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The properties of wheat straw combustion and use of fly ash as a soil amendment

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Abstract. Agriculture is one of possible producers of by-products suitable for energy purposes, such as rapeseed and wheat straw. But on the other hand, not only thanks to the support of energy from biomass grown specifically for this purpose, arable land is exposed to intense cultivation of wide-row crops indirectly supporting soil erosion and nutrient elution. The issue of recycling ash from biomass combustion on agricultural and forest land is very important to resolve. Experience with this problem is found in countries in Northern Europe such as Finland or Sweden, as well as in North America. Due to ash characteristics, it is considered a valuable soil component and a potential replacement for conventional fertilizers.
Elemental analyses of samples from wheat straw pellets were followed by combustion and emission measurements. The effects of temperature and volume of air in the combustion of wheat straw was analysed, focusing on emission concentrations and the ash content. Effect of excess air coefficient on the composition of end products after combustion was assessed in three modes (small, optimum and high coefficient of excess air). During the measurements, the excess air coefficient ranged between the values from 3.95 to 14.89. The average net calorific value of the wheat straw samples was 15.55 MJ kg^{-1} in the original state. Mineral composition analysis of solid combustion products, necessary for using these residues as a fertilizer or soil component, was performed as well.

Key words: wheat straw, elemental analysis, ash, soil amendment, excess air coefficient.

INTRODUCTION

The possibility of using agricultural by-products for energy purposes is largely possible thanks to their suitable physical and chemical properties (Liu et al., 2013). An important criterion when choosing correct processing method and selecting a suitable type of combustion device are water and ash contents in the original state of fuel, ie the biomass from which the biofuel is produced (Olsson & Kjällstrand, 2006).

Combustion under real conditions does not take place with pure oxygen, but in the presence of air, which contains nitrogen as well in addition to oxygen. Nitrogen is not participating in the reactions and passes as a ballast component into flue gases, or combines with oxygen to produce harmful components NO and NO_2 (Malaťák & Bradna, 2014).

Suitable utilization of fly ash produced as a waste product of the biomass combustion would be beneficial not only to larger operators of combustion devices but also to smaller and residential users. In most cases at present time these materials are landfilled in the Czech Republic (Tlustoš et al., 2012). However, there are not only the rising costs of energy production due to landfilling of these materials, but also significant loss of nutrients needed for the development of biomass and restoration of soil fertility. One of the possible uses for ashes from biomass energy utilization is application to agricultural soil, which returns nutrients and modifies soil reactions (Zemanová et al., 2014). Application of ash is possible only under the condition that it does not endanger the quality of soil, crops and human health (Obernberger & Supancic, 2009).

This article responds to current topic of energetic utilization of by-products from agriculture and discusses the issues of how to provide the material composition and homogeneity, as well as adequate heating value in the combustion chamber, as well as subsequent use of the combustion products as a soil component. Evaluation of the solid biofuel samples of wheat straw pellets is followed by operational measurements in which temperatures and amount of combustion air were determined and their effects analysed in the combustion process of each sample, with focus on emission levels, particularly on nitrogen oxides, and also on fly ash properties.

MATERIALS AND METHODS

Wheat straw pellets have been chosen for the experimental measurement as most suitable from the known by-products from agriculture. They were produced by the pelletizing line LSP 1800 from the company ATEA PRAHA. This line is used for production of straw fuel pellets having a diameter of 8 mm and a length of 15–30 mm.

The first task was to determine the elemental composition of samples.We examined basic parameters of fuel and monitored especially content of water, ash, volatile and non-volatile combustible matter, carbon, hydrogen, nitrogen, sulfur, oxygen and chlorine.

The elements carbon, hydrogen and nitrogen were determined by a CHN analyzer Perkin-Elmer 2400. For the determination of chlorine and sulfur, samples were burned in oxygen-hydrogen flame in Wickbold apparatus. Non combustible substances of fuels, i.e. the ash and total water content were determined by burning, respectively drying of the appropriate sample. Gross calorific value was determined by calorimetric method in the calorimeter IKA 2000.

