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Particulate Matter Production of Small Heat Source Depending on the Bark Content in Wood Pellets

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Abstract. Wood pellets as biofuel are more and more used in small heat sources in Europe. Standard wood pellets are produced from wood sawdust without bark. The paper deals about the impact of bark in wood pellets on their properties and combustion process. Special attention in this work is paid to production of particulate matter during combustion of wood pellets depending on bark content. There were experimentally produced spruce wood pellets samples with 0%, 1 %, 2 %, 5 %, 10 % and 20 % content of bark. The density, moisture content, calorific value, ash content and ash fusion temperature were detected on produced samples. Then the combustion took place in a small heat source which was tested on an experimental device designed for the measuring of heat output and emission production. Based on the achieved results we can conclude that bark content in pellets has a significant impact not only on wood pellets properties but also on performance and environmental characteristics of pellets. The results showed that growing bark content has negative impact on wood pellets properties, mainly decrease calorific value and ash fusion temperature and increase ash content. Growing bark content in wood pellets also decreased heat output of heat source and increased gas emissions and particulate matter production.

Keywords: particulate matter, bark, small heat source, combustion, biomass

1 Introduction

Approximately 14% of global energy is obtained from biomass [1, 2]. There is still a world support for the use of biomass as a source of heat and energy. Renewable energy sources are one alternative to fossil fuels. One reason is the reduction of SO_2 and NO_X in the atmosphere. Despite of this, biomass produces also emissions, as mentioned in various works [3 - 12].

One of the common forms of biomass is wood pellets. Wood pellets are mainly used in small heat sources [13]. Due to the fact that there are not only pellets made from pure wood but also pellets with bark content, it is necessary to pay attention to the impact of bark on fuel combustion characteristics (thermal performance, net calorific value) [14, 15]. Bark content in pellets influences also the fuel quality. It has impact on such parameters as moisture content, ash content, ash fusion temperature, produced emissions and particulate matter (PM). High moisture results in biofuel lower net caloric value and its incomplete combustion in the combustion appliance [16 - 19]. High content of bark, which is frequently a component of burned pellets, results in more frequent maintenance of heat sources as bark contains more ash than barkless wood [20,21]. Increased ash content also generates higher amount of particulate matter [22, 23], which belongs to the most harmful emissions [24]. Air quality impacts the state of the environment, human health, as well as the various ecosystems. Particulate matter discharged from local heat sources in combination with the weather has recently repeatedly led to smog situations having adverse impact on health and living conditions of people in a particular region. There are also other monitored emissions after biomass combustion - carbon monoxide (CO) and nitrogen oxides (NOx).

The paper deals with the impact of bark content in pellets from wood biomass on performance and emission parameters of a small heat source, mainly on PM production.

2 Material and methodology

The wood pellets samples have been produced on experimental device for pelletizing according to the scheme on Fig. 1. It consists of input material tank 1 (in which is delivered biomass for production of pellets), crusher 2 (which crush material to fractions of size max. 6 mm), crushed material tank 3 (where the crushed material is temporarily stored), dryer 4 (where is possibly wet material dried for optimal humidity), mixing machine with capacity of 50 dm^3 5 (where is dried material mixed with water and additive), pellet mill with capacity of 50 – 70 $kg.h^{-1}$ 6 (where is prepared biomass material pressed to pellets), cooler and duster with fan 7 (final product - pellets are cooled to room temperature and undusted) and produced pellets tank 8 (where are pellets temporarily stored before packing).

