COMBUSTION OF SELECTED BIOFUELS TYPES IN FURNACE BURNER*

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The aim of this article is to determine the thermal emission properties of selected solid waste fuels from biomass in burner furnace are determined. Individual analyzed samples are selected from wheat and rape straw and bark. The basic task of this work is the identification and evaluation of individual samples of the elemental composition. Theoretical calculations of combustion characteristics are performed after an evaluation of elemental analysis. Thermal emission measurement is carried out by flue gas analyzer GA-60. Thermal emission concentrations of carbon monoxide and dioxide, nitrogen oxides, and flue gas temperatures are assessed according to the excess air coefficient and statistically evaluated by regression analysis. Different parameters were determined in the resulting values of individual examined biofuels samples in elemental and stoichiometric analysis. Samples from rape straw pellets contain a high concentration of nitrogen (0.72% wt.) and sulfur (0.23% wt.) and samples from the bark fuel have high amounts of ash (13.3% wt.), which subsequently affects the combustion process. Measured emission concentrations in samples of wheat and rape straw range at low coefficient of excess air from 4 to 6 up to 2000 $mg.m^{-3}$ carbon monoxide. Based on the results of thermal emission measurements burning of the crushed bark can not be recommended on the selected burner furnace.

wheat and rape straw; bark; stoichiometric analysis; combustion device; emission

INTRODUCTION

The exhaustion possibility of fossil fuels increases due to the importance of renewable energy and is becoming one of the main suitable development conditions not only in agriculture but also for the society in general. Over the last twenty years the share of world wide biomass (mostly wood) total consumption of primary energy sources increased by 8%. This increase is reflected not only in developing countries where wood is the main energy source (four-fifths of the harvested timber in developing countries is consumed as firing wood). Nevertheless, the wood consumption as fuel is increasing also in developed countries (Gürdíl et al., 2008).

It is necessary to get the combustion process under optimal conditions for their own production energy utilization from agricultural and forest activity (but also from other materials). Combustion without these assumptions is not a contribution. It is always necessary to burn a particle fuel only in facilities which are determinated by type, structure, quality, etc. for the combustion equipment (Friberg, Blasiak, 2002; Johansson et al., 2004; Yang et al., 2005).

In order to decide on whether the biomass is suitable for burning in a particle type of combustion equipment or if it is to access the quality of bio fuels from phytomass, with regard of their use, it is necessary to know the properties of bio fuels which are adequately characterized. Stoichiometric calculations of combustion processes complement fuel characteristics and are essential for any thermal calculation. They are particularly important for solving a wide range of practical form problems as well as for controlling the work of existing combustion equipment (Nordin, 1994; Olsson et al., 2003; Kjällstrand, Olsson, 2004).

Solid bio fuels are beginning to play an important role in the common EU policy. For example solid bio fuels can partially replace fossil fuels and thereby reduce the volume of waste generated by extraction and processing, which results in contributing to the increase of resource efficiency. The use of solid fuels can be particularly important in low populated areas to ensure local energy needs. The use of solid bio fuels is also used as a mean to meet the objectives of the Landfill Directive by reducing the amount of bio degradable waste stored to land field (Hedberg et al., 2002; Malaťák, Pasian, 2011).

The article's aim is to assess the selected fuels from plant biomass and wood pellets thermal emission properties of the blast furnace. The storage point of

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measurement is to determine elemental composition of fuel samples. Based on the elements analysis are theoretical calculations, carried out for the completer combustion and coefficient of excess air which is chosen based on the requirements of the D i r e c t i v e No. 13 (2006). The determined values in this article are used for subsequent measurement of thermal emission concentration. Thermal emission concentrations are assessed according to the coefficient of excess air and are statistically evaluated by regression analysis.

MATERIAL AND METHODS

The practical part of this research involves the determination of elements analysis of each fuel sample used as a determining stoichiometric analysis which are the basis for assessing the thermal emission characteristics.

