

Influence of temperature on the production and size distribution of fine particles released from beech wood samples

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Abstract. Fine particles generated from laboratory biomass combustion are discussed in this study. The approach combines the thermogravimetric analysis during thermal decomposition of beech wood sample with detailed monitoring of the size distribution of fine particles produced. Thermogravimetric analysis (TGA) allows monitoring the exact temperature influence of a small fuel sample (wood) according to the desired schedule. The cool aerosol stream leaving TGA enters a Scanning Mobility Particle Sizer (SMPS) where the particle size fractions are separated. The monodisperse aerosol is counted by the condensation particle counter (CPC). The parametrical study was carried out to assess the influence of composition, size and surface of the wood sample on the production and size distribution of ultrafine particles

1 Introduction

Understanding of particles formation and their behaviour related to biomass burning process are objective of the intense research. Particulate matter (PM) concentration level in cities is increasing. Especially, attention is increasingly drawn to smaller fractions. Most of the particles produced by the combustion process are PM₁₀ (particles with a diameter of less than 10 μm).

These fractions have a considerable impact on the health of the population. They are easily inhalable and can penetrate deep into the human respiration system. In addition, compared to larger particles, they have a much greater active surface at the same weight; and therefore, have a high ability to bind other harmful substances [1, 2].

The highest concentrations of particulate matter are generally present in the inner parts of urban areas. Fireplaces and biomass boilers have become the main source of fine particles in these areas.

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1.1 Particulate formation

As shown in Figure 1, volatile components released from biomass have different values of partial pressure. After reaching the saturation point, the formation of a new phase begins. We call it the nucleation process. The molecules are clustered into ultrafine particles up to 0.1 μm in size. The resulting particles can be further enhanced by coagulation mechanisms (aggregation of colloidal and macromolecular organic particles into larger aggregates), by agglomeration (bonding based on the adhesion of the surfaces), and by oxidation reactions or condensation on the particle surface [3].

Particles formed in the combustion chamber are called primary particles. Secondary particles are formed in the flue gas duct and in the atmosphere. According to volatility, the resulting organic compounds are divided into volatile organic compounds (VOC) and semi-volatile organic compounds (SVOC) [4].

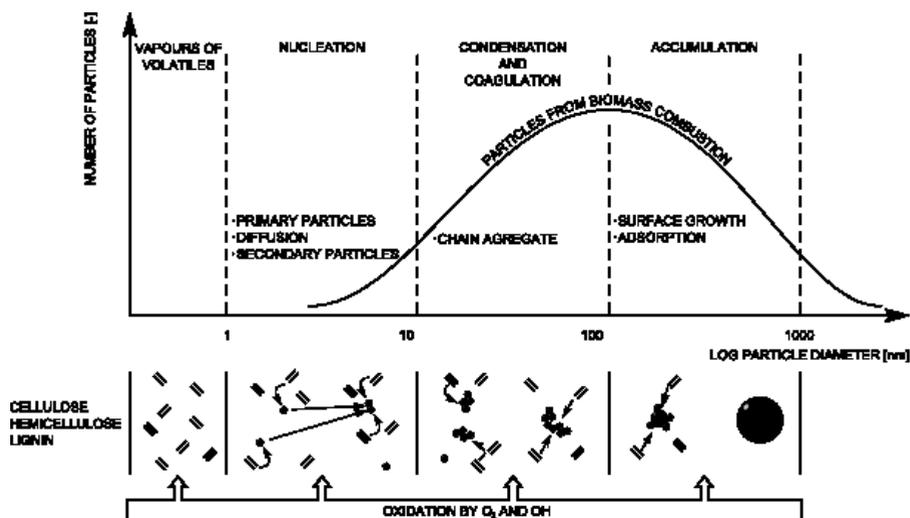


Fig. 1. Nucleation and growth of the particles in combustion process.

Describing particle formation in detail is possible only under laboratory conditions. Real biomass combustion is always associated with the fine particles formation in the flue gas. Their production depends on the properties of the fuel (humidity, granulometry, etc.) and the type of combustion device. However, mainly it depends on the combustion temperature, reaction time and volume of oxygen in the atmosphere.