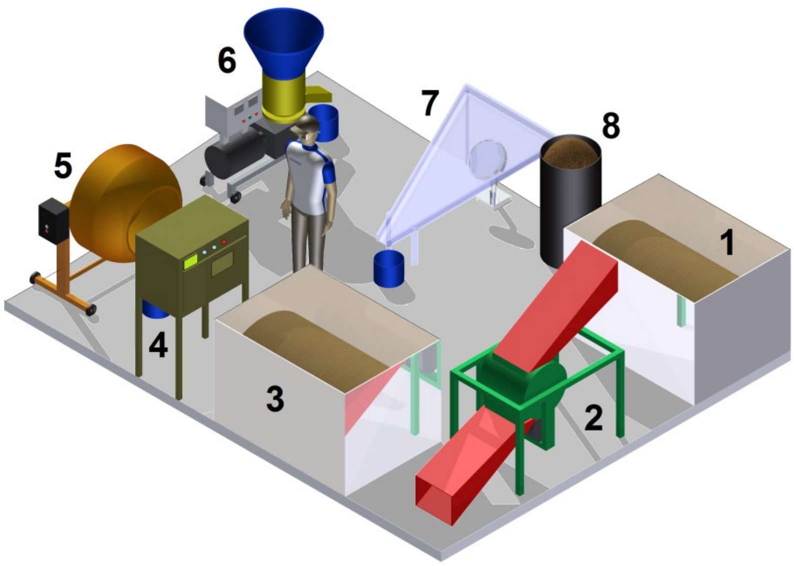

Fig. 1 Experimental device for pelletizing (1 - input material tank 2 – crusher, 3 - crushed material tank, 4 – dryer, 5 - mixing machine, 6 - pellet mill, 7 - cooler and duster with fan, 8 - produced pellets tank

As the input material was used dry spruce wood sawdust. Pellet production is complex process and it is necessary that starting material – wood sawdust must meet certain conditions [11-13]. It cannot contain undesirable objects. Biggest size of sawdust fraction must be smaller than diameter of holes in the matrix of pellet mill. The moisture of used input material had to be increase to approximately 15 – 17 %. Produced pellets had to be cooled and stored properly.

Produced pellets samples were tested for various energy and mechanical parameters:

- Density - was determined in compliance with the standard STN 49 0108 [25] in wet conditions.
- Moisture content - was determined in compliance with the standard STN EN 14774 [26] by using of weighing instrument RADWAG 50 SX.
- Gross calorific value and net calorific value, where gross calorific value of pellet samples was determined in compliance with the standard STN EN 14918 [27] with the use of a calorimeter LECO AC 500 and net calorific value was determined from gross calorific value on the basis of the relation:

$$Q_i = Q_S - 2.453.(M_{ar} + 9H_2)\ [MJ.kg^{-1}] \quad (1)$$

- Ash content - was determined in compliance with the standard STN EN 18122 [28], at which the maximum temperature of 550 °C is achieved in a muffle furnace and in compliance with the standard STN ISO 1171 [29] at which the maximum temperature of 815 °C is achieved in a muffle furnace.
- Ash fusion temperature - was done in compliance with the standard STN ISO 540 [30] by using of measuring device LECO AF 700. There were obtained these temperatures: deformation temperature "DT", sphere temperature "ST", hemisphere temperature "HT" and flow temperature "FT".

Each experiment and consequent calculation was performed at least three times for each sample and the result is an arithmetic average of the measurements.

The combustion took place in commercial small heat source USPOR 18 AUTOMAT with a rated heat output of 18 kW which was tested on an experimental device designed for the measuring of heat output and emission production. The connection of an automatic heat source to the experimental device can be seen in Fig. 2. The device is built from an experimental boiler, a heat consumption device (i.e. device for regulation of heat produced by the boiler), a gaseous emission analyser, a particulate matter analyser, measuring apparatus to which all measuring instruments are connected and a computer for the processing of measured data. Various parameters are recorded every 20 s. During the measurements constant chimney draft 12 ± 2 Pa via a flue fan is ensured. Its speed is controlled by a frequency regulator. All pellet samples with various bark content were burned at the same operating settings of the boiler – fuel feeding time of a spiral conveyor is 18 s, idle time of the conveyor is 25 s, the combustion air is set to constant air access. The boiler was operated on settings for nominal heat output during wood pellets with very good quality burning.