After the evaluation of fuel samples, thermal emission measurement follows. The methodology is therefore divided into three sub-methodologies:

Methodology for elemental analysis

- water content in the received W (w%, weight percentage) – the method of drying in an oven - the water content in the analytical test sample (C S N EN 14 774-3, 2010),
- determination of ash content in the as received A (w%) (C S N EN 14 775, 2010),
- determination of gross calorific value Q_s (MJ.kg^{-1}) (C S N EN 14 918, 2010),
- determination of the content of volatile matter V (w%) (C S N EN 15 148, 2010),
- determination of total content of carbon (C), hydrogen (H), and nitrogen (N) – instrumental methods (C S N CEN/TS 15 104, 2006),
- determination of total content of sulphur (S) and chlorine (Cl) (w%) (C S N P CEN/TS 15 289, 2006).

Methodology for stoichiometric analysis

- oxygen (air) volume required for complete combustion of the sample (kg.kg^{-1}), (m^{3}N.kg^{-1}),
- quantity and composition of flue gas (kg.kg^{-1}), (m^{3}N.kg^{-1}),
- specific volume of flue gas (V%, volume percentage).

Methodology for thermal emission measurements

- determination and analysis of the concentration of thermal-emission measurements of the combustion equipment,
- determination and evaluation of a graphical dependence of carbon monoxide and carbon dioxide on the coefficient of excess air,
- regression analysis – mathematical expression of the individual components of combustion products depending on the coefficient of excess air.

For using biomass as an energy source it is important to have an elementary analysis, which is the basis of any calculation of the thermal combustion device work. Elemental composition of the biomass affects all stoichiometric calculations, heat loss, and efficiency of combustion equipment and significantly affects the work of thermal combustion equipment. For solid and liquid bio fuels the elemental analysis is used to determine the elemental composition, identifying the percentage share by weight of carbon, hydrogen, oxygen, sulfur, nitrogen, and all the water in the original fuel. Incombustible fuels, i.e. ash and water content, shall be determined by burning and/or drying the sample. Elemental analyses of used fuel samples were performed in the Laboratory of Organic Elemental Analysis in the Institute of Chemical Technology, Prague (ICT). The elements of carbon, hydrogen, and nitrogen were determined on the CHN 2400 Analyzer (PerkinElmer, Waltham, USA). The chlorine and sulfur samples were burned by the oxy-hydrogen flame in Wick bold combustion apparatus. Stoichiometric calculations of combustion processes supplement fuel characteristics and are the basis for any thermal calculation. They are particularly important for resolving a wide range of practical design problems as well as for controlling the work of existing combustion equipment.

The measurement is carried out on the hot burner combustion equipment in conformity with C S N (Czech Technical Standard) 07 0240 "Warm water and low-pressure steam boilers. Basic regulations", with C S N 124070 "Dust collecting equipment. Measuring methods of quantity features", with C S N 44 1310 "Solid fuels – symbols of analytical parameters and formulae for converting the results of analysis of different states of fuels", and with C S N 38 5509 "Gaseous fuels". Thermal parameters of the hot air stove are shown in Table 1.

Exploitable biomass energy can usually not be used directly in combustion plants and it must be adjusted to a suitable shape and size. For the actual analysis the biomass in form of pellets and spruce, crushed bark is chosen. Pellets with a diameter of 8 mm are made of wheat and rape straw.

Measurement of emission concentration is taken, using multitask flue gas analyzer GA-60 (Madur Electronics, Austria). The principle is based on the use of electrochemical transducers. GA-60 unit comes standardly with five transmitters incorporating the sixth converter. The standard equipment is a transmitter for flue gas analysis of the following components: oxygen (O_2), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and hydrogen chloride (Cl).

During direct measurement the values of ambient temperature, flue gas temperature, and chemical

Table 1. Thermal parameters of the hot air stove

Thermal parameters:		Value
Power rating [kW]		18
Regulated output [kW]		8 - 18
Fuel consumption [kg.h^{-1}]		1.5 – 4.9
Diameter flue [mm]		80
Hot Air Outlet Temperature	at power rating [°C]	210
	at the minimum output [°C]	110
Efficiency at rated power [%]		88
Flue gas mass flow rate at the output	at power rating [kg.s^{-1}]	0.0138
	at the minimum output [kg.s^{-1}]	0.010
Rated voltage:		1 PEN 50 Hz 230 V
Electrical protection:		IP20

Rated electrical power: 92 W exhaust fan, 120 W fan, 19 W motor feed, 1500 W equipment for kindling total max = 1731 W

composition of the gases in the range of O_2, CO, SO_2, NO, NO_2 are measured. The converter signal is proportional to the volume measured component concentration in ppm.