1.2 Composition of the beechwood

Cellulose is the most common polymer in nature and it can be expressed by the chemical formula $[C_6H_{10}O_5]_n$. Individual molecular chains of cellulose are hold by hydrogen bonds and van der Waals forces creating fibrils. These cellulose fibrils are the main element of the trees and plants [5]. The cell walls components, representing the bulk of wood, are principally the lignin fraction and the total carbohydrate fraction (cellulose and hemicellulose), termed holocellulose. Residues from woody plants, such as bark and sawdust, have differing compositions.

Table 1. Chemical composition of the beech wood.

Density	730 kg/m ³
Humidity	6.1 %
Lignin	20 %
Holocellulose	78 %
α -cellulose	50 %
Extractives	2 %

The beech belongs to the group of *beech trees* with composition: Extractables (2 %), Lignin (20 %) and Holocellulose (78 %) [6].

2 Experimental Setup

This article presents a result of laboratory research of particle production during the burning of redwood sample. The laboratory procedure which was developed combines the advantages of thermogravimetric analysis with the detailed monitoring of the size distribution of produced fine particles. Thermogravimetric analysis (TGA) allows to monitor the exact temperature influence of a small fuel sample according to the desired schedule. TGA also influences the composition of the atmosphere flowing around the sample. During the test, the TGA monitors the weight of the heat-affected sample and identifies its loss. From the analysis of the development of temperature rise, it further identifies the presence of endothermic and exothermic reactions.

The measurement was carried out with utilizing the TGA device *NETZCH – Jupiter F3*. The base component of the STA-449 Jupiter analyzer is a very precise digital weighting system with vertical design. The weighting system is connected to a shielded ceramic module (TG-module) into which the analyzed samples are placed. During the measurement, the entire module is inserted into a gas-tight laboratory furnace with controlled heating rate. The result of the measurement is a TGA curve showing the weight change in dependence on the temperature of the sample.

The gaseous components released from the fuel sample during the TGA are scattered in the test atmosphere and removed from the device. Subsequent flow through the connecting pipeline cools the stream to the ambient temperature. The cool aerosol stream enters a *Scanning Mobility Particle Sizer* (SMPS) where the particle size fractions are separated. Nearly every particle has some level of electric charge. Electrostatic classifier requires aerosol to achieve a steady state of charge distribution. This is achieved by Aerosol Neutralizer device, which provides discharging and charge neutralization process. After this process, particles pass through a bipolar charger and reach equilibrium charge level on the particles. Then, aerosol flows into the electrostatic classifier where sizing occurs (Figure 2).

In a particle sizing system, the *Electrostatic Classifier* separates particles by size for high resolution measurements of particle size distribution. Scanning Mobility Particle Sizer (SMPS) allows classifying particles in the range from 10 to 1 000 nanometers in diameter. *Differential mobility analyzer* (DMA) selects flowing particles of specific size from a polydisperse aerosol. Particles are separated according to their electrical mobility. As a result, there is a highly monodisperse aerosol containing particles of a certain size. Monodisperse particles leaving the electrostatic classifier continue to a *Condensation Particle Counter* (CPC). This device measures particle number concentration. A number of particles in the particle-size fractions are identified by the condensation particle counter (CPC).

In the CPC, particles pass through a heated saturator in which Butanol is vaporized. The aerosol together with evaporated Butanol flow into a cooled condenser. Particles, as

condensation nuclei, get enwrapped by the supersaturated Butanol vapour. They become larger droplets so they are easily counted passing through an optical detector [7]. The production of fine particles during the process of burning the wood sample was measured by TSI-SMPS device (*Model 3080-Series Electrostatic Classifiers including CPC 3775, TSI Inc.*).