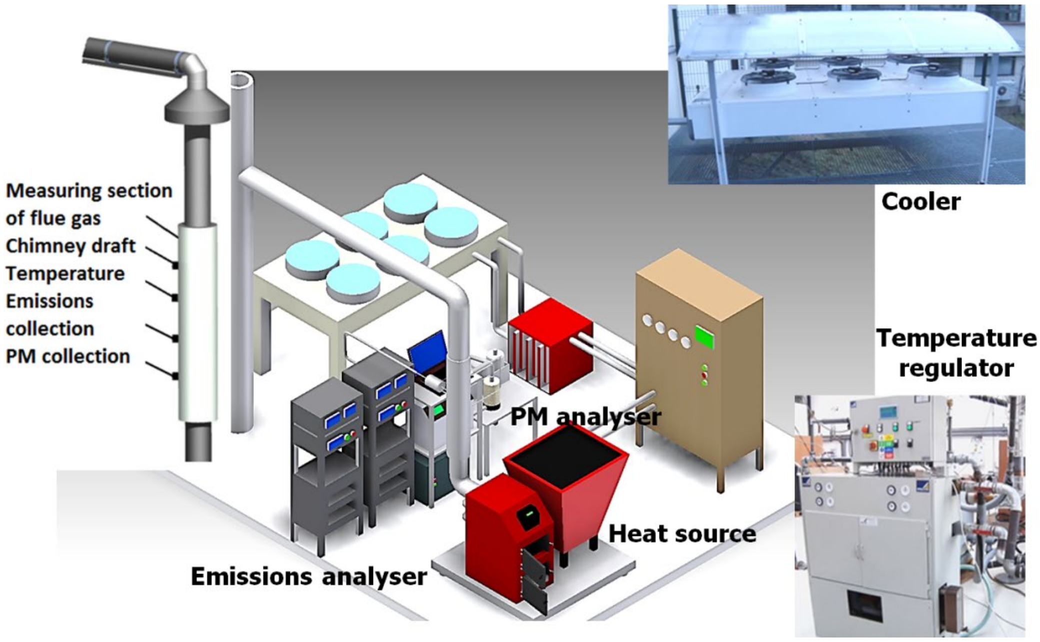

Fig. 2 Experimental device for heat source testing

The thermal power of an experimental boiler was measured by calorimetric method where the flow of the heat transfer medium (water) was measured by a magnetic flow meter YOKOGAWA ADMAG AXF with an accuracy of ±0.35 %. The temperature difference of the heat transfer medium (water) was measured by two paired resistance thermometers PT100 with a measurement accuracy ±0.4 %.

The concentrations of O_2, CO_2, CO, NO_x in flue gases were measured by a flue gas analyser ABB AO 2020 with sensor modules Uras 26 (NDIR photometer for continuous CO_2, CO, NO_x measuring) with accuracy ≤ 1 % of span and oxygen analyser module Magnos 206 (paramagnetic behaviour of oxygen) with accuracy ± 0.5%. The suction pyrometer is used for sampling exhaust gas. Pyrometer output socket connects to the flue gas analyser. The piping for the sampling operations must be incorporated with means for cooling, cleaning and drying flue gas samples. ABB analyser AO 2020 is constructed according to the requirements and nature of the measurement. Recorded the emission values in ppm units (parts per million). These values were converted to $mg.m^{-3}$ according to the equation:

$$\mathrm{Y} = \mathrm{X}.\frac{M}{22.41}.\frac{p}{101325} \qquad (2)$$

where Y represents a calculated production for one of the emissions in $mg.m^{-3}$, X is the measured emission in ppm unit, M represents the molecular weight of the components in $g.mol^{-1}$, the value 22.41 represents the standard molar volume in $dm^3.mol^{-1}$ and p represents the pressure in Pa. The normalized concentration of oxygen in the flue gas from a boiler O_{2n} is considered to be 10 %. Therefore, the measured values of each emission are recalculated according to the equation:

$$\mathrm{Y}_{10\%O_2} = \mathrm{Y}.\frac{21-O_{2n}}{21-O_{2avg}} \qquad (3)$$

where $Y_{10\%O2}$ is the normalized emission concentration in $mg.m^{-3}$, Y represents emission, which is calculated by a previous equation (Eq. 2) in $mg.m^{-3}$, O_{2n} represents the normalized concentration of oxygen in the flue gas in % and O_{2avg} represents the mean value of the oxygen concentration in the flue gas in %. This measuring device is regularly calibrated by an authorized specialist from an external company.