The converter for the determination of oxygen has insignificant dependence on the individual components of the measured gases. Converters behave similarly to determine CO and NO, they have built-in internal filters which absorb disruptive components. Other converters are responding to the concentration of other components.

GA-60 unit takes signals from all transmitters, using the characteristics of the transducer, sets the calibration of gases and then continuously calculates the concentration of individual components. At the same time it continuously replaces the selectivity transducer system of four equations with four unknown equations.

The resulting thermal emission concentrations in flue gas analyzer GA-60 ppm are converted to standard conditions and calculated both on mg.m^{-3} and the reference amount of oxygen in the flue gas or is equal to 11%, which is used for equipment according to the regulations and guidelines.

RESULTS

The resulting parameters of the elemental analysis of samples of fuels from biomass and bark are shown in Table 2.

Table 3 shows the results of the stoichiometric analysis of the original sample under normal conditions and reference oxygen content in flue gas. All weights and volumes of combustion air and flue gases are given for so-called normal conditions, i.e. at t = 0 °C and pressure p = 101.325 kPa and reference oxygen content in flue gases or is equal to 11%.

In the combustion tests of pellets samples particularly the emission levels of carbon monoxide and carbon dioxide were observed. These emission levels mainly conducted within the laboratory measurements supply the combustion air quantity into the combustion chamber. During the measurements the combustion air was controlled from minimum to maximum concentration. Overall the resulting dependencies are shown in Figs. 1–6. The amount of combustion air supply is represented in the Fig. 1–6 about the coefficient of excess air.

Due to burning wheat straw pellets, the growing amount of combustion air leads to the increase in concentration of carbon monoxide according to the equation:

$$CO = 36.259n^{1.4445} \quad (mg.m^{-3}) \quad (1)$$

And, on the other hand, reduction of concentration of carbon dioxide follows the equation:

$$CO_2 = 22.21n^{-0.9998} \quad (\%) \quad (2)$$

The calculated concentration in this experiment exceeded the excess air coefficient over thirty times. Above the larger coefficient of excess air, as shown in Fig. 1, there is a suppression of combustion process and reducing the combustion temperature limit of 110°C. The cooling gas can be defined by the equation:

$$t_{sp} = 0.0906n^2 - 6.8388n + 238.42 \quad (^oC) \quad (3)$$

The effect of nitrogen concentration on the amount of combustion air is confirmed by the measurement (see Fig. 2).

The resulting emission levels when burning pellets of rape straw for the growing amount of combustion air lead to increased concentrations of carbon monoxide and are expressed by the equation:

$$CO = 52.091n^2 - 513.51n + 2098.3 \quad (mg.m^{-3}) \quad (4)$$

Table 2. Samples analysis of wood, biomass and waste solids

Sample	Water content (w %)	Ash (w %)	Volatile flammable (w %)	No flammable volatile (w %)	Gross calorific value ($MJ.kg^{-1}$)	Net calorific value ($MJ.kg^{-1}$)	Carbon C (w %)	Hydrogen H (w %)	Nitrogen N (w %)	Sulfur S (w %)	Oxygen O (w %)	Chlorine Cl (w %)
Symbol	W	A	V	NV	Q_s	Q_i	C	H	N	S	O	Cl
Wheat straw - pellets (Ø 8 mm)	5.28	6.90	70.40	17.42	17.12	15.99	43.38	4.58	0.63	0.09	39.14	0.18
Rape straw - pellets (Ø 8 mm)	5.45	4.83	72.28	17.44	17.36	16.15	43.70	4.90	0.72	0.23	40.17	-
Bark	8.5	13.33	62.8	25.4	16.48	15.62	38.7	2.98	0.13	0.04	36.28	-

Table 3. Stoichiometric analyses of original samples of fuel under normal conditions and a reference oxygen content in flue gases or is equal 11%