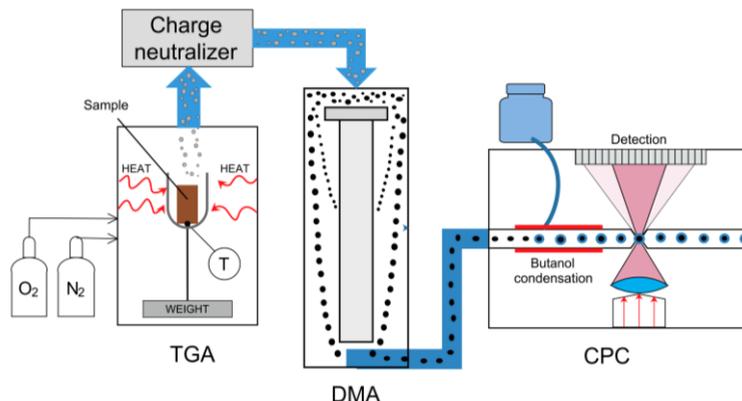


Fig. 2. Scheme of the Measuring equipment and the particle flow: TGA – Thermo-gravimetric analysis; DMA – differential mobility analyzer; CPC – Condensation Particle Counter.

3 Results and discussion

The parametrical study was carried out to assess the influence of temperature rise on the production and size distribution of ultrafine particles released during a heating of beech wood sample. Different weight and form of the beech wood samples was tested as shown in following table. Water content of 6.1 % was measured at 25 °C.

Table 2. List of tested samples.

Material	Sample dimensions	Weight
Beech heartwood	20×13×2 mm	280 mg
Beech heartwood	20×8×2 mm	150 mg
Beech heartwood	20×3×2 mm	80 mg
Beech bark	8×6×3 mm	80 mg
Beech heartwood sawdust	Particle size up to 0.4 mm	80 mg

3.1 Different size of samples

The measuring method described in the previous section was used for series of experiments with beech wood samples. The first study was carried out with the target to identify the influence of the size of the sample on particle production during controlled heating. Three samples of heart beech wood were used for this study, namely 280 mg, 150 mg and 80 mg. The samples were obtained from the same part of the wood log with water content 8 %. All experiments were carried out in oxidation atmosphere mixed in a laboratory from pressurized vessels of pure oxygen and pure nitrogen in volume ratio 21:79 %.

Thermogravimetric analysis was used for continuous increase of sample temperature. The heating sequence started at 20 °C and the temperate rise was set to 10 °C/min. The sample was heated continuously until its temperature reached 630 °C. The Figure 3 shows the experimentally obtained relationships between the temperature of the tested samples and time period (the increasing curve) and weight of the samples and time period

(the decreasing curves). With increasing temperature, the weight of the samples decreases due to volatile fraction release and solid material oxidation.

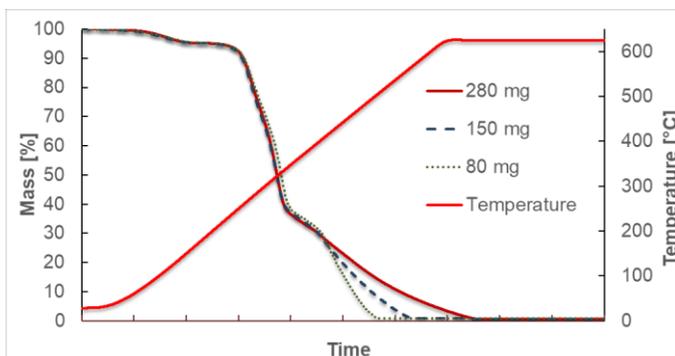


Fig. 3. Results of thermogravimetry analysis for beech wood samples of different mass.

During temperature increase up to 120 °C, water evaporates from the tested samples. In the interval 120 °C to 250 °C, light volatile compounds are released. The interval 250 °C to 300 °C is associated with the rapid loss of samples weight induced by the intensive release of other volatile compounds. Exothermic reactions are commenced at these temperatures. The associated heat generation promotes the release of other volatile compounds. The interval 300 °C to 500 °C is associated with the gradual charcoal decomposition of carbon.

