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Comparison of technologic parameters of pellets and other solid fuels produced from various raw materials

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Abstract. The article relates results of experiments and problem studies, the main goal of which was comparing four alternatives of solid biofuels suitable for heating private houses by low-power boilers. The results were obtained by burning of selected biofuels in an automatic pellet boiler specifically designed for combustion of pelletized fuels with high ash content. The emissions were set up related to the mass of burnt fuels and to the fuels' net calorific value (specific emissions), they were measured and analysed. Based on the emission concentration measurements and stoichiometric calculations, the fuel gas emissions' properties and boiler efficiency were compared at a range of power outputs of 7.5 kW, 12.5 kW and 18.5 kW. With regard to fuel properties and boiler outputs, the emissions of carbon monoxide (CO) were determined as well as emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2) were measured and compared too. The results permitted to formulate conclusions that the wood pellets were having the lowest values of measured emissions, whereby Jatropha seed cakes showed several times higher emissions in comparison with emissions from wood pellets, oil palm shells and wheat straw pellets, where the last one is a typical representative of the agricultural biomass with relatively high nitrogen content and as was shown higher emissions of NOX as compared to wood pellets. Oil palm shells measured emissions were relatively similar to wood pellets emissions, especially concerning emissions of SO_2 and CO. All tested materials were having very low combustible sulphur contents and therefore the specific SO_2 emissions were negligible at all these fuels. A very important finding was that the amount of emissions was dependent on boiler output, where with the output decreasing the amount of emissions was growing. The other linkage – dependence of the boiler efficiency on power output was also proved in the present paper.

Key words: wood pellet, wheat straw, Jatropha seed cake, oil palm shell, emissions, biomass combustion.

INTRODUCTION

In view of approaching lack of fossil energy sources (particularly future shortage of crude oil and natural gas) which deposits are estimated to meet future needs some couple of decades only. Research of new energy sources gets high importance. Especially renewable energy sources seem being of very good prospects. The so called bioenergy produced from biomass (mainly waste biomass which is very abundant in both developed and developing regions) is one of renewable sources of energy. In some regions it is the only one utilisable renewable energy source. For the above reasons much effort and many founds are yearly worldwide spent for researching new energy sources. In fact they have always been well known however their utilization is constrained by sometimes less economy (due to higher prices) or they feature some technological imperfections in comparison with fossil energy and generally have lower calorific values. On the other hand they have some properties which are superior to fossil fuels such as smaller amount of emissions or availability in distant areas.

As stated in the Abstract the present paper concerns results of testing solid biofuels made of four different raw materials in order to get more information useful for production process of biofuels as well as for their combustion.

MATERIALS AND METHODS

Two different kinds of pellets were used for experimental purposed: *wood pellets* and *wheat straw pellets*. As the substitutes to pellets *oil palm shells* and J*atropha seed cake* were exanimated, too.

The pellets are commercialized in Czech Republic and they have a diameter of 6 mm. Jatropha seed cake is untreated waste material from mechanical oil extraction. Shape composition of Jatropha seed cake was: 86% shape of flakes from 1 to 8 cm in diameter and 3 mm thin and 14% of dusty material. Oil palm shells from Malaysian palm oil industry were used as untreated substitute for pellets; 95.9% of particles (shells) reach diameter 3.15–15 mm.

The basic properties of above mentioned tested biofuels, which encompasses calorific values and chemical composition were analysed according to European standard methods and they are presented in the Table 1.

Table 1. Biofuels chemical composition and calorific values

Chemical composition, w.b (%)	Wood pellets	Wheat straw pellets	Palm shells	Jatropha seed cake
C	46.23	43.04	39.41	44.72
H	6.29	6.51	4.81	6.07
N	0.24	0.72	0.08	3.80
S	0.0	0.05	0.06	0.0
O	39.45	43.28	48.18	37.44
Moisture content, w.b (%)	7.79	6.40	7.46	7.96
Ash content (%)	1.49	6.33	3.33	5.48
NCV (MJ kg^{-1})	16.35	17.60	17.35	17.56
GCV (MJ kg^{-1})	17.93	19.19	18.59	19.11
Ash deformation temperature, °C	1,300	800	1,345	1,110

The data of moisture content, ash content and its deformation temperature for oil palm shells were also published in our previous research (Kaválek et al., 2013a) and the parameters of Jatropha seed cake, except of chemical composition were presented at Kaválek et al., 2013b.

