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Influence of biofuel moisture content on combustion and emission characteristics of stove

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Abstract. The research aim was to study the effect of moisture in solid fuel on combustion in a stove and its emissions. Analysed samples were from spruce woodchips. Four samples were prepared with different moisture contents and furthermore spruce wood was used as a reference sample. Combustion device used was a stove with a fixed fire grate. Studied parameters were ambient temperature, temperature of flue gases, coefficient of excess air, and contents of oxygen and carbon monoxide in flue gases. Laboratory measurement was performed on an analyser of flue gases whose function is based on electro-chemical converters. Measured values were first converted to a referential oxygen content in flue gases. Evaluation of these values was then made by regression analyses. The course of combustion process and its quality can be seen well in functional dependence of carbon monoxide on excess air coefficient. The area of combustion was the smallest with the least moist sample (3.2%) and increases with increasing moisture. A sample with high moisture (31.1%) was already causing the fire to gradually extinguish. Because flue gas temperature is in the same range for all samples, the overall efficiency of the stove decreases sharply with fuel moisture due to specific heat of flue gases. It has been thus confirmed that fuel moisture content has a substantial influence on combustion, especially in the chosen combustion device, which has been verified by comparison with the reference fuel.

Key words: Biomass, combustion, elemental and stoichiometric analyses, emissions, spruce chips.

INTRODUCTION

Due to the decrease in fossil fuel reserves, the importance of using renewable energy sources is increasing. Production of organic waste is very significant in terms of quantity in Czech Republic, particularly in the field of agricultural and forestry activities. For energy use of these products it is very important to run combustion process under optimal conditions. If we have to decide whether the chosen biomass is suitable for combustion in a certain type of combustion device, it will be necessary to know the properties of such biofuels that characterise it sufficiently. Elemental analysis and stoichiometric calculations are essential for assessing suitability in terms of energy (Nordin, 1994; Malaťák & Passian, 2011).

Water is contained in each solid fuel. The ash as well as water are incombustible components of each fuel, which reduce the calorific value, therefore they are undesirable in the fuel. The water content in the solid fuel varies in a wide range from 0 to 60% wt. The water content in the fuel is given in weight percent (Obernbergera & Theka, 2004;

Müller et al., 2015). In many studies, the core aim is to better understand the relationship between thermal conversion processes (drying, pyrolysis, char conversion) and their interrelationship to combustor performance (efficiency, emissions, process temperatures, scale formation, and instabilities) (Demirbas, 2004; Di Blasi, 2008; Obaidullah et al., 2012). However, due to the complexity of solid fuel (particle) conversion and fuel bed behaviour, precise modelling of all aspects of biomass fixed-bed combustion is not readily achievable (Khodaei et al., 2015). One problem is the large amount of moisture content in biofuels. Higher moisture content causes operational problems for biomass combustion, as shown by the study Svoboda et al. (2009).

The aim of this study is to assess the effect of water contained in a sample of fuel on the combustion process on the grate furnace and in particular the impact on emission and combustion characteristics. To compare the quality of the combustion process a hypothesis was determined that with higher water content the quality of combustion process decreases. This hypothesis will be tested by experimental measurement and statistical evaluation of measured values. As a reduction in the quality of the combustion process can be evaluated the low efficiency of the combustion device and high CO values.

MATERIALS AND METHODS

The method of solution to this problem is based on several methods that are based on the work progress. First of all there is a sample preparation, next is combustion process and emission concentration measurement and determininination of the combustion device operating parameters. Another extensive section is the methodology used in the analytical processing of the measured values and their statistical analysis.

Sample preparation

Spruce wood chips were selected as a sample for combusting process. Spruce logs intended for combustion in grate furnace have been transformed into chips by wood chipper AL-KO 2500. Chips had length from 10 to 60 mm. Elemental analysis of spruce wood chips is in Table 1.

Table 1. Elemental analysis of reference sample, spruce wood

Water Content (% Wt.)	Ash (% Wt.)	Gross Calorific Value (MJ kg^{-1})	Net Calorific Value (MJ kg^{-1})	Carbon (% Wt.)	Hydrogen (% Wt.)	Nitrogen (% Wt.)	Suplhur (% Wt.)	Oxygen (% Wt.)
W	*A*	Q_s	Q_i	*C*	*H*	*N*	*S*	*O*
14.28	2.8	18.74	17.16	43.6	5.88	0.17	0	33.3

Crushed chips were dipped into water, wherein the sample has reached the water content in the fuel to a value of 60%. The chips were then divided into the four subsamples of the same weight, which were subsequently dried in a laboratory dryer MEMMERT UFE 800 to different water contents in the samples.