Fuel		Wheat straw - pellets (Ø 8 mm)	Rape straw - pellets (Ø 8 mm)	Bark
Volume combustion				
O_{min}	The theoretical amount of oxygen for complete combustion ($m^3_N.kg^{-1}$)	0.79	0.81	0.63
L_{min}	Theoretical amount of air for complete combustion ($m^3_N.kg^{-1}$)	3.76	3.84	3.02
L_{skut}	The actual amount of air for complete combustion ($m^3_N.kg^{-1}$)	7.90	8.07	6.34
n	Coefficient of excess air (–)	2.10	2.10	2.10
v^v_{sp}	Volume quantity wet flue gas ($m^3_N.kg^{-1}$)	8.81	9.02	7.12
v^s_{sp}	Volume quantity dry flue gas ($m^3_N.kg^{-1}$)	7.92	8.08	6.43
v^s_{spmin}	Theoretical volume quantity dry flue gas ($m^3_N.kg^{-1}$)	3.75	3.82	3.08
v_{CO2}	Volume quantity CO_2 ($m^3_N.kg^{-1}$)	0.81	0.81	0.72
v_{SO2}	Volume quantity SO_2 ($m^3_N.kg^{-1}$)	0.00	0.00	0.00
v_{H2O}	Volume quantity H_2O ($m^3_N.kg^{-1}$)	0.89	0.94	0.69
v_{N2}	Volume quantity N_2 ($m^3_N.kg^{-1}$)	6.17	6.31	4.95
v_{O2}	Volume quantity O_2 ($m^3_N.kg^{-1}$)	0.87	0.89	0.70
Expression of the individual components of flue gas % volume.				
CO_{2max}	The theoretical volume concentration of carbon dioxide in dry flue gas (% volume)	21.48	21.22	23.35
CO_2	Carbon dioxide (% volume)	0.02	9.01	10.12
SO_2	Sulfur dioxide (% volume)	9.16	0.02	0.00
H_2O	Water (% volume)	0.01	10.37	9.70
N_2	Nitrogen (% volume)	70.04	69.93	69.55
O_2	Oxygen (%volume)	10.11	9.85	9.80

And, on the other hand, to reduce the concentration of carbon dioxide is shown by the following equation:

$$CO_2 = 20.29n^{-0.9998} \quad (\%) \qquad (5)$$

This is based on the formula above and during measurement was determined over twelve times the excess air coefficient. Above the larger coefficient of excess air – as shown in Fig. 3 – a suppression of combustion process and reduced combustion temperatures below 200°C is determined. The cooling gas can be defined by the equation:

$$t_{sp} = -0.7912n^2 + 12.234n + 192.59 \quad (°C) \qquad (6)$$

In contrast to the previous measurement, the flue gas temperature was much higher (average t_{sp} = 238 °C)

Fig.1. Emission levels of CO a CO_2 depending on the coefficient of excess air during combustion of pellets from wheat straw

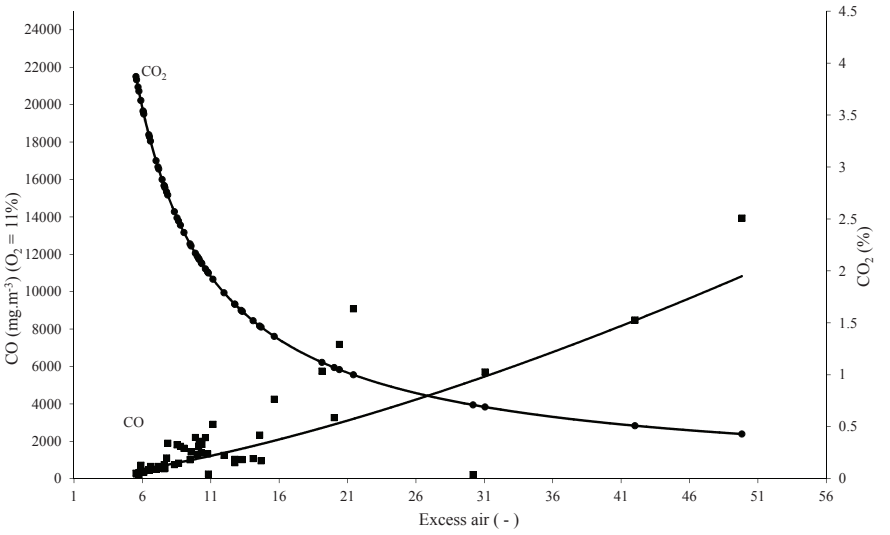


Fig.2. Emission concentration of NO_x and flue gas temperature depending on the coefficient of excess air during combustion of pellets from wheat straw

