental analyses of chosen samples were performed by the University of Chemistry and Technology Prague. Carbon, hydrogen and nitrogen were determined by a CHN analyser Perkin-Elmer 2400 (Elementar Analysensysteme GmbH, Hanau, Germany). For determination of chlorine and sulfur, the samples were burned in oxygen-hydrogen flame on the Wickbold apparatus (Koehler Instrument Company, New York, USA). Non-combustible fuel substances, i.e. ash and water content were determined by combustion and drying the sample, respectively. A certified moisture analyser Ohaus MB 25 (Ohaus Corp., USA) was used to determine the total water content. Measurements were carried out according to CSN EN 14 774-3:2010.

Gross calorific values of the examined biofuel samples were determined by burning in the calorimeter IKA C200 according to CSN EN 14 918:2010. Net calorific value was determined according to the

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following equation, in which the elemental analysis results of individual biofuel samples were used.

The relationship between gross calorific value Q_s and net calorific value Q_i was expressed by the following equation according to CSN EN 14 918:2010:

$$Q_i = (Q_s - 0.2443 \times 1,000) \times (W + 8.94 \times H) \quad \text{(kJ/kg, kJ/m}^3\text{)} \qquad (1)$$

where: W – water content in sample (% wt); 8.94 – coefficient for the conversion of hydrogen to water; H – hydrogen content in dry ash free sample (% wt); 0.02442 – value that corresponds to energy consumed in heating 1% of water at 25°C

Stoichiometric calculations define the amount of oxygen (air) required for complete fuel combustion, the quantity and composition of flue gas and the flue gas density. Calculation of air consumption and flue gas amount was performed in this work by analytical method, i.e. according to information from elemental analysis using stoichiometric equations. Elemental analysis and stoichiometric calculation of the individual samples are the basis for assessment of the combustibility of the samples. Stoichiometric calculations are converted to standard conditions (temperature 0°C and pressure 101.325 kPa) and for reference oxygen content in flue gas (O_r = 10%).

Experimental measurements were carried out on the stove KNP made by company KOVO Novák (Citonice, Czech Republic) with automatic fuel feeding and burner furnace, in accordance with CSN 07 0240:1993, CSN 12 4070:1990 and CSN 44 1310:2001. The thermo-technical specifications of this combustion device are: nominal power 18 kW, controllable output 8–18 kW, fuel consumption 1.5–4.9 kg/h, flue gas temperature at minimal power 110°C and 210°C at nominal power, efficiency at nominal power 88%.

The fuel samples were burned and the exact amount of the fuel fed into the combustion chamber was variable due to the different characteristics of each sample as mentioned above and it had to be adjusted according to the type of biofuel. This fact implies that the amount of excess air used for each biofuel is different, so it is not possible to maintain an optimal excess air coefficient during the whole measurement and for each type of selected fuels mixtures. Given this fact, the effectiveness of the selected combustion equipment was different during the measurement time (horizon of three hours) and could not be maintained throughout the measurement at all times in the nominal values. Some tests were performed with extremely high excess air coefficients and stove efficiency was varied during each test from 51 to 85 %.

Emission concentration measurement is done by multi-purpose flue gas analyser Madur GA-60 (Madur Polska Sp. z o.o., Zgierz, Poland). The values of ambient temperature, flue gas temperature and content of O_2, CO, SO_2, NO, NO_2 in flue gases are measured in ppm and converted to mg/m. Recording time of each measurement was set to one minute. The measuring device was calibrated before each measurement. Emission concentrations were converted to normal conditions and transferred to reference oxygen content in flue gas 10%.

Subsequently the results are processed by regression statistical analysis for mathematical expression of carbon monoxide, flue gas temperature and nitrogen oxides against the excess air coefficient. Excess air coefficient in the range of 2.5–7.25 times of the theoretical air amount for complete combustion is later substituted into the regression equations.

Although not performed in this work, heat efficiency could be calculated using he indirect method. This takes into account heat loss in unburned gases (chimney loss), loss of specific heat of flue gases, loss of unburned carbon that remains in ash and heat losses of the incinerator. Combustion devices of the type used in this study tend to have low content of unburned components in ash but high concentration of oxygen in flue gases. Suction of uncounted excess air was prevented in the used device during all measurements.

RESULTS AND DISCUSSION

The results of elemental analysis of samples in original state are shown in Table 1. From this table it is evident that there are significant differences in elemental composition across the samples.

The stoichiometric calculations of combustion (Table 2) supplement the sample characteristics and are the basis for any thermal calculation. These calculations determine the specific amount of oxygen (air) required for complete combustion of each sample, and the quantity and composition of flue gas, both on mass (kg/kg) and volumetric basis (m^3/kg).