The volatile vapours, particles and gaseous combustion products released during TGA are mixed with the flow of the oxygen-nitrogen mixture entering the thermogravimetric analyzer (flow rate 0.3 l/min). The final aerosol passes through the measuring device capable to identify concentration and size distribution of particulate matter. The Figure 4 shows obtained the size distribution of fine particles identified in the final aerosol generated by TGA. Obtained results are presented for four temperature levels, namely 200 °C, 300 °C, 400 °C and 500 °C.

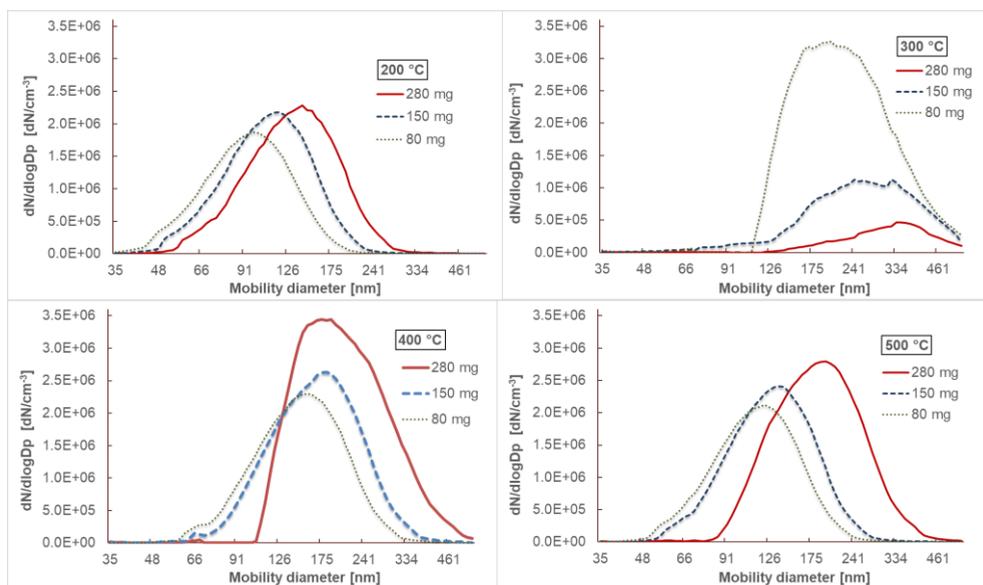


Fig. 4. Size distribution of fine particle (PM1) emitted from Beech wood sample of the weight 280, 150 and 80 mg in certain temperature levels.

The trend visible in Figure 4 shows to increase the particle concentration with increase of the tested sample of wood. The size of particles increases with the size of the sample too. An anomaly in these trends presents the temperature level 300 °C. In this temperature, the combustion of volatiles starts and process becomes to be significantly unstable. The same trend is visible in the relationship between the mass concentration of PM and size of particles expressed for same temperature levels, see Figure 5.