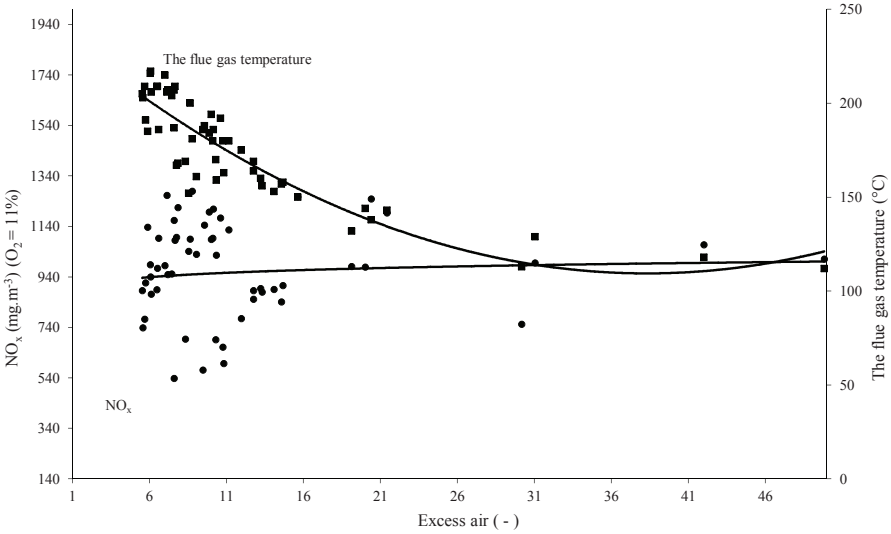
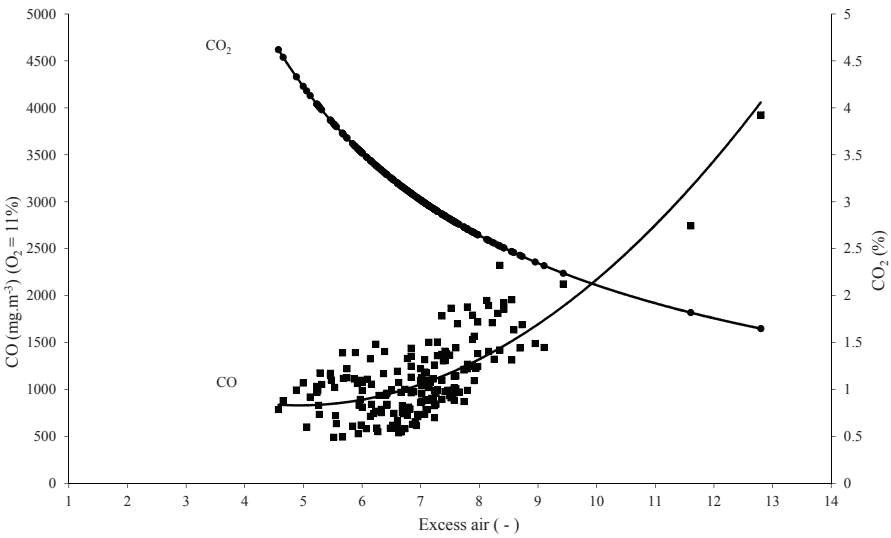


Fig.3. The emission of CO and CO_2 depending on the coefficient of excess air during combustion of pellets from rape straw



than pellets of wheat straw (average t_{sp} = 176 °C). This states an increase in emissions of nitrogen oxides depending on the amount of combustion air supplied (see Fig. 4). Due to the combustion air temperature, nitrogen reacted with oxygen to form nitrogen oxides. The effect of concentration of nitrogen oxides excess air coefficient is described by the equation:

$$NO_x = 567.94n^{0.6038} \quad (mg.m^{-3}) \quad (7)$$

During combustion tests crust occurred in areas of very low coefficient of excess air to very high concentrations of carbon monoxide emission, which increases the coefficient of excess air by the equation:

$$CO = 36.259n^{1.4445} \quad (mg.m^{-3}) \quad (8)$$

This concentration of carbon monoxide increases the excess air coefficient to 17, after crossing this limit, there is a decline in the combustion process and an increase in the re-concentration of carbon monoxide.