The resulting values of stoichiometric calculations point to very good heating and emission parameters

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Table 1. Elemental analysis of selected pellet samples in their original state

Sample No.	Water content (% wt.)	Ashes (% wt.)	Volatile combustible matter (% wt.)	Non-volatile combustible matter (% wt.)	Net calorific value (MJ/kg)	Chlorine (% wt.)
1	6.88	6.78	70.40	17.42	15.97	0.00
2	6.92	6.90	68.42	15.72	15.24	0.00
3	5.03	7.04	68.42	15.72	15.27	0.03
4	6.30	3.32	69.19	19.24	16.30	0.18
5	8.45	0.39	79.29	14.93	17.65	0.03
6	5.85	0.41	79.29	14.93	17.68	0.03
7	6.37	22.39	–	–	12.66	0.03
8	6.72	36.85	–	–	10.24	0.03
Sample No.	Carbon (% wt.)	Hydrogen (% wt.)	Nitrogen (% wt.)	Sulphur (% wt.)	Oxygen (% wt.)	
1	42.65	4.50	0.00	0.62	38.48	
2	42.80	4.97	0.82	0.07	37.30	
3	43.69	5.07	0.83	0.07	38.09	
4	44.85	6.36	0.62	0.04	38.51	
5	46.20	4.86	0.00	0.02	40.05	
6	47.52	5.00	0.00	0.01	41.18	
7	35.41	3.47	1.09	0.00	31.24	
8	29.30	2.95	1.03	0.0	23.13	

of the examined samples (Table 2). From this table it is obvious that the range of combustion air amount among fuel samples is very broad. The stoichiometric calculations of the examined biofuel samples imply that calorific value, water content and energy density influence selection and design of combustion device.

The measurements are based on previous elemental analyses and stoichiometric calculations of selected solid biofuel samples. Eight combustion measurements were done on the stove KNP (KOVO Novák, Citonice, Czech Republic). The resulting graphs are based on regression equations compiled from single sample measurements. The resulting values for each type of sample are plotted in graphs against the excess air coefficient. The purpose of the statistical regression analysis is to express the degree of dependence of the measured carbon monoxide and nitrogen oxides concentrations and flue gas temperature on the excess air coefficient. The excess air coefficient was in the range of 2.5–7.25 at all times. Regression equations are given in Table 3. The confidence level of expressed equations was in the range from 0.6 to 0.9.

The elemental analysis show high concentrations of nitrogen in the pellet samples from the compost and reed canary grass (Table 1). Nitrogen limits the possibility of using these fuels in small combustion devices. According to the requirements for pellets (Directive No. 55/2008 of the Ministry of Environment of the Czech Republic to the requirements for awarding marks – Fuel pellets of herbal phytomass) the max. permissible amount of nitrogen is 0.90%. Pellet samples of compost and oversize chips from composting process do not meet the directives criteria.

Another monitored element in fuel is chlorine. Chlorine passes in large part to gaseous phase during combustion. According to the requirements for pellets the maximum permissible amount of chlorine is 0.18%. Requirements for chlorine are met for all fuel samples except pellets from park shrubs.

Problematic component in emissions is sulphur. Sulphur transforms largely during combustion into gas phase as SO_2 or SO_3. As far as limit values are concerned sulphur emissions in combustion devices using solid fuels from renewable resources are generally not a problem, as evidenced by all samples (Table 1).

Water and ash content is crucial for thermal use of all fuels. Water content in the samples is generally

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Table 2. Theoretical combustion analysis of the pellet samples assuming complete combustion

Sample No.	Mass combustion				Volume combustion			
	oxygen for complete combustion (kg/kg)	air for complete combustion (kg/kg)	dry flue gas (kg/kg)	carbon dioxide concentration in dry flue gases (% wt.)	oxygen for complete combustion (m^3/kg)	air for complete combustion (m^3/kg)	dry flue gas (m^3/kg)	carbon dioxide concentration in dry flue gases (% wt.)
1	1.11	4.08	7.19	21.74	0.78	3.70	3.68	21.48
2	1.17	5.03	7.37	21.29	0.81	3.87	3.82	20.76
3	1.19	5.13	7.48	21.41	0.83	3.95	3.90	20.76
4	1.32	5.69	7.95	20.70	0.92	4.38	4.26	19.54
5	1.22	5.26	7.67	22.10	0.85	4.06	4.02	21.30
6	1.26	5.41	7.83	22.26	0.88	4.17	4.14	21.30
7	0.91	3.92	6.27	20.71	0.63	3.02	3.02	21.71
8	0.79	3.39	5.64	19.04	0.55	2.61	2.59	20.99

quite low, which has a positive effect on the net calorific value of individual biofuel samples. Ash content in the samples is varied. The highest amount of ash was found in samples of wheat straw pellets, pellets from park shrubs, reed canary grass pellets and pellets from compost (Table 1). This results in lower net calorific value. Max. permissible amount of ash calculated for anhydrous state is 6%. Only pellets from wood biomass meet this condition.