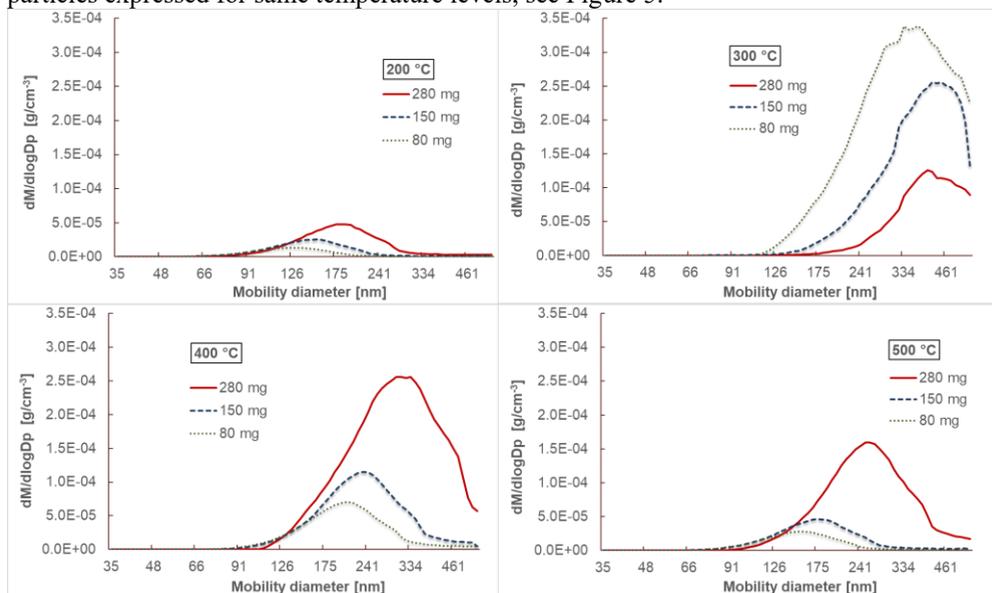


Fig. 5. The Relation between the mass concentration and the particle size for beech wood samples of the weight 280, 150 and 80 mg in certain temperature levels.

For a correct assessment of the combustion processes is necessary to sum particle production during the entire period used for heating of samples from 20 °C to 630 °C. The Figure 6 shows particle concentration and mass concentration of fine particles in form of the size distribution curves for the entire testing period. These results support two prior outcomes. Increasing size of tested sample results in the increase of the mass concentration of emitted particulate matter. Size of particles increases with the increasing size of samples too.

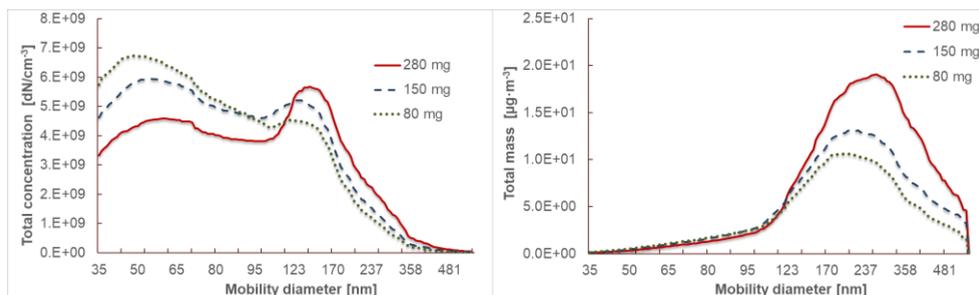


Fig. 6. The size distribution curves comparing particle production for entire testing period.

3.2 Different form of samples

Another part of the study is focused on identification of particle emission during heating of different form of the beech wood. The tests were carried out with three different samples of

wood utilized as energy biomass, namely heartwood, bark and sawdust. These samples were evaluated by same laboratory process as described in the previous section. Figure 7 shows the result obtained from TGA. It shows experimentally obtained relationships of i) the temperature of the tested samples versus time period, ii) weight of the samples versus time period. Comments to this Fig. are similar as mentioned before for Figure 3. There is visible faster combustion of sawdust and slower combustion for bark in comparison with the heartwood.

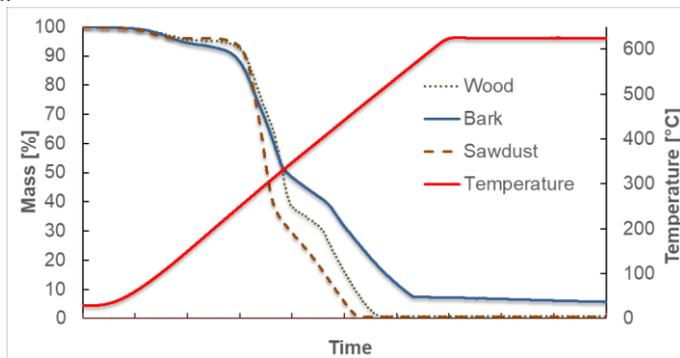


Fig. 7. Results of thermogravimetric analysis for beech wood samples of different form.