Particulate matter measurement was conducted by gravimetric method by using of the isokinetic automatic sampler TECORA Isostack Basic. Gravimetric method is given by the standard ISO 9096 [31]. It is a manual, single-use method where samples are taken by a probe from flowing gas (Fig. 3). This method gives an average value of PM for a given span of time within which a partial flow from an exhaust gas sample is taken. Exhaust gases are guided through filtration or sediment systems which catch either all particles or only those of pre-defined size. Filtration materials are weighed before and after measurements and final mass concentration is calculated from a sample volume. Sampling probes can be placed either directly into hot flow of exhaust gases or outside the flow (these systems must be heated to avoid condensation or nucleation). Solid particles are collected from flowing gas with the help of the probe. From them an average concentration of flowing gas particles is determined. Exhaust gases were taken from a chimney duct with the help of a three-stage separation impactor. The sampling was conducted at the same speed of exhaust gas flow as in the pipe. Hot gas was led from the pipe through cooling and drying equipment up to the sampling unit. In the cooling equipment exhaust gases were cooled and water vapour was removed from the exhaust gas sample. In the silica gel-water absorption tower residual moisture of exhaust gases was removed. The accuracy of this method influences various parameters, mainly differential pressure in Pitot tube ± 5 Pa, temperature of flue gas ± 0.7 % K, flow rate and volume measure ± 2 % and filter weight ± 0.1 mg. The sampling was isokinetic and the isokinetic deviation during all experiments was in the range -4.5 ÷ 3.8 %.

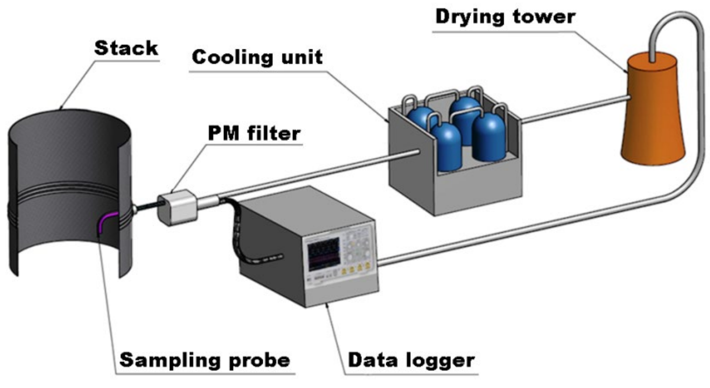

Fig. 3 Principle of the particulate matter measurement

3 Results

The Table 2 shows experimentally determined values of energy and mechanical parameters of wood pellets samples with various bark content. The density has grown with growing bark content because the density of spruce bark, used in experiments, was 465 ÷ 475 $kg.m^{-3}$ (the average density of spruce wood without bark was 428 $kg.m^{-3}$). The moisture content of samples increased with growing bark content because the bark used during experiments has the average moisture 17.51 %. Used bark comes from the same wood pieces like wood sawdust without bark – it is obvious that used spruce wood pieces had higher moisture in outside side. The calorific value of samples with bark content was lower in comparison with reference sample without bark. It is due lower calorific value of tested spruce bark. Bark content had negative effect on ash content – it increased with growing bark content in samples – 20 % addition of bark caused about 0.13 ÷ 0.15 % increasing of the ash content. The ash content of tested spruce bark was 1.07 % (550 °C) and 0.95 % (815 °C).

Table 1 Obtained energy and mechanical parameters of wood pellets samples

Mark		**Unit**	**Bark content in the pellets**					
			0%	**1%**	**2%**	**5%**	**10%**	**20%**
Density		$kg.m^{-3}$	428	428	429	431	433	437
Moisture		%	8.39	8.44	8.55	8.81	9.15	10.21
Gross calorific value		$MJ.kg^{-1}$	18.70	18.69	18.69	18.55	18.48	18.25
Net calorific value		$MJ.kg^{-1}$	17.12	17.11	17.11	16.96	16.89	16.63
Ash content	**550 °C**	%	0.33	0.34	0.34	0.35	0.37	0.48
	815 °C	%	0.26	0.27	0.27	0.28	0.29	0.39
Ash fusion temperature	**DT**	°C	1 210	1 210	1 205	1 200	1 195	1 180
	ST	°C	1 275	1 270	1 275	1 265	1 260	1 250
	HT	°C	1 315	1 310	1 310	1 305	1 295	1 290
	FT	°C	1 340	1 340	1 335	1 325	1 310	1 305