Commercially available automatic pellet boiler working with a range of 7.5–25 kW power output specifically designed for wood pellets burning was used for the experiments. The testes of the research materials were conducted at the power outputs 7.5 kW, 12.5 kW and 18.5 kW. The fuel was being loaded from a container attached to the furnace by a screw conveyer directly into the furnace. The boiler has separately distributed primary and secondary combustion air inputs. Capacity of the boiler can be controlled by adjustment of fuel loading intervals. Primary and secondary air flows are dependent on each other; because they are blown by a simple fan and cannot be controlled directly (i.e. control of the air flow by the speed of the fan is not possible). However the primary and secondary combustion air flows may be controlled by flaps. The boiler is also equipped with flue gas recirculation that is controlled by revolutions of the recirculation fan.

Fig. 1 shows schematic diagram of the boiler used for experiments, which consists of: fuel container having capacity of 25 kg and motor drive of the screw feeder to feed fuel into the combustion chamber, control panel (not shown in the figure) for controlling the feeding rate, then cyclically working grate to remove ash from the furnace, hot water heat exchanger to hand over the heat of combustion from the primary water circuit to the secondary one.

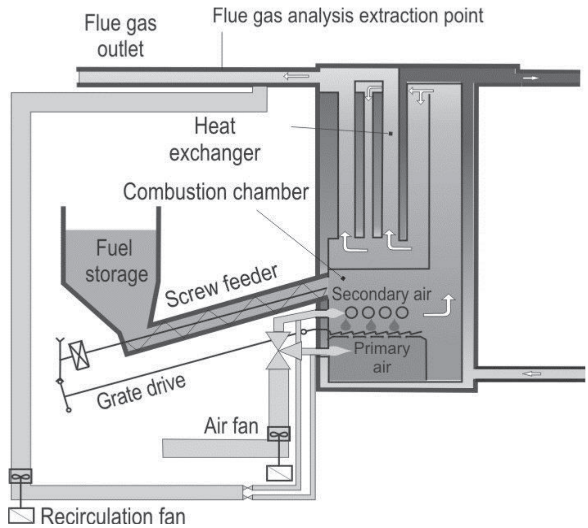

Figure 1. Schematic diagram of the boiler.

Gaseous compounds were measured continuously at the flue gas analysis extraction point (see Fig. 1) by Portable Emission Analyzer Testo 350 XL during all the experiment of the biomass combustion. CO_2, CO, NO_x, SO_2, O_2 and air excess where measured. Concentrations of O_2, CO, NO_x and SO_2 were evaluated and processed after the experiment. The concentration values were measured in volume fraction concentrations and then were converted into mass concentrations as related to dry flue gas at normal pressure and temperature and reference oxygen content, using the following equation (Dlouhý, 2007; Skopec et al., 2014):

$$C_m^X = C_V^X \cdot \frac{M_X \cdot p_{ref}}{R \cdot T_{ref}} \cdot \frac{(21 - O_{2,ref})}{(21 - O_{2,meas})} \quad (1)$$

where: C_V^X is measured volume concentration of given component X in volume ppm; M_X is molar mass in g mol^{-1}; p_{ref} is reference pressure of 101.325 kPa; R is universal gas constant equal to 8.3143 J K^{-1}mol^{-1}; T_{ref} is reference temperature of 273.15 K; $O_{2,ref}$ is reference oxygen content (for this purpose 10% given by law); $O_{2,means}$ is measured oxygen content in volume %. The final unit of mass concentration of the flue gas component is mg N^{-1}m^{-3}. Nitrogen oxides are calculated as NO_2 (Ibler et al., 2002).

RESULTS AND DISCUSSION

Average values of volume emission concentrations from the measurements were converted into mass concentrations at standard conditions and reference concentrations of oxygen. The results are presented in the Table 2 and Figs 2–4. These results show variability of boiler emissions in whole working range of boiler power output.

Specific emissions evidence strong influence of boiler power output. With increasing power output the emissions decrease. It means that the power output of the boiler significantly influence the amount of emissions.