Carbon dioxide has a decreasing trend depending on the amount of combustion air supply. These emission concentration range achieved with low excess air coefficient is about 7 CO values of 6000 $mg.m^{-3}$ and the CO_2 concentration makes around 3.5% which significantly exceeds the limits.

By increasing the excess air coefficient, as shown in Figs. 5 and 6, is achieved the suppression of combustion process and reducing the combustion temperature to the limit of 150°C. The cooling gas can be defined by the equation:

$$t_{sp} = -0.0909n^2 + 2.1036n + 217.29 \quad (°C) \quad (9)$$

Significant progress reaches concentrations of nitrogen oxides emissions. The average temperature of outgoing flue gas was around 200°C. Thus causing high temperature, as seen in the graph, which directly affects the concentration of carbon, but under the influence of atmospheric oxygen it leads to an increase of these concentrations by the equation:

$$NO_x = 899.51n^{0.1362} \quad (mg.m^{-3}) \quad (10)$$

DISCUSSION

This article addresses the urgent issues of energy use of fuels based on biomass combustion in modern facilities. The scientific works of the authors Johansson et al. (2004) and Olsson et al. (2003) show very good emission characteristics during biomass combustion in modern facilities. For a decision on using biomass, whether it is suitable for burning in a particular type of combustion device, or if it is to assess the quality of bio fuels, the properties have to be known which are sufficiently characterized in the section Material and Methods. Essential and stoichiometric elemental analyses are very important from the energetic point of view. Stoichiometric calculations of combustion processes and fuel supplement characteristics are the basis for any thermal calculation. They are particularly important for addressing a range of practical design problems, as well as in monitoring the work of existing combustion plants. These aspects need constant attention (Kjallstrand, Olsson, 2004).

These results are in requirements to the quality of fuels from biomass. High quality pellets from biomass are primarily required for combustion in small combustion plants. For larger combustion facilities that are equipped with gas cleaning and combustion process control, quality of fuel is critical. It is therefore important to distinguish between two types: for industrial plants and for home or small combustion plants (Obernbergera, Theka, 2004). Fuel quality is critical, to which the author shows the results of Olsson, Kjallstrand (2004), which tested the pine pellets from several manufacturers. From an environmental point of view it is better to use pellets made of wood for home usage and plant biomass can be used without difficulty for large combustion plants.

CONCLUSION

The results of analysis carried out in this research show that the samples have fuel properties which affect their energy use. One of the aspects of the concentrations of sulfur, chlorine and nitrogen in the samples were examined. The amount of nitrogen in plant biomass is an important factor, since the actual energy plants show a higher amount of nitrogen in fuel (biofuel specification properties to Directive No. 55 (2008)) compared to fossil fuels. In particular, the increased content of this element limits the use of these fuels directly in internal combustion devices. The samples of rape straw pellets inhabited large concentrations of nitrogen.

Sulfur also is for the most part during combustion in the gas phase as SO_2 or SO_3. Emissions of sulfur in the heating equipment, using solid fuels from renewable sources, are usually not a problem in terms of limit values, which is confirmed by the selected samples. Exceptions are rapeseed straw pellets, which in a given state of the sample concentration reached 0.23% sulfur by weight percentage. The increased concentration of sulfur in the samples can be caused by contamination of the site with sulfur oxide emissions. The decisive factor in the concentration of sulfur in the biofuel can have corrosive behavior of the combustion device. Other values of elemental analysis satisfy the optimal parameters for these samples using biofuels in combustion plants.