An exact value of the water content was not required. For spruce chips limit water content values of 5% and over 20% are the subject of discussions. Therefore, the aim was to achieve values near to these values.

For determination of the water content, a part of each sample was removed from the drying oven and analysed by a laboratory dryer OHAUS MB 25 which measured the reference value of the water content for individual samples (Table 2). Measurement methodology is based on CSN 44 1377, drying at temperature 105 °C.

Furthermore, in Table 2 the net calorific value of examined samples is converted for the water content in the fuel based on the reference sample values according to an equation, derived from calorimetric equations:

$$Q_v = Q_s - 24{,}42 \times (W + 8{,}94 \times H_h) \qquad (1)$$

where: Q_s – Gross Calorific Value (J g^{-1}); 24,42 – coefficient corresponding to 1% water in the sample at 25 °C, J g^{-1}; W – water content in the analysed sample, %; 8.94 – conversion coefficient for hydrogen to water; H_h – hydrogen content of the analysed sample, %.

Table 2. Stoichiometric analysis of samples

	Mark	Unit	Spruce wood	Sample 1	Sample 2	Sample 3	Sample 4
Water Content	W	%	14.28	3.2	9.9	15.8	31.1
Net Calorific Value	Q_n	kJ kg^{-1}	17,160	17,211	17,148	17,092	16,974
Theoretical amount of air necessary for complete combustion	L_{min}	Nm^3 kg^{-1}	4.31	6.33	5.89	5.51	4.5
Real amount of air necessary for complete combustion	L_{skut}	Nm^3 kg^{-1}	9.06	13.29	12.37	11.56	9.46
Theoretical mass amount of dry flue gas	$v_{sp,min}$	Nm^3 kg^{-1}	4.18	4.72	4.39	4.1	3.36

Combustion of samples

Measurement of the combustion process took a place in a solid fuel stove brand CALOR from the company V.J. Rousek. The stove is equipped with an internal combustion grate. As a fuel is prescribed wood or coal, fuel consumption ranged from 0.8 to 1.5 kg h^{-1}.

First reference sample was combusted and then the chosen individual fuel samples in the order from the lowest to the highest water content.

Emission measurement and evaluation

To measure the combustion process and emission concentration flue gas analyzer Madur GA-60 was used, whose measuring probe was installed in the chimney. Measurement values were automatically saved each minute. The flue gas analyser uses electro-chemical converters for the measurement of selected emission concentrations (O_2, CO) in ppm units, flue gas temperature and ambient temperature.

Emission concentrations were converted from ppm to mg m^{-3} and then further converted into normal conditions, i.e. dry flue gas temperature of 273.15 K, pressure of 101.325 kPa and a reference oxygen content of 13%.

Stoichiometric calculations were performed for each sample (Table 2). It contains the calorific value of biofuels and heat of combustion, the theoretical amount of oxygen and air for complete combustion, the actual amount of air for complete combustion, the mass and volume of wet and dry flue gas and the theoretical mass and volume of dry flue gas.

The measured values were plotted against the excess of combustion air coefficient, calculated by equation:

$$n = 1 + \left(\frac{CO_{2,\max}}{CO_2} - 1 \right) . \frac{V_{sp,\min}}{L_{\min}} \quad (2)$$

where: $CO_{2,max}$ – the theoretical volume concentration of carbon dioxide in dry flue gases, %; CO_2 – the real (measured) volume concentration of carbon dioxide in dry flue gases, %; $V_{sp,min}$ – the theoretical mass amount of dry flue gas, Nm^3 kg^{-1}; L_{min} – the theoretical amount of air necessary for complete combustion, Nm^3 kg^{-1}.

RESULTS AND DISCUSSION

The issue of emissions is very comprehensive and important. This work primarily involves itself with the complete combustion of biomass. Among the possibilities for reducing the emissions are included in particular continuous fuel supply, temperature in the combustion chamber high enough for complete combustion, intake of secondary respectively tertiary air and choosing the optimum fuel moisture (Kjallstrand & Olsson, 2004).

Low water content in the samples is a positive factor because moisture affects the combustion process and flue gas volume produced per unit of energy (Hájek & Malaťák, 2013).

The courses of the combustion process are shown in dependence of the combustion air and the flue gas temperature on time for all samples (see Fig. 1).

These dependences show the course of the entire experiment and the development of the main variables that affect the combustion process. During the measurement cycles of flaring up and burning out of samples was occurring according to the number of samples.