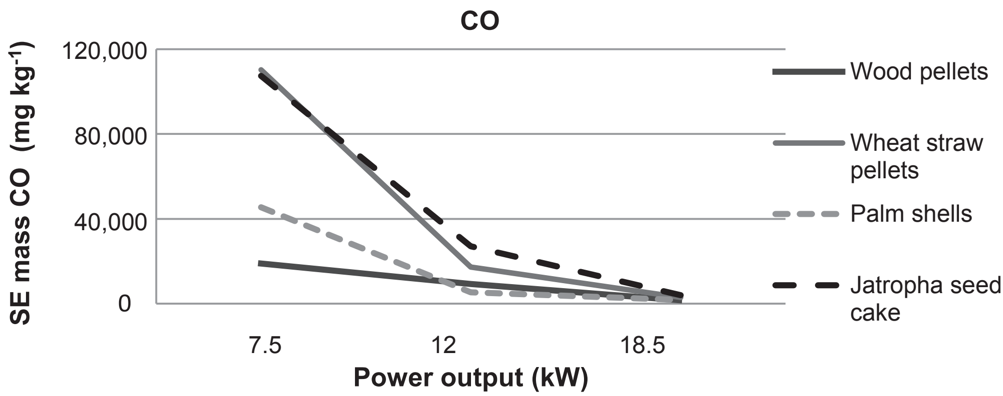

Figure 2. SE mass CO emissions.

Two kinds of specific emissions were evaluated and calculated on the basis of measured data. The specific emissions related to the fuel mass (SE mass) and the specific emissions related to the net calorific value (or low heating value) of the fuel (SE NCV). First the theoretical volume of the flue gas was calculated from the elemental composition of the fuel in order to obtain SE mass. Using oxygen concentration, the theoretical volume of the flue gas is converted to real volume of flue gas. The SE mass was obtained through multiplication by the recalculated emission mass concentration. SE NCV calculation is based on conversion of weight of the fuel to the recoverable energy stored in it. This provides an alternative way for comparison of different fuels.

In this case the differences are not fully apparent due to quite similar net calorific values of both groups of fuels.

The Fig. 2 demonstrates results of specific CO emissions' measurements from combustion of all four tested solid fuels.

CO emissions indicate the quality of the combustion process. Burning the wood pellets exhibited much better combustion stability and the boiler output was at the set up value. Burning the Jatropha seed cake showed the worse characteristics, but it was expected. In the course of the combustion of wheat straw pellets, palm shells as well as Jatropha seed cake the performance greatly fluctuated and it was necessary to set the shorter grating period especially due to the higher amount of ash content and in case of wheat straw pellets also due to the lower ash softening temperature and tendency to sintering.

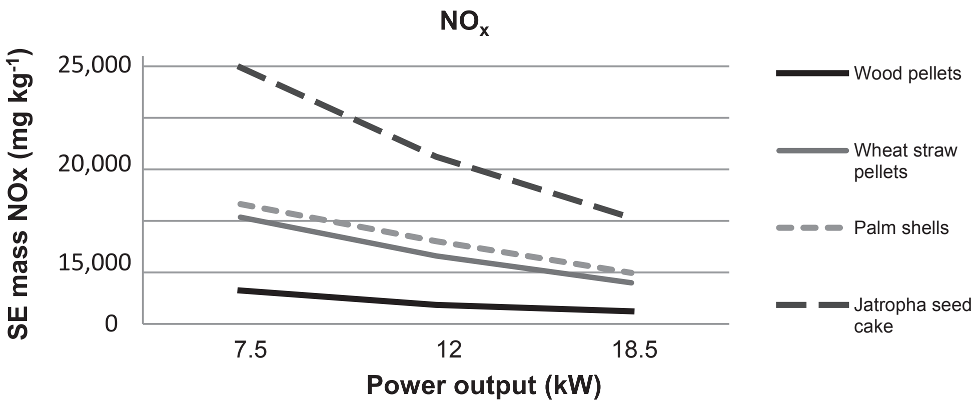

Figure 3. SE mass NOx emissions.

It is evident from Fig. 3, that the NO_x emissions from Jatropha seed cake combustion are almost ten times higher than the emissions released during the combustion of wood pellets. This finding corresponds to the nitrogen content in the fuels, as shown in the Table 1.