The Table 2 shows experimentally determined values of thermal power and gas emissions production during burning of wood pellets samples with various bark content. All mass concentrations are referred to a normalized O_2 concentration 10 %. All values in Table 2 are average from at least 3 measurements.

Table 2 Experimentally determined average values of thermal power and emissions production during burning of wood pellets samples

Mark		**Unit**	**Bark content in the pellets**					
			0%	**1%**	**2%**	**5%**	**10%**	**20%**
Thermal power		kW	11.79	11.81	11.68	11.56	11.42	11.07
Emissions	O_2	%	15.47	15.45	15.47	15.49	15.79	15.88
	CO_2	%	5.42	5.49	5.40	5.41	5.14	4.92
	$CO_{(10\%\ O2)}$	$mg.m^{-3}$	723.53	682.32	754.21	825.05	1 096.93	1 236.14
	$NOx_{(10\%\ O2)}$	$mg.m^{-3}$	93.24	96.32	101.08	114.84	129.61	127.36

Heat output was lower than nominal 18 kW because experimentally made samples of wood pellets had very low quality, mainly mechanical durability. It was caused by low compression pressure during pelletizing in experimental pellet mill. The pellets were destroyed during transport before they burned in combustion chamber of boiler. Due to this the screw conveyer transported normal volume flow but lower mass flow of wood pellets. Thermal power (heat output) of the boiler taken during the combustion of pellet was depending on wood pellets samples net calorific value. As expected from determination of net calorific value, the thermal power decreases with the increase of bark content. An exception is the pellet sample with one per cent bark content, where the taken output was 11.81 kW.

The highest O_2 concentration was taken in a pellet sample with 20 % bark content and the lowest concentration was recorded for a sample with zero bark content. The difference is 0.32 %, which is the increase by 2.1 %. On the contrary, the lowest CO_2 concentration was recorded for pellet samples with ten per cent bark content - 5.138 % and the highest concentration was measured in pellet sample with one per cent bark content - 5.487 %. These high average values of O_2 and low average values of CO_2 confirm that the pellets burning was not ideal – the boiler settings was set for wood pellets with excellent quality and wood pellets samples were burned with large excess of oxygen.

Carbon monoxide (CO) is a by-product of incomplete combustion and its amount depends on the amount of oxygen supplied to combustion. The lowest CO production was recorded for pellet samples having one per cent bark content. The lower CO production in pellets could be caused by impaired oxygen supply. According to the standard STN EN 303-5 [32], the boiler with automatic fuel supply whose output is up to 50 kW, which was used for the experiment, belongs to energy efficiency class V. The standard specifies the maximum level of CO for the respective boiler 500 $mg.m^{-3}$. From the Table 2 it can be seen that no pellet sample do not meet the limit. CO emissions are generally linked with hydrocarbon emission but they were not obtained.

The amount of nitrogen oxides (NO_x) depends on the flame temperature at which oxidation takes place, on fuel characteristics and combustion speed. Nitrogen oxides are significant air pollutants. The highest content of NO_x was recorded in samples having ten per cent bark content; the concentration was approximately 130 $mg.m^{-3}$.

The graph in Fig. 4 shows an amount of particulate matter caught in the filters during measurements. The figure compares particulate matter concentrations caught during combustion of experimental samples of wood pellets with different bark content. It is obvious that the highest amount of particulate matter was caught in pellet samples having 20 % bark content. The recorded concentrations in the mentioned samples having a particle size more than 10 µm were almost 12 times higher (17.8 vs. 1.5 $mg.m^{-3}$), those having a size in the range 2.5 – 10 µm were almost 21 times (41.3 vs. 2.0 $mg.m^{-3}$ and particles having a size up to 2.5 µm were 8 times higher (129.3 vs. 16.2 $mg.m^{-3}$) in comparison with the reference pellet sample (pellets having a zero bark content).