The flue gas temperature during the measurements fell within the interval from 410 °C to 223 °C according to the regression equation (3) at a confidence level of $R^2 = 0.74$.

The value of reliability was low, but not as significantly low as the next one.

$$T_{\text{flue gas}} = -0.086t + 362.04 \ (°C) \quad (3)$$

The excess of combustion air throughout the process grew in the interval from 2 to 10,5 according to the regression equation (5) at a confidence level of $R^2 = 0.44$.

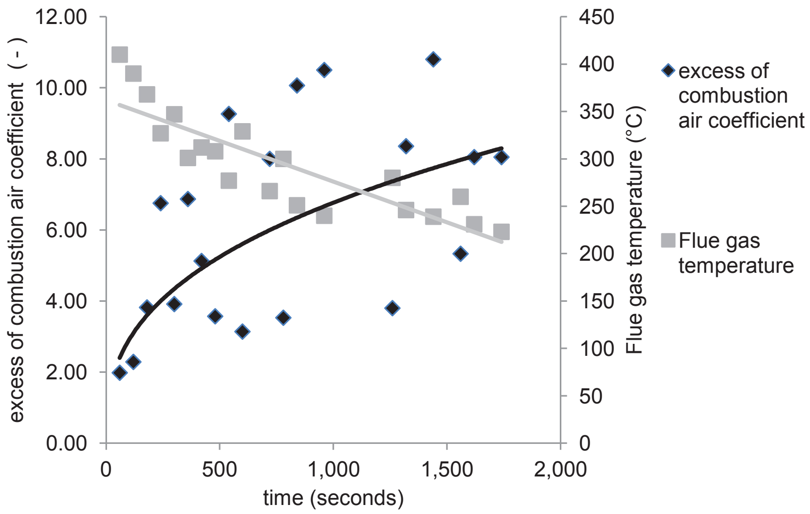

Figure 1. The dependence of the flue gas temperature and the excess of combustion air on time.

The value of reliability was significantly low, therefore this variable is a subject of the following sub-analysis.

$$n = 0.5312t^{0.3644}(-) \quad (4)$$

Fig. 2 shows the course of emission concentration of carbon monoxide in dependence upon the excess of combustion air for each sample by regression equations (5–9).

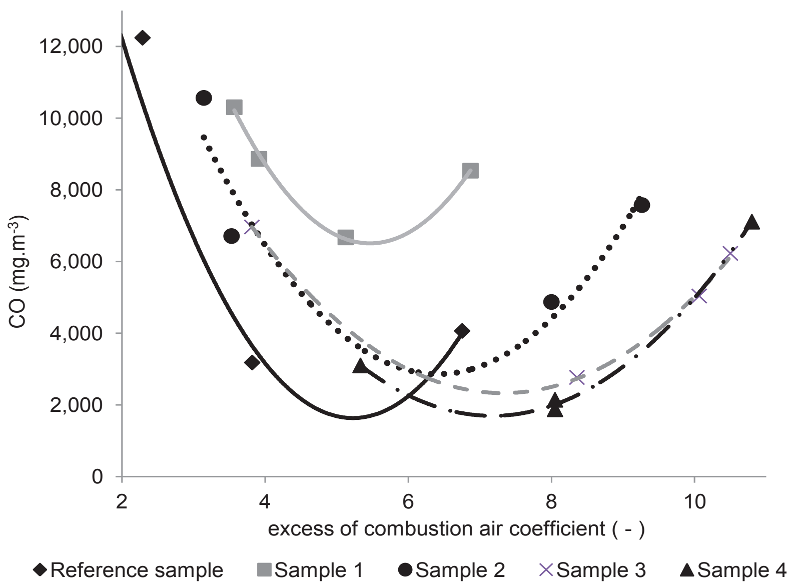

Figure 2. Emission CO concentration depending on the excess of combustion air for each sample.

The high level of confidence shows an appropriately selected regression equation during evaluating of the operating parameters of the combustion process also by other authors (Hájek et al., 2013; Müller et al., 2015; Skanderová et al., 2015).