Water and ash significantly affect both selection and adjustment of stove. Olsson et al. (2003) and Müller et al. (2015) confirm presumption, that an increased amount of ash negatively affects burner combustion device operation.

Concentrations of carbon monoxide in flue gases against the excess air coefficient were monitored during the measurements (Fig. 1a). Carbon monoxide is an important observed component of flue gas because it is a product of incomplete combustion. High concentrations of carbon dioxide were achieved during park shrubs combustion with very low excess air coefficient. For the first sample of reed canary grass pellets (sample No. 2), there was a significant increase in carbon monoxide emissions with increasing of the excess air coefficient. In the second sample (No. 3) this increase was not as high. For other fuels a constant or decreasing trend in carbon monoxide emissions was observed. These trends are described by regression equation in Table 3 with confidence level from 0.7 to 0.9.

The flue gas temperature depends on the excess air coefficient and is a significant and decisive parameter for determining efficiency and heat loss of the examined combustion device. The highest flue gas temperature was measured during combustion of the reed canary grass sample No. 3. High flue gas temperatures increase the heat loss and thus decrease the combustion efficiency. Other evaluated samples (Fig. 1b) were combusted under optimal conditions except for the sample of compost and

Table 3. Regression analysis of dependence of carbon monoxide, flue gas temperature and nitrogen oxides on the excess air coefficient

Sample No.	Carbon monoxide (mg/m^3)	Flue gas temperature (°C)	Nitrogen oxides (mg/m^3)
1	$CO = 0.0026^{4.1141}$	$T_{fg} = -0.166^2 + 4.7659 + 168.94$	$NO_x = 860.32^{0.2116}$
2	$CO = 308.3^{1.0297}$	$T_{fg} = -0.1526^2 + 4.8571n + 169.35$	$NO_x = 380.55^{0.642}$
3	$CO = -0.2511^2 + 43.39 - 594.62$	$T_{fg} = 0.1699^2 - 9.6041 + 320.2$	$NO_x = 450.5812^{0.6424}$
4	$CO = 25.13^2 - 727.04 + 5575.9$	$T_{fg} = -0.2504^2 + 6.0452 + 181.29$	$NO_x = 707.58^{0.3494}$
5	$CO = 2.7374^{1.3592}$	$T_{fg} = -0.0229^2 - 0.1329 + 164.83$	$NO_x = 179.19^{0.3968}$
6	$CO = 1.4675^2 - 29.392 + 145.35$	$T_{fg} = -0.1092^2 + 1.9242 + 210.94$	$NO_x = 972.19^{0.1187}$
7	$CO = 1.5849^2 - 46.666 + 351.37$	$T_{fg} = -0.9226^2 + 35.9 - 124.36$	$NO_x = 147.55^{0.5367}$
8	$CO = 0.0231^{2.8691}$	$T_{fg} = -0.0669^2 + 2.2656 + 175.52$	$NO_x = 580.28^{0.4056}$

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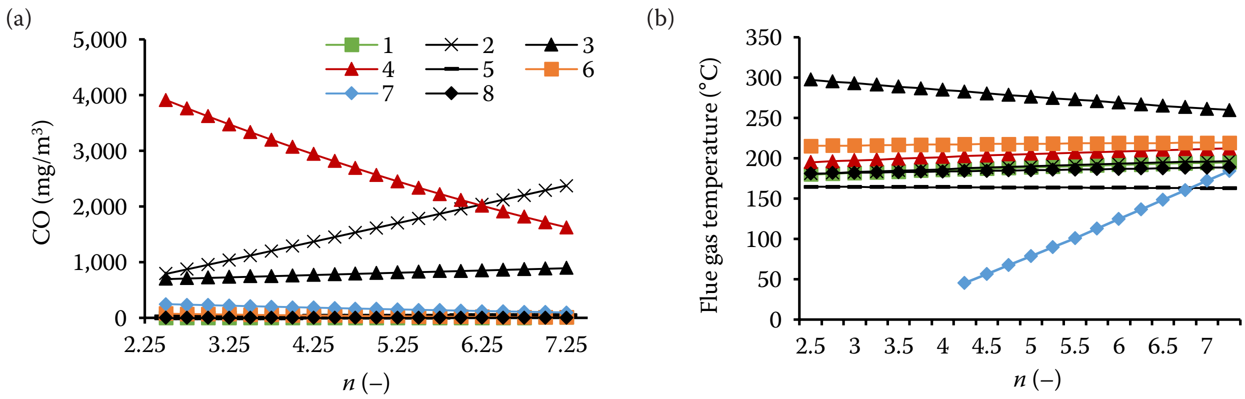