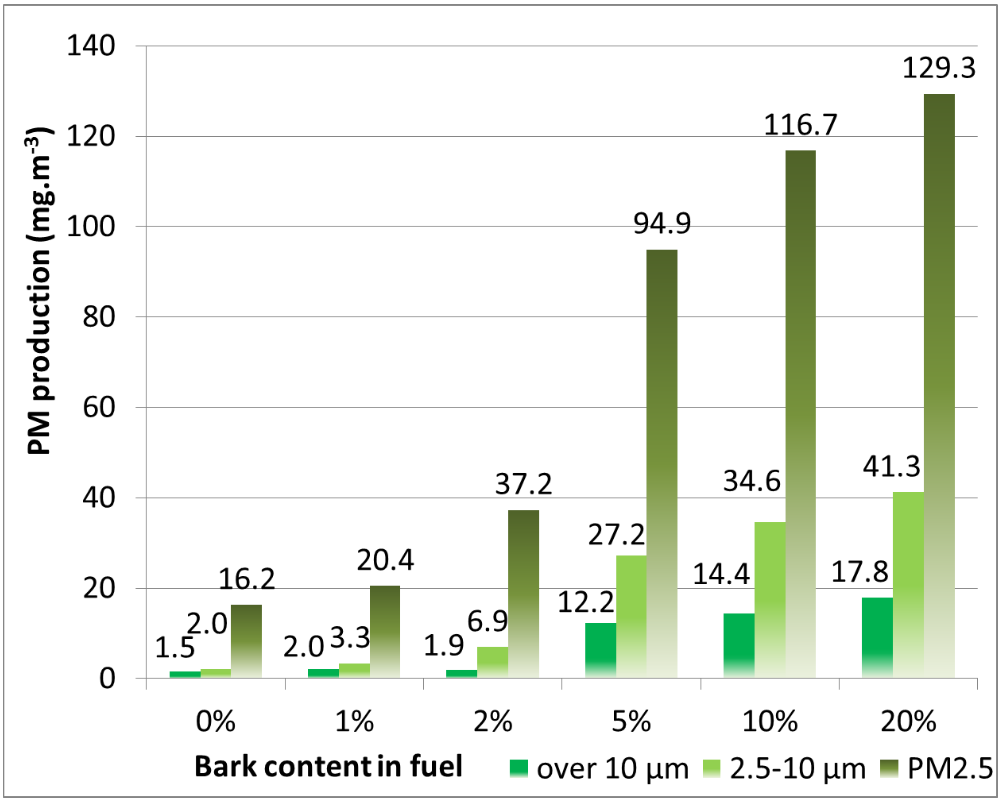

Fig. 4 Particulate matter production during burning of wood pellets samples with various bark content

4 Conclusion

The achieved results showed that bark content in wood pellets has a significant impact on particulate matter production during their burning. Results of experiments showed that higher bark content change energy and mechanical properties of wood pellets – with growing bark content grow ash content and decrease calorific value and ash fusion temperature. This change of properties has negative effect on combustion process. The higher bark content in wood pellets decrease heat output mainly because of changing of chemical composition of fuel, decreased calorific value and increased ash content. Lower ash fusion temperature could cause various problems in combustion chamber and in heat exchangers like slags, sinters or other ash agglomerations which have negative impact on combustion process. It turned out that higher bark content in wood pellets increased the carbon monoxide and nitrogen oxides production and significantly increased particulate matter production during combustion. The lowest particles, which are the most dangerous for health, were the largest part of particulate matter.

The results of the experiments could be more convincing if the impact of low mechanical parameters of produced pellets samples was removed, ideally if the pellets samples were produced instead small home pellet mill in factory conditions – higher pressure and temperatures during pelletizing.

Despite the results the energy potential of bark is very good and in compliance with the appropriate conditions could be very interesting input material for biofuels producing.

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Compliance with ethical standards

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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