After the elemental analysis stoichiometric calculations were made and the net calorific value of fuel was calculated as well as the amount of oxygen (air) required for complete combustion of fuel, quantity and composition of flue gas and flue gas density. Calculations of individual samples are converted to normal conditions (temperature = 0 °C and pressure = 101.325 kPa).

Emission concentration measurements were carried out on an automatic hot-air combustion device KNP made by company KOVO NOVAK. The stove is equipped with a burner, automatic ignition and automatic fuel supply by screw from pellet hopper. The combustion device is designed to burn pellets and energy grain. Combustion process can be influenced by adjusting the combustion air and the fuel supply.

During combustion tests on this combustion device, emission concentrations of carbon dioxide, carbon monoxide, oxygen, nitrogen monoxide, nitrogen dioxide, sulfur dioxide, hydrogen chloride and excess air coefficient (n) were all being measured. The entire measurement was monitored by a multifunction analyzer of flue gas Madur GA-60. This analyzer is based in principle on the use of electrochemical converters. This device also enables to measure both ambient (T_a) and flue gas (T_{fg}) temperatures. Based on these temperatures and chemical parameters this device performs calculation of combustion characteristics. The emission concentration values are calculated for normal conditions of dry flue gas and reference oxygen content in flue gas. Individual points in combustion characteristics were determined during tests with changing excess air coefficient.

Subsequently, the results of measurements were processed by statistical regression analysis for expressing the mathematical relationship between carbon monoxide and dioxide, flue gas temperature and total nitrogen oxides against excess air coefficient. The coefficient of determination characterizes the explanatory power of the applied regression model and variance of measured values around the model curve.

During specific periods fly ash carried by flue gas was captured by a cyclone separator. The composition and quality of the fly ash were taken into consideration. Laboratory tests were completed by an analysis of the mineral composition of the solid product with regard to its utilization as a soil amendment. The total element concentrations in fly ash were determined according to Száková et al. (2013). Available metal fractions were determined by extraction (Trakal et al., 2013). The concentrations of other elements in the fly ash samples are determined by flame atomic absorption spectrophotometry on the device Varian-400 SpectrAA.

RESULTS AND DISCUSSION

The water content contained in the samples is quite low, which has a positive impact on fuel efficiency. The ash content in the samples is relatively higher when compared with typical wood whose ash content is under one percent (Olsson & Kjällstrand, 2006). Using wheat straw pellets in the combustion device has increased the demand for removal of solid residues from combustion process and in general it also increases the amount of particulate emissions.

Moisture affects behavior during combustion and the volume of flue gas produced per unit of energy. Generally the moisture content of wood chips does not exceed 30% wt. For straw the acceptable moisture content is up to 20% wt. Biomass fuels should generally be drier for ~~a~~ combustion devices with lower heat output (Olsson et al., 2003).

The average calorific value of the analysed straw is 15.55 MJ kg^{-1} at the proportion of water and ash in the original sample. Other assessed properties of samples were the proportions of volatile and non-volatile combustibles. For assessed samples the proportion of these characteristics is different than for example in wood. These differences make it clear that it is not possible to replace wood by differing biomass fuels in combustion devices for wood (Malaťák & Passian, 2011).

For the samples of wheat straw four sets of elemental analyses were carried out. First for uncompressed wheat straw whose analysis is used for comparison to processed wheat straw. Other three samples were already compacted straw pellets. One immediately after the pelleting process, one after thirty day storage and the last one just prior to the combustion tests. The resulting values of the elemental analysis are indicated in Table 1. These values confirm the fact that for energy use of wheat straw pellets the major factor is the calorific value, which depends on water and ash contents in the fuel (Ružbarský et al., 2014).