There is no clear trend in particle size or particle concentrations obtained for the monitored temperature levels, see Figure 8. Size of the majority of generated particles is in the wide range from 40 nm to 500 nm. The temperature dependent mass concentration of particles is without any general trend too, see Figure 9.

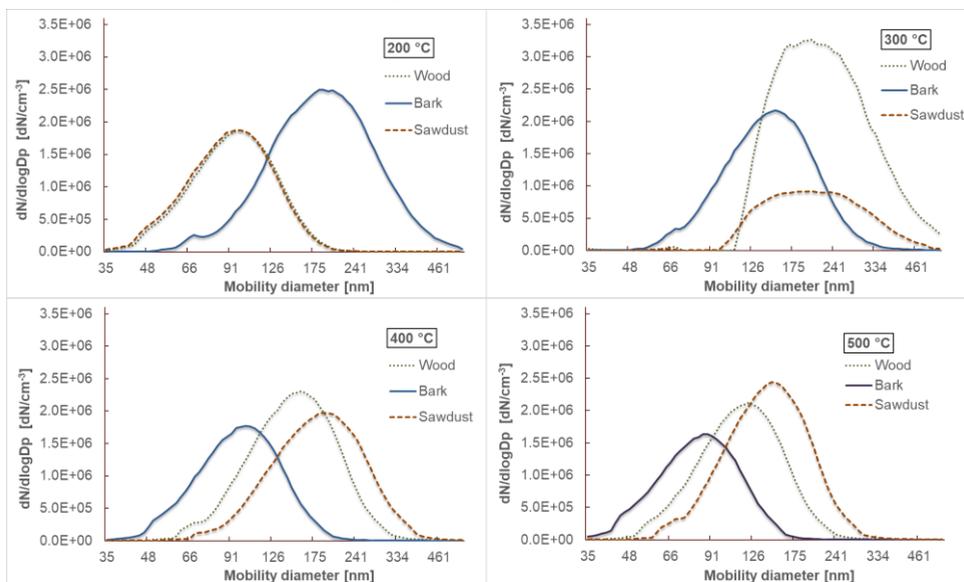


Fig. 8. Size distribution of fine particle (PM1) emitted from Beech wood sample of the weight 280, 150 and 80 mg in certain temperature levels.

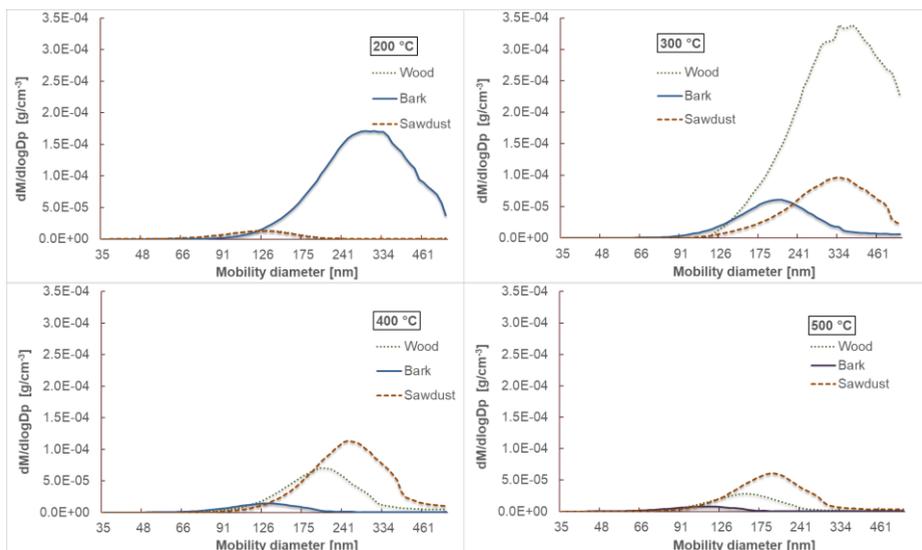


Fig. 9. The Relation between the mass concentration and the particle size for beech wood samples of the weight 280, 150 and 80 mg in certain temperature levels.