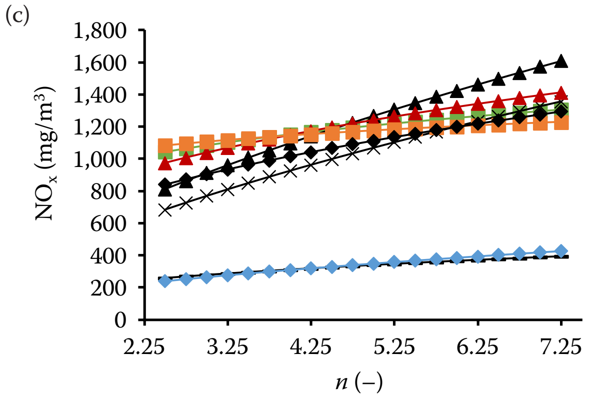

Fig. 1. Trends of (a) carbon monoxide, (b) flue gas temperature and (c) nitrogen oxides against the excess air coefficient

sawdust mixture. Complete suppression of combustion processes occurs for this sample in areas of very low excess air coefficient. This was caused by high concentrations of ash in the sample that led to clogging of the burner and thus stopping the combustion processes in areas of the low excess air coefficient. Trends of flue gas temperature against the excess air coefficient are described by regression equation in Table 3 with confidence level from 0.8 to 0.9.

The emitted concentrations of nitrogen oxide against the excess air coefficient are shown in Fig. 1c. Fuel from the compost and sawdust mixture and fuel from oak and beech mixture achieved low concentrations. The cause of low emission concentrations of these fuel samples is low flue gas temperature. Other fuels reached high concentrations of nitrogen oxides in flue gas, which increased with increasing excess air coefficient. Particularly, reed canary grass sample No. 3 has the highest nitrogen oxides concentrations at high values of excess air coefficient. This is mainly due to high flue gas temperature (Houshfar et al. 2011; Díaz-Ramírez et al. 2014).

There are other research works that also address the issue of carbon monoxide and nitrogen oxides. In the work of Eskilsson et al. (2004) we can find optimal conditions between the unburned carbon oxides and nitrogen oxides. Decreasing amount of air in the combustion chamber reduced amount of nitrogen oxides in flue gas, but on the other hand increased emissions of carbon monoxide. Finding optimal excess air coefficient for different types of fuels from biomass can help with the problem of nitrogen oxides and carbon monoxide emissions (Strehler 2000).

Solid biofuels produce high content of carbon monoxide both due to high moisture in the fuel itself and due to unsuitable design of the combustion chamber of the used combustion device. Generally, for complete combustion secondary air should be introduced. Time for which flammable gas particles remain in the combustion chamber should be at least 0.5 s and combustion temperature should reach around 1,000°C (Vierle et al. 1999).

CONCLUSION

New facts in this article stem mainly from the energy use of waste biomass, such as waste from the

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composting process, the maintenance of municipal green areas and other mixtures mentioned above. Elemental analyses and stoichiometric calculations were performed on samples of these biomass types to characterize them for further energy use.

Elemental analysis shows high content of nitrogen in samples of biomass origin, especially in pellets from compost and reed canary grass. Requirement for chlorine is exceeded only in the pellets from park shrubs. Other unwanted component is ash. High content of ash was found in the samples of pellets from wheat straw, park shrubs, reed canary grass and compost. The amount of ash reduced energy value.

Heating and emission measurements show how well the chosen combustion device works with given fuel. From an ecological point of view it is better to use pellets made of wood for small combustion devices such as the one used for our experiments. Results of this study are valid mainly for simple pellet burner devices with limited combustion control. Setting the optimum amount of air for each type of fuel from biomass can prevent excessive heat loss and thereby increase the efficiency of the used combustion device. The main issue is to resolve non-uniform fuel supply to burner and control of combustion air (e.g. by a flue gas oxygen sensor) for better results. The results of combustion tests confirmed that the excess air coefficient is a vital parameter for optimal combustion of waste biomass which affects emissions, such as the concentration of carbon monoxide, nitrogen oxides, as well as the flue gas temperature.

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