Table 1. Elemental analysis of wheat straw samples

Sample	Water Content (% wt.)	Ash (% wt.)	Volatile Combustible (% wt.)	Non-volatile Combustible (% wt.)	Gross Calorific Value MJ kg^{-1})	Net Calorific Value (MJ kg^{-1})
	W	A	V	NV	Q_s	Q_i
Wheat straw	13.1	5.08	66.43	16.5	16.03	14.64
Wheat straw pellets 1 (diameter 8 mm)	6.64	6.59	70	15.77	16.96	15.48
Wheat straw pellets 2 (diameter 8 mm)	5.28	6.9	70.4	16.42	17.12	15.99
Wheat straw pellets 3 (diameter 8 mm)	5.99	6.57	71.31	15.13	16.51	15.17
Average values wheat straw pellets	5.97	6.69	70.57	15.77	16.86	15.55
Statistical dispersion wheat straw pellets	0.68	0.19	0.67	0.65	0.32	0.41

Sample	Carbon C (% wt.)	Hydrogen H (% wt.)	Nitrogen N (% wt.)	Sulphur S (% wt.)	Oxygen O (% wt.)	Chlorine (% wt.)
	C	H	N	S	O	Cl
Wheat straw	40.67	4.89	0.49	0.11	35.56	0.1
Wheat straw pellets 1 (diameter 8 mm)	41.63	5.96	0.34	0.035	38.695	0.11
Wheat straw pellets 2 (diameter 8 mm)	43.38	4.58	0.63	0.09	38.96	0.18
Wheat straw pellets 3 (diameter 8 mm)	43	5.49	0.54	0.05	38.07	0.29
Average values wheat straw pellets	42.67	5.34	0.50	0.06	38.58	0.19
Statistical dispersion wheat straw pellets	0.92	0.70	0.15	0.03	0.46	0.09

The amounts of sulfur, chlorine and nitrogen in elemental composition of wheat straw pellets are the most important in terms of the emission concentrations. In the examined samples higher concentrations of nitrogen were found, causing noticeable increase in nitrogen emissions.

Table 2 shows the average values from emission measurements of the wheat straw pellet samples. These values confirmed the fact that maintaining the optimum excess air coefficient is essential during the combustion process. This state guarantees such combustion conditions which do not generate high emission concentrations of unburned components and do not increase the heat losses (Nordin, 1994; Friberg & Błasiak, 2002; Gonzalez et al., 2004).

Table 2. The average values of thermal properties and emission concentration of wheat straw pellets (8mm)

	Average	s^2	s	Max.	Min.
T_$_a$ (°C)	41.93	4.90	2.21	45.00	37.00
T_$_{fg}$ (°C)	180.11	643.78	25.37	217.00	123.40
O_2 (%)	17.75	1.25	1.12	19.59	15.69
n (-)	7.35	8.04	2.84	14.89	3.95
CO_2 (%)	2.33	0.73	0.85	3.87	0.91
CO (mg m^{-3})	1,040.64	341,820.15	584.65	2,444.00	157.78
SO_2 (mg m^{-3})	99.62	6,746.23	25.97	150.07	34.81
NO_x (mg m^{-3})	1,017.41	5,220.68	72.25	1,194.00	880.00

The amount of combustion air affects the combustion process itself, however, in practice it is very difficult to measure the real value of the combustion air amount required for complete combustion. This value is expressed in the form of excess air coefficient which gives the ratio of actual to theoretical air quantity for complete combustion. The excess air coefficient 1.91, which corresponds to the reference oxygen content in the flue gas of 10%, is set by legislation as nominal for small combustion devices with automatic fuel supply to combustion chamber (Act No. 201/2012 Coll., 2012).

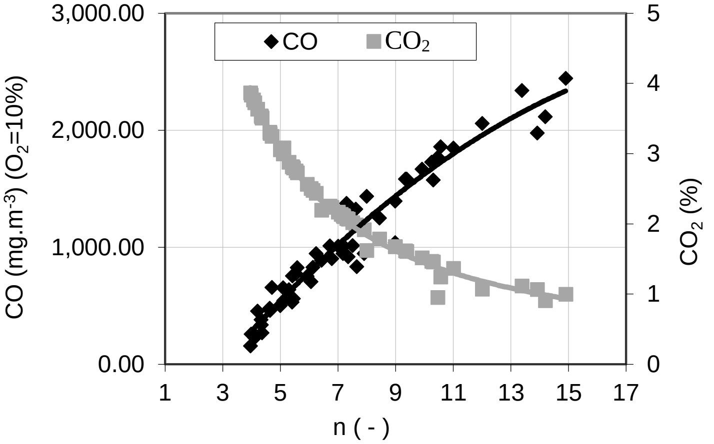

Figure 1. Dependence of carbon monoxide and carbon dioxide on the excess air coefficient – combustion of wheat straw pellets.