Ref. Sample:

$$CO = 1{,}016.5n^2 - 10{,}625n + 29{,}394 \ (mg\ m^{-3});\ R^2 = 0.91 \quad (5)$$

Sample 1:

$$CO = 1{,}032.4n^2 - 11{,}284n + 37{,}339 \ (mg\ m^{-3});\ R^2 = 0.99 \quad (6)$$

Sample 2:

$$CO = 616.35n^2 - 7{,}908.6n + 28{,}227 \ (mg\ m^{-3});\ R^2 = 0.81 \quad (7)$$

Sample 3:

$$CO = 376.9n^2 - 5{,}520n + 22{,}538 \ (mg\ m^{-3});\ R^2 = 0.99 \quad (8)$$

Sample 4:

$$CO = 412.62n^2 - 5{,}923n + 22{,}948 \ (mg\ m^{-3});\ R^2 = 0.99 \quad (9)$$

Statistical assessment is based on the CSN EN 13229 by comparing the average measured values of each sample with a reference sample. Reference sample is a typical fuel for grate furnace – firewood – logs of wood, spruce. Therefore, the sample 3, spruce chips, with the same water content has a different kinetics of combustion and thus a different course in the graph. Considered samples are compared with the ideal fuel.

Change of flue gas temperature confirms the hypothesis that the effect of water content contained in the fuel has a highly significant influence on the combustion process in all examined samples (*t-test,* $n = 4$, $P > 0.01$).

For excess of combustion air the hypothesis can be also confirmed that its influence on the combustion process increases with increasing water content. For all samples this dependency can be confirmed under decreased confidence level (*t-test,* $n = 4$, $P > 0.2$).

Growth in excess of combustion air has a negative impact also on other operating parameters of the combustion process.

The excess air value is generally high during combustion in a burner furnace and this is also reflected in the high heat losses in the flue gas (chimney losses) and even in the carbon dioxide and nitrogen oxides concentrations (Jevič et al. 2007; Skanderová et al., 2015).

The course of the carbon monoxide emission concentrations is the same for all samples. An increasing amount of excess combustion air leads to better combustion and decreased emission concentration until a minimum is reached. After reaching the minimum increase of the emission values for CO occurs again due to cooling of flue gases and of the combustion chamber.

For each solid fuel, there is a maximum achievable stoichiometric proportion of carbon dioxide CO_2 in the flue gas, which is determined by the elemental composition of combustible fuel (Mcdonald et al., 2000; Hedberg et al., 2002).

For samples 3 and 4 low statistical significance of the influence of water content in the fuel on the combustion process can be confirmed (*t-test,* $n = 4$, $P > 0.2$). This is caused evidently by low temperature of furnace. For samples 1 and 2 the influence of water in the fuel is significant and it is the only case of the hypothesis rejection.

The dependence of excess of combustion air and carbon monoxide emissions on the water content in the fuel is relatively low. It can be assumed that the type of combustion device has a certain influence on the deviation of the measurement. A suitable equipment for minimizing this deviation could be a combustion device with automatic feeding of fuel with a pellet burner and as a reference sample wood pellets.

CONCLUSIONS

Based on the emission concentrations and elemental analyses we can assess the impact of the water content in the fuel on combustion process.

Increasing water content in the selected fuel leads to the following aspects:

- increasing time of combustion process;
- for wood chips reduction of the CO emission was observed;
- enlargement of the interval in which the burning process can be operated (depending on the control of excess air);
- cooling of the flue gases;
- growth of excess combustion air;
- the reduction of the combustion device efficiency;
- reducing fuel efficiency.

While increasing the duration of fuel combustion in the furnace for some devices without automatic control may be positive, in modern automatic combustion devices it is not admissible. Declining the flue gas temperature reduces the efficiency of the combustion device depending on a particular combustion device. This also reduces possibility of its use in relation to environmentally technological requirements. In the case under review the decline in overall fuel efficiency by 1.1% due to the water content, which in measured flue gas temperatures led to a reduction in the efficiency of combustion device up to 40% when considering only the chimney losses.

It can therefore be confirmed that the water content in the fuel has a significant influence on the combustion process and its high content in the fuel is inadmissible. This is also the result of many scientific publications (Hájek et al., 2013; Müller et al., 2015; Skanderová et al., 2015). The benefit of this publication is the comprehensive view of the assessed sample. In most cases, measurements are made for a reference water content in the fuel, which is not always an optimal assessment of the fuel combustion in a particular combustion device.

Relatively extensive research on the influence of water content in the fuel confirms the hypothesis that the effect of the water content affects the temperature change of flue gas and thus the efficiency of the combustion device (Bahadori et al., 2014).

From our measurements it is apparent that there may be extremes, as in the case of sample 1 with a very low water content in the fuel and very high emissions of carbon monoxide, which is operationally unacceptable as well as a high water content in the fuel and reduction of the combustion device efficiency by chimney loss.

Alternative fuels should therefore not be assessed according to the calorific value, but there should be focused attention to the water content in the fuel.

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