The minimum calorific value of solid fuels intended for combustion in small stationary is given by

Fig.4. The emission concentration of NO_x and flue gas temperature depending on the coefficient of excess air during combustion of pellets from rape straw

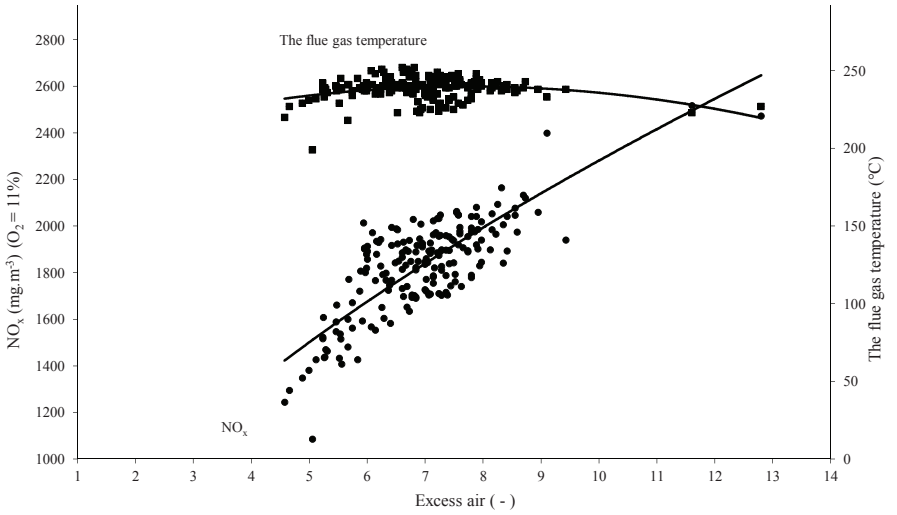


Fig.5. Emission levels of CO and CO_2, depending on the coefficient of excess air during combustion of bark

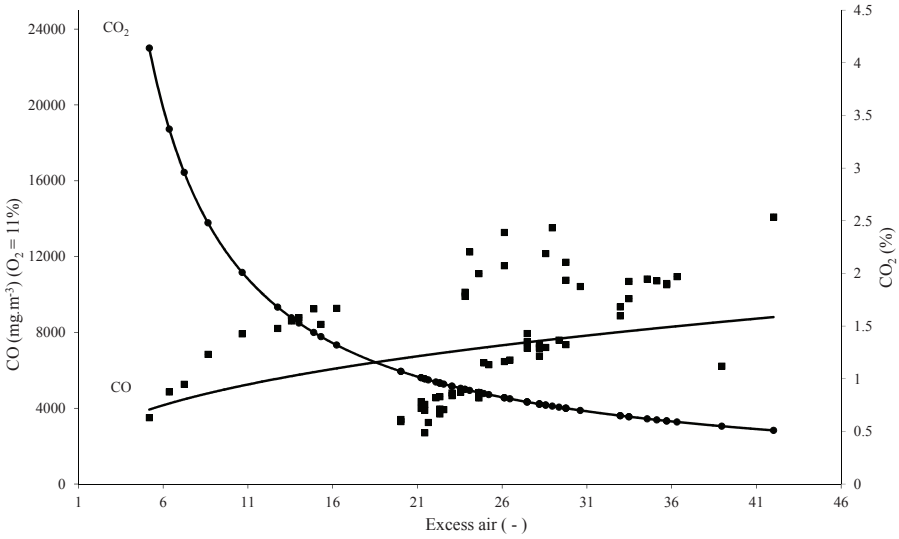
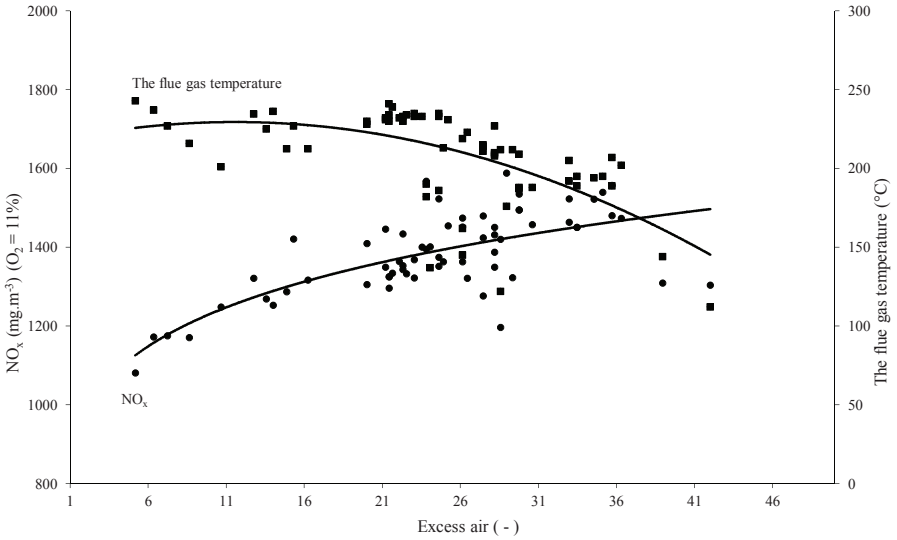