When burning pellets from wheat straw (see. Fig. 1) increasing the excess air coefficient *n* will decrease the emission concentration of carbon monoxide according to the equation:

$$CO = -7.2123n^2 + 324.48n - 897.67 \text{ (mg m}^{-3}\text{)} \tag{1}$$

With determination coefficient of $R^2 = 0.949$ when increasing *n* in range from 3.5 to 15.

This also leads to reduction in the carbon dioxide concentration (dampening the combustion process) according to the equation:

$$CO_2 = 17.427n^{-1.082}\ (\%) \qquad (2)$$

With increasing excess air coefficient, which is confirmed by Figure 2, there starts dampening of combustion processes and reduction of flue gas temperature below 200 °C. This flue gas cooling can be defined by the equation:

$$T_{flue\text{-}gas} = 0.3007n^2 - 13.658n + 261.88\ (^\circ\mathrm{C}) \qquad (3)$$

With determination coefficient of $R^2 = 0.8993$.

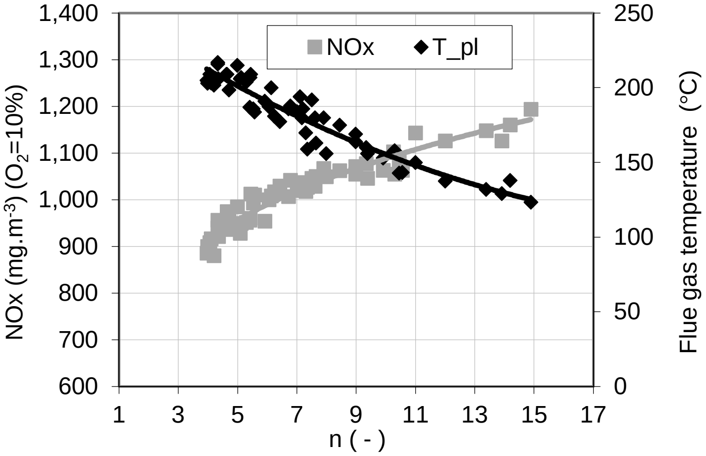

Figure 2. Dependence of nitrogen oxides and flue gas temperature on the excess air coefficient – combustion of wheat straw pellets.

The sharp increase in NO_x emissions depending on the amount of supplied combustion air was mainly caused by large quantities of supplied combustion air (see. Fig. 2). Under these conditions nitrogen reacted with oxygen to produce nitrogen oxides. Dependence of concentration of nitrogen oxides on the excess air coefficient is described by the equation:

$$NO_x = 709.25n^{0.1859}\ (\mathrm{mg\ m^{-3}}) \qquad (4)$$

With determination coefficient of $R^2 = 0.9126$.

The results of Eskilsson (2004), Gonzalez et al. (2004) and other researchers confirm the fact, that each type of combustion device has a characteristic course of the carbon monoxide emissions. Largest emission concentrations arise mainly during ignition or extinguishing of the combustion process (Fiedler & Persson, 2009). The highest concentration of carbon monoxide emissions is achieved at high excess air coefficients. High amount of combustion air cools the combustion chamber and thus results in high carbon monoxide emissions in the flue gases (Friberg & Blasiak, 2002).

Combustion device should work at nominal parameters as demonstrated by research work of Johansson et al., 2004. Any change in material supply into combustion chamber or in the flow of combustion air leads to high emissions of carbon monoxide (Wihersaari, 2005). On the other hand higher temperature and high input of combustion air has a substantial effect on the increased production of nitrogen oxides (Ponzioa et al., 2009). Decreasing the amount of combustion air has an effect on reducing nitrogen oxides emissions, but increases emissions of carbon monoxide in the flue gas (Diasa et al., 2004).

Experimental combustion tests were followed by analysis of the mineral composition of the combustion end product (fly ash). Fly ash was caught in ~~the~~ three different combustion modes: at large, small and optimum excess air (see. Table 3). The measured values were compared with the limits set in the applicable legislation.