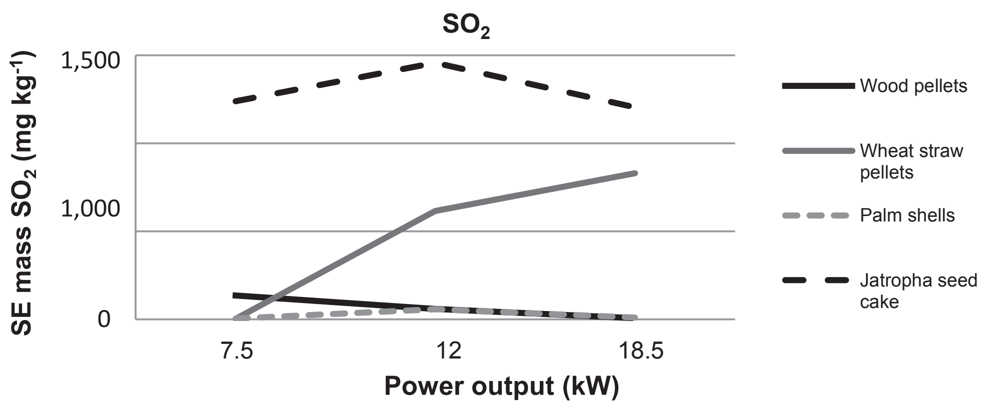

Figure 4. SE mass SO2 emissions.

SO_2 emissions for majority of tested biofuels are very low due to the low content of combustible sulphur (see Fig. 4). Only Jatropha seed cake shows increased SE mass due to its increased sulphur content.

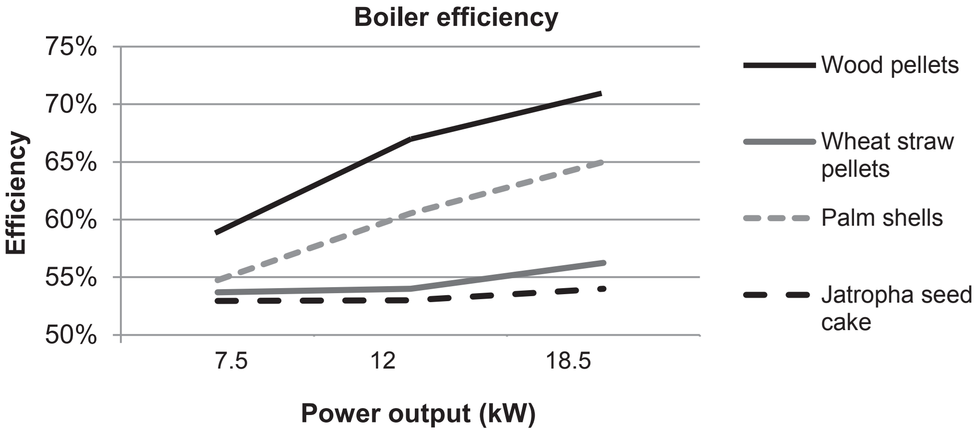

Figure 5. Boiler efficiency related to power output.

As demonstrated by Fig. 5 the boiler efficiency also shows dependence on the boiler power output. The strongest influence of power output on the boiler efficiency was found at combustion of wood pellets and the lowest one at Jatropha seed cake combustion. It can be seen, that in the case of wood pellets the boiler efficiency increased by 12% in comparison between 7.5 kW and 18.5 kW power outputs. In case of oil palm shells with increase of the boiler power output the efficiency has also increased significant (by 10%). In case of wheat straw and Jatropha seed cake the efficiency growing rate was confirmed as well, but the incensement itself was in both these cases not so rapid in comparison with two above mentioned materials.

The Table 2 gathers the overall results of specific emissions related to the fuel mass for all the biofuels tested within the present research.