The Figure 10 shows particle concentration and mass concentration of fine particles in form of the size distribution curves for the entire testing period. The highest particle concentration was identified for the ultrafine particles with the diameter close to 40 nm. The bark produces the highest number of ultrafine particles from all tested samples. The highest mass concentration was identified close to the particle diameter 200 nm for all samples. The bark produces the lowest mass concentration for dis particle size. The heartwood and sawdust produce significantly more. These outcomes are valid for assessment of the entire testing period.

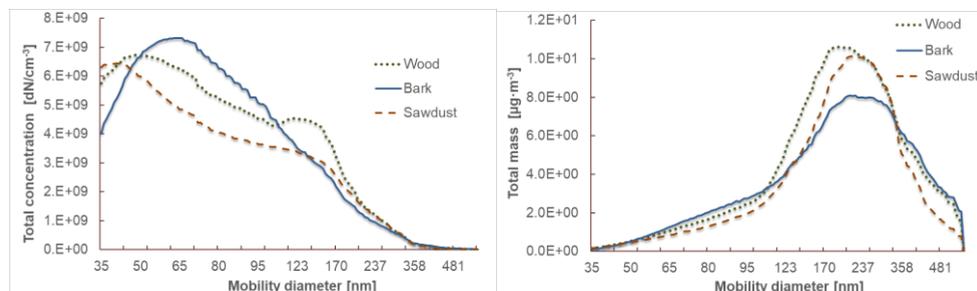


Fig. 10. The size distribution curves comparing particle production for entire testing period.

4 Conclusions

This study deals with laboratory investigation of fine particulate matter production over controlled heating of beech wood samples in the atmosphere with 21 % of oxygen. From carried out measurements follow that majority of emitted fine particles is in the range 40 nm to 500 nm. The peak number of particles is between 100 nm and 300 nm. The mass concentration of produced particulate matter increases proportionally with increasing size of the sample. The number of particles is increasing too, but not proportionally.

In the second step, the samples in form of sawdust, bark and heartwood were analyzed from the view of particulate matter production. Obtained results are strongly influenced by actual combustion conditions that significantly differ between wood samples forms. It is not

easy to find any clear trend between temperature and size distribution of produced particles. From the general view, the bark produces higher number concentration of ultrafine particles in comparison with heartwood and sawdust samples. The total weight of produced particulate matter is very close for all tested form of wood samples.

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References

1. J.A. Baldock, R.J Smernik, *Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood*. Organic Geochemistry. **33(9)**, 1093-1109 (2002)
2. T. Kaivosoja, P.I. Jalava, H. Lamberg, A. Virén, M. Tapanainen, T. Torvela, U. Tapper, O. Sippula, J. Tissari, R. Hillamo, M.R. Hirvonen A.J. Jokiniemi, *Comparison of emissions and toxicological properties of fine particles from wood and oil boilers in small (20–25 kW) and medium (5–10 MW) scale*. Atmospheric Environment. **77**, p. 193-201 (2013)
3. M. Obaidullah, S. Bram, V.K. Verma, J. De Ruyck, *A Review on Particle Emissions from Small Scale Biomass Combustion*, International Journal of Renewable Energy Research, **2**, 147–159 (2012)
4. O. Sippula, *Fine particle formation and emission in biomass combustion*, PhD Thesis, Department of Environmental Science, University of Eastern Finland, Finland (2010)
5. M. Poletto, V. Pistor, J. Ademir, *Structural Characteristics and Thermal Properties of Native Cellulose*. VAN DE VEN, Theo G.M., ed. Cellulose - Fundamental Aspects, DOI: 10.5772/50452. ISBN 978-953-51-1183-2 (InTech, 2013)
6. Di Blasi, Colomba, et al. *Pyrolytic behavior and products of some wood varieties*. Combustion and Flame, **124.1-2**: 165-177 (2001)
7. TSI Inc. Tsi.com. Available at: <http://www.tsi.com/>