Table 3. The average values of mineral composition of the fly ash

Wheat straw pellets	Small excess air	Large excess air	Optimal excess air
Al (mg kg^{-1})	477.28	985.69	792.24
As (mg kg^{-1})	2.47	0.69	1.27
B (mg kg^{-1})	155.06	296.12	65.93
Cd (mg kg^{-1})	0.22	0.24	0.04
Cr (mg kg^{-1})	4.52	5.37	3.20
Cu (mg kg^{-1})	19.23	23.74	23.25
Fe (mg kg^{-1})	2386.68	1,953.00	1,102.95
Mn (mg kg^{-1})	604.83	687.46	686.63
Mo (mg kg^{-1})	1.85	1.99	1.99
Ni (mg kg^{-1})	2.54	3.47	2.21
Pb (mg kg^{-1})	3.36	3.65	0.38
S (mg kg^{-1})	925.43	1,243.19	415.26
Zn (mg kg^{-1})	77.89	66.65	11.69
P (mg kg^{-1})	4,071.26	4,924.94	5,939.50
K (mg kg^{-1})	17,964.31	16,720.70	35,219.43
Ca (mg kg^{-1})	15,801.02	16,053.62	28,517.81
Mg (mg kg^{-1})	4,296.68	4,952.62	7,245.79

When comparing results of analyses to the limits given by Act No. 271/2009 Coll. (2009) applicable for soil amendments, we find that the values of cadmium and lead in fly ash from wheat straw are on average significantly below the limit of 1 mg *Cd* kg^{-1} and 10 mg *Pb* kg^{-1} respectively. These elements in fly ash would therefore pose no threat when applied to soil.

Biedermann & Obernberger (2005) recorded contents of arsenic in fly ash from combustion of wood and straw between 0.1–0.2 mg kg^{-1}. In comparison with their results, the content of fly ash in our case was higher. Chromium (maximum content in soil substance is limited to 50 mg kg^{-1}) would meet the limit in this case. Phosphorus was present between 4,000–6,000 mg kg^{-1}, the highest content was found in the fly ash of wheat straw at optimum excess air coefficient. A higher potassium content is due to higher levels of this nutrient within the input material.

The higher calcium content in fly ash lead to increased *pH* values and these materials could be used for treatment of soil reaction in particular strongly acidic or heavy soils (Obernberger & Supancic, 2009). Magnesium content in fly ash ranged from 4,300–7,300 mg kg^{-1}. Higher values were obtained when the optimum excess air coefficient was used during combustion process. Scientific literature also indicates the magnesium content in fly ash from the combustion of biomass around 1%. For instance higher values of magnesium were found in the fly ash of rape straw 2.1% (Hytönen, 2003) or cereal grains 10.4% (Eichler-Löbermann et al., 2008).

CONCLUSIONS

Eskilsson (2004) found compromise between production of ~~non-combusted~~ carbon monoxide and nitrogen oxides, similar trends have been measured in this paper. Decreasing the amount of air in combustion chamber reduces the amount of nitrogen oxides in the flue gas, but on the other hand it increases emissions of ~~non-combusted~~ carbon monoxide. Finding the optimum setting of the excess air coefficient for different types of biofuels could solve the problem of nitrogen oxides and carbon monoxide emissions. The content of carbon dioxide can show the quality (efficiency) of combustion. For each type of fuel there is a maximum attainable proportion of carbon dioxide (ie. CO_{2max}) in the flue gas, which is given by the elemental composition of combustible matter in the fuel. Olsson & Kjällstrand (2006) confirmed that this value is unattainable in combustion devices in practice.

Based on the results of analyses of selected samples of fly ash from biomass can be categorized by the raw material put into the process. These end products of combustion can be recommended for direct application into the soil, according to applicable legislation on fertilizers. Ash from biomass thanks to its physical and chemical properties offers not only a wide range of potential applications. It also closes the nutrient cycle by returning nutrients to the soil, reduces the landfill of such materials and not at the least causes the reduction in expenses for mineral fertilizers in agricultural production. If the ash from the combustion of biomass returns back into the soil, then the energy production from biomass can truly be a sustainable technology.

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