Table 2. SE mass comparison

	Specific emissions CO (mg kg^{-1})			Specific emissions NO_x (mg kg^{-1})			Specific emissions SO_2 (mg kg^{-1})		
Power output (kW)	7.5	12.0	18.5	7.5	12.0	18.5	7.5	12.0	18.5
Wood pellets	18,935	9,244	1,542	3,234	1,852	1,214	135	59	6
Wheat straw pellets	110,215	17,278	2,999	10,353	6,596	3,999	1	616	830
Palm shells	45,490	5,409	1,777	11,629	8,034	4,962	3	56	9
Jatropha seed cake	107,364	27,121	4,060	24,882	16,230	10,288	1,239	1,458	1,204

The results of specific emissions related to the net calorific value and their comparison with the other previously published data are presented in the Table 3. The SE NCV values measured at the nominal and minimal power output (18.5 kW and 7.5 kW, respectively) within this study were compared with specific emissions taken from the EMEP/EEA air pollutant emission inventory guidebook (Troozzi, 2006) and with specific emissions taken from Czech Hydrometeorological Institute (CHMI) (Horák, 2011). The values from EEA are related to small boilers with nominal capacity lower than 50 kW for burning wood and similar wooden waste. The values from CHMI are related to the combustion of wood. There is no published data found concerning the same parameter for biofuels made of agricultural biomass.

Table 3. Comparison of measured SE NCV with SE NCV available from EEA and CHMI

Pollutant	EEA	CHMI	Wood pellets		Wheat straw pellets		Palm shells		Jatropha seed cake	
Power output (kW)	-	-	18.5	7.5	18.5	7.5	18.5	7.5	18.5	7.5
CO (g GJ^{-1})	4,000	68.5	94	1,160	170	6,260	102	2,620	231	6,110
NO_x (g GJ^{-1})	120	205.5	74	198	227	588	277	670	586	1,420
SO_2 (g GJ^{-1})	30	68.5	0.4	8.3	0.5	47	0	0.7	70	70

Table 3 shows, that SE NCV of CO obtained by EEA for the same (wooden) material are extremely high in contrast with CHMI data and the results of this research. The EEA data seems to be unreliable since measured experimental data as well as the data from CHMI are much lower; even in comparison to the case of lower power outputs are EEA values four times higher. However, EEA emission values of CO are comparable to the values of Jatropha seed cake emissions and emissions from wheat straw pellets at minimal power output. Due to the lowers ash softening temperatures the burning process of wheat straw pellets could be assessed as difficult and highest CO concentrations are produced. CHMI values of CO emissions are close to emission values for wood pellets obtained in the present research at the boiler power output 18.5 kW.

On the other hand, the values of NO_x emissions published by EEA seem to be more accurate for nominal power output; the CHMI values are closer to our values measured at minimal power output. The measured NO_x values for wheat straw pellets, oil palm shell and especially Jatropha seed cake are much higher than EEA and CHMI values, mainly concerning to the minimal power output.

The values of SO_2 specific emissions are completely different from both the above information sources in comparison with our measured data. There is no reliable explanation for such a high discrepancy. The most probable problem resides in the applied measurement method for SO_2 concentration measuring, which is in the case of EEA and CHMI unknown. The SO_2 measurement methods/technique might be not enough precise and suitable for the low concentrations and might therefore be a source of errors. Unfortunatelyy, EEA and CHMI didn't mention any method used for their data meas

CONCLUSIONS

The specific emissions of CO, NO_x, CO_2, and SO_2 related to the mass of fuel burnt and the net calorific value of fuel was determined based on the emission concentration measurements and stoichiometric calculations done for four different types of solid biofuels at three different boiler power outputs. It was confirmed that wood pellets generally have much lower emission concentrations of harmful pollutants than other biofuels. Oppositely, Jatropha seed cake shows the highest concentrations of all tested pollutants. Oil palm shells showed similar values of CO emissions comparing to wood pellets. Wheat straw pellets are typical representative of agricultural biomass with relatively high nitrogen content. Therefore, their specific emissions of NO_x are several times higher in comparison to wood pellets and are comparable (similar) to NO_x emissions obtained from oil palm shells. All fuels have very low combustible sulphur content, except from Jatropha seed cake, while their SO_2 emissions are also quite negligible.

Comparison of calculated specific emissions with literature data provided different results. Specific emission of CO better corresponds to CHMI data, while NO_x values to EEA. However, there are uncertainties regarding experimental procedure and boiler used in these published references. According to Skopec et al. (2014), generally, a development and modernization of boiler construction should lead to their better efficiency and improved emission reflected in lower specific emissions. The boiler efficiency calculated in this study showed dependency of efficiency on the boiler power output.

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