Fig.6. NO_x concentration and temperature of flue gases depending on the coefficient of excess air during combustion of bark



Directive No. 13 (2006). On establishing fuel quality requirements for stationary sources for the protection of air, may be in the anhydrous state less than 12 $MJ.kg^{-1}$. The minimum calorific value of solid fuels intended for combustion in stationary medium may be in anhydrous state less than 10 $MJ.kg^{-1}$. These conditions are considered for all samples.

The volume of all the water contained in the samples is quite low, which has positive benefits in fuel efficiency. Humidity affects the behavior of the combustion and exhaust gas volume per unit of generated energy. Generally, the moisture content of wood chips should not exceed 30% wt. The straws acceptable moisture content is up to 20%. The smaller furnace heat output should be drier fuel.

Ash content in the original samples of pellet fuel compared to wood mass is low, as seen from the analysis in selected elements of bio fuels. More than twice as much fuel ash samples are from the bark. Consequently the large amounts of ash are significantly affecting the thermal properties of considered solid fuels and the combustion device selection and setting.

The resulting values of the stoichiometric analysis show the difference in thermal emission parameters examining samples of fuels. The following parameters of the fuels under consideration influence the selection and design of combustion equipment: calorific value, water content, and energy density. The concentrations of N (nitrogen), S (sulfur) and Cl (chlorine) in the examined samples (the samples are confirmed by analysis) are relatively high. The resulting emission levels when burning pellets of wheat straw, in areas of very low coefficient of excess air, show very low emission levels of carbon monoxide and on the other hand relatively large concentration of carbon dioxide, which is a product of perfect combustion. This emission concentrations range is achieved with low excess air coefficient (around 5.2) to 1000 $mg.m^{-3}$ CO and 3.8% CO_2.

This final concentration indicates the optimum threshold of the excess air coefficient for wheat straw pellets in burner furnace of combustion device. The optimal threshold for combustion is in the range from 4 to 9 of excess air coefficient. Exceeding these limits leads to an increase in the disproportion in the concentration of combustible components (CO at 2000 $mg.m^{-3}$) and subsequent cooling of the combustion flame supply air. Rape straw, unlike wheat straw, has improved stoichiometric properties, which is shown in the combustion tests. In areas of very low coefficient of excess air there will be very low concentrations of carbon monoxide emission and contrast to the relatively large concentrations of carbon dioxide, which is a product of perfect combustion. These emission concentration ranges are achieved with low excess air coefficient (about 5), to 1000 $mg.m^{-3}$ 4.5% CO and CO_2, which is positively reflected in the actual combustion process.

The results show the emission concentration limit of the optimal excess air factor for rape straw pellets to the combustion device burner furnace. The optimal threshold for combustion is in the range from 4 to 6 excess air coefficient. Exceeding these limits leads to a disproportionate increase in the concentration of combustible components (CO at 2000 $mg.m^{-3}$) and subsequent cooling of the combustion flame supply air.

The measurement of bark, which is burned in the blast furnace as finely crushed bulk material, is observed with the focus on emission levels of carbon monoxide and carbon dioxide. In areas of very low coefficient of excess air it can lead to high concentrations of carbon monoxide emission, which increases the coefficient of excess air which is constantly growing.

All measured concentrations of each emission point leads to the excess carbon dioxide emission limits in all measured areas for coefficient of excess air. Given that the incinerator burner is set to a smaller amount of combustion air it is not recommended to burn crushed bark on the furnace burner.

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